PENNSTATE

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April 1, 2016

Kevin R. Kline, PE, District Executive
PennDOT Engineering District 2-0
1924 Daisy Street - P.O. Box 342
Clearfield County, PA 16830

Dear Mr. Kline:

Reference. PennDOT Engineering District 2-0, Statement of Work, subj: Concept Design for Vehicle Bridge over Spring Creek along Puddintown Road in College Township, Centre County, PA, dated September 11, 2015.

Statement of Problem. The bridge over Spring Creek along Puddintown Road in College Township, Centre County, PA has been destroyed by flooding. As a result, traffic has had to be rerouted about ten miles out of the way of its original route and is therefore causing a great inconvenience as well as a great concern for safety. The bridge was of very significant importance to local and commercial traffic, and it provided crucial access to Mount Nittany Medical Center.

Objective. A new bridge must be designed and implemented as quickly as possible.

Design Criteria. The bridge is to include standard abutments, no piers, medium strength concrete with a thickness of 0.23 meters, and no cables. The bridge must be able to support a load of 225kN or two AASHTO H20-44 trucks. The deck span will be 40 meters and the elevation should be 20 meters. Evaluate both the Warren and Howe through truss bridges.

Technical Approach.

Phase 1: Economic Efficiency.

The software Engineering Encounters Bridge Designer 2015 (EEBD 2015) was used as a template for making the bridge under all constraints. In the software the size and material of all members could be manipulated. Through a process of trial and error and trying different material and thickness combinations, the lowest cost bridge that supports itself, as well as the required load could be developed.

Phase 2: Structural Efficiency.

Following the design prepared in EEBD 2015, prototypes of the bridges were constructed using a maximum of 60 popsicle sticks and Elmer's glue for the joint connections. After all groups constructed the two bridges, the weight of each bridge was measured and recorded. Then the bridges were tested for the load at failure by using a block and chain to hang a bucket from the bridge, then adding weight to the bucket until the bridge failed. The bucket with the weight was then placed on a scale to measure the total

load at failure. Structural efficiency of each bridge was calculated by dividing the load at failure by the mass of the bridge.

Results.

Phase 1: Economic Efficiency. In accordance with Attachment 1, both bridges were designed member by member by the analysis of tension and compression forces within the members to produce a bridge that was the most cost efficient. The Warren truss bridge was overall the least costly to produce with a final value of $203,843.22.

Phase 2: Structural Efficiency. In accordance with Attachment 2, the bridge prototypes were constructed from a maximum of 60 popsicle sticks and Elmer's glue, then loaded to failure to calculate the structural efficiency of each bridge type. The Warren truss bridge had a higher structural efficiency rating than the Howe with a rating of 733.

Best Solution.

As shown by comparing Table 1 and Table 4, the total cost of the Warren through truss bridge is $10,511.71 cheaper than the total cost of the Howe through truss bridge. Additionally, the Warren through truss bridge has a greater structural efficiency (SE) when comparing the minimum, maximum, average, and geomean of each bridge's lab tested structural efficiency values shown in tables 7 and 8. Furthermore, the comparison of the overall design efficiency (found by dividing the costs of the bridges in tables 1 and 4 by the structural efficiency of the bridges found in tables 7 and 8) of the two bridges reveals that our Warren truss bridge has a design efficiency of $278.09/ SE whereas our Howe truss bridge has a design efficiency of $386.23/SE. The design efficiency for the Howe according to the geomean SE is $674.07 /SE whereas the Warren is $520.01/SE in which the Warren truss bridge offers a higher structural efficiency in addition to a lower design efficiency .The Warren truss bridge uses 5 different types of materials whereas the Howe truss bridge uses only 4. Referring to Table 1 and 4, the total cost of materials for the Warren truss bridge totals $95,643.22 which is $12,311.71 cheaper than the materials for the Howe truss bridge. The Howe truss bridge uses a total of 40 connections compared to the Warren's 42 connections, causing the Howe connections to cost $800 less than the Warren connections. Additionally, the Howe requires 13 products and the Warren requires 14. At $1000 per product, the total cost of the products for the Howe is $1000 less than the total cost of the products for the Warren. The site cost for each bridge is the same at $77,400. The net cost of each bridge warrants that the Warren is cheaper overall and more easily constructable than the Howe truss bridge. Taking all of these variables into account, the Warren Truss bridge is the best solution to the problem.

Conclusions and Recommendations.

After completing our evaluation of the structural efficiency, economic efficiency, and estimated build cost, is it recommended that PennDOT proceed with the Warren through truss design for the replacement bridge over Spring Creek. Beyond our initial investigation, to ensure a severe flood event does not undermine the integrity of the new structure in the future, it is recommended that a geotechnical engineer is hired for a site investigation, Their findings are imperative, as they could reveal issues in the surrounding area that emerged after the flood event that could worsen over time. These informative

findings could influence the Final Design, and should be conducted prior to design drafting and construction.

Respectfully,

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ATTACHMENT 1

Phase 1: Economic Efficiency

Howe Truss.

To evaluate the Howe truss bridge for its economic efficiency, the program Engineering Encounters Bridge Designer 2015 was used. The program has built in functions that calculate the overall cost of a bridge based on the size and type of members used. It has built in costs for each of these different types of members at different sizes and with different compositions of materials. For example, a member composed of a hollow bar of quenched and tempered steel will be more difficult for a company to manufacture than a solid bar of the same material so it will be more expensive overall. Although this will be more expensive, it will save costs in the long run because it is a lighter material and will cut down on the dead load of the bridge. If the bridge is not as heavy, less material will be needed to keep the bridge structurally sound. As a result the bridge can be made more cheaply in the long run. Although, there is a certain point where the design will go beyond an efficiency equilibrium and eventually become more expensive to produce if all of the same light and high strength material is used so a balance must be found.

In order to carry out the structural and cost analysis for the Howe truss, the Bridge Designer program was directly used. To start, a basic template of the Howe truss bridge within the design constraints was laid out. In this initial template every member was laid out such that each had equal size and material. Each member was then analyzed to see which were under tension forces and which were under compression forces. Because most of the members preform well under tension, any members that displayed a significant tension as opposed to compression force under load were thinned out as well as set to the most cost effective material as possible one by one until a failure occurred. After this failure occurred the members were then manipulated such that the failure would then not occur again. The overall goal was to achieve a ratio between the tension force and the force applied to the bridge as close to one as possible to ensure that each member was being used as efficiently as possible for maximum cost efficiency. When this process was complete for the tension forces, it was repeated for the compression forces. The members under compression were identified and gradually thinned out until they were performing most efficiently to ensure the most efficient costs.

When the Howe truss bridge was designed to be as low in cost as possible, all compression and tension forces were evaluated and adjustments were made to get ratios of force to member strength close to one. Having a ratio close to one The member with the highest compression ratio according to Table 2 was member number twenty six. Under load, the member had an overall compression of 1557.29kN with a maximum compression strength of 1565.86kN. Using members with high compression force to compression strength ratios or high tension force to tension strength ratios will result in the most efficient use of a member and therefore a more cost effective bridge.

After using Bridge Designer to evaluate all aspects of the Howe Truss bridge, the overall cost could be evaluated. The program took into account all material based on type and by assigning a monetary value per kilogram of the material, the size of each member, the excavation, the abutments, and decking and provided a total cost of $214,354.93 according to table 1.

Warren Truss.

In order to conduct the economic analysis for the Warren truss bridge, the program Engineering Encounters Bridge Designer 2015 was used. The program uses functions that yield an estimate of how much a bridge will cost based on the size, type, and material of a member as well as analyze the structural formation of the bridge to deduce whether the bridge will cost more or less as whole. Specifically, in the program the size and material of every member can be varied. Based on how the member was varied, a different value could be obtained. Normally, this variance corresponded with a higher cost for members

with higher thickness and the converse of this for members that were thinner. The material and type of the member also had a specific impact on the cost. For example, The quenched and tempered steel hollow bar is more expensive than the solid bar because it will be more expensive for a company to manufacture. If a hollow bar is used, however, it saves weight, and therefore there is less dead load for the bridge to sustain. The ultimate goal was to find almost a point of equilibrium where a more expensive member could be used to make the bridge more structurally efficient but save costs in the long run as a result of this increased structural efficiency. The Bridge designer program has the costs of these members built in so taking the cost of the material for the member per kilogram and the size of the member the program can calculate an overall cost for each member.

