Northern Arizona University
Department of Civil Engineering, Construction Management, and
Environmental Engineering

Final Design Report

2017-2018 Northern Arizona University Steel Bridge Team

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CENE 486
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ACKNOWLEDGEMENTS

The Steel Bridge Team acknowledges the individuals and companies who have aided the Steel Bridge Team in the completion of their project. The Steel Bridge Team recognizes the services of Page Steel, K-Zell Metals, Mingus Union High School Welding, Copper State Nut and Bolt Co. The Steel Bridge Team also received technical guidance of Thomas Nelson and Mark Lamer. Page Steel donated all steel tube that was used to construct the steel bridge, K-Zell Metals provided steel plate and laser-cutting services, Copper State Nut and Bolt Co. supplied nuts and bolts, and Mingus Union High School Welding provided all welding services required for the steel bridge. Thomas Nelson and Mark Lamer provided technical feedback and support on the teams' analysis, design, fabrication, and construction methods.

1 PROJECT INTRODUCTION

1.1 PURPOSE OF PROJECT

The purpose of the Steel Bridge Project is for students to create a 1:10 scale steel bridge that is to be used in a feasibility study for the design of a limited access, short span bridge for the Burgeon County Transportation Commission (BCTC). BCTC hopes to identify a bridge design to serve their growing populations. The bridge is intended to carry only mass transit, bicycles, pedestrians, and emergency vehicles, similar to the Portland's Bridge of the People.

The bridge is to be designed, fabricated, and constructed in accordance with the rules and guidelines of the 2018 National Student Steel Bridge Competition (NSSBC) in order to compete in the event. The NSSBC is open to universities across the United States as well as some regions of Canada and other select international regions. The Steel Bridge Team will be competing against other teams in the Pacific Southwest region. This includes the states of Arizona, California, Nevada, and Hawaii. Each bridge submitted for competition will be judged according to stability, strength, serviceability, construction economy, structural efficiency, and aesthetics [1].

1.2 THE NATIONAL STUDENT STEEL BRIDGE COMPETITION

The NSSBC is a competition that occurs annually at both the regional and national levels. The Steel Bridge Team will be participating in the regional competition at the Pacific Southwest Conference (PSWC), held April 12-14, 2018 at Arizona State University in Tempe, AZ. During this time, the team will compete in areas of structural efficiency, construction economy, lightness, stiffness, display, and aesthetic appeal. To place well and advance to the national level, each team must perform exceptionally in a majority of the categories listed above.

1.2.1 2018 NSSBC RULES

The rules for the 2018 NSSBC involve material and component specifications, structural specifications, functionality, usability, inspectable qualities, construction regulations, pre-construction conditions, and safe construction practices [1]. Sub-sub-section 1.2.2 outlines the categories considered as criteria for scoring the bridges in the competition, and will be used by the Steel Bridge Team as the constraints and limitations of the project.

1.2.2 CATEGORIES OF SCORING

The scoring of the steel bridge will be dependent on the categories provided in the rules for the 2018 NSSBC. These categories include display, construction speed, lightness, stiffness, construction economy, structural efficiency and overall performance [1].

1.2.2.1 Display

The score related to display is dependent on the appearance of the bridge, considering balance proportion, elegance, and finish. The bridge is also required to permanently display the name of the university on the structure. Lastly, a poster must be displayed that will describe the design process and comply with the poster rules found in Section 6.2.1.3 of the 2018 NSSBC Rules [1].

1.2.2.2 Construction Economy

The scoring for construction economy is dependent on total time in minutes, number of builders and any incurrence of load test penalties. The formula used to calculate this score is found in Section 6.2.5 of 2018 NSSBC Rules [1].

1.2.2.3 Structural Efficiency

The scoring for structural efficiency is dependent on the bridge weight, aggregate deflection, and load test penalties. Specifications of scoring for lightness and stiffness are outlined in Sections 6.2.3 and 6.2.4 of the 2018 NSSBC rules, respectively. The formula used to calculate this score is found in Section 6.2.6 of 2018 NSSBC Rules [1].

1.2.2.4 Overall Performance

The overall performance score is the sum of structural and construction costs. The team with the lowest score achieved will be placed first in the 2018 NSSBC.

1.3 Objectives of the Project and Unique Deliverables

The objective of the Steel Bridge Project is ultimately to develop structural engineering skills and an understanding of the processes required of accelerated bridge construction. Students involved in this project will obtain these skills through the completion of the various tasks described in the sub-sub-sections below.

1.3.1 Structural Design and Analysis

The Steel Bridge Team will develop the design for the bridge to be used in competition at the 2018 Regional Student Steel Bridge Competition. The task of designing is to include the selection of the type of bridge structure, determination of connections that will be used, selection of member sizes and shapes, as well as grades of steel that will be used in the bridge. In completion of each of these design objectives, the Steel Bridge Team will ensure that all aspects of the design adhere to the 2018 NSSBC Rules.

In accordance with the design of the bridge, the Steel Bridge Team will model and analyze the expected performance of the bridge throughout the design process, making iterations and modifications as necessary to achieve a more effective and efficient design. The Steel Bridge Team will utilize the structural modeling capabilities of RISA 3D to model the performance of the bridge.

1.3.2 Shop Drawings

The Steel Bridge Team will also prepare shop drawings that may be used to direct the fabrication and construction of the bridge. These shop drawings will include all dimensions and details needed to direct the fabrication and construction of the bridge. The Steel Bridge Team will use AutoCAD to prepare all shop drawings for the bridge.

1.3.3 Material Research and Selection

The Steel Bridge Team will research various grades of steel that will be available for use in the construction of the bridge. The various grades of steel will be analyzed according to their material properties and their intended use within the bridge. The Steel Bridge Team will consider the cost of a given grade of steel, the availability of the steel, the strength of the steel, and the expected cross-sectional area needed for the various members of the bridge.

