Northern Arizona University
Student Steel Bridge Competition 2023

Final Design Report

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Abbreviations

AISC – American Institute of Steel Construction

CECMEE – Civil Engineering, Construction Management and Environmental Engineering

ISWS – Intermountain Southwest Student Symposium

KSI – Kips per square inch

SSBC - Student Steel Bridge Competition

Acknowledgements

The Student Steel Bridge Competition 2023 capstone team would like to acknowledge the contribution of all sponsors. Page Steel, located in Page, provided the team with the necessary steel to fabricate all bridge members. Page Steel made sure to deliver the material to Flagstaff, allowing the team to obtain the material easily. Similarly, K-Zell Metals, located in Phoenix, helped the team by cutting all connections and name plate for the bridge. Copperstate Bolt & Nut, located in Flagstaff, provided the team with a small lecture on the different properties of bolts and donated all bolts necessary for bridge connections. Loven Contracting Inc. helped the team cut the full-length pieces of metal. The team also acknowledges the technical advisor, Sabrina Ballard, for the generous contributions to design and technical work.

1.0 Project Background

1.1 Introduction

The Student Steel Bridge Competition (SSBC) is a yearly university program organized by the American Institute of Steel Construction (AISC). The AISC is an institute that focuses on making steel the material of choice; therefore, they focus on code development, education, advocacy, and more [1]. Every year, Northern Arizona University (NAU) organizes a team to participate in the competition as part of their senior Capstone project, in order to demonstrate their knowledge of both the technical and procedural aspects of engineering design. The team has been contracted by the client, Mark Lamer, to design, build, and assemble a bridge that fulfills AISC's competition guidelines and solicitation. This year, the mock client is the San Diego National Wildlife refuge, who has requested for competing teams to design and fabricate a 1:10 scale model bridge that will be used to replace the existing bridge across the Sweetwater River. This bridge will reduce traffic along an area frequented by both wildlife, as well as patrons of the park. Both the river and the refuge are depicted in Figure 1, with the existing bridge marked with a red pin. Enclosed with a red border is the area where the modeled bridge will be constructed, the specific coordinates were not provided, the team only knows it will be located further down the existing bridge. To accomplish this, the team will need to design a bridge that meets the design constraints outlined in the SSBC 2023 Rulebook. Prior to fabrication, an analytical model will be prepared to predict stresses in the structure and aid the team in designing a bridge to alleviate these stresses. The team will also need to either find and coordinate with skilled tradesmen for fabrication or acquire the necessary skills to accomplish this themselves in a safe manner. This project provides students with the opportunity to participate in engineering design while still in school, while also raising awareness about the increasingly detrimental effects that encroachment on native wildlands is having on both native wildlife and humanity at large.

Figure 1. Project Site Map (Location Marked in Red)

To successfully design and fabricate the model, the capstone team needs to consider 6 different vertical load cases for competition. The load case that will be tested will be determined at competition, though the team needs to be ready to be able to withstand any chosen load. The team will compete for different categories, including construction speed, cost, aesthetics, and weight. The constraints for the competition include member size, magnetic material, and overall bridge length, width, and height.

1.2 Competition Overview

The Intermountain Southwest Student Symposium (ISWS) is a four-day event that hosts multiple types of competitors and activities, one of them being the Student Steel Bridge. On one of the days, all steel bridge teams will go to the designated building area to begin construction. Each team will have their designated location and every team will begin construction at the same time. Once construction is completed, the judges will proceed to load each bridge one by one. To receive the results, which will include the results of every competition category, the team will send their captain to the judges.

1.3 Competition Design Considerations and Criteria

The competition requires the bridge span length be between 23-24 feet. Prior to load testing at competition, a judge will roll a die that will determine which load case, N, will be used for all competitors. These six potential load cases can be found in *Table 1*. The locations of these load cases are measured from the end of the bridge along the 23-24 ft. span. The bridge is loaded via three-foot-wide decks with a center point listed in *Table 1*. Figure 2 and Figure 3 demonstrate the locations of L1, L2, and S [2].

Table 1. Possible Load Locations

N	L1	L2	S
1	4'-0"	7'-6"	7'-0"
2	4'-6"	8'-6"	7'-0"
3	7'-0"	13'-0"	10'-0"
4	8'-6"	13'-6"	13'-0"
5	10'-0"	15'-0"	10'-0"
6	11'-6"	16'-0"	13'-0"

Figure 2: Locations L1 and L2

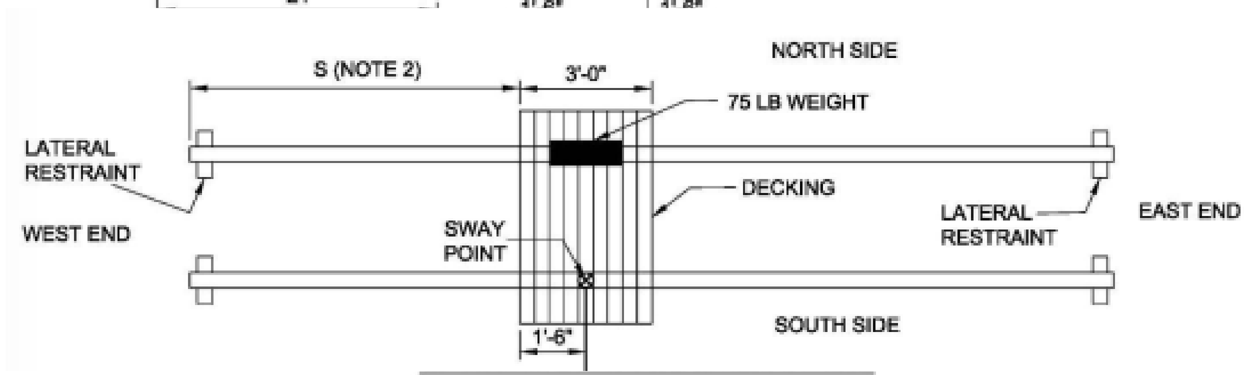


Figure 3: Location S

Location L1 indicates a load of 1,300 pounds, L2 indicates a loading of 1,100 pounds and S indicates a lateral load of 50 pounds. In order to progress to nationals, the team must achieve the lowest overall performance score. This score is based on the team's overall structural efficiency and construction efficiency.

1.3.1 Construction Economy

The team with the lowest overall performance score will proceed to nationals. One of the two categories for scoring overall performance is the construction economy. This category is determined by the bridge construction time and persons present. The following equation shows how the construction economy score is calculated.

Equation 1. Construction Economy

$$C_c = \text{Construction time (minutes)} \times \text{number of builders (persons)} \times 100{,}000\ (\$/\text{person-minute}) + (\text{Total time} - \text{Construction time}) \times 250{,}000\ (\$/\text{minute}) + \text{load test penalties } (\$).$$

1.3.2 Structural Efficiency

The other category used for determining overall performance is structural efficiency. This category is determined by the relationship between the bridge weight and overall deflection. The following equation shows how structural efficiency is calculated.