To determine which bridge would be most economically efficient, a basic template of the Warren truss bridge was used. The member type and thickness for each member was the same. The members were then analyzed for their tension and compression. Because the members usually perform better under tension, those that were under the most tension force were gradually thinned out so that these members could be made out of the thinnest and lowest costing materials. When this was finished, the members being acted upon by a compression force were addressed. The same idea that was used for the members acting under tension was used for the members acting under compression. These members were gradually thinned out until failure or structural inefficiencies caused the program to calculate an increase in the price for a higher cost of manufacture to compensate.

To ensure that the bridge would be the most economically efficient, the ratio of the force in comparison to the tension and the force in comparison with the compression was also taken into account. When this ratio was as close to one as possible for all members under tension or compression without failure, the bridge would be the most cost effective while still fulfilling the load requirements.

After all tension and compression test were carried out and the cost of the bridge was the lowest possible, the force analysis as displayed in Table 5 was evaluated. In this evaluation, it was possible to tell which members were being used most efficiently. While some members were still carrying a load that was less than their maximum tension and compression strength, others were carrying loads that were extremely close to their tension and compression strength maximums. Member number 10 on the Warren bridge was the member that happened to have on of the highest force to compression ratio of approximately one. According to Tables 5 and 6, the member was taking a compression load of 1548.67kN with a maximum compression rating of 1551.67kN with a length of 4.5 meters. Any use of a member with either a high force to tension or force to compression ratio results in a very efficient use of that member and therefore most likely a lower overall cost of the bridge.

After preforming these specific evaluations, a final cost could be calculated. According to Table 4, when taking into account the size and material of each member, the material of the deck, the abutment costs, and excavation costs, the final cost of the bridge was projected to be $203,843.22. This is, once again, after making the most efficient structural use of each of the members.

ATTACHMENT 2

Phase 2: Structural Efficiency

Howe Truss

Prototype Bridge.

While designing our prototype for the Howe Truss bridge, we followed a structural member placement template generated by Engineering Encounters Bridge Designer 2015 for the overall bridge shape. Using the John Hopkins University Virtual Bridge Designer software, we determined which structural members would experience the greatest load. These high load areas were determined to be the joints between the diagonals and the verticals along the lower chord, particularly in the center of the bridge. Using this information, we adjusted our top and bottom chord design to accommodate these stresses.

Before construction, the Popsicle sticks were sorted and color coded according to perceived structural integrity. Higher grade sticks were used for high-stress members, with poor quality sticks allocated to low-stress members. Furthermore, prior to gluing, each member was lightly sanded with low-grain sandpaper and finely scored in x-patterns to facilitate a better bond with the polyvinyl acetate adhesive.

To accommodate a gusset plate-like reinforcement on the center vertical member, a 3-stick wide top and bottom chord was used to allow the center vertical member and the end posts to anchor inside gaps in the top and bottom chords. This way, the two innermost diagonals would abut the center vertical, allowing one gusset plate to be glued onto each side of the center vertical, overlapping the vertical and one of the diagonal members. The outer two diagonals had contact areas on the chords themselves and partial contact area with one side of each vertical that they join. After each halve was constructed, the remaining Popsicle sticks were used for portal bracing and floor beams.

Once constructed, the bottom chord was 13.5 inches in length, and the top chord was 9 inches. The height of the bridge was 4 inches, with a total 54 Popsicle sticks used evenly between each of the halves. The remaining six sticks were used for two portal braces on the top chord and four floor beams across the bottom chord, all of which were hot glued into place. See **Figure 3** for a photograph of the prototype Howe Truss bridge and a visual aide for member placement.

Load Testing.

Once load testing was completed, the performance of each group's design was calculated, and its summary can be seen in **Table 7**. The lowest load supported was 32.6 lbs by Groups 3 and 8. The highest load supported was 101.1 lbs by our design, Group 6. In terms of structural efficiency, calculated from the ratio of load to bridge weight, the highest was Group 6 with 555 points and the lowest was 201 points, with a range of 354 points.

Most of the groups supported a load between 50-70 lbs, and had a bridge weight between 60 and 84 grams. Bridge weight and structural efficiency do not seem to be seem to be intrinsically related, since the 66.6 gram design from Group 3 performed 21 points better than the 73.7 gram design from Group 8. Also, Group 2 and 4 had the same mass of 80.8 grams, and Group 2's design performed 52 points better.

Forensic Analysis.

During load testing, the bridge eventually succumbed to the load stress and failed. However while watching the load test, there was not an initial member failure that caused a cascade, but rather a small imbalance in the construction caused the bridge to tilt to one side. In the beginning of the load test, there was a moment where the bridge noticeably settled. This imbalance caused the eventual tilt, which was not

countered by portal braces. Once the tilt began, the force of the load caused the two portal braces and two of the floor beams to snap, as seen in **Figure 4a**. The tilt also put progressively more stress on the bottom chord of one halve, which caused a chord member failure and a subsequent joint failure as seen in **Figure 4b** and **Figure 4c**.

To remedy this failure, more sway struts or perhaps lateral bracing on the top chord will be necessary, as only having portal bracing was insufficient. Beyond that, is is necessary to ensure each chord is level, and all vertical members are at 90 degrees from the top and bottom chords. These measures are fairly simple to implement, and could increase the structural efficiency significantly.

Results.

After calculating the structural efficiency of our design and comparing it to the performance of other Howe Truss designs, it can be seen from **Figure 7** that our design performed beyond expectations and achieved the highest structural efficiency rating of all participating groups. Among the other groups, our Howe Truss design weighed the second most, but was quite near the mass of other bridges by a few grams. However, we achieved a significantly higher efficiency rating, therefore that added mass is negligible.

Warren Truss.

Prototype Bridge.

The Warren Truss bridge design followed a template generated from the Engineering Encounters Bridge Designer 2015. Using the John Hopkins University Virtual Bridge Designer software, we determined which structural members would experience the greatest stress during the load test. The centers of the both the top and bottom chords would experience the greatest load, with the bottom chord experiencing tension and the top chord undergoing compression. Each diagonal would experience relatively similar yet tension/compression depending upon the member, with inward pointing members undergoing compression and outward facing members undergoing tension. The design and reinforcement of each member reflects this information.

Prior to construction, a model of our design for the Warren truss was generated in AutoCAD to test member placement and make assembly easier. The bottom chord was three Popsicle sticks wide 13.5 inches long with 3 joints. The top chord was 10 inches long, with 2 joints, and the overall height was 4 inches. The joints allowed open spaces in the middle of the top and bottom chords, where the diagonal members would join. To accommodate the high member stress in the center of the bridge, the center diagonal members were three Popsicle sticks wide; one member placed in the gaps of the top and bottom chords, with the remaining two members of the same diagonal placed on the outside of the chord, parallel with the middle member. The end posts were adhered to the outside of the chord. The outward facing diagonals, joining the center diagonals and the end posts, are nestled in the gaps of the top and bottom chord and are just one member. Prior to placement, all pieces were cut and measured according to the CAD design, and each joint area was lightly sanded before being bonded with polyvinyl acetate glue.

Each halve of the bridge was made with 26 Popsicle sticks, for a total of 52 sticks with 8 remaining. Four floor beams joined each halve along the bottom chords. The two top chords were joined with two portal struts and two sway struts. These last eight members were hot glued in place rather than bonded with polyvinyl acetate glue. See **Figure 5** for a visual of the Warren truss prior to load testing.

Load Testing.

