THE AMAZING BRIDGE

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ABSTRACT:
For this project, we define the outcomes and objectives as elements of the learning process for the course. We decided to focus on both, the trusses, and the loading member, since are the most important elements to balance the forces, and maintain the structure united; based on our force distribution diagrams. In the team, each of us submitted a proposal of the structure of the bridge, with the explanation of our reasons to think that this was a good idea to proceed.

Our consensus brought the idea of making a bridge that relies on trusses, a solid lane, and strong center poles that would carry the tension from each side. It was very important for us to comply with the dimensions and constraints for this project, therefore we paid close attention to details like material optimization, assembly precision, and efficiency of joints and members. With these elements and an appropriate teamwork we ensure the quality and performance of our project, relying on the creativity and effort of each member of the team.

We started the project as if it were and individual project so that way we shared our individual thoughts of what the bridge should look like. For the purpose of this Project we decided to start by sharing a design that we think it will work. This was the first part of our idea to get a good bridge, by sharing our design and telling why it was the best when we met for the first time we discuss how to improve the bridge design that we chose. While building the bridge we were discussing the possible failures that the bridge probably would have. When we tested the bridge we compare our previous conclusion with the conclusion that we got during the test of the bridge. When we tested the bridge we were able to see how the bridge handled the weight.

All of the members of the bridge react, for instance, the members that were from the middle to the edge were in compression since the spaghetti started to showed a deform, but the deform was a curve to inner part of the bridge, we conclude that the members were in compression. But the other member that was also from the middle to the edge did not show that sign of deformation, unlike it was doing nothing later in the calculation we got that it was a zero force-member. Right after the collective decision there was yet another brainstorm. The intention was that now that the base design was selected to modify or we to add or subtract certain elements for a more complete design.

INTRODUCTION
The motivation of the project is the interest on the structural analysis and the application of the engineering in the structural design field. We are
doing this project to gain experience on the technical skills and the teamwork attributes for our formation as engineers.

As we started the development of our initial draft, we had to perform a preliminary research about the bases and background of the bridges using structures of trusses. As a first element to help in our bridge design, we reviewed the classification and types of bridges, in which case we selected the best. We started the project as if it were and individual project so that way we shared our individual thoughts of what the bridge should look like.

On which topic we went quite further in terms of efficiency, accidents, and even the geographical conditions were those bridges were located. One remarkable point of the background information that we used, is the fact that we had to determine our truss system based on historical structures such as the Golden Gate and the Brooklyn Bridge. That as we mentioned before gave us the decisive elements to integrate a truss-composed platform held in tension by a series of cables connected as joints to the platform.

The important factors in the design of our bridge that required most of our focus were elements such as the loading section of the bridge, the supporting vertical main beams, and the stability of the full symmetrical body that looks good and supports a considerable weight applied. Things that we consider that should be avoided are such as wasting material, ignoring the rules, and mislead the calculations or the drafts.

An important point of the rules mention that the members must not be reinforced with glue, and glue must only be used for the joints; this point was in fact something that we found challenging, since the formation of spaghetti structures need somehow the reinforcement of the exterior of internal strings. Yet we followed this line and avoid the use of glue for other purposes that were not the joints. Now, considering the previous elements involved, we had to integrate the things learned in the course to the production of our bridge, in which case is important to mention that each and every chapter was used for this purposes, the most remarkable were the 3D vectors, as the Center of Mass, the Moment and the Structural Analysis of force members. The way how we applied them was in a particular way different than what was expected. First of all, the forces are and will be unknown up until the testing event, also, the angles and body geometry of the bridge is imperfect, what lead us to make use of Distributed Load techniques, which required in fact more time to calculate.

Knowing our spectrum of possibilities in terms of knowledge and capacity, we had to come up with clear objectives as a team, in which we considered:

- To construct a bridge with the wise application of the best precision possible that complies with the requirements, and represent the best of our effort and applied skills.
- To conform a convergent team capable of solving problems together, with responsible and hardworking members; in order to develop an experiences as a team, and as students of engineering.

Taking into consideration this objectives in common, now we had to agree on a ultimate goal, in which case was to deliver a product on time and manner, as we gained experience, enhanced our skills, and proposed ideas as a team. At the end of the day, our main motivation was the curiosity, the challenge, and the interest on applying the most of the topics discussed during class as possible.

On the following sections of the report, you will find information narrowed to the aspects of design, calculations, and the outcome of the activity. Each of which are important components to show the achievement of our stated main goal.

To start off the project of building and bridge we first saw some types of bridges and what it was that made that bridge a good bridge, when we got an idea of what a bridge should look like we started to get our own conclusions of what our bridge should look like, that was the beginning of our design. Many bridges had failed in real life, but much more had been a good bridge. We took as an example the New York’s bridges and California’s bridges, that later on the Golden Gate was our main reference to our bridge. Since the built of the Golden Gate Bridge was for California a milestone, we decide that our bridge
should a milestone for us to apply what we learn through all the semester in our statics class.

**DESIGN IDEAS**

As a team, we decided that everyone should take direct part on the designing. The most agile way was for each of the members to make a relatively vague design for themselves to shoe to the rest of the team, and “relatively vague” meaning to take in consideration its own elements and force components without actually making profound calculations; this technique allows a team to make quick and responsive decision, and in this case it worked. Here I have some of the sketches of the brainstorm:

Right after the collective decision there was yet another brainstorm. The intention was that now that the base design was selected to modify or we to add or subtract certain elements for a more complete design. The decisions taken by the team contemplated variables that were evident and would play an important role on the prototype and the final model. The most important design ideas discussed in the team were:

- An arch
- A system of K trusses
- A system of truss members as a platform
- A strong beam supported by a frame of trusses.

The discussion inside the team rounded on the feasibility and the easiness to construct a model that can by the same time give accessible calculations. The first two being discarded were the arch and the system of two trusses. Our team selected this design because it has several joints in which tension and compression are used and it is possible to add more support structure in order to make it able to carry more weight.

The support structure is called trusses. The reasons for them to be discarded were difficult conditions to obtain a perfect arch that could obtain an appropriate and significant amount of load being applied in the radial segment. After that, the next consideration was to avoid the over-constraints of the model, by choosing a structure that would balance the force equally on most of the sides, therefor we selected to work with the truss members as a platform, that way we would bet the best of the force resistance, at the same time that we could reduce the weight of the bridge. This and more decisions were taken in order to come up with a consensus and start working on a prototype that could consider each idea proposed for the objective.

**PROTOTYPE DESIGN**

The prototype was mainly improvisation where we used different spaghetti construction techniques. This techniques used to test different type of pastas for construction and reinforcement to use as different ways or to make a building with ease. This prototype helped us identify what the different types of pasta we could use to build a better and more efficient bridge. The next image shows the prototype:

The use of different types of pastas proved an improvement because it gives different kinds of supports and help with the distribution of the weight. An example of different pastas in the bridge is the ziti pasta; we used this to reinforce the joints between spaghettis to reinforce the spaghettis beams by locating them around the spaghettis beam. Other types of spaghettis that we used were manicotti, lasagna, rigatoni, and linguine. With the linguine offered an easier method to put beams together because of its long and rectangular shape which gave us our base where the vertical beams had a perfectly horizontal
base that gave it balance and an even better weight distribution. The lasagna became the perfect road bed and saved time during the construction where instead of sticking spaghetti string throughout only a few pieces of lasagna covered the area required. The rest of the pastas mentioned where used in the same way as the ziti, the only thing that changed is the sized of the different sizes of the pastas.

To start off the project of building and bridge we first saw some types of bridges and what it was that made that bridge a good bridge, when we got an idea of what a bridge should look like we started to get our own conclusions of what our bridge should look like, that was the beginning of our design.

One more element to consider is the type of glue that would be used for the joints, and the one that would work better for the platform lane, and the loading member. We had in fact to experiment with different types of glue to come up with the decision of which would be the most resistant to the tension and compression exerted on the full truss system.

During the day of the prototype test, we had to deliver a rough model in the given time frame. Because of that, we spent several hours working on models and materials, experimenting ways to join the spaghetti stings with different commercial types of glue, and that would lead us to know more about the first steps of the building of this structure, and would give us the needed experience to perform an appropriate final model. The day of the test, we had the following issues regarding our prototype:

- The total length of the bridge
- The bearing member (U Bolt)
- The stability of the entire structure
- The height.

After comparing our prototype with others’ we could understand the areas to improve, and the particular details to pay attention to when working over the final bridge. Also, it gave us an idea of how the event would be, where the scale meter would be placed, how the static supports would hold each side of the bridge and how the members would react. During the test, weight was applied—was in fact more weight that that applied to the final bridge—and by subjecting our bridge to a large mass, we could see the behavior of each tension cable of spaghetti. This was in fact a very useful base to part at the time of making the final structure.

The prototype design was the most important part of the project since in this part we saw how the bridge design will handle in real life with the weight on it, also with this part we conclude if our calculation were on the right path or were going bad. But what it really made the prototype the most important part of the project it was that it gave us the opportunity to watch the failures so that way we knew were to improve the bridge in order to make it even more stronger that the prototype.

Choosing what kind of bridge and why to choose it what a very interesting part since as a team we decided to upload a design for each member, we end up with five possible designs. In order to choose the design, the team member explained to the entire team why it was a better design than the others. In this part we applied all the knowledge that we acquired in the statics class, since we used trusses and in some designs we did not use trusses.