1.3.4 Connection Analysis and Testing

The Steel Bridge Team will perform analysis and design of all connections that will be used in the bridge and testing of critical connections. The connections will be designed to maximize rigidity at joints and facilitate an efficient construction time. All connections will be designed in accordance with the American Iron and Steel Institute (AISI) North American Specification for the Design of Cold-Formed Steel Structural Members (AISI S100) using output obtained from the RISA 3D model [2].

1.3.5 Fabrication

The Steel Bridge Team intends to use the services of Mingus Union High School Welding to perform all required welding. Additionally, the Steel Bridge Team has partnered with K-zell Metals to acquire all necessary connection plates and laser cutting services. The Steel Bridge Team has ensured that all components of the bridge are fabricated to the appropriate specifications per the approved shop drawings. Any components that are not fabricated to the predetermined design specifications will be analyzed with respect to rule compliance, steel code compliance, and bridge functionality before being implemented or rejected.

1.3.6 Construction

The Steel Bridge Team will develop a strategy for completing the construction of the bridge with respect to the specifications of the 2018 NSSBC Rules. The Steel Bridge Team will decide the amount of construction workers to be used, the tools to be used, and the order in which the construction workers will assemble the various components of the bridge. After determining the accelerated bridge construction methods to be used, the Steel Bridge Team will practice constructing the bridge. The goal for the Steel Bridge Team will be to minimize construction errors and the overall time taken to construct the bridge. The Steel Bridge Team will construct their bridge at the 2018 PSWC.

2 STRUCTURAL ANALYSIS AND DESIGN

The structural analysis and design of the bridge was separated into conceptual and detailed design phases. Conceptual design focused on developing a strategy with which to develop a competitive bridge design. In the conceptual design phase, the Steel Bridge Team considered various bridge types, bridge geometries, and connection types in order to arrive at the final bridge type and geometry.

Detailed design involved detailing all dimensions of the bridge, all member sizes and grades, and all connections. Detailed design was performed using RISA 3D structural modeling software and the 2018 AISI North American Specification for the Design of Cold-Formed Steel Structural Members [2]. In addition, the bridge was designed to withstand any of the possible load combinations given in the 2018 NSSBC Rules [1].

2.1 Conceptual Analysis and Design

The conceptual analysis and design may be separated into four major categories; bridge type, bridge geometry, lateral-force-resisting-system (LFRS), and connection types. Each of these categories are discussed in the following sub-sub-sections.

2.1.1 Preliminary Bridge Type

The Steel Bridge Team considered two bridge types for the design; a truss bridge and a beam bridge. The strengths and weaknesses of each alternative with respect to the goal of the competition are discussed below.

2.1.1.1 Beam Bridge

The primary advantages of a beam bridge are simplicity and ease of construction. In general, beam bridges will require less members and connections than truss bridges. For this reason, beam bridges are advantageous because they will likely achieve a faster construction time than a truss bridge will. Fewer members and connections may also contribute to less demands in the fabrication phase.

The primary disadvantage of a beam bridge is more inefficient use of material, resulting in less stiffness. Beam bridges are designed to resist load in bending, meaning that the maximum stresses in the bridge will occur only at the top and bottom of the beam cross-section, with no stress occurring along the neutral axis of the beam. Material may be concentrated towards the top and bottom of the cross-section, but all of the material will still not be stressed to its potential. Additionally, beam depth is limited to six inches by the constraints of the competition, restricting the amount of beam depth that may be used.

2.1.1.2 Truss Bridge

The primary advantages of a truss bridge are more efficient use of material and greater stiffness due to the potential for a deeper bridge. Truss members are designed to act primarily in tension or compression, meaning that all points in the cross-section of a truss member will be stressed equally during loading. Truss elements more efficiently distribute load and therefore allow for less material to be used while still providing sufficient strength and stiffness.

The primary disadvantage of a truss bridge is the complexity due to a greater number of members and connections. This disadvantage most importantly impacts the construction time of the bridge, but also has an effect on the fabrication of the bridge. During construction, a truss bridge will likely require more members to be aligned and more bolts to be inserted than a beam bridge would. During fabrication, the importance of minimizing dimensional tolerances is heightened, as issues due to slipping joints will be compounded as the number of connections increases.

2.1.1.3 Bridge Type Decision

The Steel Bridge Team decided to use a truss bridge for the design. This decision was made due to a truss bridge's theoretical stiffness and lightness.

Due to the allowed building envelope specified by the 2018 NSSBC Rules, the Steel Bridge Team was able to use a truss extending over the deck of the bridge or under the deck of the bridge [1]. This gave the Steel Bridge Team the allowance to develop a wide variety of design solutions.

2.1.2 Preliminary Truss Geometry

The Steel Bridge Team analyzed three alternative truss geometries before selecting the final geometry of the bridge. Each of these alternatives are described below.

2.1.2.1 Double Howe (KK) Truss

The geometry of the Double Howe (KK) Truss was considered due to its simplicity and effectiveness, as proven in its historical use for roof structures. A truss with a geometry such as this could be designed to meet the parameters of the competition with the use of 26 members and 18 connections per truss and constructed with relative ease. However, the design was not chosen due to the required lengths of each of the designed members. The 2018 NSSBC Rules states that all members must be less than three feet in their longest dimension, meaning that mid-chord connections would be needed for chords longer than three feet in length. Additionally, the unbraced length of these chords would be likely to result in the design being controlled by buckling. In the geometry shown in Figure 2-1, the top chords are approximately six feet in length.