Once load testing was completed, the performance of each group's design was calculated, and its summary can be seen in **Table 8**. The highest mass design was our design, Group 6, with 82.5 grams. The lowest mass design was Group 4 with 57.6 grams. Our design also had the highest structural efficiency

rating at 733 points. The lowest rating was Group 2 with 237 points. The range was 496 points, with an average of all the groups coming to 415 points.

The highest load supported was 133.3 lbs by Group 6 (our design), and the lowest was Group 2 with 41.1 lbs. Most groups supported a load of 50-65 lbs, with a few groups edging out beyond that.

Forensic Analysis.

While loading the bridge with weight, there was never any noticeable bowing or cracking of the structural members and joints. When the bridge failed, it occurred all at once, caused by the failure of a lower structural member shown in **Figure 6.** The member that failed appears to have been warped before it was implemented into the prototype build. In addition, the truss with the member failure is slightly lower than the other truss, causing it to receive more force than its counterpart, which contributed to the failure of the member. The initial failure of this member led to various joint failures in the vicinity.

In order to prevent such a failure in the future, the quality of each member should be carefully inspected for flaws before being implemented into the structure of the bridge. Moreover, extra care should be taken to verify the symmetry of the trusses during construction.

Results.

After calculating the structural efficiency of our design and comparing it to the performance of other Warren Truss designs, it can be seen from **Figure 8** that our bridge design had the highest structural efficiency. Our design weighed the most out of all the tested designs, however it also achieved the highest efficiency rating. Other designs with similar masses did not even approach the efficiency rating of our design. Therefore this added mass is more than negligible.

TABLES

Table 1:
Bridge Designer 2015 Cost Calculation Report for the Howe Truss Bridge

Type of Cost	Item	Cost Calculation	Cost
Material Cost (M)	Carbon Steel Hollow Tube	(355.6 kg) x ($6.30 per kg) x (2 Trusses) =	$4,480.63
	High-Strength Low-Alloy Steel Hollow Tube	(1447.5 kg) x ($7.00 per kg) x (2 Trusses) =	$20,264.55
	Quenched & Tempered Steel Solid Bar	(2928.1 kg) x ($6.00 per kg) x (2 Trusses) =	$35,136.60
	Quenched & Tempered Steel Hollow Tube	(3121.6 kg) x ($7.70 per kg) x (2 Trusses) =	$48,073.15
Connection Cost (C)		(20 Joints) x (400.0 per joint) x (2 Trusses) =	$16,000.00
Product Cost (P)	7 - 50x50 mm Quenched & Tempered Steel Bar	(%s per Product) =	$1,000.00
	4 - 55x55 mm Quenched & Tempered Steel Bar	(%s per Product) =	$1,000.00
	2 - 75x75 mm Quenched & Tempered Steel Bar	(%s per Product) =	$1,000.00
	4 - 90x90 mm Quenched & Tempered Steel Bar	(%s per Product) =	$1,000.00
	2 - 100x100 mm Quenched & Tempered Steel Bar	(%s per Product) =	$1,000.00
	2 - 150x150x7 mm Carbon Steel Tube	(%s per Product) =	$1,000.00
	2 - 160x160x8 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	2 - 170x170x8 mm High-Strength Low-Alloy Steel Tube	(%s per Product) =	$1,000.00
	2 - 190x190x9 mm High-Strength Low-Alloy Steel Tube	(%s per Product) =	$1,000.00
	1 - 190x190x9 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	4 - 200x200x10 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	1 - 220x220x11 mm High-Strength Low-Alloy Steel Tube	(%s per Product) =	$1,000.00
	4 - 240x240x12 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
Site Cost (S)	Deck Cost	(10 4-meter panels) x ($4,700.00 per panel) =	$47,000.00
	Excavation Cost	(19,400 cubic meters) x ($1.00 per cubic meter) =	$19,400.00
	Abutment Cost	(2 standard abutments) x ($5,500.00 per abutment) =	$11,000.00
	Pier Cost	No pier =	$0.00
	Cable Anchorage Cost	No anchorages =	$0.00
Total Cost	M + C + P + S	$107,954.93 + $16,000.00 + $13,000.00 + $77,400.00 =	$214,354.93

Table 2:
Bridge Designer 2015 Load Test Report for Howe Truss Bridge

#	Material Type	Cross Section	Size (mm)	Length (m)	Compression Force	Compression Strength	Compression Status	Tension Force	Tension Strength	Tension Status
1	HSS	Hollow Tube	220x220x11	5.66	1965.64	2076.87	OK	0	3013.99	OK
2	QTS	Hollow Tube	160x160x8	4	1389.92	1390.76	OK	0	2241.09	OK
3	QTS	Hollow Tube	200x200x10	4	2470.64	2530.55	OK	0	3501.7	OK
4	QTS	Hollow Tube	240x240x12	4	3240.54	3958.27	OK	0	5042.45	OK
5	QTS	Hollow Tube	240x240x12	4	3698.55	3958.27	OK	0	5042.45	OK
6	QTS	Hollow Tube	240x240x12	4	3677.78	3958.27	OK	0	5042.45	OK
7	QTS	Hollow Tube	240x240x12	4	3199.01	3958.27	OK	0	5042.45	OK
8	QTS	Hollow Tube	200x200x10	4	2408.34	2530.55	OK	0	3501.7	OK
9	QTS	Hollow Tube	160x160x8	4	1357.21	1390.76	OK	0	2241.09	OK
10	QTS	Hollow Tube	200x200x10	5.66	1919.39	1930.33	OK	0	3501.7	OK
11	QTS	Solid Bar	55x55	4	0	74.51	OK	1385.58	1393.77	OK
12	QTS	Solid Bar	50x50	4	0	50.89	OK	1127.75	1151.88	OK
13	QTS	Hollow Tube	200x200x10	5.66	1602.43	1930.33	OK	0	3501.7	OK
14	HSS	Hollow Tube	190x190x9	5.66	1236.92	1323.29	OK	0	2135.62	OK
15	QTS	Solid Bar	50x50	4	0	50.89	OK	868.35	1151.88	OK
16	HSS	Hollow Tube	170x170x8	5.66	869.9	947.42	OK	0	1699.06	OK
17	QTS	Solid Bar	50x50	4	0	50.89	OK	608.52	1151.88	OK
18	CS	Hollow Tube	150x150x7	5.66	502.38	550.3	OK	90.1	950.95	OK
19	QTS	Solid Bar	50x50	4	0	50.89	OK	621.41	1151.88	OK
20	CS	Hollow Tube	150x150x7	5.66	457.69	550.3	OK	134.79	950.95	OK
21	QTS	Solid Bar	50x50	4	0	50.89	OK	576.92	1151.88	OK
22	HSS	Hollow Tube	170x170x8	5.66	825.21	947.42	OK	0	1699.06	OK
23	QTS	Solid Bar	50x50	4	0	50.89	OK	836.74	1151.88	OK
24	HSS	Hollow Tube	190x190x9	5.66	1192.23	1323.29	OK	0	2135.62	OK
25	QTS	Solid Bar	50x50	4	0	50.89	OK	1096.15	1151.88	OK
26	QTS	Hollow Tube	190x190x9	5.66	1557.29	1565.86	OK	0	3002.25	OK
27	QTS	Solid Bar	55x55	4	0	74.51	OK	1353.34	1393.77	OK
28	QTS	Solid Bar	55x55	4	0	74.51	OK	1389.92	1393.77	OK
29	QTS	Solid Bar	75x75	4	0	257.63	OK	2470.64	2591.72	OK
30	QTS	Solid Bar	90x90	4	0	534.22	OK	3240.54	3732.08	OK
31	QTS	Solid Bar	90x90	4	0	534.22	OK	3698.55	3732.08	OK
32	QTS	Solid Bar	100x100	4	0	814.24	OK	3844.31	4607.5	OK
33	QTS	Solid Bar	100x100	4	0	814.24	OK	3844.31	4607.5	OK
34	QTS	Solid Bar	90x90	4	0	534.22	OK	3677.78	3732.08	OK
35	QTS	Solid Bar	90x90	4	0	534.22	OK	3199.01	3732.08	OK
36	QTS	Solid Bar	75x75	4	0	257.63	OK	2408.34	2591.72	OK
37	QTS	Solid Bar	55x55	4	0	74.51	OK	1357.21	1393.77	OK