While testing and getting the calculation we decide to not use the U-Volt for the following reasons:

- We must take in consideration the weight that it would has.
- We must make the connection stronger in the part of the U-Volt
- The weight of it affected directly to the spaghetti.
TEST PERFORMANCE

When we started working on our prototype we did not make it with the dimensions we needed neither the load but we did it with the same material and the dimensions were a scale of what we wanted in the final project. According to the calculations we did, the bridge made without the scale was going to be able to sustain at least 8 pounds of weight.

When the prototype testing day came our bridge was not tested because the dimensions were not correct. Despite our bridge was not tested we saw the performance of the other team’s bridges. We saw what they did and we got our conclusions on why they broke and guess how our bridge will work when we were going to test it. Finally when we tested our bridge it supported almost 9 pounds and it was a smaller bridge than the others, when we were putting the weight to test the bridge we saw how some parts were compressing and others were tensioning. So we found out that it was our final design and was the one we chose for the final project but we could still improve our designs in some points to make it able to sustain more weight.

In our prototype we saw how the weight was distributed in the trusses and how the compression and tension worked. For the final project we will just need to make the dimensions bigger to accomplish what we wanted. We chose the final design because when we tested the prototype we saw how the weight is distributed along the parts of the bridge through the trusses, joints and the supports. All of the members of the bridge react, for instance, the members that were from the middle to the edge were in compression since the spaghetti started to showed a deform, but the deform was a curve to inner part of the bridge, we conclude that the members were in compression.

When we finally tested the final design in the day the bridge was due we saw that we focused too much on the base of the bridge than in the trusses because we thought that this could improve the ability to sustain more weight and that is why we lost focus on the upper part of the bridge, and when it was being tested it could only hold 3.62 pounds on the final test.

Despite our prototype was smaller it was able to bear with more weight. This happened because we did not focused on making a better upper part. But we learned in what we should have focused.

STRUCTURAL ANALYSIS

BACKGROUND:
As we perform our structural analysis of this project we apply the Method of Sections to analyze our structure. On each member of the bridge we analyze if the equilibrium requires of tension or compression. As we use the prototype to see how much the bridge will support, we also notice about how the members act. We notice which members where used as a tension or compression, and we make an Idea how to improve that Theory on our structure. On our final structure we tried to apply the equilibrium equations to sum the points and determine about the moments and the force summations to maintain an equilibrium on our structure. We determined how the members act on a need of equilibrium, and how it would act supporting the bridge and the weight.

Even though there were certain doubts when it comes to applying the previous knowledge given in class, homework, and example problems; it was
necessary for us to obtain information more focused on bridge construction and truss analysis to ease the complete process.

Techniques such as the resistance of materials, the formation of a perfect beam, and the applied lead over a pointed area with distributed loads were the ones that we had to somehow perform with more periodicity this time in order to understand the structural analysis mentioned in the books that we used as references. In most of the cases this processes involved particular skills of physics, calculus, and a different approach of statics that in some cases leaded to make us understand principles of dynamics.

THEORETICAL APPROACH:
Under the process of analysis and calculations, we decided to treat the analysis exactly as we would do with a test problem. Based on the selected structure, we had to ensure that what we designed matched with what we calculated. For this, we developed an experimental protocol of trusses, sections and joints in order to apply the problem solving methods learn in class. Firstly, we draw a clear draft of our bridge considering the static supports, all the trusses and members that would fit around the given dimensions. Even though that we performed this calculations, for objective and more practical information we decided to consider the final conditions given at the time of the final test. Also, contemplating a good outcome in terms of the Ranking ratio.

Most of the analysis for the theoretical calculations was obtained from the pages cited and several practice problems analyzed during class that lead us to understand more about trusses, joints, sections and members. But even when complex calculations had to take place, a simple algebraic balance was enough to understand the actual behavior of the bridge and the physical necessities for it to overcome the test. Thus, equations of balance and simple moment calculations were the main key to perform most of this analysis. Parting from the premise that under certain conditions, 2D analysis using computer was to be permitted and would be an aid for the final analysis.

Based on our free body diagrams, our Knowns were:
- Positions, Weight load applied, joints

And the unknowns were:
- The forces FA, FB, GH, GI, DI, CH, Ay and By.

We will use the calculations as an artifact, but the most remarkable calculations were:

\[ \sum \langle+\rangle M = F \times d \]
\[ \sum F_y = 0 \]

Method of Joints
Method of Sections
Separation of free body diagrams
Giving the following results:

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<table>
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<tbody>
<tr>
<td>$A_y$</td>
<td>1.8 lb</td>
</tr>
<tr>
<td>$B_y$</td>
<td>1.8 lb</td>
</tr>
<tr>
<td>$A_F=F_B$</td>
<td>2.54 lb Tension</td>
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<tr>
<td>$D_B$</td>
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<td>Equals $D_I$</td>
</tr>
<tr>
<td>$A_C$</td>
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</tr>
</tbody>
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Because the full equilibrium of forces, there are no over-constrained or Zero force members in the structure. For this process, we considered $C_H$, $H_G$, $G_I$, and $I_D$ as a new free-body diagram in order to separate the full body and analyze it more clearly. The member with the highest force is the equilibrium at the joint $F$, which involves $A_F$ and $F_B$ both in tension. Based on the calculation of bridge weight over the attached mass, our result was 0.255556 as $R$. This tells us that the bridge had a load of four times its weight.

**NUMERICAL APPROACH:**

In this section is where we as a team we discussed the forces that were acting on the members of the bridge using the software called “Autodesk: Force effect” in which we draw the bridge as we wanted, plug in a force in which our case was the weight in $N$. The program gave us a calculation of the moment that will be generated by the force and by clicking in each part of the bridge the program showed us the forces that were generated on it. After evaluating with the aid of this software the possible moments, tensions and compression for the entire body, we determined that the joints with the highest forces reacting would be $F$ and $G$.

The numerical approach were the calculations we got from applying the knowledge we acquired in the statics class. More than applying it, we discover one of the ways to apply the knowledge from the class. The data we got from the calculations we compared it with the information that the software we used to design the bridge gave us. The software we used it was a simple but very useful software since just by drawing the design and applying a force on the bridge gave us a lot of information. The software is also capable of giving a full detailed report in which we observed the data and with this data we knew what we were doing badly on the design, even though that we performed this calculations, for objective and more practical information we decided to consider the final conditions given at the time of the final test. Also, contemplating a good outcome in terms of the Ranking ratio. Despite our prototype was smaller it was able to bear with more weight. This happened because we did not focused on making a better upper part. But we learned in what we should have focused.

As future engineers we know that the data is the most important thing in any design and in anything. When we were calculating the data we knew that we must not get anything wrong because in real life a tiny mistake can lead to huge catastrophe, in which many people can result injured. An engineer must be able to calculate data in a fast way but what is more important than time is the precision, an engineer must be able to get precisely data. In this part is where we prove that the prototype is very important to the entire project since we can watch if the data we got is truly right or if it has some mistakes.

Even though the data is correct, the prototype is useful to see where we have to make more calculations to improve the entire design of the bridge. The first time we did calculations we knew that we might have some mistakes and we concluded it when we tested the bridge. At the end that is the main purpose of the data, to know our failures and see where we should focus more, I mean where the most
part of the weight will go on the members of the bridge.

In fact, after performing the final bridge test, we were able to re-design the structure and locate less force on those two joints, therefor we had to change the shape. As a result of the actual weight resisted during the test, we obtained the following 2D diagram:

In which we can observe that the member FB and FA has a tension force parting from F of 3.058lb. This is under consideration of the 3.6 lb. resisted during the test. Also, with the aid to the mobile app TrussMe! We were able to model our structure and simulate a load applied, and how the trusses would react. Also, in this worst case scenario, how our bridge would look like after the load force is applied to it. Tension forces are shown in red, and compression forces in blue.

Comparing the hand calculations with the simulations the following similarities and differences were observed. The hand calculations were approximated with a 70N load due to the expectations of the members of the team. After the actual test we were able to know that unfortunately this approximation was not accurate. Also, some of the Zero force members obtained in the calculations, came up to be in actual compression when parting from a different joint, or considering the moment in another sense. By the other hand, we found similarities such as the distribution of moment in general, the distances where the joints were better applied, and the constraints of the body. It was in fact unexpected to identify this differences after evaluating the hand calculations, yet it is very important for the success of a structure to be evaluated several times, under several conditions.

**Final dimensions Table**

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<tr>
<td>Height</td>
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</tr>
<tr>
<td>Length</td>
<td>71.12 cm</td>
</tr>
<tr>
<td>Weight</td>
<td>0.448</td>
</tr>
</tbody>
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Sources and Software used for this section:
- [https://forceeffect.autodesk.com/](https://forceeffect.autodesk.com/)

**CONCLUSION**

Our team selected this design because it has several joints in which tension and compression are used and it is possible to add more support structure in order to make it able to carry more weight. This support structure is called trusses. But also we learned better how a structure act and how to determine with logical and use of calculation on the structure because we presence what we learned on class in a project applied on real life application. According to what we learned if we increase the size of the bridge, the beam has more mass and material to resist the tension created along the parts of the bridge so once the top part of the bridge compresses downward as a result of the weight that is being exerted by a bucket then all of the force would spread throughout the bridge.