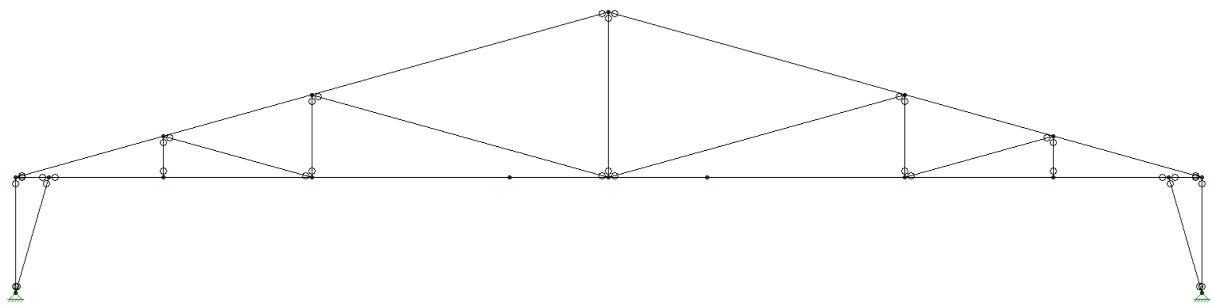

Figure 2-1: Double Howe (KK) Truss Alternative Elevation View

2.1.2.2 Parker (K) Truss

The Parker (K) Truss geometry was considered due to its ability to maximize the use of the allotted design envelope provided within the 2018 NSSBC Rules, while segmenting the members of the bridge to not exceed the maximum length requirement of three feet [1]. As the envelope provided within the 2018 NSSBC Rules allows for the bridges decking, or stringers, to be a maximum of 1'-11" above grade, and allows the bridge to extend vertically to 5'-0" above grade, a total of 3'-1" is allotted for the Parker Truss height. The maximization of this height in combination with the arched, angular segmentation, allows the bridge to maintain rigidity and strength. However, in order to comply with all parameters of the 2018 NSSBC rules, the bridge requires the use of 33 members and 20 connections for each complete truss. Additionally, with the materials and equipment available at the Northern Arizona University CECMEE Field Station, accuracy would be jeopardized in fabricating the 18 angular connections. Figure 2-2 provides visual representation of the Parker Truss design.

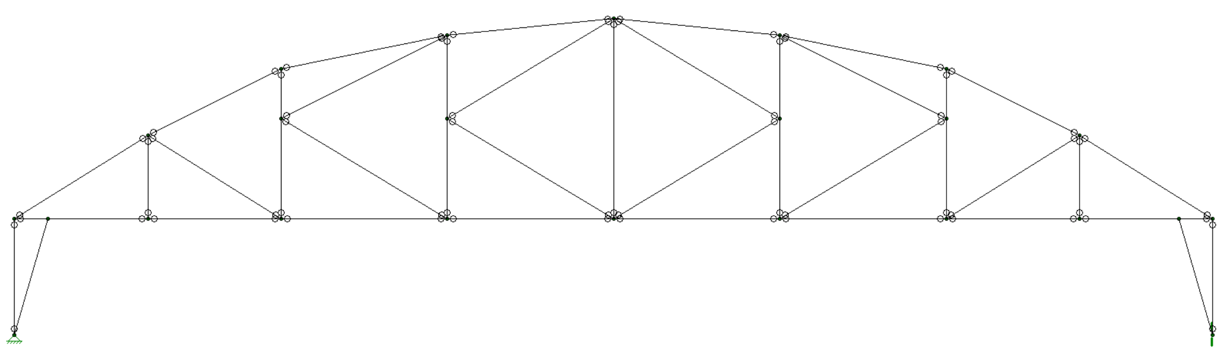

Figure 2-2: Parker (K) Truss Alternative Elevation View

2.1.2.3 Underslung Howe Truss

The Underslung Howe Truss geometry was considered and ultimately selected due to its superior ease of construction and fabrication compared to the other considered alternatives. The alternatives with trusses extending over the deck of the bridge, while stiffer, are much more complex and would likely result in more complications in fabrication and construction of the bridge. The underslung truss bridge takes advantage of the given building envelope allowance of space underneath the deck of the bridge, which allows for 1' – 3 ½" of depth below the deck of the bridge. This truss geometry requires 21 members and 12 connections in each truss. Figure 2-3 shows a side view of the underslung truss bridge alternative.

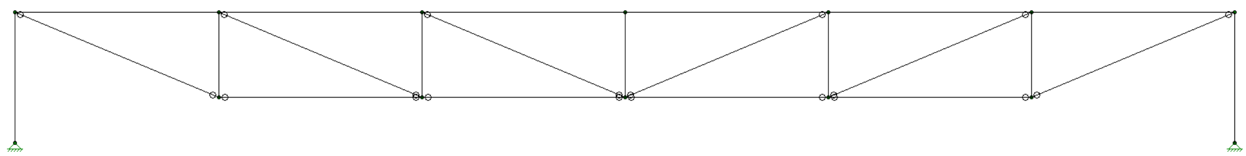

Figure 2-3: Underslung Howe Truss Alternative Elevation View

2.1.3 Preliminary Lateral Stability System

During conceptual design of the lateral-force-resisting-system (LFRS), the Steel Bridge Team determined that the system would need to resist both twisting of the truss structures and swaying of the bridge under lateral loading. To provide resistance against twisting of the truss structures, the Steel Bridge Team determined to design cross-bracing frames that would brace the truss verticals on each side of the bridge to each other. To provide resistance against swaying under lateral loading, the Steel Bridge Team decided to design lateral diagonal bracing that would transfer load from the point of application of lateral loading to the footings.

2.2 Detailed Analysis and Design

2.2.1 Computer Modeling

The Steel Bridge Team used RISA 3D structural analysis software to analyze and aid in the design of the bridge. The model was created primarily using members connected by pin-pin connections to model the behavior of a truss. Fixed connections were used where the Steel Bridge Team intended to use moment resisting connections, such as in the cross-frames in the LFRS and in the connections between the footings and the end of the top chords of the top truss.

To aid in the design of the bridge, the Steel Bridge Team utilized the unity check feature on RISA 3D, which displays a ratio of the experienced stress to the maximum allowable stress of a given member. Member cross-sections and grades were selected, the calculations were performed for all load cases considered, and the design was iterated according to the results. The final RISA 3D model can be found in the attached RISA 3D file “Final Design.r3d”.