Table 3:
Bridge Designer 2015 Member Detail Graph for the Howe Truss Bridge

Member List | Member Details

Member 26

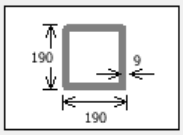
Material Properties:

Material	Quenched & Tempered Steel
Yield Stress (Fy)	485000 kN per sq. meter
Modulus of Elasticity (E)	2.00E+08 kN per sq. meter
Mass Density	7850 kg per cubic meter

Dimensions:

Cross-Section Type	Hollow Tube
Cross-Section Size	190x190x9
Area	0.0065 sq. meters
Moment of Inertia	3.57E-05 meters^4
Member Length	5.66 meters

Section (mm):



Cost:

Unit Cost	$393.86 per meter
Member Cost	$2228.01

Strength vs. Length: Graph all tabs Member:

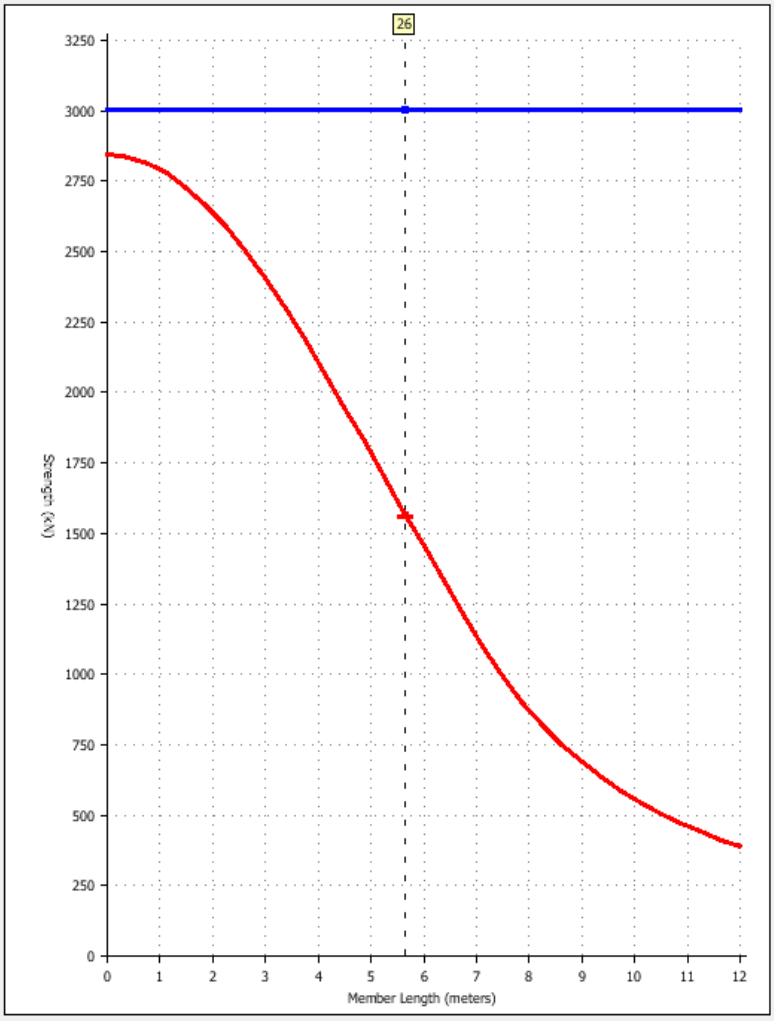


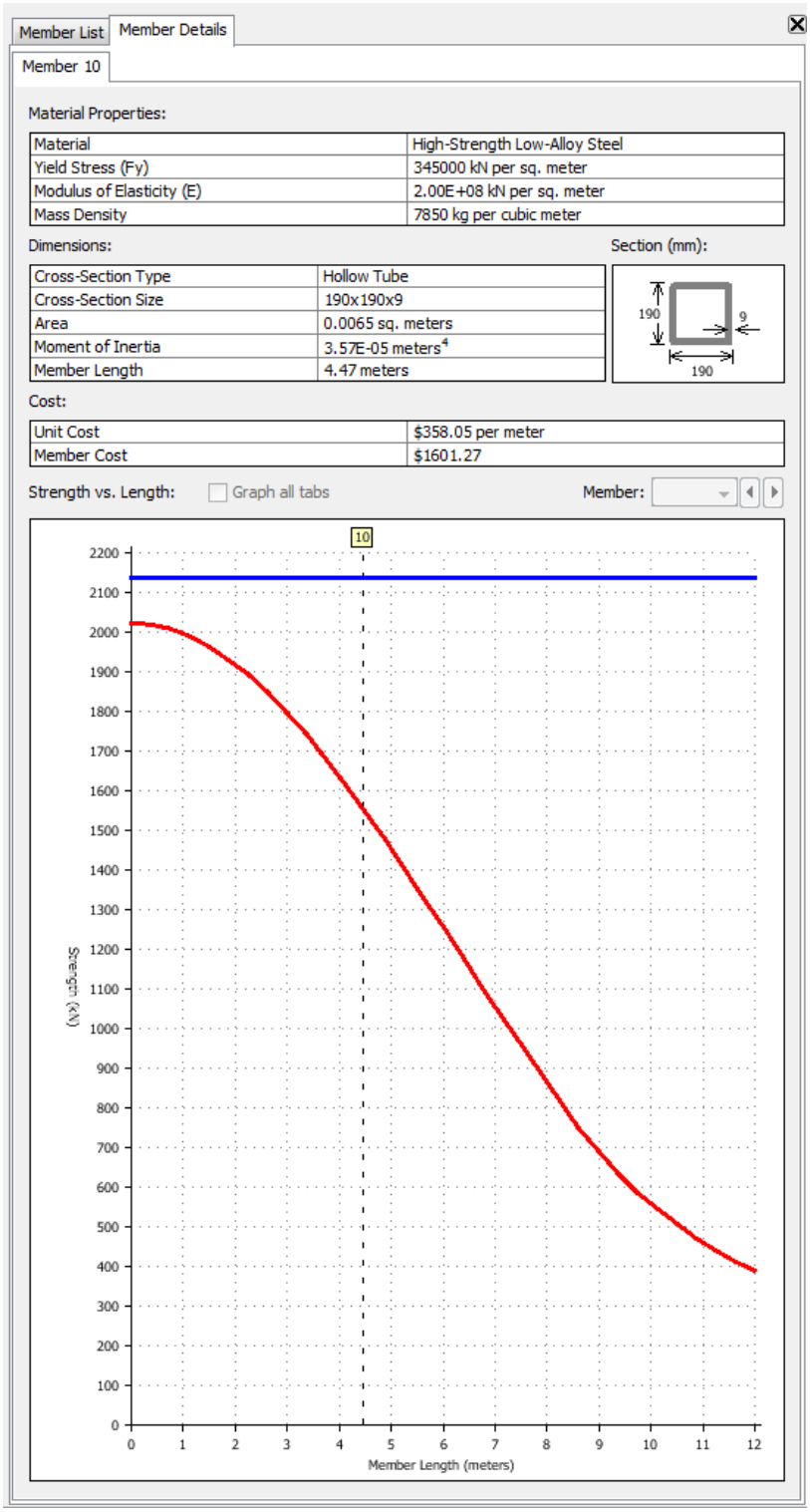
Table 4:
Bridge Designer 2015 Cost Calculation Report for the Warren Truss Bridge