Equation 2. Structural Efficiency

$$\begin{aligned} C_s = {} & [\textit{Measured weight} \text{ (pounds)}]^{1.85} \times 45 \text{ (\$/pound}^{1.85}) \\ & + (\textit{Total weight} - \textit{Measured weight}) \text{ (pounds)} \times 2{,}500 \text{ (\$/pound)} \\ & + \textit{Aggregate deflection} \text{ (inches)} \times 2{,}750{,}000 \text{ (\$/inch)} \\ & + \textit{Load} \text{ test penalties (\$).} \end{aligned}$$

Considering both the construction economy and the structural efficiency during design was important since it directly impacts the team's overall score. The estimated weight, predicted deflections, and practice time are items the team is using to improve their overall score.

1.3.3 Overall Performance

The overall performance category is an aggregate of the bridge's performance in several different categories. These are Construction Economy, Structural Efficiency, and Aesthetics.

1.3.4 Cost Estimation

The cost estimation category is calculated prior to competition and for all six of the given load cases. This category is given to the team with the closest estimation to their overall performance score.

1.3.5 Aesthetics

Prior to load testing, each bridge is evaluated for aesthetics. This category includes the appearance of the bridge as well as evaluation of the accompanying poster.

2.0 Bridge Design

2.1 Bridge Type Selection

In order to bridge the gap between project proposal and delivery of the finished design, the team engaged in several key steps. Initially, the team developed sketches to outline potential solutions in the form of bridges and cross-sections. Ideas which were well-received by the client and the team went on to the modeling phase, where an analytical model of this sketch was created and fine-tuned. This model was meticulously designed and scrutinized, to ensure deflections were as close as possible to the finished structure. With the analytical model finished, fabrication documents were drawn up based on the member length found within. Connections at critical points were identified, designed, and checked to ensure they could withstand the expected loading.

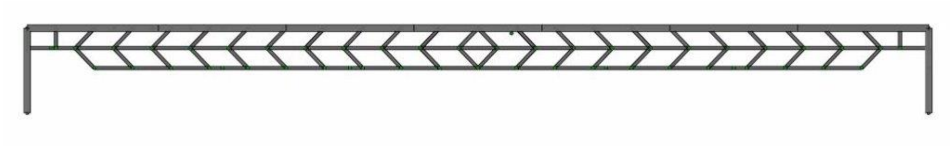


Figure 4: Deck Bridge

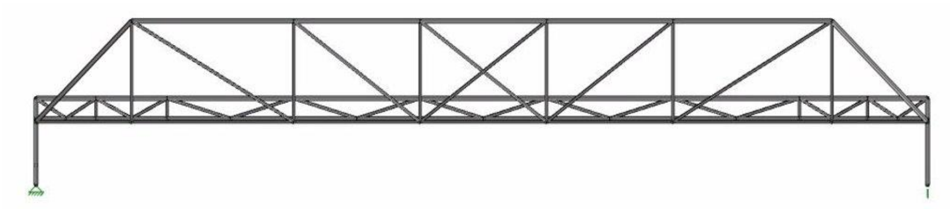


Figure 5: Truss Bridge

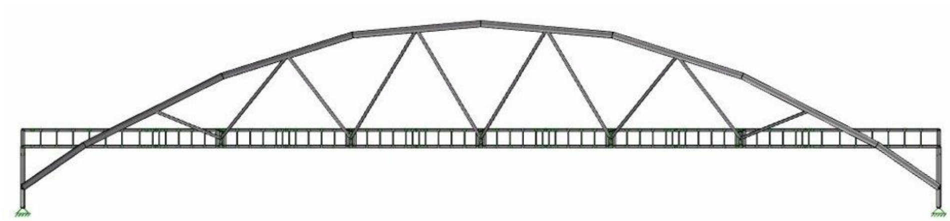


Figure 6: Arch Bridge

The first task associated with design was for the team to select exactly what type of bridge was to be built. To this end, the team came up with several drawings of possible bridges to show to and discuss with the client. These sketches took into consideration the rules and guidance provided by the competition coordinators, as well as research into the pros and cons of each type. During the client meeting, these different bridges were discussed, and any feedback incorporated into the team's list of bridge characteristics. These are summarized in the table below.

Table 2: Summary of Bridge Characteristics

Bridge Type	Pros	Cons
Arch	• Low deflection • Potentially lightest • Potentially lower build times	• Angles critical to performance • Difficult fabrication process • Hard to analyze
Truss	• Low deflection • Reasonable analysis	• Potentially heavy • Complex fabrication process • Long assembly time
Beam	• Easy analysis • Simple fabrication process • Quick assembly	• Heavy • Lacking support at middle span

Table 3: Decision Matrix

Bridge Type Selection			
Criteria	**Beam**	**Truss**	**Arch**
Complexity (15%)	3	2	1
Aesthetics (5%)	1	3	3
Lightness (20%)	1	2	3
Stiffness (25%)	1	3	3
Fabrication (20%)	3	1	2
Construction (15%)	3	1	2
Total	2.0	2.0	2.4

As shown in the decision matrix above, the arch bridge was eventually chosen as the base for the final design. The scoring for each category ranged from 1 to 3, with 1 being actively detrimental to the design process (either through additional time expended, serious shortcomings, or simply risk of failure associated with implementing it), and 3 being extremely beneficial with limited compromises. Complexity denotes the expected difficulty of developing a bridge that meets the requirements. Bridge types were rated by their potential visual appearance under the aesthetics category. Since weight is a major component of this competition, expected bridge weights for functional designs were also evaluated. Stiffness was a measure of how well the bridge type was likely to handle loadings, particularly at midspan. Fabrication was an assessment of the team's skills in carrying out necessary manufacturing tasks, with 1 being extremely complex operations and 5 being basic tasks. Finally, construction was how long these bridges generally take to build during competition, with 1 being longest, 5 taking the shortest amount of time. Generally, structural performance was considered to be most important, and so construction time, stiffness, weight, and overall complexity were given relatively high ratings. Factors related to the actual fabrication of the bridge were second most important, followed by general appearance (or aesthetics) of the bridge.

The team decided to move on with an arch bridge, since its performance fell somewhere between the two other options. For example, deck bridges, while the simplest bridge type the team could bring to competition, are roughly analogous to a simply supported beam. Given that the span must be at least 23ft, a deck bridge would create a large deflection at center span. Trusses meanwhile are able to handle the same weight with significantly lower deflection as a result of their arrangement, which places most members either in tension or compression. This comes at the cost of difficult fabrication and long assembly times during competition. The arch, though difficult to design and hard to manufacture correctly, was somewhat simpler than the truss, while being much lighter and stiffer than the deck bridge. Like a truss, the team's bridge uses webs in tension or compression, allowing for a better distribution of loads across the structure when compared to the deck bridge.

2.2 Member Design

Table 4: Cross-Sections and Material Shapes

Cross-Section		**Material Shape**	
Triangular	• Complex Composite Shape – Difficult to design and manufacture	**Square Tube Steel**	• Poor bending resistance • Excellent Machineability
Monolithic	• Uses members themselves as cross-section - Inefficient	**Circular Pipe**	• Excellent strength to weight • Difficult to work with
Box	• Composite Shape – Easier to analyze and manufacture	**Solid Stock**	• Strongest bending resistance when loaded on stronger axis • Potentially Heavy • Good Machinability

Throughout modeling and analysis, the team tested a variety of cross-sections. Discussions with sponsors informed the team that pipe grades (including both rectangular and circular pipe) come in A-53 or A-500, depending on pipe diameter, with solid round stock coming in A-36. A-53 will be used for pipes with an outer diameter of 1-inch or greater and has an ultimate strength of 60 ksi. A-500 will be used for the remaining pipe and has an ultimate strength of 58 ksi. The solid stocks of A-36 have an ultimate strength of 58 ksi. The cross-sectional properties of circular and rectangular tubing were compared, with circular tubing having a higher moment of inertia (and thus higher resistance to bending) for the same amount of material. The cross-sections that were ultimately incorporated into the design are included in Appendix E.

