PENNSTATE
School of Engineering Design, Technology and Professional Programs
213 Hammond Building
University Park, PA 16802-2701

March 31, 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. A bridge across Spring Creek along Puddintown Road in College Township, Centre County, PA has been destroyed due to a recent 100-year flood. This bridge was deemed structurally deficient. It's location is in the Pennsylvania Department of Transportation (PennDOT) Engineering District 2-0 and is in a heavily travelled local road. This road and more importantly the bridge is vital roadway to get to Mount Nittany Medical Center located in State College, PA. With this bridge collapse, traffic has been re-routed 10 miles around the bridge. This causes the a disruption in residential traffic flow, local commerce and is no longer easy access for police and emergency vehicles to College Township and to Mount Nittany Medical Center.

Objective. With the bridge destroyed by the flood, the Pennsylvania Department of Transportation (PennDOT) Engineering District 2-0 has set up a project to design a new bridge as a replacement for the previously failed one.

Design Criteria. PennDOT District 2-0 has established the criteria for the replacement bridge to include: standard abutments, no piers (one span), deck material consists of medium strength concrete (0.23 meters thick), no cable anchorages. It must also be designed take the load of two AASHTO H20-44 trucks (225kN) with one in each traffic lane. The bridge deck elevation is set at 20 meters and the deck span is exactly 40 meters. Both a Warren through truss bridge and a Howe through truss bridge shall be analyzed. Steel member type, cross section type and size are left to the design teams.

Technical Approach.

Phase 1: Economic Efficiency. Economic efficiency (cost) shall be determined using the Engineering Encounters Bridge Design 2015 (EEBD 2015) software based on the requirements, constraints, and performance criteria specified herein.

The design objective is to use EEBD 2015 to perform a systematic and iterative analysis to design a stable Warren and Howe through truss bridge that has been optimized to keep the cost of the replacement bridge as low as possible. It is also required the replacement bridge can support its own weight (dead load), plus the weight of a standard truck loading (live load).

Phase 2: Structural Efficiency. A prototype (i.e., a scale model bridge) bridge shall be designed and built for both a standard Warren through truss bridge and a standard Howe through truss bridge by each design team. Each prototype bridge shall be load tested in the lab to catastrophic failure. The truss bridge type that exhibits the best structural efficiency when tested to failure in prototype shall be determined. Structural efficiency is the ability of the truss bridge to safely dissipate live loads. Structural Efficiency (SE) is calculated by dividing the load the bridge supports at catastrophic failure by the weight of the prototype bridge. The design objective is to determine and report which prototype through truss bridge design is more effective at dissipating the force of a load, a Howe through truss bridge or the Warren through truss bridge.

A prototype bridge for both one Howe through truss bridge and one Warren through truss bridge shall be constructed using standard (4-1/2 x 3/8 x 1/12 inch) wooden (white birch) Popsicle (craft) sticks and Elmer's white glue only. Hot glue may only be used to attach no more than eight (8) struts/floor beams between the two adjacent truss sections. Typical examples of a prototype Howe through truss bridge are shown in Figures 2, 3, and 4. Typical examples of a prototype Warren through truss bridge are shown in Figures 5, 6, and 7.

To keep the results consistent, each prototype bridge shall have a maximum of sixty (60) Popsicle sticks, with approximate final bridge dimensions of 13.5 inches in length, 4 inches in height and 4.5 inches in width. All materials used to construct the prototype shall be provided by PennDOT District 2-0.

Each EDSGN100 design team shall design and built one prototype Howe through truss bridge and one prototype Warren through truss bridge. All prototype bridges will be tested in the lab to catastrophic failure by test loading the top cord of the truss with a loading block attached to a dead load suspended from the block, as shown in Figure 8. The weight of each bride type shall also be calculated (estimated) based upon a weight study of typical bridge members. All prototype bridges shall also be accurately weighed and measured prior to load testing and recorded. The load at failure of the prototype bridge shall also be accurately measured and recorded.

When a structure fails, there is an investigation to find out why it failed. After loading and bridge failure, one must perform a forensic engineering investigation to determine the cause of bridge failure. The forensic investigation shall include: why did it fail; where did it fail; and how did it fail. The investigation shall be documented with photographs, sketches, measurements, and

analyses. All structural members and joints of each bridge shall be uniquely identified and marked prior to loading and failure. Both trusses shall be suitably and uniquely marked and these markings shall be used in identifying the location and type of failure. A recommendation of how to improve the design or construction of the prototype bridges shall also be provided.