The project it was a very good way to meet new people in the class, since is a very crowd class it was hard to meet all the people that were in that class. Meeting new people is important since you will be seeing them throughout the entire career, and who knows? Maybe we will see ourselves in the senior project with people that were in this same statics class and we meet them until the end of the semester.

As a team we conclude that getting the data right and doing a few test of the bridge before building the final is very important since in these two
parts of the project is were you can watch the failures, in numbers and the eye. More than learning we were very grateful with this project since we learn more than in the class, we learn more in the sense of experience, because all the knowledge is worthless if you do not know how and where to apply it. The class taught us were the data came from and how to get all that data, the project taught us how to apply it. Knowing many thinks makes you an educated person which is very important since information is power, but knowing how to apply all the information is more than power because the experience of applying the information gives you the idea of how can you use all that information.

When we finished our bridge had a mass of 456 grams but we did not tested before the competition because our prototype performed well in the tests we performed in it. Since our prototype succeeded we made no changes to the final project. Our main objective was to make the bridge that could carry the more weight and when it break only break in a part that could resist a lot of weight but we could not accomplished it because we focused more in other parts of the bridge that we thought that can be improved because we were confident in our prototype design but it did not. It only supported 3.62 pounds. So we learned what parts of the bridge were really important because we focused more on the base than in the upper part.

By the end of the project all the students in the class should have understood better the forces acting on structures now that they tested and saw it working. Especially they should have understood compression and tension forces that are the ones that act in trusses and several other metal and concrete beams. What we considered the advantage of having this projects was that the student gain more knowledge throughout the course with hands-on projects. We expect that now the students of this course have a better understanding and feel more intrigned by structures and would start learning more about it.

The prototype design was the most important part of the project since in this part we saw how the bridge design will handle in real life with the weight on it, also with this part we conclude if our calculation were on the right path or were going bad. But what it really made the prototype the most important part of the project it was that it gave us the opportunity to watch the failures so that way we knew were to improve the bridge in order to make it even more stronger that the prototype.

If we needed to build another bridge for future purposes we will change several things that would change our bridge structure. Once we saw and investigated the different type of bridges that the other teams brought to the final testing we would have focused more in the upper part of the bridge. We learned that beside the base, the trusses are the ones that make above the bridge help significantly toward hanging a bigger amount of weight. We understood that when the weight is applied to the bridge, the upper beams compress and push themselves downward to the base. When we were calculating the data we knew that we must not get anything wrong because in real life a tiny mistake can lead to huge catastrophe, in which many people can result injured. Because of this, if we rebuild the bridge we would have created a better truss system on the upper part. By adding the truss system more mass would be added but it would not matter because the bridge will be able to sustain more weight this will create a smaller R constant which is
the whole objective of this project. With all this said, this project was a great experience to have in our way to understand all of the things that our major needs.

RECOMMENDATIONS

We learn from this project, not only to work and collaborate in team but also in design skills, and to use the methods learned on class to apply them in this project. We work making the structure to be able to hold as much without exceeding the weight limit of the project. But also we learned better how a structure act and how to determine with logical and use of calculation on the structure because we presence what we learned on class in a project applied on real life application.

If we have the chance to improve something about our structure, we would improve the road deck of the bridge, we believed that that was a fundamental part, and the cause of why the bridge did not hold more weight. We thought that if we would have improved that part of the bridge, we would have a better result.

Also we would improve the part where the trusses where supposed to be, where the loading platform was located, so it would support more weight. If we had to do it again, we would change or improve the part of the base or road deck, but we as a team believed that the design of the bridge was excellent, and if the bridge was constructed with what we now to improve, it would support more weight. So we learned what parts of the bridge were really important because we focused more on the base than in the upper part.

At the end of the project all the students in the class should have understood better the forces acting on structures now that they tested and saw it working based on the analysis. One recommendation for this project, is to give more days to prepare for this project, we rush to finish this project because we did not have more days to prepare.

By the other hand, another point to consider for all the teams is to be conscious of the time frames, deadlines and the amount of materials to be used. That makes us think in the idea that perhaps building not only one but two or maybe three prototypes would be appropriate for succeeding on this type of teamwork.
REFERENCES


ABSTRACT

The purpose of the spaghetti bridge project is to apply concepts we have learned throughout the course of statics to a real world situation.

We had to start off our bridge brainstorming process by analyzing many different bridge designs, throughout history, in order to decipher which design concept would be the most simple and efficient to build. From there, we each drew a model of what we thought the design should look like. Afterwards, we decided on the best bridge design for us to build.

After we built our prototype design, we tested it by adding weights until it reached its breaking point in order to decipher what areas on the bridge were in extreme tension and compression. From there, we made several modifications to the design to improve our final bridge’s performance. Our final bridge design withheld 9.37 pounds. Afterwards we conducted a structural analysis of the bridge using a program. We also conducted a structural analysis of the bridge by hand. From there, we compared the two to highlight the similarities and difference between the two types of calculations.

This report will cover all the aforementioned procedures in detail.

INTRODUCTION

Throughout the course of this semester, we have been introduced to several different concepts that are essential to understanding statics. These concepts are the method of joints, the method of sections, frictional forces, the normal force of an object, the shear force of an object, the moment between different sections of an object, shear and moment diagrams, and much more.
Statics is extremely important in the engineering world due to the fact that it helps us to better understand dynamics. Over the course of the semester, while we were in the process of learning the concepts of statics, we completed many different example problems as a class. In addition, we each completed different variations of statics problems for homework on our own. This was done in order to ensure that we understood the statics concepts thoroughly.

Although understanding theoretical concepts and completing theoretical problems helps us to understand statics, we will, most likely, not be completing theoretical problems throughout our entire careers as mechanical engineers. Even if your job does consist of theoretical calculations, it is still a good practice for any engineer to implement theoretical concepts in small scale, real world situations. This is due to the fact that the most ideal theory may not be the most efficient to implement physically due to time constraints, materials, complexity, and many other factors. It is always best to test a theory before stating it is the most ideal. Therefore, the motivation behind this spaghetti bridge project is to apply the concepts we have learned throughout the statics course to a real world situation.

Bridges have changed and evolved so much since the time of their creation. They have been formed out of dirt, wood, steel, concrete, pasta, and many other materials. In addition, each bridge has its own unique design. Several of these bridge designs include [1] beams, arches, cantilevers, suspension, cable-stayed, trusses, pontoons, and bow-string arches.

In order to find a suitable design for this competition, we researched several different bridge designs that were successful in the past. What we observed was that some of the most simple and stable bridges contained trusses. Through further analysis, we found out that a truss is, according to the Merriam Webster Dictionary [2], “a strong frame of beams, bars, or rods that supports a roof or bridge”. We also analyzed many different variations of trusses in order to discern which would be the most suitable for our design; such as [3] the Pratt truss, the Warren truss, and the K truss.

When we were deciding what design we should use for the spaghetti bridge project, we focused on three main factors. First off, we focused on the strength to weight ratio of the bridge. We wanted to ensure that the bridge held the most amount of weight with the least amount of mass. The next factor that was key to our design was symmetry. We wanted to ensure our bridge was symmetrical about the center loading point. This was done in order to ensure that the load was distributed evenly across all the members of the bridge. Finally, our third factor was following the constraints set by the project overview.

On the other hand, the main factor we tried to avoid was weight. As aforementioned, we wanted to ensure the weight to mass ratio of the bridge was as small as possible.

The way to accommodate all the factors and constraints of the bridge design while making an efficient bridge is to use concepts learned throughout the statics course. One can use Newton’s Second Law of Motion [4], “Force is equal to the change
in momentum (mV) per change in time. For constant mass, force equals mass times acceleration.” , to create the equations of equilibrium in statics. From there, these equations can be used to solve for the support reactions and resultant forces of the bridge. In addition, the method of joints can be used to solve the forces acting on each member of the bridge.

Throughout the course of this project, our team’s objective is to create a bridge that is stable, efficient, and follows all the requirements and constraints for this project. Our ultimate goal is to apply the concepts we have learned in statics to a real world situation effectively in order to reaffirm the concepts we have learned.

This report will cover our brainstorming process, how we selected our design for the prototype, the creation of the prototype, and how the prototype fared in its testing procedure. In addition, it will cover the changes made to the prototype design, the theories required to properly analyze the structure of the final bridge design, the results of a bridge modeling program’s structural analysis, our hand calculations of the structural analysis, and the similarities and difference between the two. The report will conclude with recommendations as to how to improve the bridge design.

DESIGN IDEAS

When we first started brainstorming our spaghetti bridge design, each team member researched several different successful bridge designs throughout history. Each group member examined at least ten different examples of bridges. Some of the bridge designs we examined were [5] arch bridges, beam bridges, and truss bridges of varying types.

From there, each team member created their own design concept.

After everyone had completed their research and presented their design concept for the bridge, we had a total of four concept designs. The reason why we only ended up with four concept designs instead of five is due to the fact that two of our group member’s designs were identical. In addition, all of our design concepts were composed of some form of truss due to their simplicity, stability, and their ability to hold a load over a long distance.

During our analysis of each bridge design, we focused on finding the design that would work efficiently in sustaining the most weight while being as light as possible. Another key factor as to what type of design to use was the number of zero force members within each bridge’s structure.

The deciding factor on our bridge design, and our motivation for the project as a whole, was centered around the K.I.S.S. method. The K.I.S.S method, or “Keep It Simple, Stupid” focuses on a comparison between the complexity of the possible bridge design versus our own abilities as well as project constraints. We believed that if we kept our bridge simple and symmetrical, we would be able to distribute the applied load more evenly. This will help avoid causing undue stress on one side, or one member, more than the other. If the load is unevenly distributed, our truss is more likely to fail sooner. In addition, the simpler the design is, the easier it is to identify an issue and correct it.