3.0 Structural Modeling and Analysis

After selecting a bridge type to proceed on with, the team moved onto developing an analytical model, with RISA 3D selected as the program of choice. This structural calculator includes an expansive catalog of material properties, a vast array of loading types and patterns, and a built-in feature to analyze deflections during simulation [7]. The team worked closely with an outside advisor throughout the modeling process, who provided advice on design decisions and guided the team through the more complicated operations in this program. For the purpose of design, several assumptions, both by the team and by the program itself were made. During competition, the supports are only restrained from translation by friction. In order to constrain the structure, it was necessary to assume that the bridge was acting either as a pinned-pinned connection, or a pinned-roller support. The actual bridge performance is expected to be close to the average for these two conditions. The program itself makes numerous assumptions concerning load transfer into abutting surfaces, as well as at connection locations. Because of this, the team decided to utilize moment releases at member ends to model internal forces more closely and designed all connections outside of the program using values pulled from the software. [8]

3.1 Modeling Considerations

The initial stage of modeling was to develop a simple “working” model, with the general dimensions and footprint falling within the constraints. This assembly was used as a template for future operations. This included defining the load cases the bridge could be exposed to during competition. This initial model allowed the team to identify areas of concern for major bridge components, which it tackled (generally) one at a time. When an issue was identified, the team would discuss potential solutions and see how they affected the simulation. No decision matrices were employed at this step, as solutions were generally iterative.

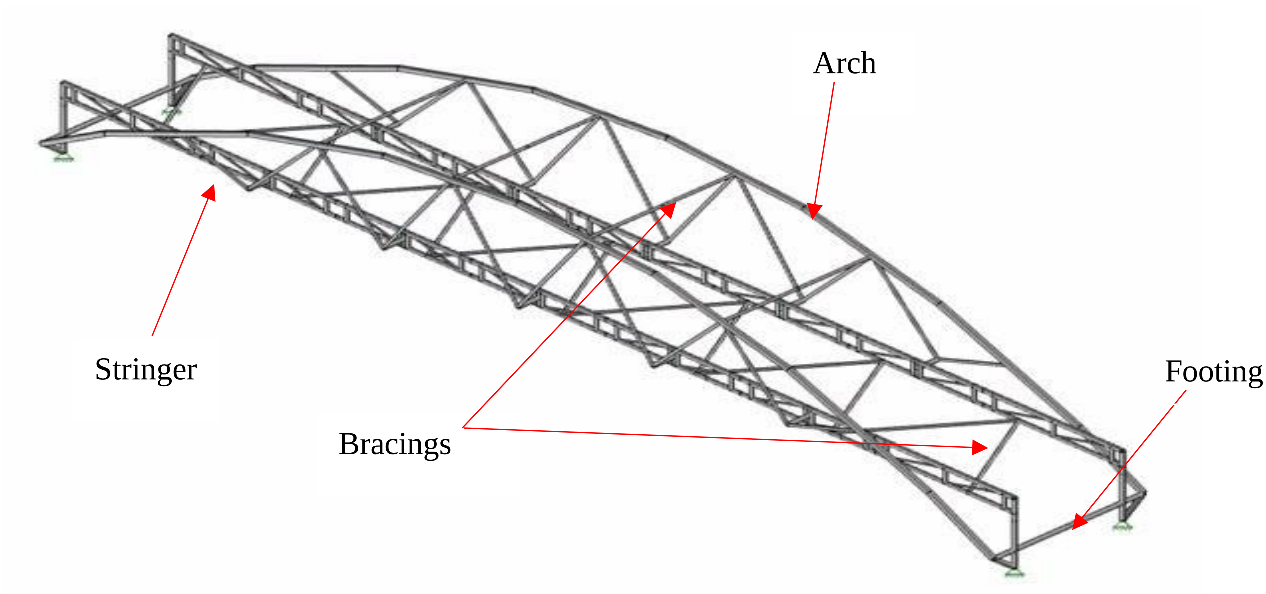


Figure 7: Bridge Terminology

3.1.1 Stringer

As the bridge component that would directly bear live loading during competition, proper design of the stringers was critical. Since this is an arch bridge, much of the weight would ideally be carried by the arch and the truss. This meant that for the stringers, rigidity was key, since changes in the geometry due to deflection could result in stresses that the bridge is not designed to handle. To this end, the team tested different patterns of vertical bracings to control deflections, as well as different sizes of pipe and orientation to increase stiffness. The final design for the stringers ended up being two pipes, (the top chord being 1” pipe, the bottom being 3/4”), with vertical braces every few feet to improve rigidity. In addition, a miniature truss pattern composed of 0.25” solid stock in a Pratt arrangement was laid out in order to distribute forces away from the loading location and allow the stringers to deform together as a single composite member.

3.1.2 Arch

A significant component of the arch design involved where connections should be placed to tie the arch and stringer together. Ideally, these points would relieve stress across the stringers evenly, without spikes in stresses due to changing load patterns. A major obstacle encountered at this step was extreme under-utilization of the arch. This meant that the stringers were failing well before the arch, since they were carrying a proportionally higher load. The team had to develop a way to tie the stringers to the arch in such a way that allowed load paths to travel from the point of application directly into the arch, and then into the supports via compression. The team tested various points, and ultimately settled on a Warren-Type pattern, with locations along the outside edges of the 5 interior stringers. This solution solved many of the issues the team was seeing, while adding minimal complexity to the fabrication and assembly of the bridge.

3.1.3 Footings

The footings, or contact points for the bridge to the floor, were the last component designed using stresses as the primary evaluation criteria. Since structural steel tubing is excellent in compression-tension but weaker in longitudinal bending, the primary focus was identifying any potentially eccentric loads (like where the stringers and arch connected to the supports) and trying to come up with a layout that placed these members into compression.

For the stringers, it was possible to place the stringers directly above the footings themselves, allowing the supports to carry much of the weight as compression. While buckling is a concern for members in compression, the even distribution of weight coupled with the relatively short pipe section meant that risk for this was minimized.

In the case of the arch, this was functionally impossible, and so an alternate solution was to increase the number of potential load paths from the arch to the support, and from the support to the floor. Member lengths that made up these load paths were minimized as much as possible to improve rigidity and limit the potential for failures in bending. Finally, the team tried to ensure that the footing was composed of a single member on the side which connected to the arch, since any bolted connections here would have likely failed in shear regardless of the number, pattern, or orientation of the bolts. This led to the development of an upside-down “4” shape for the support, with the connection to the arch being welded in place, and two pipes; one connecting horizontally to the pipe holding up the stringers, and another short section running directly to the bottom of the footing.