Results.

Phase 1: Economic Efficiency. For the Warren Bridge, the total cost of the bridge is $221,458.51. About $113,973.51 comes from materials that is used for the simulation on EEBD 2015. The connection cost is $16,800.00, the site cost is $81,400.00 and the product cost is $9,000.00. The Howe Bridge is $325,481.99. Much of the cost is from the materials cost which is about $219,081.99, the connection cost is $16,000.00, the product cost is $13,000.00 and the site cost is $77,400.00.

Phase 2: Structural Efficiency.

WARREN: We tried to innovate the design of our warren truss bridge by trying to stick two popsicle sticks together by using gusset plates.However, on load testing, the truss could take a weight of 33.6 lb, a load bit dissatisfying for us. As we load tested, the gusset plate connecting the popsicle sticks on the right(b on the figure) broke. After that the gusset plate on the opposite side broke connection with the popsicle sticks. This increased the pressure on the bridge , causing it to collapse One important thing that was noticed here is that not much happened to the floor beams and the straits, which confirms that the bridge failed because of the gusset plates used for connecting the popsicle sticks.After watching the bridge design of our peers,we observed that the bridges made without using gusset plates for connection lasted longer.Besides, we saw that the best truss design had maximum symmetry in it. Moreover it had,more popsicle stick concentration at the center, Which kind of explains its efficiency scientifically that since maximum load is given on the center, maximum stick concentration on the center will help.

Howe: The Howe truss was able to withstand 33.9 lbs of load before resulting in failure. Upon calculation the structural efficiency is 208, which was on the lower end of the design teams structural efficiencies. The floor beams and the struts were the parts that broke off from its joints and between the actual popsicle. This is due to the problematic geometry of the popsicle as many of them are crooked on one end, have knots in the wood and have some parts shaved off upon receiving the popsicle sticks. In addition only 56 of the original 60 popsicle sticks were used.

Best Solution.

1)ECONOMIC EFFICIENCY:When comparing the two bridges, the best solution is to take a variation of the Warren Truss bridge as the cost of making the bridge is more than $100,000. This is presented in the Tables 1 and 4. The main contributor to this is the material cost that takes up a bulk of the total cost.The Warren bridge was economically efficient than the Howe truss .

2)STRUCTURAL EFFICIENCY:Our group has a structural efficiency of 188.39 for the Warren and 208.64 for the Howe.

AVERAGE MEAN AND GEOMETRIC MEAN: Howe Bridge, the average and the geometric mean is 327.45 and 299.22 respectively. The minimum and maximum is 194.01 and 631.77 respectively.
3)DESIGN EFFICIENCY: For the design efficiency, the cost was divided by the structural efficiency. The Warren Bridge has a design efficiency of 604.99. The Howe Bridge had a design efficiency of 1560.02. Judging from this amount and the assumption that the lower the design efficiency is what is sought after, the Warren Bridge is much more favorable.

4)CONSTRUCTABILITY: The constructability of the Warren bridge is also much more favorable because of the cost and the items that is needed to make the bridge. Its requirements to make the bridge is much less extensive and utilizes the more materials in an efficient manner., while the Howe Bridge is much harder to construct because of the materials that is needed to make it.

Conclusions and Recommendations. While our truss bridge did not have the highest structural efficiencies, it is recommended that the Warren truss bridge is to be used overall because of the structural efficiency. Because of the cost analysis that is provided from the EEBD 2015, it is more favorable to have Warren Bridge design. Overall, neither of our designs have a high structural efficiency, however with variations of the materials and support structures, it would be more cost effective and able to withstand greater loads.

Respectfully,

Name: Shirley Banh
Engineering Student
EDSGN100 Section 001
Design Team 5
Design Team Squirrel Pants
Soup-A-Stars
College of Engineering
Penn State University

Name: Dylan Kolb
Engineering Student
EDSGN100 Section 001
Design Team 5
Design Team Squirrel Pants
Soup-A-Stars
College of Engineering
Penn State University

Name: Utsav Patel
Engineering Student
EDSGN100 Section 001
Design Team 5
Design Team Squirrel Pants
Soup-A-Stars
College of Engineering
Penn State University

Name: Nicole Song
Engineering Student
EDSGN100 Section 001
Design Team 5
Design Team Squirrel Pants
Soup-A-Stars
College of Engineering
Penn State University