2.2.2 Load Combinations

The bridge model was analyzed in RISA 3D under all possible load cases included in the 2018 NSSBC Rules. In addition to the load cases shown in the 2018 NSSBC Rules, the bridge was analyzed with all possible intermittent loading phases. For example, the bridge was modeled under loading of only one of the two loading locations and under loading of both loading locations, for a total of 18 total vertical loading cases. As the load case values were already known, additional load factors were not applied. In addition to the vertical loading cases, the bridge was also analyzed under the lateral load tests described in the 2018 NSSBC Rules.

2.2.3 Analysis and Design of Member Cross-Sections and Steel Grades

Truss member cross-sections were determined with respect to the internal forces that are expected to occur in the truss members and the constructability of the bridge. The acceptability of trial member cross-sections was determined using the unity check feature on RISA 3D.

Steel grades were determined based on allowable stresses and material availability. For all members included in the truss, the Steel Bridge Team planned on using a minimum material strength of 46 ksi. Members in the LFRS were expected to see small amount of stress, so the Steel Bridge Team deemed that a material strength as low as 36 ksi would be acceptable for these members.

The team utilized the 13th Edition Manual of Steel Construction (AISC Steel Manual) to check the maximum compression force allowed before buckling would occur. This parameter was checked in accordance with section E1-E5 of the AISC Steel Manual. It was found that there would be no problems with buckling within the compression members. The results of this calculation can be found in attached excel file “BucklingStressCalculator.xlsx”.

RISA 3D is capable of providing deflection calculations with respect to the programmed load cases without complex connection modeling. As result, the team utilized pin-pin boundary features to conservatively estimate the deflection values under each load case. A maximum theoretical deflection of 0.42” was calculated at mid-span under load case 4.

2.2.4 Analysis and Design of Connections

2.2.4.1 Gusset Connections

The gusset plate connections were analyzed and designed according to the AISI S100. The following parameters shown in Table 2-1 were checked for strength according to each parameter’s respective Section within the AISI S100 [2].

Table 2-1: Connection Calculation Design Code References

Parameter	Section of AISI S100 Used
Tension Capacity of Plate	D1
Shear Capacity of Bolt	Table J3.4-1
Block Shear	J6.3
Tensile Rupture	J6.2

2.2.3.1.1 Tension Capacity of Plate

The tension capacity of the gusset plates were calculated in accordance with section D1 of the AISI S100. This calculation took into account the reduced area due to bolt holes. Results of this calculation can be found in attached excel file “Connection_Calcs_Final.xlsx”.

2.2.3.1.2 Shear Capacity of Bolt

The shear capacity of each bolt was calculated in accordance with section J3.4 of the AISI S100. This calculation did not take into account the additional diameter added to the bolt by threads, making it a conservative evaluation of the shear strength of each bolt used in connection. The results of this calculation can be found in attached excel file “Connection_Calcs_Final.xlsx”.

2.2.3.1.3 Block Shear

The block shear capacity of each gusset plate connection was calculated in accordance with section J6.3 of the AISI S100. This calculation was done acknowledging how many different planes existed where block shear would be present during loading and resulted in a very high capacity. Additional discussion of this will be completed in section 2.5.6.6 below. The results of this calculation can be found in attached excel file “Connection_Calcs_Final.xlsx”.

2.2.3.1.4 Tensile Rupture

The tensile rupture capacity of each gusset plate connection was calculated in accordance with section J6.2 of the AISI S100. This calculation was performed on all members that were known to be in tension excluding diagonal lateral bracing. The reason for this connection being excluded will be discussed in section 2.2.4.4 below. The results of this calculation can be found in attached excel file “Connection_Calcs_Final.xlsx”.

2.2.3.1.5 Compression Capacity

The AISI S100 does not directly contain a section regarding compression capacity of plated connections. However, it was decided by the team that the connection’s compression strength was less critical due to the fact that the members in compression were bearing on one another. Therefore, there will be no capacity of the plates in compression found in the calculation sheets provided.

2.2.3.1.6 Discussion on Factor of Safety in Connections

Prior to designing the gusset plate connections used within the project, the team came to a unanimous decision that connections had to be strong and stiff enough to ensure the connections would not yield when fully engaged under loading. Consequently, the gusset plates were originally designed conservatively using the strength values of the plate strength provided by Page Steel; roughly 36 ksi. However, when the team received news that K-zell Metals, the company that donated laser cutting services, was going to donate the steel plate as well, the factor of safety (FOS) jumped from the original values to a considerably higher FOS. The plate provided by K-zell Metals was roughly 62 ksi. The largest factor of safety that can be found in the plate connections is in block shear. The factor of safety presented in this connection parameter was roughly 11. While the smallest factor of safety in the connections was present in the bolts themselves. Each bolt had a factor of safety of 2.35 without taking into account any shear strength that would be included due to the threads.

2.2.4.2 Moment-Resisting Footing-Chord Connections

The connections between the outermost top chords of the truss and the footings were designed to resist moment in order to increase the stiffness of the bridge. This type of connection was achieved through the use of an 11ga steel plate welded to the top chord that would connect to the footing through a bolted connection, as seen in Drawing S05 in "Shop Drawings_2018 NAU STEEL BRIDGE.pdf". The welds connecting the plate to the top chord are oriented such that a force couple will be developed in the weld group to resist the moment generated at the connection. The bolted connection of the plate to the footing consists of two bolts in order to create a force couple between the bolts to resist the moment generated.

2.2.4.3 Lateral Bracing Cross-Frame Connections

The lateral bracing cross-frame connections were designed to act as a tension-compression couple between the two trusses to prevent any twisting that may occur in the trusses under loading. The cross-frames were designed as rigid members that would be connected to the truss verticals through bolted connections.

2.2.4.4 Diagonal Lateral Bracing Sleeve Connection

The diagonal lateral bracing members were designed to resist lateral loading of the bridge to ensure that the deflection of the bridge under lateral loading is kept within the allotted bounds.

The diagonal lateral braces are required to span approximately 3'-8" and were thus designed as two individual members to be connected to each other at their ends in order to meet the maximum member length of 3'. The Steel Bridge Team designed these connections as sleeves that would extend from one piece of a diagonal lateral brace to the other to be connected as a bolted connection.