3.1.4 Bracings

Once overstressing issues were addressed, the team then switched to minimizing deflections in the bridge. By minimizing stresses in the components, generally vertical deflections were also kept to a minimum as a byproduct. It was observed, however, that the arch and stringers tended to deflect horizontally by nearly 6 inches at midspan, depending on the location of the deck load, and the 50-pound lateral load test. The team tried bracing the bridge with simple horizontal brackets but found them insufficient at controlling deflections in all but at the top of the arch. It was discovered that a zig-zag cross bracing running the length of the stringers brought these deflections within competition guidelines.

3.2 Finalize Design

The team evaluated the state of the analytical model in mid-January, to determine if it was possible to proceed with fabrication. Stresses in the model were examined according to LRFD load combinations and modifiers, with a capacity-to-demand ratio of 75% set as the absolute limit for allowable. These stress values were evaluated at the 6 locations for each load case described in Section 1.2. For the loading, Load Combination 2 was identified as most appropriate, since the competition live loading controlled:

Equation 3: LRFD Load Combination 2

$$LC2 = 1.2(D) + 1.6(L) + (0.5(L_r \text{ or } S \text{ or } R)$$

$$LC2 = 1.2(SW) + 1.6(L)$$

Where:

D = Applied Dead Load,

L = Applied Live Load,

$(L_r$ or S or $R)$ Refers to the Live Roof, Snow, or Rain Loads,

And SW = Self Weight

The goal for deflections was set at 1 inch for vertical and ½ inch for horizontal displacement, to allow for differences between the model and finished structure due to manufacturing tolerances. RISA predicted a final deflection of 0.933 inches vertically, and a lateral displacement of 0.312 inches for the design based on the competition loading. The final bridge weight is estimated to be 429 pounds before connection design. Deflection reports for various nodes may be found in the Appendix B.

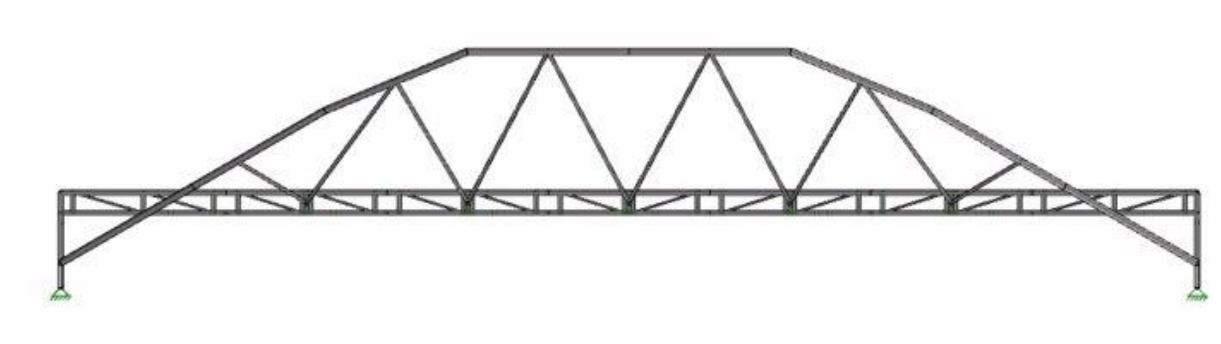


Figure 8: As Built Elevation View

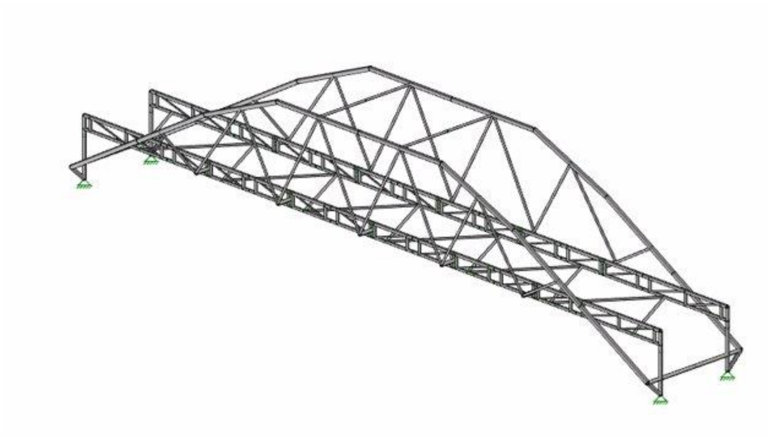


Figure 9: As Built Iso-View

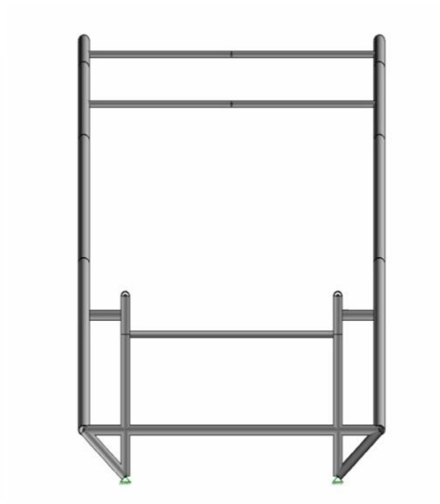


Figure 10: As Built Through-View

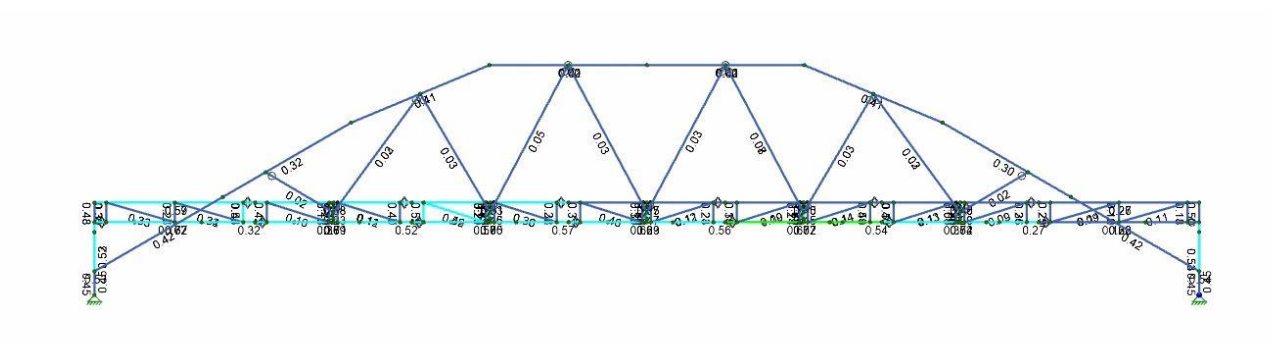


Figure 11: Absolute Stresses in Envelope

4.0 Connection Analysis

The following table includes equations and tables in the AISC Steel Manual for each of the components of the connecting members.

Table 5. Steel Manual Connection Sections

AISC Steel Manual Sections for Connection Analysis	
Tensile and Shear Strength for bolts	Chapter 7 (Section J3)
Bearing strength at bolt holes	Chapter 7/9 (Section J4)
Strength of plates	Chapter 9/10 (Section J1)

The team then deconstructed the bridge into its connection types. The following figure and table show the total number of connection types in the bridge, as well as the section of failure mechanisms.