ATTACHMENT 1

Phase 1: Economic Efficiency

Howe Truss. The overall cost of the Howe Truss bridge is $325,481.99. This cost includes the site cost, product cost, connection cost, and material cost. The material cost makes up the bulk of the cost, making up $219,081.99 of the total cost. The reason as to why this is a large part of total cost because of the types of materials that is used. For this bridge, there is a variety of materials used. Carbon steel, high-strength low alloy steel and quenched and tempered steel are used, with two different types of items used for each material, solid bars and hollow tubes.In addition, there are different sizes of materials ranging from 100x100mm and up to 160x160mm with components in increasing 10mm dimensions. These products cost $1,000 per material part, pertaining to both solid bars and hollow tubes. The site cost is fixed at $77,400 as these are part of the criteria that is outlined by PennDOT for the deck, excavation and abutment. The connection cost is for connecting the 21 joints on the 2 trusses; individually, it costs $400 per joint. These results are outlined in Table 1.

Table 2 outlines the load testing that is done on EEBD 2015. In this table, it highlights the compressions force/strength and tension force/strength ratios for each member of the bridge. It also give the slenderness and length of each component. Table 3 points the highest compression force/strength ratio, which in this case is member 16 with a ratio of 1.

Warren Truss. The design of the Warren Truss uses Carbon Steel, high-strength low-alloy and Quenched and tempered steel. For the carbon steel and the high-strength low alloy parts both the solid bar and hollow tube is used, however for <Attachment one shall include all pertinent detailed results from the economic efficiency study in the form of descriptive paragraphs and shall include appropriate discussion and details, as well as output results from EEBD 2015 for the Warren Truss. EEBD 2015 results must include: (i) a tabulated cost calculation report as Table 4; (ii) a tabulated load test report as Table 5, (iii) a tabulated member detail report as Table 6 (NOTE: identify the structural member, by member number, with the highest compressive or tension force/strength ratio and provide a "member details" image, as a properly cropped *Prt Scrn* image, for only that member), and (iv) a EEBD 2015 image(s) of the warren truss bridge design as Figure 2.>

ATTACHMENT 2

Phase 2: Structural Efficiency

Howe Truss.

Prototype Bridge. This bridge is utilizes the traditional Howe truss bridge design, and with vertical reinforcements on the back of the main truss to stabilize the vertical and hip vertical components of the Howe truss bridge. The diagonals of the bridge are overlapping both the vertical components. For the overall design, 56 of the total 60 popsicle sticks were used. Both the struts and the floor beams have popsicle sticks that was crooked at on end. The dimensions of the bridge is 3.25 inches in height, 4.50 inches in width and 13.25 inches in length. The weight of the bridge is 73.7 grams. A photograph of the prototype is provided in Figure 3. The structural efficiency of the bridge is calculated by taking the weight of the failure and dividing it by the dead load, which is the overall weight of the bridge. For this bridge, this is 33.9lbs and dividing it by 73.7 grams which is 0.16246lbs. The overall structural efficiency is 208.64.

Load Testing. The bridge that was able to hold the most load was Group 4 where it was able to sustain and distribute the 108.5 lbs of load. Because of that this was able to have the greatest structural efficiency. The bridge that was in our group was much well under the average structural efficiency, 299.229 and the geometric mean which is 327.454, however it was not the bridge with the minimum structural efficiency, with 194.016. The groups that was close to the geometric mean and the average is groups 1 and 2 respectively. Such data is tabulated in figure 7.

Forensic Analysis. For our group, when the load was placed on the bridge, it fell sideways. Upon looking at the overall structure, the trusses itself was not bent or broken at the joints, rather it seems that the problem is the

Results. <An EXCEL bar chart (graph) shall be included as Figure 7 comparing Structural Efficiencies as presented in Table 7.>

Warren Truss.

Prototype Bridge.

MATERIALS: A prototype bridge for Warren through truss bridge was constructed using 60 standard (4-1/2 x 3/8 x 1/12 inch) wooden (white birch) Popsicle (craft) sticks and Elmer's white glue . Hot glue was used to attach the struts and the floor beams.