The diagonal lateral braces were designed to connect directly to the top of the lateral bracing cross-frames, and will thereby transfer force as a Warren Truss acting in the horizontal plane of the bridge.

The capacity of each of these members was determined using RISA 3D modeling software. However, the capacity of the bolted connection between them was not calculated because of the minimal amount of force that was present under all load combinations possible. From the modeling in RISA 3D, the team was aware that these members would only undergo approximately 65 pounds of force whether this be compression or tension. Referring to the tensile capacity of the gusset connections discussed above, it was deemed unnecessary to run the calculations for such a small magnitude of force that would be present in the connection.

3 FINAL DESIGN RECOMMENDATION

3.1 Final Design

In order to optimize the use of the envelope without jeopardizing the scoring in the weight, deflection, and construction economy criteria, the 2018 NAU Steel Bridge team has selected the Underslung Howe Truss bridge design. In order to tie the two trussed bridge profiles together, a Warren Truss lateral bracing system was designed. Figure 3-1 provides visual representation of the selected bridge design as modeled through the RISA 3D program.

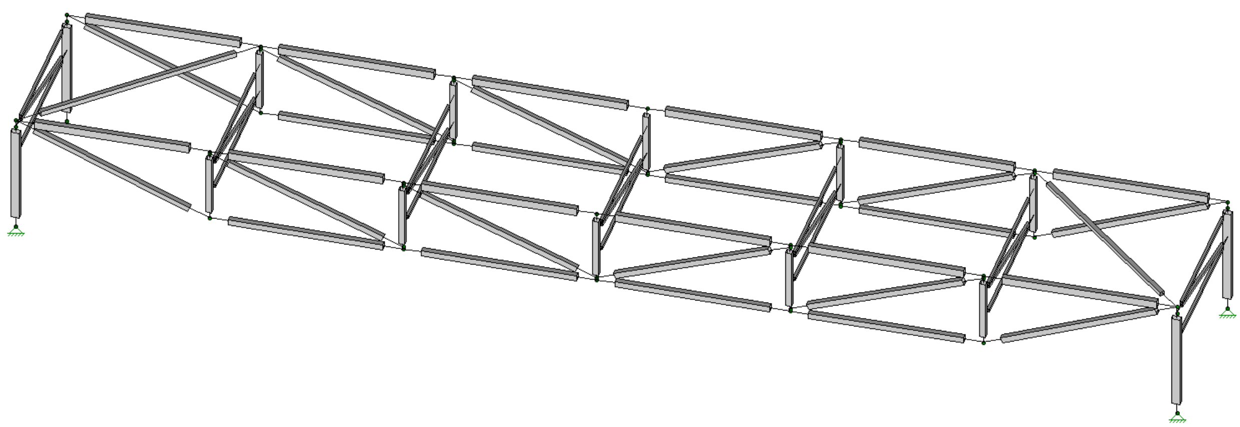

Figure 3-1: Isometric View of Final RISA 3D Model

In total, the bridge stands 1'-10 ¾" tall at the height of the decking, or stringers. The underslung truss is 1'-3" in height, therefore elevating the bridge 7 ¾" above the surface at center-span. The final length of the bridge is 17'. Each side of the bridge consists of twenty-three members and has twelve gusset plate connections. The lateral bracing system consists of eleven members and has sixteen connections. Both of the lateral bracing connections are c-channel connections, while the remaining eleven are plate connections located at each lateral cross-frame. The shop drawings shown under "Shop Drawings_2018 NAU STEEL BRIDGE.pdf" provide complete visual representation of each aspect of the final design.

3.2 Shop Drawings

To display and communicate the final design of the bridge, the Steel Bridge Team has prepared and attached final shop drawings of the bridge under the filename "Shop Drawings_2018 NAU STEEL BRIDGE.pdf".

4 FABRICATION

4.1 Preparation and Cutting of Steel Members

The following sub-sub-sections describe the work accomplished by the Steel Bridge Team in making the initial preparations of the steel for the rest of the fabrication process.

4.1.1 Cleaning of Surface of Steel Members

All steel used to construct the bridge was donated by Page Steel. After receiving the steel from Page Steel, the Steel Bridge Team cleaned the grease and oil from the surface of the steel with shop rags and dish soap. The Steel Bridge Team did this to facilitate the fabrication of the bridge, allowing them to mark and work with the pieces more easily during the sizing and welding processes.

4.1.2 Cutting and Initial Grinding

All members were measured with a measuring tape and marked with soapstone chalk. After all members were measured according to the shop drawings, they were cut using either a chop saw or band saw. In general, members were cut slightly longer than specified and were grinded down to ensure the precise dimension requirements would be met for all members.

4.2 Fabrication of Connections

The connections along the profile of the bridge were designed as typical gusset plate connections. The lateral bracing connections varied from sleeve connections to additional variations of gusset plate connections. The services of K-Zell Metals, Inc. were utilized to laser cut the plates out of steel plate with a yield strength of 60 ksi. K-Zell Metals guarantees a tolerance of +/- 0.004” on all laser cutting services, which provides sufficient accuracy at the scale to which the 2018 NAU Steel Bridge is to be built.

4.3 Welding

As the bridge design requires the connections to be welded accurately to each appropriate member, the services of Mingus Union Welding were utilized to complete the welding process. The crew consisted of six individual welders utilizing the tungsten inert gas (TIG) welding technique. Ultimately, the welding crew was able to weld all necessary connections within a 7 hour time period. Additional tack welding was required to be performed by the Steel Bridge Team in order to weld each of the bridge’s nuts to their respective bolt holes. This process will serve to reduce the construction time of the bridge during competition and reduce the potential for penalties.

4.4 Finishing

In order to ensure the selected design would perform in all aspects of the 2018 NSSBC, the members of the bridge were lightly painted. The utilization of a minimal color palette served to increase the overall aesthetic of the bridge without losing focus on the design's steel composition. A standard paint and primer spray was used to complete the finishing process in house. Powder coating techniques were considered as a method of providing high quality coloration, but were ultimately avoided due to the thickness the powder coating would add to each member.