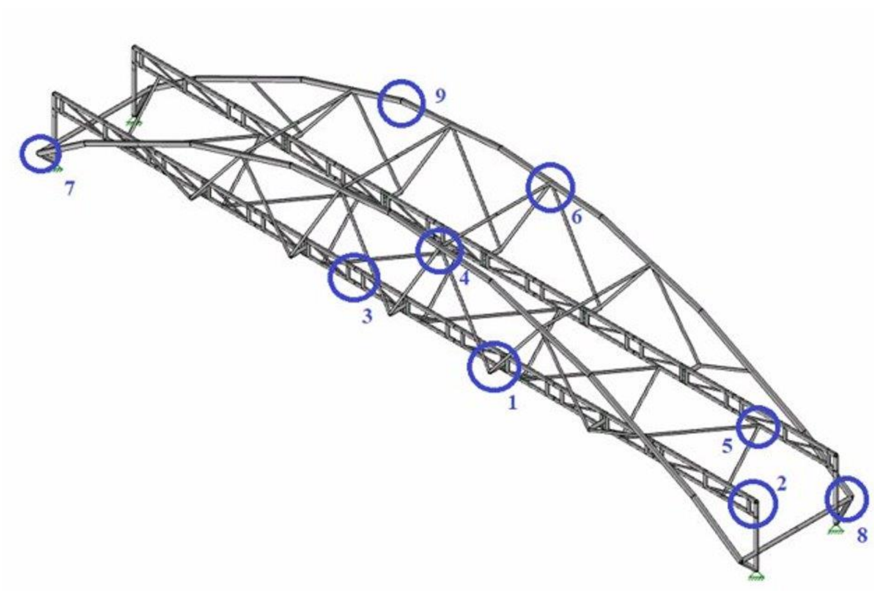


Figure 12. Bridge Connection Types

Table 6. Connection Types and Failure Mechanisms

Connection Number	Type of Connection	Failure Mechanisms
1	Shear*	Shear rupture, block shear
2	Shear	Shear rupture. block shear
3	Telescope + Shear	Buckling, block shear
4	Shear	Shear rupture. block shear
5	Shear	Shear rupture. block shear
6	Shear	Shear rupture. block shear
7	Telescoping + Shear	Buckling, block shear
8	Telescoping + Shear	Buckling, block shear
9	Telescoping + Shear	Buckling, block shear

**As per SSBC, all connections must be accompanied by a nut and bolt, thus all connections must be analyzed for shear capacity*

4.1 Design of Connecting Elements

Section nine of the Steel Manual specifies requirements and design considerations for connecting elements, including angles, plates, tees, and gussets. These methods include a gross area, effective net area, and Whitmore section. Gross area is specified in section B4.3 and effective net area is an area reduction for bolt holes which can be found in Table 9-1. Section J 4-1 determines the strength of elements in tension including tensile rupture of these elements. Section J4-3 determines the strength of elements in shear including calculating shear rupture of the connecting element. The final section for connecting elements, J4-5 determines block shear strength for the connecting elements.

4.2 Design Considerations for Bolts

Section seven specifies requirements and design considerations for bolted joints. This includes fastener components, proper bolt length, washer requirements and nut requirements. Parts 10 through 15 of this section detail design for simple shear, moment, bracing and other connections which will be used for the purpose of design. Included in Appendix D is the NUCOR sheet for Grade 8 bolts including shear capacity for both the bolts and nuts.

4.3 Design Considerations for Welds

Section eight specifies requirements and design considerations for welded joints. This includes general requirements as well as welding in structural steel which is utilized in members with a diameter of 1-inch or greater. Section J2.4 and Table J2.5 show the available strength of welded joints. These design calculations will only be done for critical sections of the bridge.

5.0 Fabrication

5.1 Material Procurement

Page Steel has once again agreed to donating stock lengths for the construction of the bridge. Contact was made January 25th and material order was provided shortly afterwards. The material order receipt is provided in Appendix C, which includes the sizing and quantity of material ordered. The material was received February 3rd and is currently being stored at the CECMEE Field Station.

5.2 Safety Binder

A thorough inspection of the location where fabrication would take place was required to receive permission to work on school property. The purpose of this inspection was to identify hazards, locate emergency equipment, and develop safety plans or mitigation strategies in the event of an emergency. In addition, the team made a list of tools it expected to need, catalogued what was present onsite, to determine if any purchases or department material requests needed to be completed. These were collected in a lab safety binder, reviewed by the lab advising faculty member, and discussed in a safety meeting prior to approval.

5.3 Fabrication Documents

A set of technical documents for each bridge member was prepared, both to aid student fabricators, and any donors willing to assist the team. These documents were expected to communicate all critical dimensions, fitting/tolerance necessities, and guidance for fabrication. Concurrent with this step was material take-off, where member lengths were recorded, rounded up by several inches, and collected into a list. This minimized the chances for errors during material cutting due to imprecise cuts, slight design changes, or simple human error. The following figure shows a sample fabrication document for the footings of the bridge.