FINAL BRIDGE DIMENSIONS: LENTH= 13.5 inches
WIDTH= 3.5 inches
HEIGHT= 4 inches

Load Testing. The maximum structural efficiency was group 3 with a structural efficiency of 648.151 and a load of 114.6 pounds. The minimum structural efficiency load was withstood by our group with a structural efficiency of with a load of 0.415. One important thing to notice is that we got a the lowest structural efficiency even though we did not have the lowest weight withstood (lowest weight =32.7)The range of structural efficiencies was 459.762. The average load withstood by the groups for warren truss was 62.814 lbs. The average structural efficiency was 365.864 and the geometric mean is 434.675. After watching the bridge design of our peers, it was observed that the bridges made without using gusset plates for connection lasted longer. Besides, it was noticed that the best truss design had maximum symmetry in it. Moreover it had, more popsicle stick concentration at the center, which may explain its efficiency scientifically since maximum load is felt on the center. The minimum load capacity group had a unsymmetrical structure and hence it failed most quickly. Our group made use of gusset plates for connection between pop sticks and was a little unsymmetrical and thus it didn't work to the expectations we had.

Forensic Analysis. As the load test was conducted , the gusset plate connecting the popsicle sticks on the right(b on the figure) broke. After that the gusset plate on the opposite side broke connection with the popsicle sticks. One astonishing thing we saw with this guust plate was that it lost connection after a portion of a popsickle stick it was connected to ripped off . This means that there was no problem with the gluing, it was a problem caused due to the existence of the gusset plates. The existence of the gusset plates made it structurally inefficient. One of the strut used also lost connection, a defect caused due to a unsymmetrical structure. This increased the pressure on the bridge , causing it to collapse. One important thing that was noticed here is that not much happened to the floor beams and the struts, which confirms that the bridge failed because of the gusset plates used for connecting the popsicle sticks.

Results. <An EXCEL bar chart (graph) shall be included as Figure 8 comparing Structural Efficiencies as presented in Table 8.>

Howe Truss Bridge
Table 1: Bridge Designer 2015 Cost Calculations Report for the Howe Truss Bridge **Table 2: Bridge Designer 2015 Load Test Report for the Howe Truss Bridge** **Table 3: Bridge Designer 2015 Member Detail Graph (PrtScn)1 for the Howe Truss Bridge** **Table 7: EXCEL table providing the EDSGN100 design team numbers versus truss bridge weight (grams), truss bridge weight (lbs), load at failure (lbs) and the calculated structural efficiency calculations for all eight Howe truss bridges** **Figure 1: Howe Truss Bridge Model from Bridge Designer 2015 (PrtScn)** **Figure 3: Photograph of the prototype Howe truss bridge BEFORE load testing** **Figure 4: Photograph of the prototype Howe truss bridge AFTER failure** **Figure 7: EXCEL clustered column chart (graph) comparing Structural Efficiencies calculated in Table 7**

Warren Truss Bridge
Table 4: Bridge Designer 2015 Cost Calculation Report for the Warren Truss Bridge **Table 5: Bridge Designer 2015 Load Test Report for the Warren Truss Bridge** **Table 6: Bridge Designer 2015 Member Detail Graph (PrtScn)2 for the Warren Truss Bridge** **Table 8: EXCEL table providing the EDSGN100 design team numbers versus truss bridge weight (grams), truss bridge weight (lbs), load at failure (lbs) and the calculated structural efficiency calculations for all eight Warren truss bridges** **Figure 2: Howe Truss Bridge Model from Bridge Designer 2015 (PrtScn)** **Figure 5: Photograph of the prototype Warren truss bridge BEFORE load testing** **Figure 6: Photograph of the prototype Warren truss bridge AFTER failure** **Figure 8: EXCEL clustered column chart (graph) comparing Structural Efficiencies calculated in Table 8**

TABLES

Table 1
Howe Truss Bridge
Cost Calculation Report from Bridge Designer 2016

Type of Cost	Item	Cost Calculation	Cost
Material Cost (M)	Carbon Steel Solid Bar	(8410.1 kg) x ($4.30 per kg) x (2 Trusses) =	$72,326.75
	Carbon Steel Hollow Tube	(116.9 kg) x ($6.30 per kg) x (2 Trusses) =	$1,473.36
	High-Strength Low-Alloy Steel Solid Bar	(3229.2 kg) x ($5.60 per kg) x (2 Trusses) =	$36,166.63
	High-Strength Low-Alloy Steel Hollow Tube	(233.9 kg) x ($7.00 per kg) x (2 Trusses) =	$3,274.14
	Quenched & Tempered Steel Solid Bar	(8420.7 kg) x ($6.00 per kg) x (2 Trusses) =	$101,048.06
	Quenched & Tempered Steel Hollow Tube	(311.2 kg) x ($7.70 per kg) x (2 Trusses) =	$4,793.05
Connection Cost (C)		(20 Joints) x (400.0 per joint) x (2 Trusses) =	$16,000.00
Product Cost (P)	8 - 100x100 mm Quenched & Tempered Steel Bar	(%s per Product) =	$1,000.00
	2 - 110x110x5 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	3 - 120x120x6 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	1 - 130x130x6 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	7 - 140x140 mm Carbon Steel Bar	(%s per Product) =	$1,000.00