Throughout development and testing, we noticed that the design concepts with the single beams reinforcing the rectangles across the concept designs of trusses were under extreme compression. This caused the maximum weight to be held by the truss to decrease significantly. Therefore, those designs that had such members were either discarded or modified to reinforce them.
In the end, we chose a concept design that was a combination of the Pratt truss and the Howe truss. This will be covered in more detail in the next section.

**Prototype Design**

As previously stated, we had four design concepts that we considered for our bridge design.

The first concept design consisted of a traditional trapezoidal truss that was divided up into even rectangles along the entire span of the truss, with the exception of the two triangular ends of the truss. The rectangles are reinforced with diagonal beams in order to ensure the truss’ stability. The first beam connected the top left hand corner of the first rectangle to the bottom right hand corner. From there, the next beam connected the bottom left hand corner of the second rectangle to the top right hand corner. After that, the pattern of the beams within the rectangles repeated.

The second concept design consisted of a traditional trapezoidal truss that was divided up into even rectangles along the entire span of the truss, with beams across them to reinforce them. On the ends of the truss are right triangles. This design connected the bottom left hand corner of a rectangle to the top right hand corner of on the left side of the truss. On the right side of the truss, the beams connected the bottom left hand corners of the rectangles to the top right hand corners. The middle rectangle has two beams connecting the four corners of the rectangle that intersect in the middle. In addition, there is an undercarriage that spans the length of the bridge. Although this design, minus the undercarriage, is very similar to the Howe truss, it is modeled after the Pratt truss. The [7] Pratt truss and the Howe truss are identical with the exception of the way the diagonal beams are oriented.

The final concept design has the same trapezoidal configuration as the others however, the reinforcing beams are different. Instead of having one beam to reinforce the rectangles in the truss, there are two to connect all four corners of each rectangle. Each rectangle’s beams intersect in the middle to look like Xs. In essence, this style of truss is a combination of the Pratt truss and the Howe truss.
In the end, we chose the last concept design with one key modification. We added a “basket” to reinforce the U-bolt connection site underneath the road deck. The other design concepts were discarded due to the fact that the single beams connecting the corners of each rectangle were not strong enough to hold the amount of weight required for the project for the amount of time that was required.

As aforementioned, we used our final concept design with the addition of a “basket” underneath the road deck of the bridge. Now that we had a design in mind, it was time to decide what pasta materials we should use.

In order to decipher which pasta to use for our bridge design, we tested several different types and brands of pasta. These brands of pasta include Great Value (Spaghetti, Linguini, and Whole Wheat Spaghetti), Barilla (Spaghetti, Thick Spaghetti, and Fettuccine), Daily Chef (Spaghetti), Skinner (Spaghetti), and American Beauty (Spaghetti). We each taped one inch of a pasta strand to a table. From there, we placed paper clips on the end to test the strand’s breaking point. We then weighed the paper clips in order to understand the maximum weight a single strand of pasta can hold. We conducted the same experiment for both joints and trusses. We concluded that Barilla Fettuccine was the best pasta for our bridge due to the amount of weight it withheld.

The road deck was made of lasagna. We used Lasagna as the road deck instead of aligning several strands of pasta along the bridge because we believed the lasagna would be stronger. In addition, installing the lasagna was less time consuming and more simple.

After testing each pasta, we decided on the dimensions for our bridge. The entire length of the bridge was 700 millimeters. This was done so that 50 millimeters would be on the table on each side of the bridge. The height above the road deck was 160 millimeters. The height of the “basket” below the road deck was 30 millimeters. The “basket” itself was located exactly in the middle of the truss. The width of the truss was 80 millimeters. Underneath the road deck, there was a series of rectangles. Each of these rectangles, much like the section above the road deck, had two beams that connected the four corners of the rectangle to reinforce them. Finally, to make mounting the loading platform for the U bold easier, we added three vertical bars to that section instead of the traditional Xs.

Designing and constructing a bridge does not come without challenges. Developing our dimensions while staying in the constraints set be the project was quite
challenging. Therefore, we checked the requirements regularly during our design process to ensure our design followed those constraints. We also employed the measure twice, cut once technique when building the bridge to ensure it followed our dimensions. This was also done to ensure that each part of the bridge fit with the other.

One of our biggest challenges occurred during the construction of our prototype. We were trying to find a way to attach the U-bolt to our bridge that was secure yet lightweight. We couldn’t hot glue the bolt to the underside of the lasagna, due to the fact that the weak connection would break easily when the load was applied. To solve this problem, we brainstormed some ideas to attach the U-Bolt to our bridge. Finally, we came up with the solution to use the plastic packaging the U bolt came in as the loading platform. It was lightweight, strong, easy to attach, and it did not weaken the road deck of lasagna.

Another difficulty we faced was during the assembly process. Hot glue is not one of the stronger adhesives therefore, if you glued a piece together and it did not bond well, you have to try again. The worst part was that you had to attempt to remove the old glue altogether. This is due to the fact that fresh glue does not bond very well with old, dry glue. After breaking multiple pasta strands, we decided to start melting the pre-existing glue so as to avoid breaking any more strands. In addition, we reinforced the joints by going over them with a second coat of glue.

**TEST PERFORMANCE**

Our team’s prototype design met all the requirements and constraints given to us according to the project presentation and instructions.

This was further validated on prototype testing day. Our prototype’s weight was under the maximum weight of 450 grams. Our official weight on the day of prototype testing was 276 grams. Our team followed the material constraints, that stated we could use any type of commercial pasta, through the use Barilla Fettuccine as our bridge material. Further we hot glued the members only at the joints and did not use any additives or paint on our prototype. Following the height restrictions of the prototype, our team dimensioned and built the prototype to be 160 mm. This height did not including the loading platform (required minimum height of 150 mm). The span of the bridge was 700 millimeters wide (Required span distance of at least 600 mm). The lowest point of our prototype was the loading platform. It was measured to be 30 millimeters below the road deck, which is well under the 60 mm limit. Going back to the material aspect of the bridge, we used American Beauty Lasagna pasta as the prototypes road deck, which fulfilled another design requirement. During prototype testing a block of 40 mm x 40 mm x 100 mm was inserted inside our bridge prototype. There was no obstructions blocking the pathway of the inserted block, thus our prototype passed this requirement. Further the vertical and width clearance of the prototype were both in harmony with the requirements and constraints given. In addition, we used and connected the U-bolt with a piece of plastic as the prototypes
loading platform, given that we could use any material as our loading platform. Finally, we did not use the vertical edges of the tables as supports in any way. Thus we have fulfilled all the requirements assigned due to validation by the Teacher’s Assistants (TA’s).

Our prototype was very different and unique when compared with the other team’s prototype bridges. When we tested our bridge on prototype testing day we found that it supported 6.7 pounds (which is the equivalent of 3039.07 grams) of weight before breaking. One of the TA’s told us, while they were taking the initial measurements, that the center part of the bridge, where the loading platform was located, is the weakest point in the bridge. The TA’s advice and our initial predictions were correct when our bridge finally failed at the center point after supporting 6.7 pounds. Although the center was the weakest point the very ends of both sides of the bridge, where the angled members formed the trapezoidal design, also showed signs of weakness. During the test the angled members at the ends bent inward and or outward (depending on the side). The weakness of those members put more stress, in the form of tension and compression, towards the center.

Based on our team’s observations of other team’s performances, we observed that other teams had constructed bridges with far more weight than our own. Furthermore, most of the other teams constructed a trapezoidal type bridge, however all the designs were very different from our own. In addition, we also observed a team that supported 10lb or more with a triangular design with a far heavier loading platform. Although we do not know the exact ranking of our prototype among other teams we believe that it did very well due to the fact that our prototype’s weight was the lowest one which gave us a very small R ratio.

After examining other team’s prototypes as well as observing the weaknesses of our own prototype, we brainstormed and implemented modifications to our prototype design in order to improve the performance of the final design. We, as a team, decided not to completely change the entire design modify the areas under extreme stress. The ends were in extreme compression therefore, we reinforced them by doubling the strands of fettuccine. We did the same thing to the center crossed beams in order to increase their support and stop them from bending. Further, we changed the design of the “basket”. We first put Xs underneath the road deck across the entire span of the bridge. In addition, we decreased the height of the “basket” so that it would be touching the plastic loading platform of the U bolt. Lastly we added an angular strand to both sides of the loading platform so that we may distribute the load more evenly.

**STRUCTURAL ANALYSIS**

**BACKGROUND**

The Theories that were needed to perform a structural analysis on the bridge were the method of joints, the equations of equilibrium, zero force members, and the equations to find out whether or not an object is statically determinant.

We used the equations of equilibrium to find out the support reactions
applied in the y direction (if the supports were rollers). The support reactions were at points B and J of the bridge truss. However, we were not able to find the forces in the x direction of the support reactions at B and J using any of the equilibrium equations. Since we were not able to determine the forces in the x direction we were unable to determine the forces in each of the members. We also found out that the whole structure was statically indeterminate. A statically indeterminate structure is, according to the Engineering Dictionary, [8] “one where there is more than one distribution of internal forces and/or reactions which satisfies equilibrium”. Due to the fact that there was very few knows and many unknowns, the equilibrium equations would not work in this case.