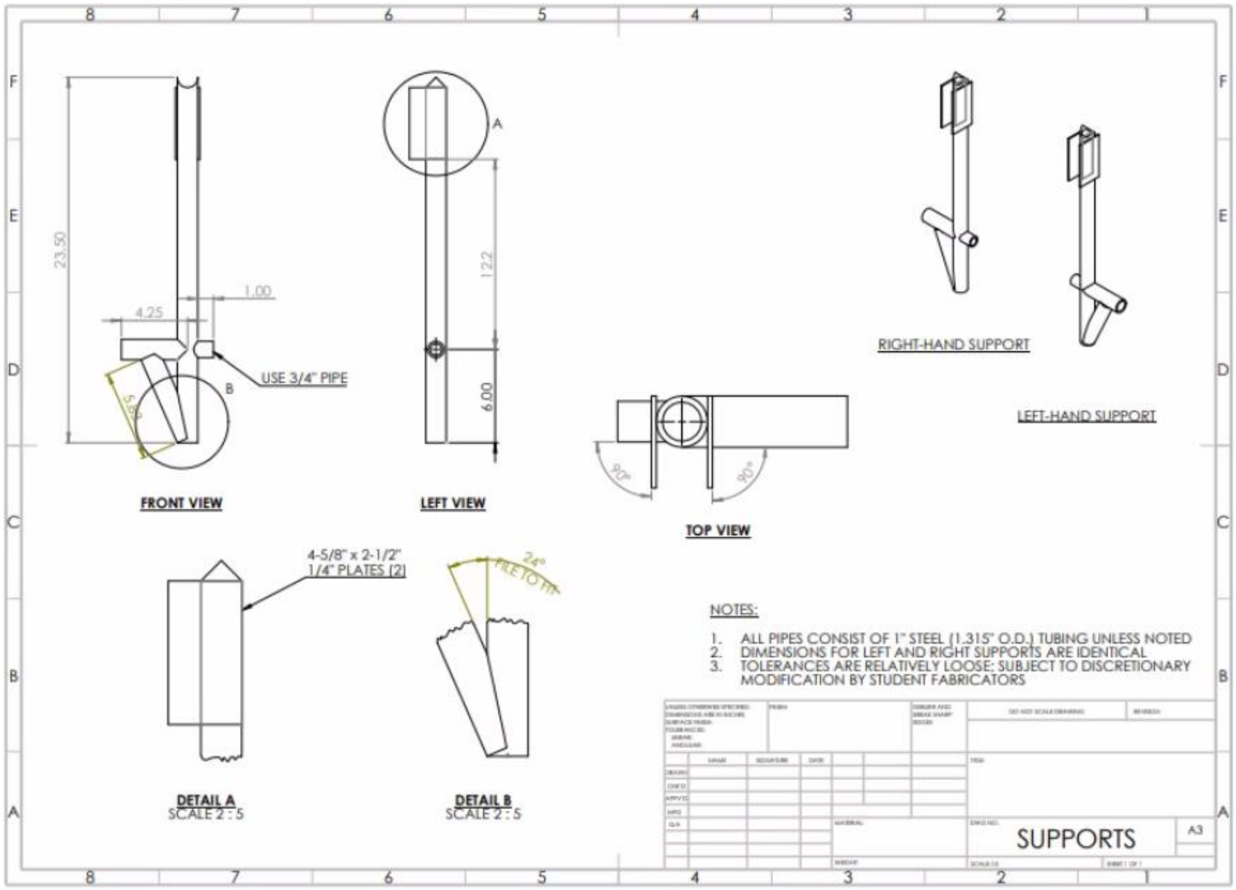


Figure 13. Footing Fabrication Document

5.4 Fabrication Oversight

The bulk material cutting for this project was performed by an outside contracting company, willing to donate time to assist the team and support local schools. A member was present during this step, in order to call out lengths, answer questions, and assist as needed. The remaining work was completed by the team. This includes precise cutting, tube notching, grinding for telescoping connections, grinder sharp edges, and welding. The following figures show parts of fabrication.


Figure 14: Fabrication Members


Figure 15: Welding Example

5.5 Challenges

Due to budget and time constraints, the team decided to complete fabrication of the major bridge components themselves, as opposed to local welders/specialists. A team member with previous experience in welding performed the numerous welds required, while the rest of the team cut, fitted, or otherwise prepared the parts to be welded.

Our first challenge that the team encounted was the fitment of our metal to build the srach. The team noteced after the final design had been chosen and all the members had been cut, the metal that was designated for the arch did not match what the team had ordered. This had caused the fittings at the connections to be larger than anticipated for the telescpoing process. Now the arch had a lot of play in the sense of it not being able to stand on its own so modifications had to be made to make the fittings tighter. The team concluded that adding some welds on male portion of the telescoping pipes would allow for a tighter fit by providing more contact surfaces at those elbows.

The second challenge the team faced was the overall height of the bridge, from ground to top of arch. The top of the arch was over 5.5 feet, which was a problem since the maximum height per guidelines is 5 feet. The team had to adjust the arch, changing some 10-degree elbows to straight connections. The images below give an idea of how the arch was changed.

Figure 16: Initial Design, Violates Guidelines

Figure 17: Modified Design, Meets Guidelines

6.0 Testing

At the request of the client, no vertical load testing was conducted prior to competition to avoid potential damages prior to competition. This was due to concerns about unintentional damage. Instead, the client requested that the bridge be inspected simply for safety and compliance with rules. To this end, the team performed a sway in-line with the rules after installation of cross-braces. The team also checked several points along the arch and at the supports, to correct any instabilities/unsafe connections prior to competition. While sway testing would not be performed at these points, judges have the authority of discretionary disqualification if a bridge is deemed too unsafe to load.

7.0 Competition

7.1 Preparation

The team practiced staging and assembling the bridge while at a conference in Reno. The team also sought clarification for several rules that could lead to penalties during competition and incorporated these into the strategy for the timed build event.

7.2 Aesthetics Competition

The first event of the competition took place Thursday afternoon (April 13th). This included a relaxed setup of the bridge and summary poster display, outlining the team's process for design and fabrication. This event was used to judge the aesthetics category, where judges rated how well each team demonstrated the engineering design process, and produced a result that was both visually appealing and confidence inspiring. Figure 14 shows the bridge at the aesthetic competition, one day before timed build and load testing.

7.3 Timed Build and Load Testing

The timed build event took place on Friday, April 14th. Due to miscommunication with the judging staff during staging, and between builders during the competition, the team exceeded the estimated build time by a significant margin. The final time prior to penalties was 43 minutes, as well as an additional 5 minutes afforded to the team to resolve disqualifying violations (loose nuts, missing bolts etc.) The team also had numerous time-related penalties related to the actual design of the bridge connections, which were not apparent in the rules. These challenges lead to the team's disqualification from the construction economy portion. The team was allowed to advance to the loading portion of the competition for structural efficiency.

The team then proceeded on to the lateral and vertical load test. The team was assigned load case "3", with the 1400 lb. and 1100 lb. loads at 7' and 13', respectively, and a 50 lb. lateral sway test at 10'. The team passed the horizontal sway test but was eventually disqualified at 1900 lbs. when the sway during loading exceeded the prescribed safety margin of 1". The following image shows how the loading was applied to the decks on the stringer.

Figure 18: Twenty-five-pound Weights on Bridge

7.4 Results

(Will be updated in Final Report when official results become available)

Table 7. Final Results

Results	**Deflection (in)**	**Build Time (min:sec)**	**Weight (lbs)**	**Aesthetics (1-10)**
Anticipated:	0.95	20:00	500.0	9.995 +/- 0.005
Actual:	1.65	43:19	511.3	8.5

8.0 Summary of Engineering Work

8.1 Design

The analytical modeling was carried out in RISA 3D, a structural analysis calculator with advanced shading and textures for visual representation. This allowed the team to discuss design ideas, potential changes, and view the results in a collaborative manner. Progress on the model was slow at first, due to the learning curve associated with the program. Because of this, the time allotted for this phase extended nearly a month past the anticipated completion date. The updated GANNT chart can be found in Appendix F.

8.2 Material Procurement

Due to the additional time required for the analytical model, material procurement was pushed back as well. However, the turn-around time for was considerably lower than expected, with materials delivered to the NAU Farm within 1 week. This put the team back on schedule for design.

8.3 Connection Design

Connection modeling and analysis has been moved from task 2.4 to 2.6. This task was not essential to material procurement and so was placed further down in task 2. Current work on connection modeling and analysis has begun, along with fabrication documentation. A draft of the fabrication documents, including connections, will be completed by February 17th.

8.4 Fabrication

Fabrication was to be done by a local fabricator. However, due to a conflict of availability and scheduling, the team was required to complete the majority of fabrication. This resulted in a larger number of hours being delegated to the fabrication task then anticipated which led to alterations later in the schedule. The total sum of hours for the final project will be discussed in the staffing changes section of the summary of engineering costs.

8.5 Staffing Hour Changes

The following table summarizes the hour breakdown between the proposed and final project schedules.

Table 8. Staffing Hour Breakdown

Task Name	Proposed	Actual	% Difference
Task 1.0 Background Research	43	43	0.00%
Task 2.0 Designing	188	230	22.3%
Task 3.0 Fabrication	121	182	50.4%
Task 4.0 Testing Prior to Competition	85	55	-35.3%
Task 5.0 Practice	64	12	-81.3%
Task 6.0 Competition	41	50	22.0%
Task 8.0 Deliverables	128	128	0.00%
SUM	670	700	4.48%

9.0 Summary of Engineering Costs

The staffing breakdown had an original personnel cost of $64,255 but with the changes in fabrication arrangements, the team had lost time towards tasks 4 and 5. The final staffing breakdown cost for the project is $62,485. With this change to the personnel hours, the following table shows an updated cost of engineering services with updated supplies and personnel cost.