Type of Cost	Item	Cost Calculation	Cost
Material Cost (M)	Carbon Steel Solid Bar	(402.4 kg) x ($4.30 per kg) x (2 Trusses) =	$3,460.32
	Carbon Steel Hollow Tube	(209.0 kg) x ($6.30 per kg) x (2 Trusses) =	$2,632.80
	High-Strength Low-Alloy Steel Hollow Tube	(1060.5 kg) x ($7.00 per kg) x (2 Trusses) =	$14,846.86
	Quenched & Tempered Steel Solid Bar	(2406.0 kg) x ($6.00 per kg) x (2 Trusses) =	$28,872.53
	Quenched & Tempered Steel Hollow Tube	(2976.0 kg) x ($7.70 per kg) x (2 Trusses) =	$45,830.71
Connection Cost (C)		(21 Joints) x (400.0 per joint) x (2 Trusses) =	$16,800.00
Product Cost (P)	4 - 55x55 mm Carbon Steel Bar	(%s per Product) =	$1,000.00
	4 - 55x55 mm Quenched & Tempered Steel Bar	(%s per Product) =	$1,000.00
	4 - 65x65 mm Quenched & Tempered Steel Bar	(%s per Product) =	$1,000.00
	2 - 80x80 mm Quenched & Tempered Steel Bar	(%s per Product) =	$1,000.00
	1 - 80x80x4 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	4 - 90x90 mm Quenched & Tempered Steel Bar	(%s per Product) =	$1,000.00
	1 - 90x90x4 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	2 - 130x130x6 mm Carbon Steel Tube	(%s per Product) =	$1,000.00
	2 - 140x140x7 mm High-Strength Low-Alloy Steel Tube	(%s per Product) =	$1,000.00
	2 - 160x160x8 mm High-Strength Low-Alloy Steel Tube	(%s per Product) =	$1,000.00
	4 - 170x170x8 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	2 - 190x190x9 mm High-Strength Low-Alloy Steel Tube	(%s per Product) =	$1,000.00
	2 - 200x200x10 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	5 - 240x240x12 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
Site Cost (S)	Deck Cost	(10 4-meter panels) x ($4,700.00 per panel) =	$47,000.00
	Excavation Cost	(19,400 cubic meters) x ($1.00 per cubic meter) =	$19,400.00
	Abutment Cost	(2 standard abutments) x ($5,500.00 per abutment) =	$11,000.00
	Pier Cost	No pier =	$0.00
	Cable Anchorage Cost	No anchorages =	$0.00
Total Cost	M + C + P + S	$95,643.22 + $16,800.00 + $14,000.00 + $77,400.00 =	$203,843.22

Table 5:
Bridge Designer 2015 Load Test Report for Warren Truss Bridge

#	Material Type	Cross Section	Size (mm)	Length (m)	Compression Force	Compression Strength	Compression Status	Tension Force	Tension Strength	Tension Status
1	QTS	Hollow Tube	170x170x8	4	1383.39	1559.03	OK	0	2388.53	OK
2	QTS	Hollow Tube	200x200x10	4	2458.82	2530.55	OK	0	3501.7	OK
3	QTS	Hollow Tube	240x240x12	4	3224.89	3958.27	OK	0	5042.45	OK
4	QTS	Hollow Tube	240x240x12	4	3680.28	3958.27	OK	0	5042.45	OK
5	QTS	Hollow Tube	240x240x12	4	3824.9	3958.27	OK	0	5042.45	OK
6	QTS	Hollow Tube	240x240x12	4	3659.81	3958.27	OK	0	5042.45	OK
7	QTS	Hollow Tube	240x240x12	4	3183.93	3958.27	OK	0	5042.45	OK
8	QTS	Hollow Tube	200x200x10	4	2397.38	2530.55	OK	0	3501.7	OK
9	QTS	Hollow Tube	170x170x8	4	1351.5	1559.03	OK	0	2388.53	OK
10	HSS	Hollow Tube	190x190x9	4.47	1548.67	1551.67	OK	0	2135.62	OK
11	QTS	Solid Bar	65x65	4.47	0	116.28	OK	1544.67	1946.67	OK
12	QTS	Hollow Tube	170x170x8	4.47	1263.47	1420.38	OK	0	2388.53	OK
13	QTS	Solid Bar	55x55	4.47	0	59.61	OK	1258.37	1393.77	OK
14	HSS	Hollow Tube	160x160x8	4.47	976.77	1036.79	OK	0	1594.18	OK
15	QTS	Solid Bar	55x55	4.47	0	59.61	OK	970.41	1393.77	OK
16	HSS	Hollow Tube	140x140x7	4.47	688.22	707.46	OK	0	1220.54	OK
17	CS	Solid Bar	55x55	4.47	0	59.61	OK	681.38	718.44	OK
18	CS	Hollow Tube	130x130x6	4.47	398.98	444.49	OK	69.42	706.8	OK
19	CS	Hollow Tube	130x130x6	4.47	363.33	444.49	OK	105.07	706.8	OK
20	CS	Solid Bar	55x55	4.47	0	59.61	OK	645.73	718.44	OK
21	HSS	Hollow Tube	140x140x7	4.47	652.57	707.46	OK	0	1220.54	OK
22	QTS	Solid Bar	55x55	4.47	0	59.61	OK	934.77	1393.77	OK
23	HSS	Hollow Tube	160x160x8	4.47	941.13	1036.79	OK	0	1594.18	OK
24	QTS	Solid Bar	55x55	4.47	0	59.61	OK	1222.72	1393.77	OK
25	QTS	Hollow Tube	170x170x8	4.47	1227.82	1420.38	OK	0	2388.53	OK
26	QTS	Solid Bar	65x65	4.47	0	116.28	OK	1509.03	1946.67	OK
27	HSS	Hollow Tube	190x190x9	4.47	1513.02	1551.67	OK	0	2135.62	OK
28	CS	Solid Bar	55x55	4	0	74.51	OK	692.59	718.44	OK
29	QTS	Solid Bar	65x65	4	0	145.35	OK	1896.06	1946.67	OK
30	QTS	Solid Bar	80x80	4	0	333.51	OK	2790.9	2948.8	OK
31	QTS	Solid Bar	90x90	4	0	534.22	OK	3375.56	3732.08	OK
32	QTS	Solid Bar	90x90	4	0	534.22	OK	3674.25	3732.08	OK
33	QTS	Solid Bar	90x90	4	0	534.22	OK	3690.21	3732.08	OK
34	QTS	Solid Bar	90x90	4	0	534.22	OK	3396.05	3732.08	OK
35	QTS	Solid Bar	80x80	4	0	333.51	OK	2790.91	2948.8	OK
36	QTS	Solid Bar	65x65	4	0	145.35	OK	1875.58	1946.67	OK
37	CS	Solid Bar	55x55	4	0	74.51	OK	676.64	718.44	OK
38	QTS	Hollow Tube	80x80x4	4.47	75.6	91.76	OK	392.8	560.27	OK
39	QTS	Hollow Tube	90x90x4	4.47	111.29	132.87	OK	357.11	633.99	OK

Table 6:
Member Details Report from Bridge Designer 2015 for the Warren Truss Bridge Member with the Highest Compression Force/Strength Ratio



Member List | Member Details

Member 10

Material Properties:

Material	High-Strength Low-Alloy Steel
Yield Stress (Fy)	345000 kN per sq. meter
Modulus of Elasticity (E)	2.00E+08 kN per sq. meter
Mass Density	7850 kg per cubic meter

Dimensions:

Cross-Section Type	Hollow Tube
Cross-Section Size	190x190x9
Area	0.0065 sq. meters
Moment of Inertia	3.57E-05 meters^4
Member Length	4.47 meters

Section (mm):

Cost:

Unit Cost	$358.05 per meter
Member Cost	$1601.27

Strength vs. Length: Graph all tabs Member:

Table 7:

HOWE Truss Bridge				
Design Team No.	**Actual Bridge Weight (grams)**	**Bridge Weight (lb.)**	**LOAD at Failure (lbs)**	**Structural Efficiency**
1	83.8	0.1847	65.3	353
2	80.8	0.1781	57.4	322
3	66.6	0.1468	32.6	222
4	80.8	0.1781	66.7	374
5	76.4	0.1684	52.3	311
6	82.6	0.1821	101.1	555
8	73.7	0.1625	32.6	201
			Minimum	201
			Maximum	555
			Range	354
			Average	334
			Geomean	318