Although the structure is statically indeterminate, we can still solve for the members using equations and theories not from statics. The new theory that we studied to be able to find out how to solve and find the forces in the bridge was statically determinacy. Statically determinacy is when a body has more unknown loadings then equations of equilibriums available for their solution.

THEORETICAL APPROACH

The 2-D hand calculation attached to the report show the work to find the y components of the reaction forces where the bridge is supported. Once again, we were not able to determine the forces in the x direction of the support reactions. Using the support reactions in the y direction, we were able to calculate four zero force member. These members are member AB, AT, LK, and JK.

We were not able to determine the member with the highest force due to its static indeterminacy. However, we were able to determine, through a slow-motion video, the member that broke first during our final bridge testing. The member that broke first is the member that had a highest amount of force acting on it.

The members in tension and compression were also unable to be calculated due to the static indeterminacy of the bridge system. However, we were able to discern that some of the members were in extreme compression through the video including members AT and LK. We also observed that many of the crossed members supporting the rectangles across the truss were in extreme tension.

The results of the calculations is that we calculated both By and Jy (the y components of the support reactions from the chairs that the bridge was resting on.) were 4.905 Newtons, but we were not able to determine the forces in the x direction on either B or J. However, we were able to determine that the forces in the x direction of B and J are equal to each other but in opposite directions. In the calculations we used the equations of equilibrium. Including the sum of the forces in the y direction and the sum of the moments around point B in order to determine the results of our calculations. We tried to solve for the x directions of the reaction forces using the sum of the forces in the x direction and the sum of the moments around point T but we were only able to determine that they were equal and opposite to each other.
Method of Joints

Exclude joints with support reactions and applied loads (B, F)

\[
\begin{align*}
A_y \sum F_x: & \quad F_{AB} \cdot \cos(\theta) = 0 \\
& \sum F_x: & F_{AB} - F_{AT} \cdot \cos(\theta) = 0 \\
& & -F_{AB} + F_{AT} \cdot \sin(\theta) = 0 \\
& & F_{AB} = 0, \quad F_{AT} = 0 \\
& \sum F_y: & F_{SK} = 0, \quad F_{LK} = 0
\end{align*}
\]

\[
\begin{align*}
K + U & \\
& \sum B_y, I_y = 0 \\
& F_{AT}, F_{BC}, F_{DS}, F_{EC}, F_{CO}, F_{FR}, F_{EG}, F_{DE}, F_{FE}, F_{EP}, F_{Eq}, \\
& F_{EG}, F_{ES}, F_{EP}, F_{SH}, F_{UM}, F_{SG}, F_{EN}, F_{SK}, F_{LK}, F_{SM}, F_{UD}, \\
& F_{UE}, F_{UX}, F_{UX}, F_{EV}, F_{UV} = ?
\end{align*}
\]

Positions: 9.81 m

\[
\begin{align*}
(0, 550) + (0, 650) + (4.905 - 8y) \cdot 200 = 58.67
\end{align*}
\]
\[ \sum F = 0 \]
\[ \sum F_x = 0 \]
\[ \sum F_y = 8_y + 9.81 N = 0 \]
\[ \sum M = (9.81 N \cdot 300 m) + (8_y \cdot 600 m) = 0 \]
\[ -2943 Nm + 600 I_x m = 0 \]
\[ 600 I_x m = 2943 Nm \]
\[ I_x = 4.905 N \]
\[ 8_y + 4.905 N - 9.81 N = 0 \]
\[ 8_y = 4.905 N \]
NUMERICAL APPROACH

The Numerical Analysis of the 2D Bridge performed by AutoDesk ForceEffect, is statically indeterminate due to the two support reactions. Our bridge was simulated and scheduled to be tested on two non-fixed supports. Making these the supports otherwise known as rollers. The program was unable to calculate a result due to the static indeterminacy of the bridge.

Due to the fact that the bridge is statically indeterminate, the member with the highest force was unable to be calculated. It was presumed by the prototype testing that the member with the highest amount of internal force would have been one of the vertical members.

It is extremely important to compare the hand calculations of a prototype to the physical test results as well as the prototype’s results from a computer simulation. Unfortunately, due to the static indeterminacy of the bridge, the program and our hand written calculations are impossible to compare. The program determined the bridge statically indeterminate and our calculations are impossible to solve due to this anomaly. Not only does this make comparison impossible but it makes the contrast between the two impossible as well.

A simple conjecture could be made that the only difference between the two could be that if we had input a weight greater than that which broke our test bridges into our calculation or program, the forces recorded in the members would be misleading. This is due to the fact that the maximum amount of pressure or force certain members take is determined and set when the force applied is equal to that which made our bridge fail.

CONCLUSION

In conclusion, we conducted mass amounts of research on the different styles of bridge designs throughout history. From there, each team member worked diligently and came up with a unique concept design. Each concept design consisted of some form of trapezoidal truss. The first concept design had the traditional trapezoidal truss however, the beams reinforcing the rectangles were in a zig zag formation. The second concept design was a simple Howe truss. The third concept design was a Pratt truss with an undercarriage and a cross in the middle. The fourth concept design was a truss with cross connecting each rectangle/As a team we analyzed each design for three key factors, efficiency, bridge weight, and simplicity. We used these factors because we wanted to ensure our bridge was light in weight, strong enough to hold a large amount of weight, and simple enough to build easily.

After a careful analysis of each bridge design, taking into account these factors, we decided on a design that was a combination of the Pratt truss and the Howe truss with a “basket” underneath to support the loading platform of the U bolt.

After we decided on a design, we tested many different brands and variations of pasta ranging from spaghetti to fettuccine. Through our experiments, we found that the Barilla Fettuccine was the strongest pasta.

Soon thereafter, we built our prototype design to the dimensions we had discussed. We made sure to follow the
dimensions exactly in order to stay in the range of the project requirements.

After designing and building the prototype, it went into testing, where it held 6.7 pounds. From there, we made several modifications to our prototype, including shortening the “basket” and doubling members that were under extreme tension or compression.

Our final bridge design met all the requirements set by the project Power Point. The span of the bridge was 700 millimeters long. Above the road deck, the bridge was 160 millimeters. Underneath the road deck, the bridge was less than 30 millimeters. The width of the bridge was 80 millimeters. We made the “basket” smaller than the prototype design in order to help support the U bolt better.

In the end, our final design held 9.37 pounds, which translates to 4250.161 grams. In addition, our team got third place in the competition between our classmates.

RECOMMENDATIONS

Over the course of this project, we learned that working cohesively as a team is the most important part in designing, building, and testing a structure. Each group member made significant contributions to our bridge in order to make our bridge stronger, more efficient, lighter, and stable. Each team member listened to everyone’s ideas and proposals with an open mind. From there, we decided, as a team, whether or not to accept or reject the idea based on whether or not it would lead to the most efficient outcome.

As stated previously, in order to improve the performance of our bridge, we doubled the strands of fettuccine on both ends of the bridge as well as on the middle crossed beams. This increased our maximum weight from 6.7 pounds to 9.37 pounds. Due to the fact that this worked so well, we would add the double supports on all the sides of the bridge. This would mean instead of an “X” made of two strands of pasta, it would be an “X” consisting of four pasta strands (an x on top of an x). In addition, the beams connecting the two sides of the truss would also be doubled so that the upper beam is secure. Also, we would attach the two sides of the trusses together with crosses, similar to the upper section of the truss in our final design, to add to the stability of the bridge. The final revision to our bridge design that we would, possibly, implement would be to split the upper section of the bridge into two levels to increase the stability and decrease the pressure on each member.

If we had to do this project all over again, we would want to test the bridge, using circular trusses. Being that the circle is one of the strongest shapes, we would want to test and see if we could make a better bridge than what we have already done.

Due to the massive time constraints on the project, we believe that it would have been more beneficial to us if we, as a class, had gone over the rules of this project sooner. We believe this would have given everyone a better chance to gain further clarification on the rules as well as more time to do outside research.

APPENDIX
Spaghetti testing

Bridge Building
REFERENCES
ABSTRACT (10 POINTS)

The spaghetti bridge project has been implemented as being a key experience for students to harness what they’ve learned from statics, physics, and calculus. From this, team members will design and construct a bridge believed to hold the most weight under certain constraints that will allow them to adapt and apply their developing engineering knowledge. From understanding the basic history of bridge development, reviewing the basic lessons of statics, and collaborating creative structural ideas as a team, our team (D.V.A. Squad) was able to derive efforts and create our own spaghetti bridge. The final bridge design was a chosen truss bridge that we calculated to find that it would give us the best outcome to withstand the greatest amount of force. It incorporated triangular trusses that extended to the maximum height allowed which created stability and helped dissipate the weight throughout the members. From our resulting efforts, our concluding spaghetti bridge weighed 341g and held a maximum applied weight of 8.55 lbs., placing it #8 out of 28 total bridge designs.

INTRODUCTION (15 POINTS)

The motivation for this project is to conceptualize a bridge design using our knowledge of statics, and successfully build the spaghetti bridge that has a low weight-to-load ratio, adheres to the construction specifications, and that will rank among the top places at the final competition. These motivations will allow us to work successfully as a team so that we may complete our combined goal of accomplishing a successful project. In order to begin our calculations and construction of the bridge, we will have to research the history of bridges so that we may get a better understanding of the systematic theories and designs of bridges. Through this research, we will be able to develop and design our own unique bridge that we can be assured will hold a great deal of weight and meet all the requirements of the design.