Table 9. Cost of Engineering Services

Cost of Engineering Services						
Classification	**Details**	**Rate**	**Quantity**		**Cost, $**	
1.0 Personnel	**Title**	**$ per hr.**	**Proposed**	**Actual**	**Proposed**	**Actual**
	Senior Engineer	$180.00	124	120	22,320	21,600
	Project Engineer	$140.00	130	121	18,200	16,940
	Engineer in Training	$70.00	165	170	11,550	11,900
	Drafter	$75.00	85	85	6,375	6,375
	Intern	$35.00	166	162	5,810	5,670
	Total Personnel				64,255	62,485
2.0 Supplies	Members	$3/lb	250	400 lb	750	1,200
	Bolts	$0.01/unit	200	200	2	2
	Plates	$3/lb	10	50 lb	30	150
	Supplies Cost				782	1,352
3.0 Subcontract	Labor	$65.00	60	60	3,900	3,900
4.0 Travel Expenses	Lodging	$170/person/night	4 nights	4 nights	2,720	2,720
	Rental	$68/day	5 days	5 days	340	340
	Mileage	$0.45/per mile	691x2 miles	691x2 miles	622	622
	Travel Cost				3,682	3,682
Total Project Cost					72,619	71,419

10.0 Impact Analysis

The team was to analyze various impacts throughout the process of this capstone. Those impacts include social, environmental, and economic. The positive and negative aspects of each of these impacts are discussed in the following sections.

10.1 Social Impacts

Positive impacts for this project include connecting Arizona fabricators with local students which helped create a sense of pride in the creation of the project. Furthermore, as this is a competition capstone, the ISWS helped bring together young engineers to form lasting career friendships and relationships.

10.2 Environmental Impacts

For the creation of the bridge, recycled steel parts were used for plates on various connection types. This helped reduce the overall environmental footprint of the project. Although the team creates steel waste which can be a potential negative impact, future teams can use this steel for analysis as well as choose to recycle any leftover steel eliminating the environmental footprint.

10.3 Economic Impacts

Many of the materials acquired for this project were donated by various sponsors. These donations helped to reduce the overall economic impact on both the members of the team, and the school.

11.0 Conclusion

The objective for the team was to design, build, and assemble a bridge that meets AISC competition guidelines. The team succeeded in meeting the objective. The team was able to create design drawings though it took an extra month to complete than what was initially estimated. This then shortened the time for construction. However, the team initially didn't count on starting fabrication a month earlier, instead, the time had been allocated for material acquisition. The bridge was assembled only once, the day before the competition. The team's selection of the arch bridge provided various challenges throughout the design and fabrication process. Compromises needed to be made, such as testing and practice, in order to meet the project deadline and as a result the as built bridge was not as satisfactory as designed. While the team did not perform as well as anticipated, thanks to the generosity of team sponsors, the team was able to experience some success and serve as a model for future steel bridge teams.

12.0 References

1. AISC. “About Us” Chicago, IL 60601. [Online.] Available: About Us (aisc.org).
2. AISC, “Student Steel Bridge Competition - 2023 Rules,” Chicago, IL 60601. [Online.] Available: Rules and Clarifications | American Institute of Steel Construction (aisc.org) [Accessed: September 25, 2022]
3. AISC. Steel Manual 14th Edition
4. Google Earth. [Online.] Available: Sweetwater River Bridge Vicinity [Accessed: October 03, 2022]
5. AARoads California Roads. [Online.] Available: Sweetwater River Bridge Truss [Accessed: September 26, 2022]
6. ADA, “State of Arizona Accounting Manual 5095 - Maximum Mileage, Loading, Meal, Parking and Incidental Expense Reimbursement Rates” [Accessed: November 14, 2022]
7. Nemetschek Inc., “Rapid Interactive Structural Analysis 3D,” Munich, Germany, 2019 Edition.
8. RISA Tech Inc., “RISA 3D General Reference,” Foothills Ranch, CA 96210. [Online.] Available: https://risa.com/assets/documentation/General_Reference_3D.pdf [Accessed: Mar 21, 2023]
9. Benson, Mark. Engineering Clicks. Types of Bridges: The 7 Main Types. September 04, 2019. Available: https://www.engineeringclicks.com/types-of-bridges/#Beam. [Accessed: April 24, 2023]

Appendix A: Member Dimensions and Properties

Type 1 - 1 1/4" A500 Round Pipe	
I.D. (in)	1.25
O.D. (in)	1.66
Gross Area (in^2)	0.937058549
Fy (ksi)	42
Fu (ksi)	58
Type 2 - 1" A500 Round Pipe	
I.D. (in)	1
O.D. (in)	1.315
Gross Area (in^2)	0.572731976
Fy (ksi)	42
Fu (ksi)	58
Type 3 - 3/4" A53 Round Pipe	
I.D. (in)	0.75
O.D. (in)	1.05
Gross Area (in^2)	0.424115008
Fy (ksi)	35
Fu (ksi)	60
Type 4 - 1/2" A53 Round Pipe	
I.D. (in)	0.5
O.D. (in)	0.84
Gross Area (in^2)	0.357827403
Fy (ksi)	35
Fu (ksi)	60
Type 5 - 1/2" A-36 Solid Round Pipe	
Diameter (in)	0.5
Area (in^2)	0.196349541
Fy (ksi)	36
Fu (ksi)	58

Appendix B: Sample RISA Outputs

Member Code Check

Member	Shape	Code Check	Loc[in]	LC	Shear Check	Loc[in]	Dir	LC	phi*Pnc [lb]	phi*Pnt [lb]	phi*Mn y-y [lb-ft]	phi*Mn z-z [lb-ft]
M170	PIPE_.75	0.816	26.667	6	0.66	21.25		6	4736.188	9828	247.275	247.275
M218	PIPE_.75	0.726	10	2	0.554	18.75		4	4736.188	9828	247.275	247.275
M83	PIPE_.75	0.722	2.5	6	0.786	2.5		6	9716.536	9828	247.275	247.275
M163	PIPE_.75	0.701	38.01	1	0.236	27.333		2	4564.351	9828	247.275	247.275
M169	PIPE_.75	0.698	21.25	6	0.63	26.667		4	4736.188	9828	247.275	247.275
M109	PIPE_.75	0.697	2.5	6	0.757	2.5		6	9716.536	9828	247.275	247.275
M165	PIPE_.75	0.695	21.25	1	0.289	26.667		4	4736.188	9828	247.275	247.275
M217	PIPE_.75	0.69	10	1	0.382	10		2	4736.188	9828	247.275	247.275
M82	PIPE_.75	0.684	2.5	6	0.484	2.5		4	9716.536	9828	247.275	247.275
M79	PIPE_.75	0.679	2.5	3	0.748	2.5		4	9716.536	9828	247.275	247.275
M216	PIPE_.75	0.669	38.01	1	0.144	20.5		1	4564.351	9828	247.275	247.275
M104	PIPE_.75	0.655	2.448	4	0.78	1.094		4	9716.536	9828	247.275	247.275