5 CONSTRUCTION

5.1 Determining Construction Plan

To determine the most efficient construction plan for use at competition, the team had to employ trial and error to determine what methods worked and which did not. The team had to decide which pieces would be put together first, as well as how many people would be on the construction crew.

5.1.1 Number of Builders

Because construction time directly affected the scoring of the bridge in the construction time and construction economy categories, it was clear that the team needed to utilize the fewest amount of construction workers and get the fastest construction possible. The team had a total of six construction practice sessions in which the bridge was constructed with two, four, and six builders on the construction team.

The run with two individuals only was meant as a preliminary run to ensure that all pieces of the bridge were fitting together as they should and the time was recorded, but is irrelevant due to the fact that a minimum of four members was required to construct the team's bridge.

The practice with six individuals on the construction team resulted in a time of 01:03:28 (HH:MM:SS). This time was less than when attempting to construct with only two individuals, but the time was still passed the time constraint of thirty-minutes. The team ultimately decided that having so many individuals had a more negative impact on the construction time than they had hoped, and thus did not use this construction team at competition.

5.1.2 Order of Construction

Using only four builders for the construction team meant that someone would have to support the bridge at all times while parts were attached. In order to minimize the time of the construction crew holding the bridge, the team decided it was beneficial to connect either the top or bottom chord at mid-span as quickly as possible and then fill in the remaining pieces once the bridge could stand on its own without touching the river at mid-span. The team initially tried fitting the top chords together and then filling in diagonals and bottom chord members. However, this resulted in a problem with some pieces not fitting quite as readily as the team would have hoped, so after the first three attempts, this method was dismissed as not viable.

The team then attempted construction with a similar idea, except connecting bottom chords and diagonals first before filling in the top chord members. This method worked the best overall. As the bottom chord was completed first, it made setting the top chord in considerably easier due to the fact that the individuals would not have to support the top chord members as they fit them into place; they would be held up by the gusset plate connections that were already attached at the bottom. Employing this method, the horizontal lateral bracings were attached as necessary to ensure stability of the bridge once connected at mid-span. The diagonal lateral bracing was attached as the final member of the construction process.

5.2 Construction Practice

Once the Steel Bridge Team determined the appropriate order of construction, the team began construction practice. The majority of construction practices were done with a construction team of four builders, which resulted in the best practice time the team had achieved of 00:21:47. This time was obtained through the use of hand tools, whereas the official 2018 NSSBC rules allow for the use of power tools. During practices, the team had decided that Ian, Isaac, Manny, and Taylor would be the four builders doing the construction at competition as a result of achieving the best practice time with this orientation of team members.

6 SUMMARY OF ENGINEERING COSTS

6.1 Personnel Costs

The following sections include employee billing rates, labor hours required by the Steel Bridge Project, and a breakdown of the labor costs for the Steel Bridge Project.

6.1.1 Billing Rates

Table 6-1 shows the staff position who worked on the Steel Bridge Project along with their billing rates.

Table 6-1: Project Team Positioning

Staff Member	Abbreviation	Rate ($/hr)
Principle Engineer	PRE	175
Project Engineer	PJE	135
Project Manager	PM	150
Engineer in Training	EIT	75
Intern	INT	45
Administration	ADM	60
Drafter	DRF	60

6.1.2 Labor Required

Table 6-2 shows the total number of hours spent by the Steel Bridge Team to complete the Steel Bridge Project and the cost associated with this labor.

Table 6-2: Division of Labor Costs

Task	Number of Hours							Task Total Hours	Task Total Cost ($)
	PRE (1)	**PJE (1)**	**PM (1)**	**EIT (4)**	**INT (4)**	**ADM (1)**	**DRF (2)**		
1: Research	1		2	10	20			**33**	$ 2,125.00
2: Fundraising			2	2	4			**8**	$ 630.00
3: Analysis	6	6	6	225	0	0	0	**243**	$19,635.00
3.1: Member Analysis	2	2	2	75				81	$ 6,545.00
3.2: Connection Analysis	2	2	2	75				81	$ 6,545.00
3.3: RISA Model	2	2	2	75				81	$ 6,545.00
4: Fabrication	3	7.5	6	146	40	0	0	**202.5**	$15,187.50
4.1: Member Preparation	1	2.5	2	50	20			75.5	$ 5,462.50
4.2: Connection Preparation	1	2.5	2	40	20			65.5	$ 4,712.50
4.3: Professional Welding	1	2.5	2	56				61.5	$ 5,012.50
5: Construction Practice	1	10	2	30	20			**63**	$ 4,975.00
6: Competition	3	0	0	28	40	0	0	**71**	$ 4,425.00
6.1: Transportation	0.5			24	24			48.5	$ 2,967.50
6.2: Display	0.5				4			4.5	$ 267.50
6.3: Construction	1			4	4			9	$ 655.00
6.4: Loading	0.5				6			6.5	$ 357.50
6.5: Score Reporting	0.5				2			2.5	$ 177.50
7: Displaying Results	3	0	0	58	4	0	50	**115**	$ 8,055.00
7.1: UGRADS				16				16	$ 1,200.00
7.2: Final Design Report	1			28				29	$ 2,275.00
7.3: Drawings	2			8			50	60	$ 3,950.00
7.4: Website				6	4			10	$ 630.00
8: Project Management	8	0	11	60	60	2	8	**149**	$10,850.00
8.1: Meetings	4		4	60	60		8	136	$ 8,980.00
8.2: Scheduling	2		5			1		8	$ 1,160.00
8.3: Budgeting	2		2			1		5	$ 710.00
Staff Total	25	23.5	29	559	188	2	58	**Total Hours:**	**884.5**
Staff Total Cost ($)	$4,375.00	$3,172.50	$4,350.00	$41,925.00	$8,460.00	$120.00	$3,480.00	**Total Cost:**	**$65,882.50**

*Note: The number of staff used is indicated by the number in parentheses to the right of the staff abbreviation (i.e. EIT (4) signifies that 4 EIT's were used)

6.1.3 PERSONNEL COST SUMMARY

The total labor cost for the Steel Bridge Project is $65,882.50 with 884.5 hours of labor used. The cost and hours projected in the Project Proposal are $54,670.00 and 728 hours, respectively. This difference is due to the fact that the design, fabrication, and documentation required by the project all took significantly longer than expected. The team spent more time performing analysis and design than expected during the design and analysis phase of the project and spent more time cutting, grinding, and welding members of the bridge than expected during fabrication. The major difference in the time required for documentation is that it took the Steel Bridge Team approximately 60 hours to complete the shop drawing of the bridge, where they had anticipated that it would take them about 25 hours to complete the shop drawings in the Project Proposal.