Table 8:

WARREN Truss Bridge				
Design Team No.	**Actual Bridge Weight (grams)**	**Bridge Weight (lb.)**	**LOAD at Failure (lb.)**	**Structural Efficiency**
1	80.1	0.1766	59.7	338
2	78.6	0.1733	41.1	237
3	73	0.1609	48.2	299
4	57.6	0.1270	54.1	426
5	73.9	0.1629	76.8	471
6	82.5	0.1819	133.3	733
8	72.6	0.1601	64.4	402
			Minimum	237
			Maximum	733
			Range	496
			Average	415
			Geomean	392

FIGURES

Figure 1:

Picture of HOWE (from Bridge designer)

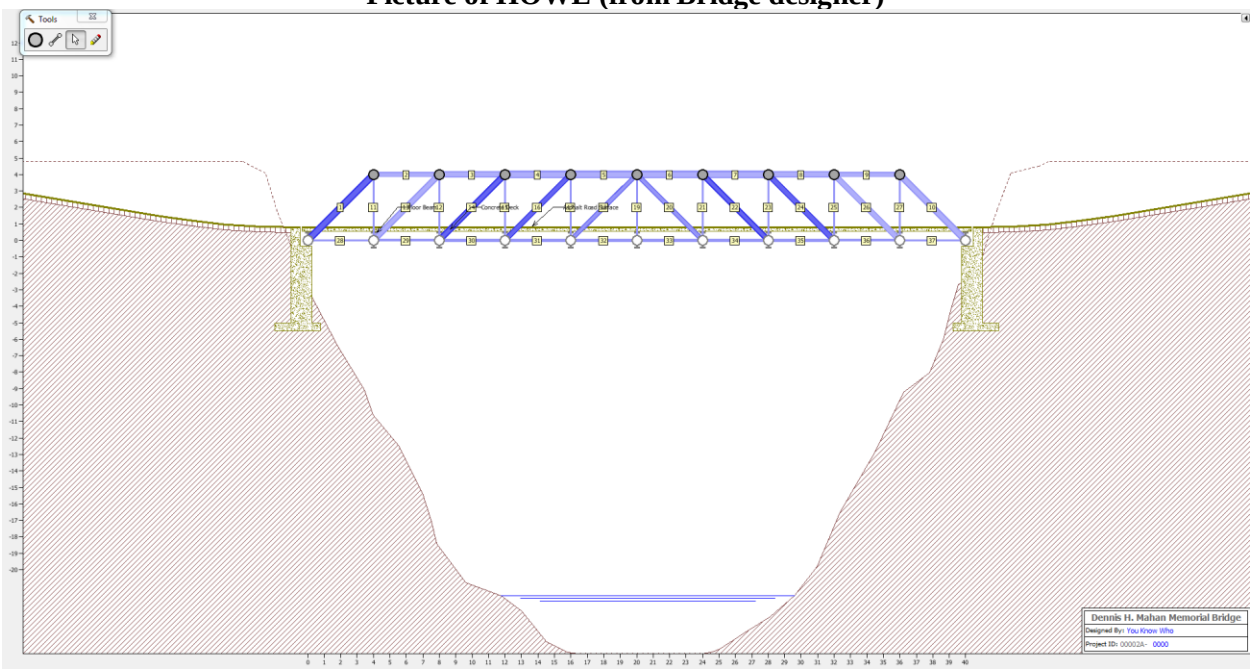


Figure 2:
Warren Truss Bridge Design from Bridge Designer Software

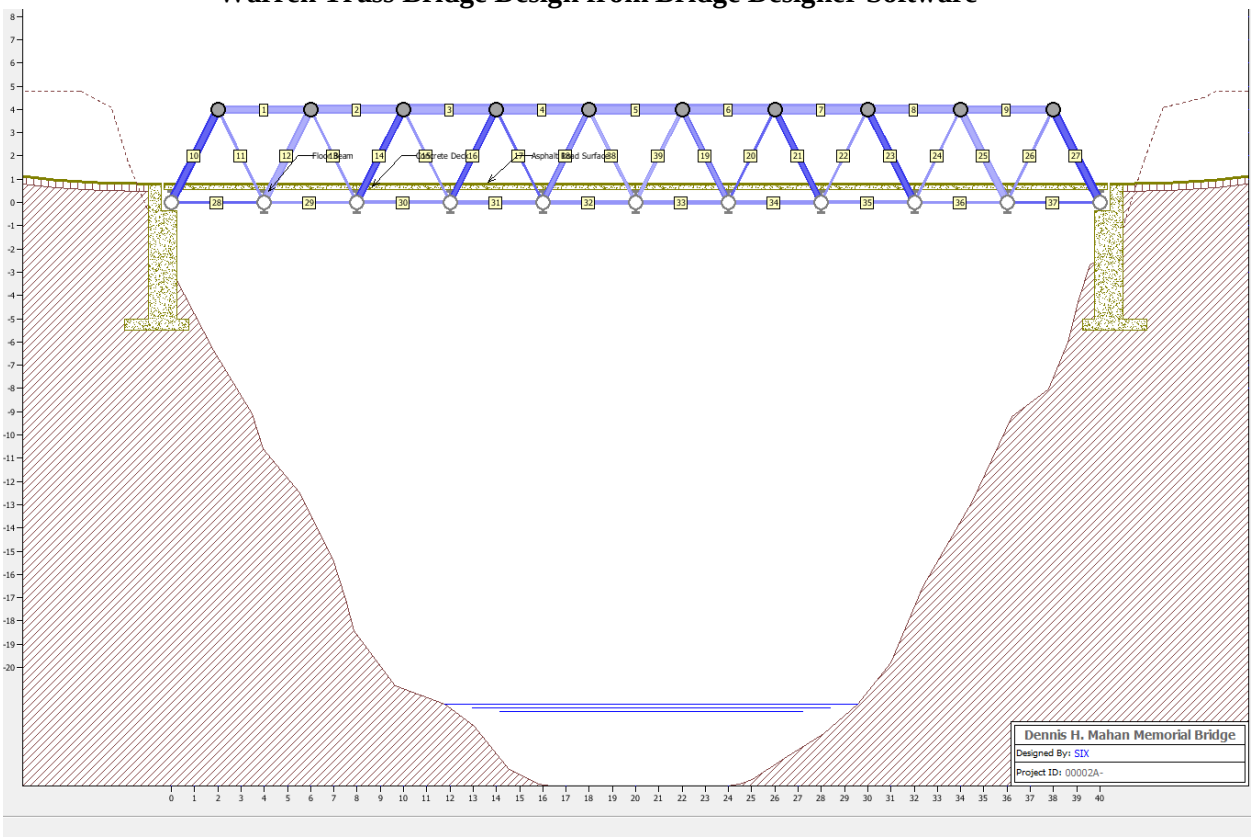


Figure 3:
Howe Truss Bridge Prototype Prior to Load Testing

Figure 4a:
Howe Truss Bridge Prototype Failure

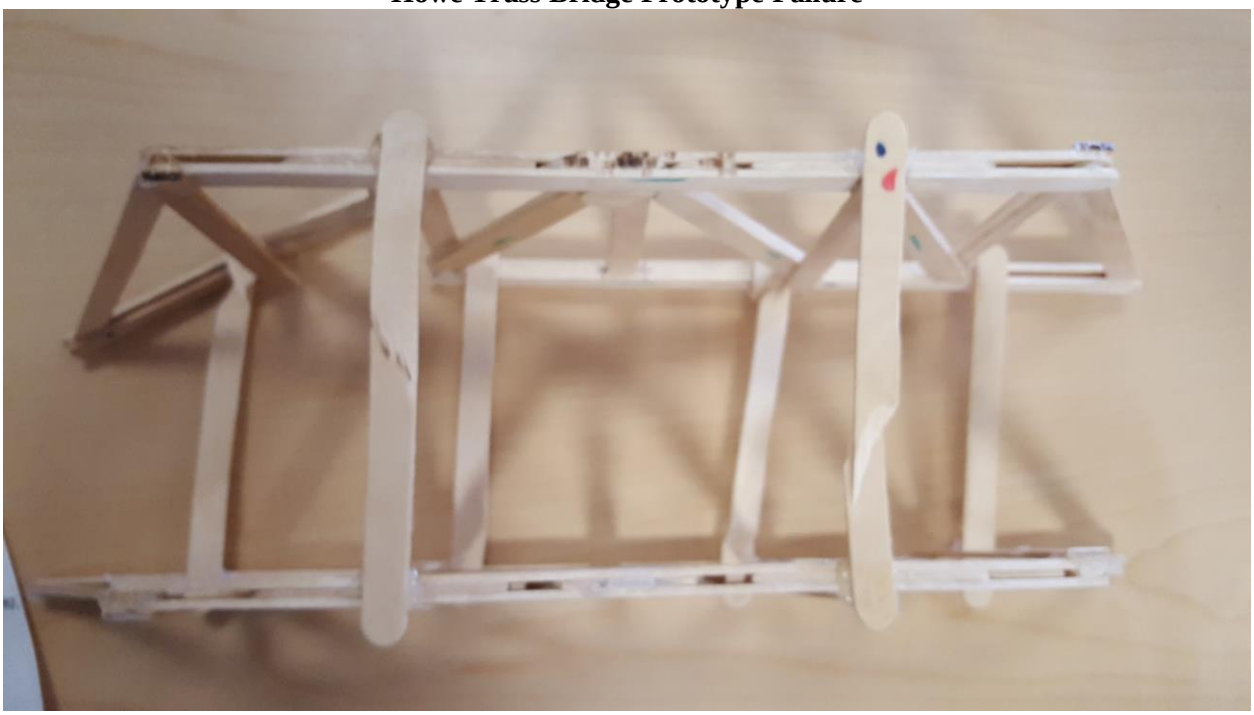


Figure 4b:

Figure 4c:

Figure 5:
Warren Truss Bridge Prototype Prior to Load Testing

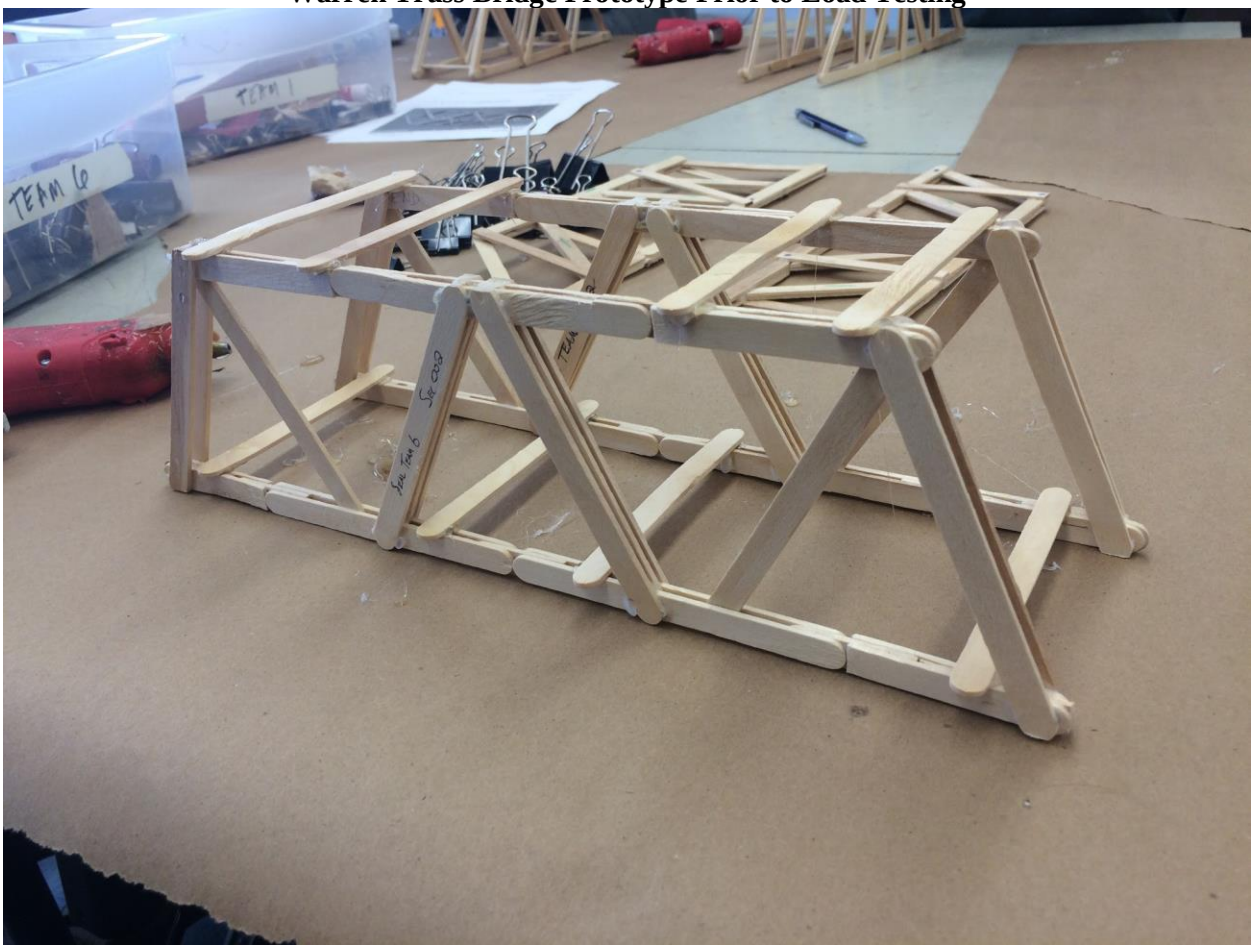


Figure 6:
Warren Truss Bridge Failure

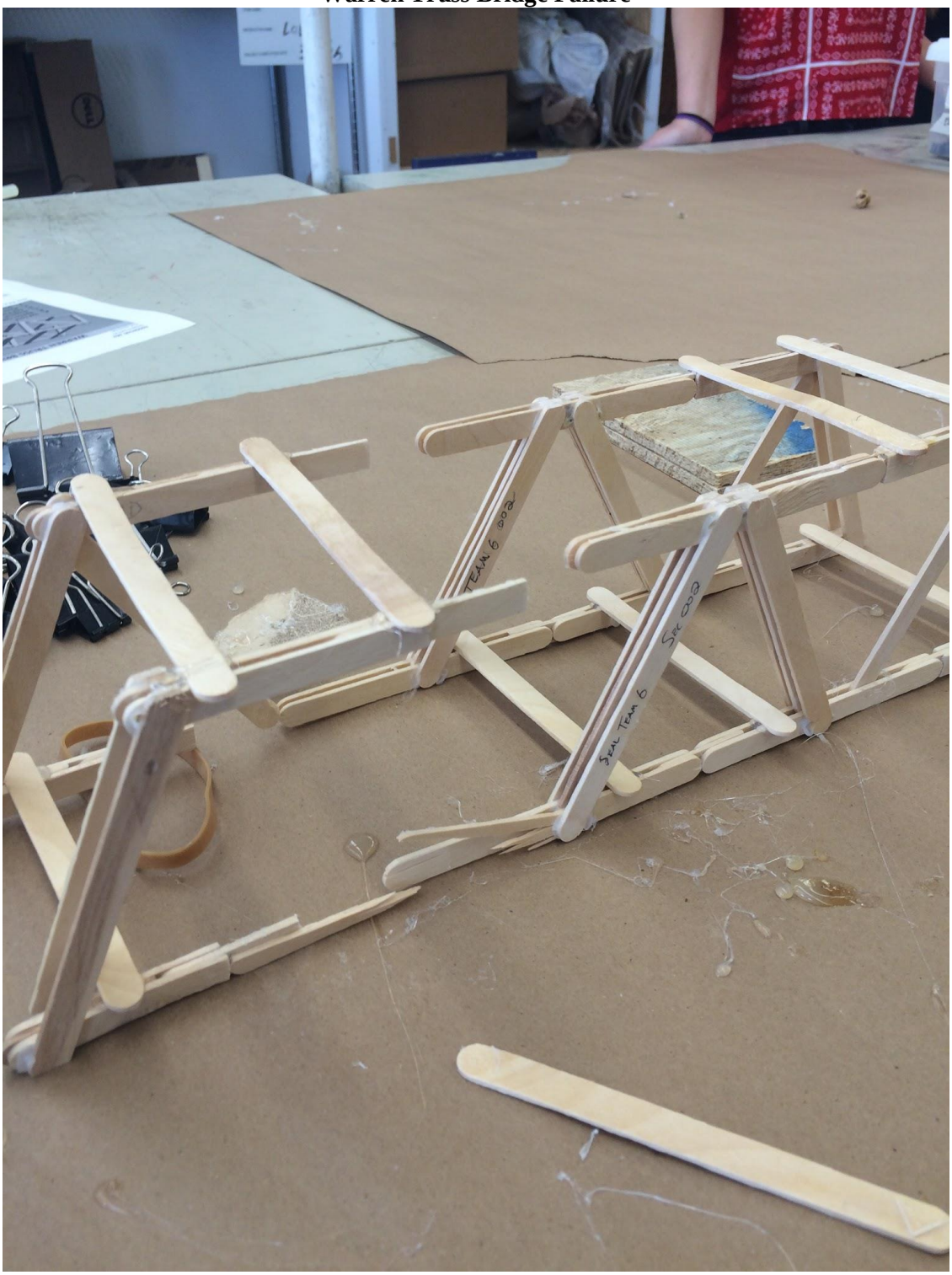


Figure 7:

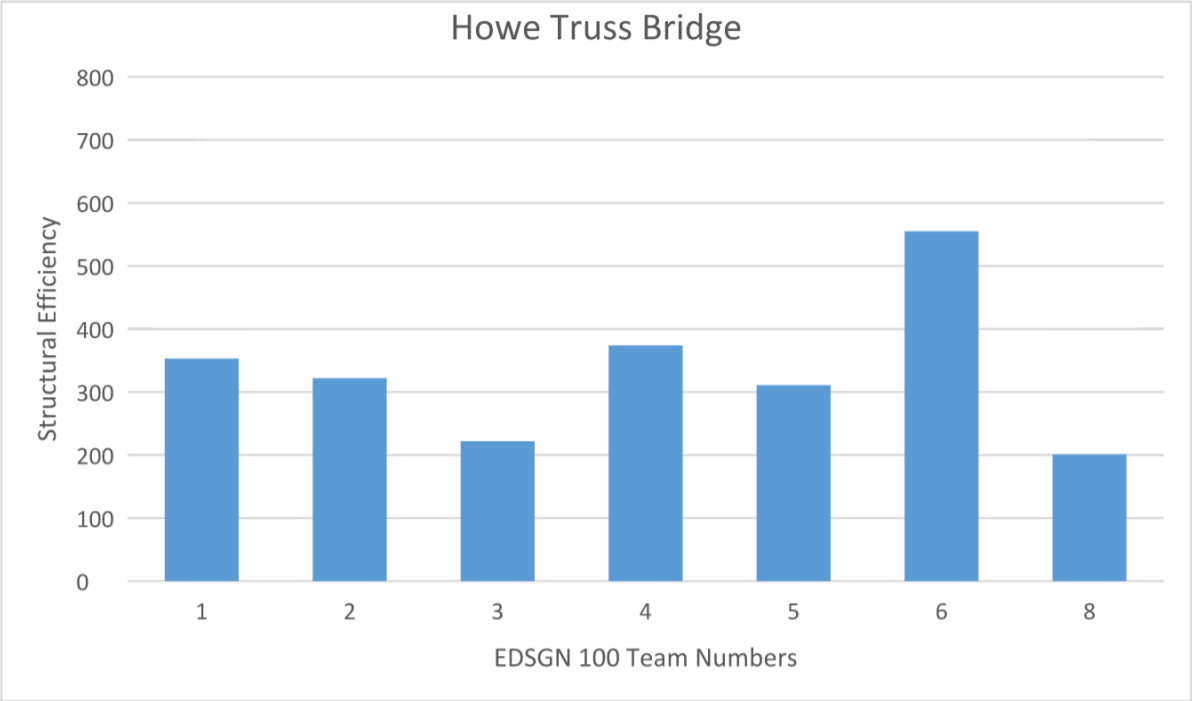