Node Deflections

Nod...		X [in]	LC	Y [in]	LC	Z [in]	LC	X Rotation [rad]	LC	Y Rotation [rad]	LC	Z Rotation [rad]
	min	-0.078	6	-0.933	6	0.007	2	3.252e-2	1	-2.686e-3	4	1.875e-5
N261	max	0.208	1	-0.518	1	0.303	6	6.035e-2	6	2.872e-3	2	5.768e-3
	min	-0.08	6	-0.933	6	0.167	1	3.348e-2	1	7.428e-4	6	6.731e-5
N262	max	0.235	1	-0.518	1	0.012	3	5.97e-2	6	-3.076e-4	1	5.723e-3
	min	-0.08	6	-0.933	6	0.003	2	3.252e-2	1	-1.681e-3	5	-1.174e-4
N114	max	0.208	1	-0.5	1	0.3	6	5.749e-2	6	3.663e-3	3	6.132e-3
	min	-0.081	6	-0.933	6	0.158	1	2.779e-2	1	1.864e-3	6	1.1e-3
N277	max	0.208	1	-0.483	1	0.295	6	5.749e-2	6	3.153e-3	3	5.962e-3
	min	-0.082	6	-0.93	6	0.151	1	2.779e-2	1	1.537e-3	6	1.076e-3
N255	max	0.235	1	-0.483	1	0.018	3	5.456e-2	6	7.22e-4	3	5.795e-3
	min	-0.077	6	-0.93	6	0.011	2	2.695e-2	1	-2.854e-4	2	1.103e-3
N244	max	0.209	1	-0.512	1	-0.144	1	-3.211e-2	1	-6.809e-5	6	5.804e-3
	min	-0.08	6	-0.925	6	-0.306	6	-5.905e-2	6	-2.769e-3	2	1.984e-4

Appendix C: Material Order Receipt

STRAIGHT BILL OF LADING

ORIGINAL - NOT NEGOTIABLE

SHIPPER NO: 5672

CARRIER:

CARRIER NO:

DATE: 01/25/2023

TO:
CONSIGNEE
N.A.U. BRIDGE TEAM
C/O BUDDY'S WELDING
7007 N. HIGHWAY 889
FLAGSTAFF, AZ 86004
Phone: (928) 523-4557
GREG PIERCE
480-586-0774

P.O. #: NAU BRIDGE TEAM

FROM:
SHIPPER
PAGE STEEL
2040 INDUSTRIAL DRIVE
PO Box 1687
PAGE, AZ 86040
Phone: (928) 645-8826
SALESMAN: ROCK/DOUG
** DONATION **

EMERGENCY RESPONSE PHONE NO.

VEHICLE NUMBER

NO. SHIPPING UNITS	HM*	KIND OF PACKAGING, DESCRIPTION OF ARTICLES, SPECIAL MARKS AND EXCEPTIONS	WEIGHT (subject to correction)	RATE	CHARGES
3.000		HR ROUND 1/2"DIA. A-36 X 20'	40		0.00
7.000		BPE PIPE 1/2"(.84"OD) SCH40 A-53 X 21'	125		0.00
5.000		BPE PIPE 3/4"(1.05"OD) SCH40 A-53 X 21'	119		0.00
5.000		BPE PIPE 1"(1.315"OD) SCH40 A-500 *UNCOATED* X 21'	176		0.00
4.000		BPE PIPE 1-1/4"(1.66"OD) SCH40 *UNCOATED* X 21'	191		0.00

When transporting hazardous materials include the technical or chemical name for n.o.s (not otherwise specified) or generic description of material with appropriate UN or NA number as defined in US DOT Emergency Communication Standard (HM-126C).
Provide emergency response phone number in case of incident or accident in box above.

REMIT C.O.D TO ADDRESS
P.O. BOX 1687
2040 Industrial RD
PAGE, AZ 86040

Company Check OK? ______

COD AMT: $ 0.00

C.O.D FEE: $ 0.00
____PREPAID ____COLLECT

NOTE - Where the rate is dependent on value, shippers are required to state specifically in writing the agreed or declared value of the property.
The Agreed or declared value of the property is hereby specifically stated by the shipper to be not exceeding
$ ______ per ______

This is to certify that the above named materials are properly classified, described, packaged, marked, and labeled, and are in proper condition for transportation according to the applicable regulations of the Department of Transportation.
______ Signature

Subject to Section 7 of conditions, if this shipment is to be delivered to the consignee without recourse on the consignor, the consignor shall sign the following statement.
The carrier shall not make delivery of this shipment without payment of freight and all other lawful charges.
______ (Signature of Consignor)

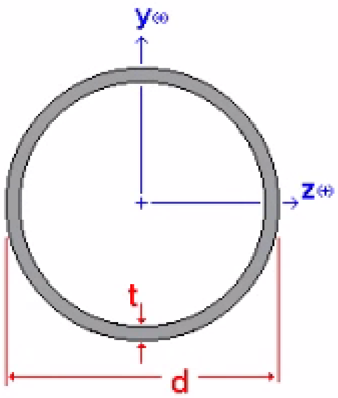
TOTAL CHARGES: $ 0.00

FREIGHT CHARGES
____PREPAID ____COLLECT
____3RD PARTY

Appendix D: Nucor Data Sheet

NOMINAL DIA OF PRODUCTS AND THREADS PERINCH	SAE GRADE 8	
	PROOF LOAD, LB.	TENSILE STRENGTH MIN, LB.
1/4 - 20	3,800	4,750
5/16 - 18	6,300	7,850
3/8 - 16	9,300	11,600
7/16 - 14	12,800	15,900
1/2 - 13	17,000	21,300
9/16 - 12	21,800	27,300
5/8 - 11	27,100	33,900
3/4 - 10	40,100	50,100
7/8 - 9	55,400	69,300
1 - 8	72,700	90,900
1-1/8 - 7	91,600	114,400
1-1/4 - 7	116,300	145,400
1-3/8 - 6	138,600	173,200
1-1/2 - 6	168,600	210,800

Appendix E: Member Shape Geometry



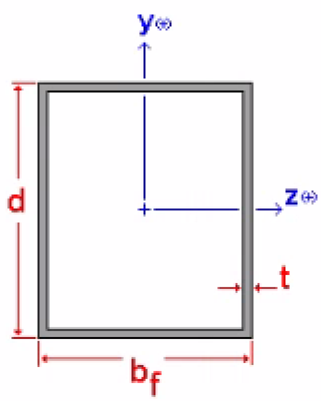
Shape Name: PIPE_1.0

Geometric Properties

d	1.315	in	t	0.124	in

Section Properties

Z	0.177	in^3	I_{yy}	0.083	in^4
Area	0.469	in^2	I_{zz}	0.083	in^4
J	0.166	in^4			



Shape Name: 1X1X16_HRA

Geometric Properties

d	1	in	t	0.12	in
b_f	1	in			

Section Properties

I_{yy}	0.056	in^4	Z_{yy}	0.14	in^3
I_{zz}	0.056	in^4	Z_{zz}	0.14	in^3
Area	0.422	in^2	J	0.082	in^4