6.2 MATERIAL AND LOGISTICAL COSTS

Table 6-3 shows the anticipated and actual costs for material and logistical costs of the Steel Bridge Project along with the anticipated and actual labor costs.

Table 6-3: Anticipated and Actual Labor, Material, and Logistical Costs

Item	Cost per Unit ($/unit)	Units	# Units	Anticipated Cost	Actual Cost
Total Personnel Cost	-	-	-	$54,800	$65,833
Steel	~ 0.50	pounds	500	$250	$0
Welding	70	hours	45	$3,100	$0
Van Rental	80	day	4	$320	$320
Lodging	30	room/person/night	12	$360	$360
Total				**$59,000**	**$66,513**

The Steel Bridge Team proposed the project as if they would need to buy steel and welding services to complete the project. However, all steel and welding received by the team was donated.

7 SUMMARY OF ENGINEERING WORK

The Steel Bridge Team fell behind schedule during the design and analysis phase of the project but caught up and remained on schedule to meet fabrication deadlines throughout the remainder of the project. The amount of time required to become proficient in RISA 3D modeling was underestimated by the team and resulted in a major bottleneck for design during this phase of the project. The early setbacks that arose during the design and analysis phase of the project ultimately caused use to rearrange the team's design process in order to ensure a bridge design was finalized by our December 21st, 2017 deadline. Upon completion of the design, the ordering of bridge materials, completion of shop drawings, and finalization of fabrication remained on schedule throughout the remained of the project.

Name	Begin date	End date
Task 1: Research	9/5/17	4/12/18
Steel Design	9/5/17	12/22/17
Steel Fabrication	1/16/18	3/13/18
Construction Methods	3/14/18	4/12/18
Task 2: Fundraising	12/22/17	4/5/18
$500 Raised Total	12/22/17	12/22/17
$1000 Raised Total	1/15/18	1/15/18
$2000 Raised Total	4/6/18	4/6/18
Task 3: Analysis	9/19/17	12/21/17
Preliminary Analysis	9/19/17	11/6/17
Final Design	11/7/17	12/21/17
Place Steel Order	12/22/17	12/22/17
First Draft of Shop Draw...	12/23/17	12/23/17
Winter Break	12/22/17	1/14/18
Task 4: Fabrication	1/15/18	3/13/18
Preparation	1/15/18	2/12/18
Welding	2/13/18	2/13/18
Finish Fabrication	2/13/18	3/13/18
Task 5: Construction Pra...	3/14/18	4/13/18
Competition Poster Pre...	3/26/18	4/13/18
Task 6: Competition	4/14/18	4/14/18
Task 7: Displaying Results	3/19/18	4/29/18
Project Design Report	3/19/18	4/29/18
Project Website	4/16/18	4/29/18
NAU UGRADS Presen...	4/27/18	4/27/18
Task 8: Project Manage...	9/21/17	4/25/18
Course Deliverables	9/5/17	12/14/17
Background Research	9/5/17	9/14/17
Project Understanding	9/11/17	9/20/17
First Draft Project Sc...	9/20/17	10/17/17
Scope and Scheduling	10/17/17	10/31/17
Staffing	11/1/17	11/9/17
Webpage	11/13/17	11/30/17
Reflection	12/4/17	12/7/17
Final Proposal	11/27/17	12/14/17