As the history of bridges has developed, following bridges have grown to become more successful. Throughout the years, bridges have capitalized upon one another by mirroring prominent designs. Through these developments, Petroski stated that [1] engineers have pushed the limits of
bridges in order to create “lighter structures for aesthetic and economic reasons.” The history of bridges can date back to the beginning of man when daily obstacles were overcome with a system of basic materials to cross over a river or other inconveniences. However for our research, [1] the first iron bridge was created in 1779 in England. This “Ironbridge” developed an idea of newly chosen materials with which a bridge could be made out of. With the use of iron the bridge would be able to combat the force of being pulled apart more so than bridge constructions made of stone could. During the following years, bridges constructed out of iron would continue to prove to be the stronger and safer choice as opposed to wood and stone. Bridges made out of iron would also compete as a leading material because of its cost effectiveness and the abundance of the amount of the material. Although the bridges were noted for their successes, the history of bridges was highlighted by, as Petroski claims, the “acknowledgement that many ambitious designs did fail.” From this information, bridges would soon face drastic developments, especially during the time of the Industrial Revolution.

During this time, (the Industrial Revolution) the beam bridge was the type of bridge that was developed the most. The beam bridge is the simplest bridge, with a horizontal structure over two supports. Its simple design needs to endure both the tension (with the most tension occurring at the bottom of the beam) and compression (with the most compression occurring at the top) forces when holding a load, which is why the structures were made of iron. To aid in load distribution, it is better to have a tall bridge so that tension is distributed all throughout. This, along with the materials used to create a beam bridge, dictate the distance that the bridge can span. As a way to add more support to a tall beam structure, trusses started to be implemented as a way to add stability and rigidity, which in turn helps in distributing the load even further. “The design of a truss, which is usually a variant of a triangle, creates both a very rigid structure and one that transfers the load from a single point to a considerably wider area [2].” There are four major types of bridges including the two which we have already discussed: beams, arches, trusses, and suspensions. Their difference in construction can be mainly attributed to the length they can each cross, which depends on how each bridge is able to handle two important forces: tension and compression.

These two forces “are both capable of damaging part of the bridge as varying load weight and other forces act on the structure [2].” While tension pulls on the members of the bridge, compression pushes them together. It is important to handle these forces in order to prevent snapping (when tension is too great and the members can no longer hold the lengthening force, so they break) or buckling (when members are in too much compression, the force of the members pushing into each other also causes the members to break. “The best way to deal with these powerful forces is to either dissipate them or transfer them. With dissipation, the design allows the force to be spread out evenly over a greater area, so that no one spot bears the concentrated brunt of
In transferring force, a design moves stress from an area of weakness to an area of strength [2].”

Arch bridges go back to more than 2000 years ago, and they are still widely used today due to their special shape. A feature of the arch is that it distributes the compressive forces all through the shape of the arch. Tensile forces are negligible and concentrated at the bottom of the bridge, but they do vary according to the degree of the curvature: the greater the degree of the arch, the more the tensile forces will act on the bottom of the bridge. A bridge of this type cannot have a big arch that will overtake in the tension forces and ultimately cause it to fail.

The suspension bridge gets its name because it is suspended by cables, ropes, or chains that attach from supports such as towers, which end up supporting the majority of the weight. As this happens, compression is happening by pushing down on the deck and tension runs up to the cables. Lastly, there are the cable-stayed bridges, which look similar to the suspended bridges but look and work different. Cable-stayed bridges only require one tower and cables go up directly from the road and meet at the tower, where all the weight is held. For this type of bridge, the tower “responsible for absorbing and dealing with compressional forces [2].” These four types represent the four most common “fixed (non-movable) bridge types, but there are so many structural possibilities within each of them, considering that each type still varies in span, material, placement of road deck, and form [4].

Although the different types of bridges are used for different have their own contractual purposes, there are some underlying concepts that all bridges use. Two of the main concepts that are essential when designing a bridge are the forces that must be taken into consideration: namely tension and compression. These are two forces that determine how a bridge is going to behave under load. Since these two are the only forces we learned about in class when analyzing a bridge we will focus on them for the remainder of the project; when designing our bridge, we need to see how the members behave under load and notice whether the members are in tension or compression.

In order to be successful with the project, we need to have most members be under tension so that the load can be distributed throughout the members and not at the joints (as it would happen in compression), which would minimize the risk of having the bridge buckle (which it will once we reach the maximum load the bridge can carry). This is when our knowledge from statics will come into play. An analysis of the members will be important in determining how the design behaves, and we will be able to perform the calculations using the method of joints or method of sections. We will also be able to find any zero-force members that might be unnecessary, although load could eventually be transferred to them at some point, which would be beneficial to our case. We will analyze the bridge assuming two main forces act on it: the minimal weight required that the bridge holds (1000g), and also the final weight of the completed spaghetti bridge. These two forces will both be concentrated in the middle of the bridge since the load will be attached at the center, and because the bridge is symmetrical.

There are of course, certain limitations. Since our knowledge of bridges is limited to statics there are various concepts we do not understand, one of them being that we have only done 2D analysis as opposed to 3D. This is where research and software will help us enhance our knowledge and also to develop a better bridge.

The objectives of this project is to reach an end product of a bridge that can withstand the greatest amount of weight. Due to the fact that our grade depends on the successes and failures of the other teams, we
must carefully construct a spaghetti bridge design that calculates for our team to gain the best possible outcome. This outcome would be our bridge placing as being a top competitor in the competition. As a team, our objective is to also learn from one another. Throughout our career paths as engineers we will constantly be working with others. With that in mind, we hope to also develop our communication and team working skills so that we may have a greater chance of having successful skills for our future interactions.

**DESIGN IDEAS (10 POINTS)**

Team D.V.A. Squad came up with the five bridge designs which are presented below:

Based on the research performed prior to the beginning of the project, the team determined we would either be doing a truss or an arch bridge. We all watched YouTube videos, looked up bridge structures online and developed several prototype ideas together. Based on the successes of other people in similar projects, we wanted to do an arch bridge. As a result, two of the five designs were arch bridges. Unfortunately, we never learned about how to perform calculations for arch bridges; we did not know how to analyze them. We thought that instead of having an arch, we could have small, straight segments that would simulate an arch (the smaller the segments, the more rounded the curve would look), however, that would mean that we would calculate a system of trusses (which we could do) but we would have too many segments and ultimately, the weight would be large. Therefore, we got rid of the two arch designs (fig 3a, and 3d). For figure 3b, our concern was with weight and so we opted to abandon that design. Figure 3c represents one of two designs we analyzed. Just analyzing it directly, we were concerned with the height and how that would affect the displacement of weight. Nevertheless we decided to analyze this design and the one we ultimately chose, fig 3e. The last figure is the design we ultimately chose as our final prototype draft. With its system of trusses with 2D triangular designs [5], and by implementing a strong supporting base, we knew we wanted to look into detail.

**PROTOTYPE DESIGN (10 POINTS)**

During the prototype design stage, our team was able to keep modifying the design as we encountered factors that we did not first take into account. Below is a picture of the prototype.

It featured the following:

A 635mm-long by 60mm-wide base. The length of the bridge was constructed in three sections, each section consisting of 6 spaghetti strands lightly twisted to add stability to the members but not causing strain.
On top of the sides used to create the span of the bridge we added groups of 3 spaghettis spaced every 63.5 mm apart along the width of the base, forming a sort of ladder. At every square in the ladder, we then added two other groups of 3 spaghettis, crossing them over the diagonals to increase stability to the bridge. The ladder-like structure served as a base for the road deck that needed to be incorporated as part of the requirements. Initially we planned on doing the road deck out of spaghetti strands, adding individual pieces across the width of the base. Since the road deck needed to be continuous (with gaps not bigger than 1 mm apart along the length of the bridge), and since we planned on doing layers of it, we concluded that doing so would use up a great amount of hot glue and spaghetti and therefore affect the final weight. We also took into account our delayed meeting times due to our various schedules and wanted to get the majority of the work done the Friday before our prototype testing. Since we had the option to use any commercial pasta we decided to incorporate it into the design. We quickly concluded that the lasagna would easily break (because of its property of being thin and long and therefore brittle), and so we would only use the lasagna as the bridge’s walkway because it is lightweight and its shape would facilitate in the creation of the road deck. Thus, we opted to construct the base as the support (as described), and to add lasagna noodles on top so that the load would not rely on the lasagna. To add to the look of the road deck, we even shaved down the lasagna pieces to make our bridge look neat and aesthetically appealing. Although the look of the bridge’s parts that would not be helping the support of the bridge were not required to look their best, we decided to incorporate the aesthetical aspect with regards to our reading of bridges. As an engineer, it is important to consider all aspects of your structure, meaning the look of the design as well.

To do the main structure (sides) of the bridge, we first sketched the design with the actual measurements, on a large sheet of paper, and then we proceeded to create the individual members of the truss. Paying attention to the length of each member and the number of members we needed, we would first cut the spaghetti to the desired lengths, group them accordingly, and glue the members from each end. As mentioned before, each member consisted of 6 spaghetti strands that were slightly twisted (for increased stability since we could not reinforce the members with glue,) and glued on each end. The tallest part of the bridge measured at 295 mm. After we had all the members completed, we used the drawing as a guide by placing the members on top of it and starting to glue at the joints. We repeated the process two times to create the two sides of the bridge. This way, we would have decreased our margin of error when aligning and mirroring the two sections to one another. When we completed our three pieces (the base and the two sides) we were then able to glue it all together. We started with the base and one of the sides. We aligned the side with the base while two people held the structure, a third one would hot glue the joints. Once that side was done, we repeated the process for the other side. After the bridge started coming together, it was necessary to connect the two sides.