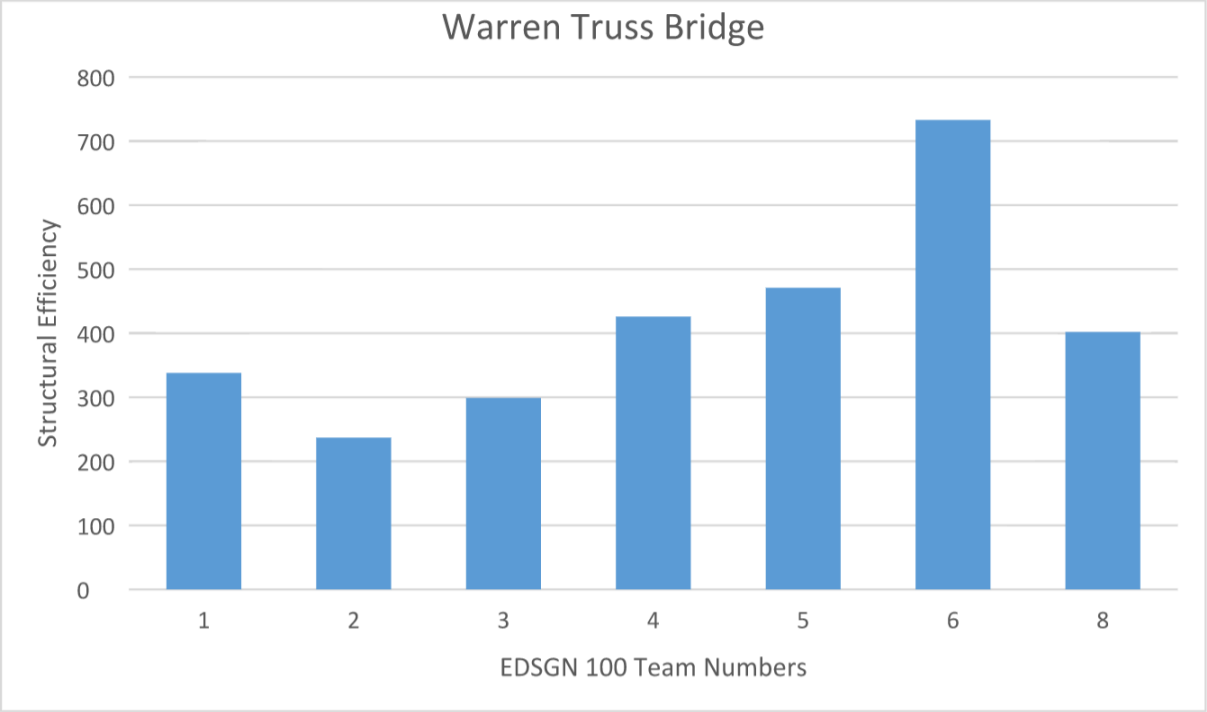

Howe Truss Bridge
800
700
600
500
400
300
200
100
0
Structural Efficiency
1
2
3
4
5
6
8
EDSGN 100 Team Numbers

Figure 8:


Warren Truss Bridge
Structural Efficiency
800
700
600
500
400
300
200
100
0
1
2
3
4
5
6
8
EDSGN 100 Team Numbers