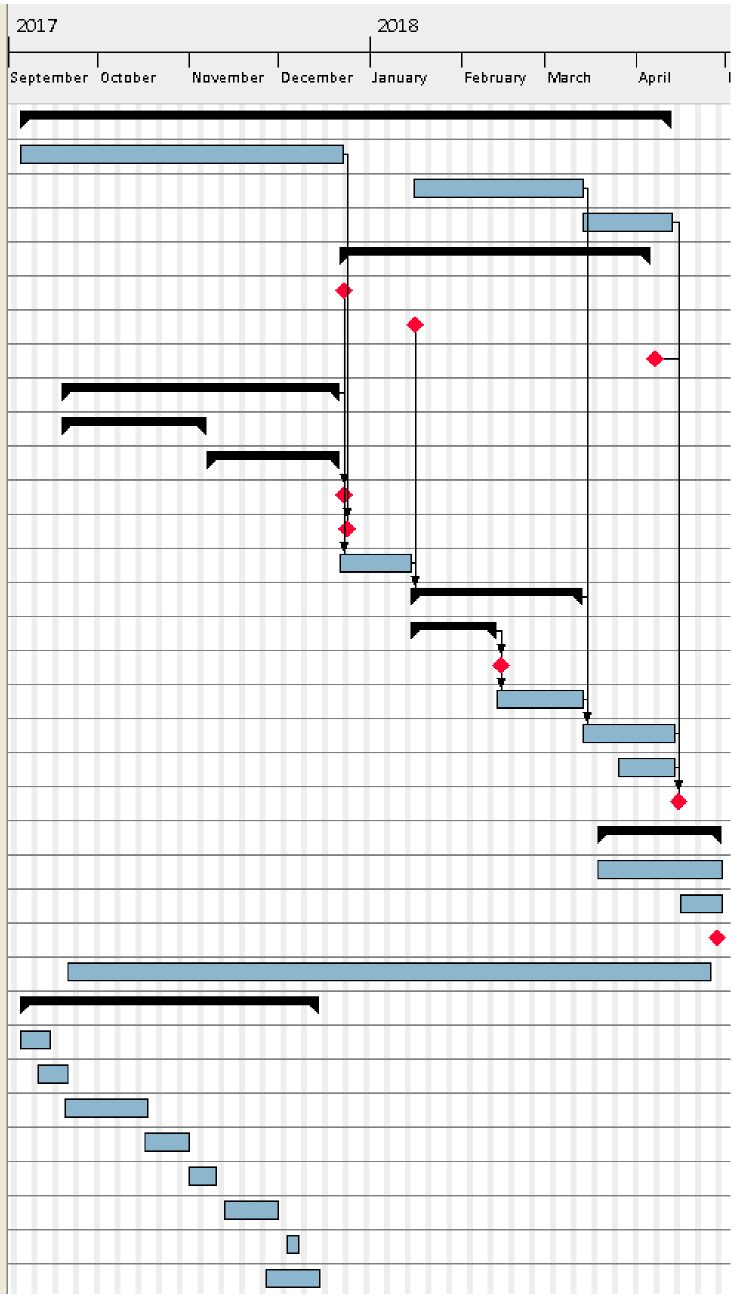

Figure 7-1: Original Project Schedule

8 COMPETITION RESULTS AND DISCUSSION

The Steel Bridge Team successfully competed at the Pacific Southwest Conference that occurred between April 12th and April 14th, 2018, at Arizona State University located in Tempe, Arizona. The Steel Bridge Team participated in both display on April 12th and the timed construction and loading competitions on April 14th. Display day involved the team erecting the bridge along with a poster that included information pertaining to the design of the bridge, such as a free body diagram, shear force diagram, bending moment diagram, and relevant accelerated bridge construction methods. The purpose of display day is so that judges can critique the bridge based on aesthetics, proportionality of the bridge, and overall relevance the poster to the designed bridge.

The remaining portions of the 2018 NSSBC that the Steel Bridge Team participated in were the timed construction and loading competitions. These competitions included tasks such as timed construction, bridge inspection, lateral loading, and vertical loading. The four builders on the construction team performed the timed construction at a level that was less than anticipated. As the bridge was being put together, the team was having difficulty with a bolt hole not lining up between the vertical member and the respective bolt hole on the footing connection. This resulted in a total building time of 00:38:10 before penalties and 3:07:45 after penalties. Post competition, the team inspected the area of issue and noticed that two of the vertical members had been mislabeled. The Steel Bridge Team believes that the mislabeling could have occurred during the painting process or during relabeling before timed construction.

Additionally, the other challenge that the Steel Bridge Team encountered during timed construction involved the safety of one of the builders on the construction team. As the team was midway through timed construction, the builder had sliced his hand on one of the sharp edges of the connection plates. Unfortunately, due to safety concerns, the team was asked to stop building, without penalty, as the team member was taken care of. Unfortunately, since the builder was unable to continue building, the Steel Bridge Team needed to substitute another builder into the construction zone to aid the team in finishing the bridge.

During the bridge inspection, the Steel Bridge Team incurred a weight penalty due to the vehicle template hitting the lateral cross-frame at the west end of the bridge. An additional weight penalty was incurred due to a building envelope violation of approximately 3/8" at one point on the bottom chord. These issues resulted in a weight penalty of an additional 118 pounds to the team's 161 pound bridge. Once the bridge was inspected, the bridge was moved to the loading location.

The first load that was applied was the lateral load of 50 pounds at approximately mid-span. This load was applied by attaching a piece of string around the top chord of the bridge and pulling with 50 pounds of force. Once the load was applied, the bridge passed the tolerance of 1" required in order to move on to the vertical loading.

To apply the vertical loading, the Steel Bridge Team was required to attach a plumb bob and two strain gauges to the bridge in order to read the overall deflection of the bridge once the load was fully applied. With respect to the load case determined the day of competition, the team was required to place the two steel grates 6'-8" (L1 location) and 1'-0" (L2 location) measured from the east end respectively. The team began the vertical loading process by first placing 100 pounds of pre-load to one steel grate and then continued to place the remainder of the load to the bridge. This brought the total load at that location to be 1500 pounds with the second location having a total load of 1000 pounds. Therefore, with the total vertical load of 2500 pounds on the bridge at the specified locations, the total aggregate deflection was calculated to be 0.70".

8.1 Scoring Results

Overall, the Steel Bridge Team is satisfied with the overall product and competition performance. The results acquired following the competition can be found in the table below:

Table 8-4: Pacific Southwest Conference 2018 Results

Scored Category	Value	Placement
Display	N/A	3rd place
Stiffness	0.7" aggregate deflection	4th place
Lightness	279 pounds	5th place
Structural Efficiency	$2,895,000	4th place
Construction Speed	187.75 minutes	9th place
Construction Economy	$65,712,500	8th place
Overall	**$68,607,500**	**8th place**

In reference to Table 6-4, the placement in areas of construction speed, construction economy, and overall are the lowest due to the challenges explained in section 9.0. However, the team placed within the top five rankings in all categories directly dependent on engineering and design capabilities.

9 CONCLUSION

The selection of the Underslung Howe truss enabled the team to place well in all structural based categories of the 2018 NSSBC. The team took a conservative approach in the design of the bridge, ensuring that all members and connections were designed with a significant factor of safety. While the team did not place as well as anticipated in the construction aspects of the 2018 NSSBC, the Underslung Howe truss remains practical and efficient in its use of material with respect to overall weight. Ultimately, through the generosity of the 2018 NAU Steel Bridge team sponsors, the design was successful in competition and in serving as model for future NAU Steel Bridge teams to come.

10 REFERENCES

[1] Student Steel Bridge Competition 2018 Rules, 1st ed., ASCE / AISC, 2017.
[2] American Iron and Steel Institute North American Specification for the Design of Cold-Formed Steel Structural Members, 2016.