Using the same method used for the base (creating groups of 3 spaghettis of the desired width—the width of the bridge) we started connecting one side of the bridge to the other at the joints.

For the platform and attachments needed to be placed under the bridge we considered the recommended U-bolt. Our first decision was on what type of U-bolt to get so we decided on the smallest one, and chose an aluminum one over stainless steel because of the weight. When brainstorming on how we were going to attach it we considered using
balsa wood. The wood is very lightweight (which was good because this also affected the final weight of the bridge) but when we inserted the U-bolt, the bolt could easily slip out and with the added weight of the load, it would detach from the attachment surface. This resulted in our decision to not implement balsa wood as the connector. The next step would be to use a (regular) wood platform; it would be the safest and smartest choice. Once we had both the U-bolt and the wood we thought long on how we would position it on the bridge. It had to be attached to the bottom of the bridge but we had to take into consideration that the U-bolt could not go through the bridge (through the road deck) because it was specified that a block needed to pass unobstructed through the bridge. We did think of different ways to position it, but ultimately determined that it would weigh more and it would also put the stress/tension of the weight primarily in the center. Due to the fact that we were not limited to only the use of the U-Bolt, our team did some research and chose to use paracord as a substitute. Paracord is lighter in weight and we decided that it would be best to wrap it along multiple supporting rods along our bridge, distributing the load. From this decision, we felt that we would have a better chance of limiting the amount of stress from being directly in the center of our design. After that, we were done with the prototype design and our final design.

An important decision we had to make was on how to create all the members of the bridge. The first factor we took into consideration was to realize the type of materials we needed to work with: spaghetti, lasagna, and hot glue. Spaghetti, being much longer than its width makes it extremely susceptible to breaking. It does not take much strength to break a single spaghetti strand and that was easily found by taking a strand, grabbing it from each end and bending upwards—it breaks fast. It was not hard to decide we needed to make small bundles to create each member. We tested small bundles with different number of spaghetti strands and performed the same little test as with the single strand; we opted with to use 6 strands for the sides of the bridge. After determining this number, we grabbed the spaghetti and hot glued from each end. If force was applied at each end (pushing in), the strands would separate, as is illustrated by the image 2a. In trying to determine how to make it more stable (keeping in mind that we could not use glue as member reinforcement), we thought to twist them slightly (intertwining them with each other). As soon as we did this, the members felt sturdier, and when force was applied to the end in the same manner, it not only felt a little harder to do so but the member also behaved different. Since we wanted to create our members this way, we needed to hot glue them on each end so that it would be easier to join them to other members, and so this is how our joints were created. As far as testing the trusses, we based our expected results off of our mathematical calculations. We did this because of our constraining time to make another truss system and our confidence in our calculated results.

We did face some challenges along the way in the transition between designing and building the bridge. The first difficulty we observed was in the prototype design when we tried to do the arch bridge but then realized we would not be able to do the calculations since we have never done an arch analysis before. We thought that instead of doing the analysis of an arch we could simulate an arch but instead of a continuous circular member, we would add really small segments that together would look like an arch, and then since we just needed to calculate their angle, we could run an analysis like the ones we're used to doing. We then realized that we would have too many members, not only making the calculations difficult but also creating a heavy bridge that would most likely be over the weight limit. We quickly moved to another design.
After we decided on the design we actually carried out, we encountered an obstacle when we got to building the bridge; we realized that we would have more joints than expected. This is because we did our calculations and drawing based on the height (because we knew we wanted to use the maximum height allowed), but we did not take into account the length of the spaghetti. For our bigger members (those that exceed the length of a spaghetti strand) we had to complete the lengths by gluing two members together to represent a long one, continuous member, like we originally planned. After that, we realized that we had not taken into account the dimension (height) of the base and since we chose the maximum height, we had to cut out the bottom parts of the trusses so that we could assemble it on top of the base. This meant that some of the members that had been twisted became loose from the bottom. It became a little bit of a challenge when we tried to glue the members to the base because not only were the members lose from one end but also because we had to continually adjust (cut) the bottom so that both sides were at the same height, and so that they could both fit on the base. It became an issue of going back and forth between the trusses, but ultimately we found the right lengths and were able to glue everything together.

TEST PERFORMANCE (15 POINTS)

Upon our arrival at the Machine Shop our group’s greatest concern derived from discovering how much our bridge actually weighed. Another one of our concerns was that we may have missed/forgot to follow all requirements listed within the PowerPoint.

As the TA's checked our bridge we were glad to be given the approval by them, stating that we met all the requirements. Our overall weight was substantially lower than the max weight of 450g, whereas our bridge was at 266g. This made our team feel a bit of relief because we would be able to strengthen our base as hoped. Our length of our bridge passed as well as our height. We did come in a little close to the maximum height of 300 mm. Our bridge’s height was at 295 mm.

When given the option of testing our bridge, we concluded as a group that it would be best to just keep our prototype because we weren’t definitively sure we would be able to complete making a completely new bridge in by Thursday. Therefore, we withheld our ability to test and created added in strips of spaghetti to our base and supports. When comparing our prototype bridge with the other groups, we were relieved to see that we at least met the dimensional requirements unlike several others who didn’t.

Within the time we had between Tuesday and Thursday, we made several specific upgrades to our bridge. Our first decision we made as a team was to build upon the bases framework. We noticed that several other teams seemed to have bridges with extremely strong bases and, therefore, would make their bridge less susceptible to failure. We then cut four sections of spaghetti with six strands in each pairing to glue upon the inside of the base, following the spanning length of the bridge’s base. After gluing, we reweighed our bridge and were pleased to denote that the total weight was still under the max at 328g. From this we wanted to redo the same previous process, only this time put these added pieces on top of the bridge’s outer frame. As a result, our base had less bending moment that would allow our base to uphold itself under an increased amount of stress.

From here, we wanted to implement as much support for the two trusses to have with each other. We ended up adding three more 40 mm connectors to the 3D model. These connectors were attached to the center highest members of the complex truss as well as the inner two, small simple trusses. With the added glue and supports, we felt that our bridge would have an opportunity to compete.
against the other bridges. The following picture depicts our placing in the spaghetti bridge competition.

carry 8.55 lbs. successfully until the right side of our bridge’s base framework snapped, causing it to slip. Our bridges final weight was 341g. We concluded that perhaps if we had made our bridge span a bit further than our 635 mm, our bridge would have definitely been able to carry more weight. At the end of the competition our team ranked at #8 out of 28 teams. Although disappointed from not reaching our intended goal of placing as one of the top three within the competition, we were pleased we ranked above half of the class.

Constructing our bridge was directly correlated from our failures as well as the lessons we covered in Statics. For our analysis, we will attempt to give a brief background of what we’ve studied. Also, we will display our theoretical and numerical approaches.

From our spaghetti bridge project we used several theories to perform our structural analysis calculations. To start off we used the method of joints while using method of sections to find each individual joint on one side of our bridge helping us find the zero force members and where the bridge would need more support in the spaghetti. This knowledge of statics helped with acknowledging how the load that was going to be added on to it was going to affect our bridge. The different methods helped us find the correct calculations for each member while we also found out if the member was in tension or compression. The method of joints gave us each individual member and if it was in tension or compression [6]. The method of sections gave us the symmetry in our bridge that helped us simplify the calculations by letting us divide the bridge in half to perform the work [6]. In the calculations we were able to find the zero force members and determine how we would be able to help the other member support the work while the zero force member just served as reinforcement for the bridge.

Within the designing of the bridge we didn’t incorporate the redundant constraints and over-constraining of several members. Some theories we didn’t learn in statics were stress and pressure that were put in the members [7]. We also had to use displacement and medium in the bridge not assuming it was a perfect rigid body. The displacement in our bridge was shown in the measurements of the individual members as they changed when we connected the members with the glue, as it changes the calculations we determine and the way the load is distributed along the different members. The medium of our bridge may have been affected by not having the correct distances where the forces were going to be acting on the bridge, leaving our bridge with a not perfect rigid body [7]. Our bridge wouldn’t have a perfectly rigid body, as it will expand as weight is being added. Therefore, changing the distances and leaving the calculations differently at various weights. We also had to know the strength of our materials and at what moment would the fracture occur [7]. The
different strength of the spaghetti throughout the bridge had to be changed to help support the loads being applied to the members. By determining the strength we also had to determine at what moment it would create a fracture and would break. This process would help us show how much support (addition of spaghetti or glue) we were going to add to different members in order to be able to support more weight.

THEORETICAL APPROACH (10 POINTS):

In our theoretical approach, we first developed a Free-Body Diagram of our design in order to analyze the forces acting upon bridge. From here we were able to identify our knowns and unknowns from our Free-Body Diagram. In our knowns, we were able to identify the positions from the Free-Body Diagram. After converting our initial weight of 1000 grams into newton’s using an online converter, we concluded the weight to be 9.81 newtons. Analyzing our unknowns, we were forced to solve for all the force members, missing angles, identifying the zero-force members, and determining which force members are in compression or tension.

After concluding the initial force (9.81 N) acted upon the bridge we assumed the vertical components of our two fixed supports to be half of the force, equaling (4.91 N). Due to only one vertical force acted upon the bridge, we also assumed that there are no horizontal components for the fixed supports. This would eventually cause the sum of the forces in the x-direction to equal zero. Analyzing the Free-Body Diagram, we recognized both side of the bridge to be mirroring each other. This would allow us to use the Method of Joints to solve for our unknowns.

Before using the Method of Joints, we first had to calculate the missing angles for all the joints. We carefully identified six missing angles from our Free-Body Diagram as: Θ, β, α, γ, φ, δ. We would solve for each angle as shown below:

- \( Θ = \tan^{-1}(150/80) = 61.78° \)
- \( β = 180 - (2 * α) = 123.56° \)
- \( α = 90 - Θ = 28.22° \)
- \( γ = \tan^{-1}(195/157.5) = 51.07° \)
- \( φ = 180 - (2 * Θ) = 56.44° \)
- \( δ = \tan^{-1}(157.5/195) = 38.93° \)

After solving for our missing angles, we began using the Method of Joints to calculate the force members. This procedure provides a system for analyzing the system of trusses embedded into our bridge design. Beginning with the free-body diagram for joint G allows us to determine the external reactions. Since Joint G is a fixed support, this provides two unknowns and one known. Regarding the orientation of the x and y axes from the free-body diagram, we are able to solve for their x and y components by using the two-equilibrium equations \( ΣF(x) = 0 \) and \( ΣF(y) = 0 \). From our calculated results from Joint G we continued to analyze each of the other joints using the Method of Joints. In our calculations, we carefully identified the members that were in compression if it was negative, and members that were in tension if it was positive. This procedure gave us visual as to which members were in compression (pushing) on the joint and which members were in tension (pulling) on a joint.

were FIL and FIK.
NUMERICAL APPROACH (10 POINTS):

Considering our need to implement a 2D structure analysis using a desired software, we chose to use the Autodesk ForceEffect [8]. From this software, our team hopes to successfully prove how our calculations compared to one another, discover distinct similarities between the two, and list our highest force member. When using Autodesk ForceEffect [8] we found that member “IL” and member “IK” are the members with the highest forces having identical forces of 10.185 N according to our hand calculations. According to the simulations, member “DI” is the member with the highest force with a force of 9.812 N. A table listed in the appendix will display these comparisons.

There are a few similarities and differences between our hand calculations and our simulations with the Autodesk ForceEffect software [8]. Members BM, CJ, CD, CK, DE, EL, EH, FN, HI, and IJ in our hand calculations were all similar to our software calculations. The reason these members were similar were because we had similar lengths and angles as the 2-D bridge design on the Autodesk ForceEffect software [8] causing for similar results when we compared them to each other. On the other hand, our differences were found to be between members AB, AM, BC, DK, DL, DI, EF, FG, GN, HN, IL, IK, and JM. The reason the hand calculations of these members were different from the simulations is due to unprecise measurements of the bridge such as the lengths causing slight differences in angles which then causes faintly different calculations.

CONCLUSION (5 POINTS)

In conclusion, our prototype performed well. Although we did not get to place in the top (3) teams, we ranked #8 out of 28 teams, so that means we performed better than about 70% of the class, which we felt was a success parallelizing our goals. Similarly, our bridge was about among the top 7 as one of the lightest bridge. Having weighed a total of 341g, our bridge withheld 8.55lbs or about 3878g, making the weight-to-load ratio about .08783. As we were watching the bridge when more weight kept on being added, we did not expect for the bridge to fail when it did. We thought that one of the joints would fail, making the bridge collapse, and so we were expecting for individual spaghetti strands to start breaking. Instead, the end of the base suddenly caved in and put the weight in one of the members connecting the two trusses which ultimately broke immediately. Since we never learned how to do a 3D analysis, we never expected this outcome. We placed our focus on strengthening the trusses that we did not focus our analysis on other important parts of the structures. However, there are some factors that changed the day of the competition which we believe could have affected the results. The bridges were supposed to be placed between two straight tables, and instead, our bridges were place between two chairs that 1) were placed a little bit over 600 cm apart, and 2) were not flat. This made our bridge sit pretty closely to not being able to reach because we only allowed about 3 cm of room for it to rest on the tables. Since the chairs were at an angle, the support simulated by the chair touched the bridge at only a small section, instead of the end of the base like we had thought. This is why we believe our bridge failed at the base instead of at a joint. Perhaps it would not have held much more weight, but we think these changes did prevent our bridge
to add some weight to its final number. Nevertheless, we were able to design, analyze, and build a successful spaghetti bridge that also allowed us to learn how to work together towards a common objective.

**RECOMMENDATIONS (5 POINTS)**

Throughout this whole process of starting with an idea and making our design come to life, we have learned a great deal along the way. One of the greatest learning lessons we encompassed was further identifying structural members as being in compression/tension and which are zero force members. We’ve also learned information outside of our lessons from class such as the historical background of bridges and separate analytical theories. We gathered data with regards to several different constructions of bridges such as beams, suspensions, arches, and trusses. This project also taught us how to actually implement our teachings in real life situations, forming a structural supported design out of weak materials. This introduced us to the theory engineers must use that dictates their limited resources to build strong bridges, buildings, etc.

One aspect of our bridge our team wants to reiterate is that we should have increased the total length of the bridge longer by about 10-20 mm. We also considered our fault I not adding enough amounts of spaghetti that were glued together. Due to our bridge’s low weight, we should have capitalized on that benefit and bunched up more strands in order to strengthen our overall curvature of the complex truss.

If we had the chance to do the spaghetti bridge project all over again we would change many things that complicated the process of building the bridge. We would probably start by changing the communication we had at the beginning because not all of us had each other’s contact information. With not having the contact information it also comes with the organization we had. We weren’t exceptionally organized at the start of the project, which caused us to lose time. If we had prepared ourselves from the beginning by planning different types of bridges and their calculations, it would have saved us time with the planning and deciding which bridge we were going to pick. We could have also worked on different parts of the bridge instead of everyone focusing on the same part. If we had spread the work of the construction more evenly, we may have sped up the construction process. Also, we could have used different methods of building the frame. As a result, we would have been set up for measurements and ways to connect each member much faster. We could have drawn the blueprint of the system of trusses out first in order to start making all the cuts in the spaghetti. From these, we would have known how many how many spaghetti pieces we’d need and what size we would require each strand to be.

If we would have done the bridge by sections and done the connections at the end, we could have had a lot less fractures in the bridge throughout the construction. We would have been able to add the supports of the members easier as we would have been able to determine what support seemed weaker without having to mess around with the bridge as much to add supports. Having it drawn out would have helped with final calculations, something we had to do out of the measurements we had from the prototype not thinking anything had changed. In case we had to rebuild the bridge we would have been able to replicate the bridge a lot faster as we would already have all the dimensions and faces of the bridge.

As a group, we would recommend giving us more time to build the bridge and do the planning of the different designs. We would also recommend giving a better explanation of the rules of the project. We felt as though some of our concerns were left to self-interpretation. Listing the different types of materials we
could use for the bridge would have also been helpful in order for us to organize/design the bridge around those objects. Another recommendation we would like to address is the report instructions. We suggest perhaps organizing the format and desired information a bit more so that there would be less confusion among students. This would also allow each report to be include similar structures to be read upon grading.

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Autodesk ForceEffect Simulation 0.664 N | 2.351 N | 0.664 N | 0.301 N | 2.387 N | 0.838 N | 1.27 N | 0.00 N | 0.00 N | 9.032 N |
**Hand Calculations**

\[ \sin(31.9379) \cdot 100 \quad \theta = 31.9379 \]

**Joint A**

\[ \Delta F_e \cdot F_{P1} \cdot \cos(31.9379) + F_{P1} \cdot \sin(31.9379) = \theta \]

\[ F_{P1} = 3.7799 \text{ kN} \]

\[ F_{PE} = 1.8771 \text{ kN} \]

**Joint D**

\[ \Delta F_e \cdot F_{P1} \cdot \cos(31.9379) + F_{P1} \cdot \sin(31.9379) = \theta \]

\[ F_{P1} = 10.183 \text{ kN} \]

\[ F_{OE} = 2.1628 \text{ kN} \]

**Joint E**

\[ \Delta F_e \cdot F_{P1} \cdot \cos(31.9379) + F_{P1} \cdot \sin(31.9379) = \theta \]

\[ F_{P1} = 3.138 \text{ kN} \]

**Joint F**

\[ \Delta F_e \cdot F_{P1} \cdot \cos(31.9379) + F_{P1} \cdot \sin(31.9379) = \theta \]

\[ F_{P1} = 2.6966 \text{ kN} \]

---

**Inclined**

**Equations of Equilil:**

\[ F_e = 9.81 \text{ m} \]

\[ \Delta F_e = \theta \]

\[ F_e + F_y = F \]

\[ F_x + F_y = 0 \]

**Assume**

\[ A_y = 4.905 \text{ m} \]

\[ B_y = 4.905 \text{ m} \]

**Unknowns**

- Force Members
- Zero Force Members
- No Horizental Forces

**Method of Joints**

\[ \theta = \tan^{-1}(150/80) = 61.779^\circ \]

\[ \theta = 180 - (2 \theta) = 56.11^\circ \]
REFERENCES (5 POINTS)