	1 - 140x140x7 mm Carbon Steel Tube	(%s per Product) =	$1,000.00
	2 - 140x140 mm High-Strength Low-Alloy Steel Bar	(%s per Product) =	$1,000.00
	2 - 140x140x7 mm High-Strength Low-Alloy Steel Tube	(%s per Product) =	$1,000.00
	1 - 140x140 mm Quenched & Tempered Steel Bar	(%s per Product) =	$1,000.00
	2 - 140x140x7 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	4 - 160x160 mm Carbon Steel Bar	(%s per Product) =	$1,000.00
	2 - 160x160x8 mm Carbon Steel Tube	(%s per Product) =	$1,000.00
	2 - 160x160 mm Quenched & Tempered Steel Bar	(%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**	**$219,081.99+ $16,000.00 + $13,000.00 + $77,400.00 =**	**$325,481**

TABLE No. 2
Howe Truss Bridge
Load Test Results Report from Bridge Designer 2016

#	Material Type	Cross Section	Size (mm)	Length (m)	Slenderness	Compression Force/Strength	Tension Force/Strength
1	HSS	Bar	140	4.00	98.97	0.00	0.23
2	QTS	Bar	100	4.00	138.56	0.00	0.56
3	QTS	Bar	100	4.00	138.56	0.00	0.74
4	QTS	Bar	100	4.00	138.56	0.00	0.84
5	QTS	Bar	100	4.00	138.56	0.00	0.88
6	QTS	Bar	100	4.00	138.56	0.00	0.84
7	QTS	Bar	100	4.00	138.56	0.00	0.73
8	QTS	Bar	100	4.00	138.56	0.00	0.73
9	QTS	Bar	100	4.00	138.56	0.00	0.55
10	HSS	Bar	140	4.00	98.97	0.00	0.22
11	QTS	Bar	160	5.66	122.47	0.76	0.00
12	CS	Bar	140	4.00	98.97	0.54	0.00
13	CS	Bar	140	4.00	98.97	0.96	0.00
14	CS	Bar	160	4.00	86.60	0.87	0.00
15	CS	Bar	160	4.00	86.60	0.99	0.00
16	CS	Bar	160	4.00	86.60	1.99	0.00
17	CS	Bar	160	4.00	86.60	0.88	0.00
18	QTS	Bar	140	4.00	98.97	0.83	0.00
19	CS	Bar	140	4.00	98.97	0.56	0.00

20	QTS	Bar	160	5.66	122.47	0.78	0.00
21	CS	Bar	160	4.00	86.60	0.00	0.24
22	HSS	Bar	150	5.66	130.64	0.81	0.00
23	QTS	Tube	130	4.00	78.92	0.00	0.85
24	CS	Bar	140	5.66	139.97	0.82	0.00
25	QTS	Tube	110	4.00	93.21	0.00	0.92
26	QTS	Bar	140	5.66	139.97	0.57	0.00
27	HSS	Tube	140	4.00	73.57	0.00	0.51
28	QTS	Bar	120	5.66	163.30	0.61	0.01
29	CS	Tube	140	4.00	73.57	0.00	0.70
30	QTS	Bar	120	5.66	163.30	0.55	0.02
31	HSS	Tube	140	4.00	73.57	0.00	0.48
32	QTS	Bar	140	5.66	139.97	0.55	0.00
33	QTS	Tube	110	4.00	93.21	0.00	0.89
34	CS	Bar	140	5.66	139.97	0.79	0.00
35	QTS	Tube	120	4.00	85.83	0.00	0.90
36	HSS	Bar	150	5.66	139.97	0.79	0.00
37	CS	Bar	160	4.00	86.60	0.00	0.23

Table 3
Howe Truss Bridge
Member Report Details
Member with the Highest Compressions Force/Strength Ratio

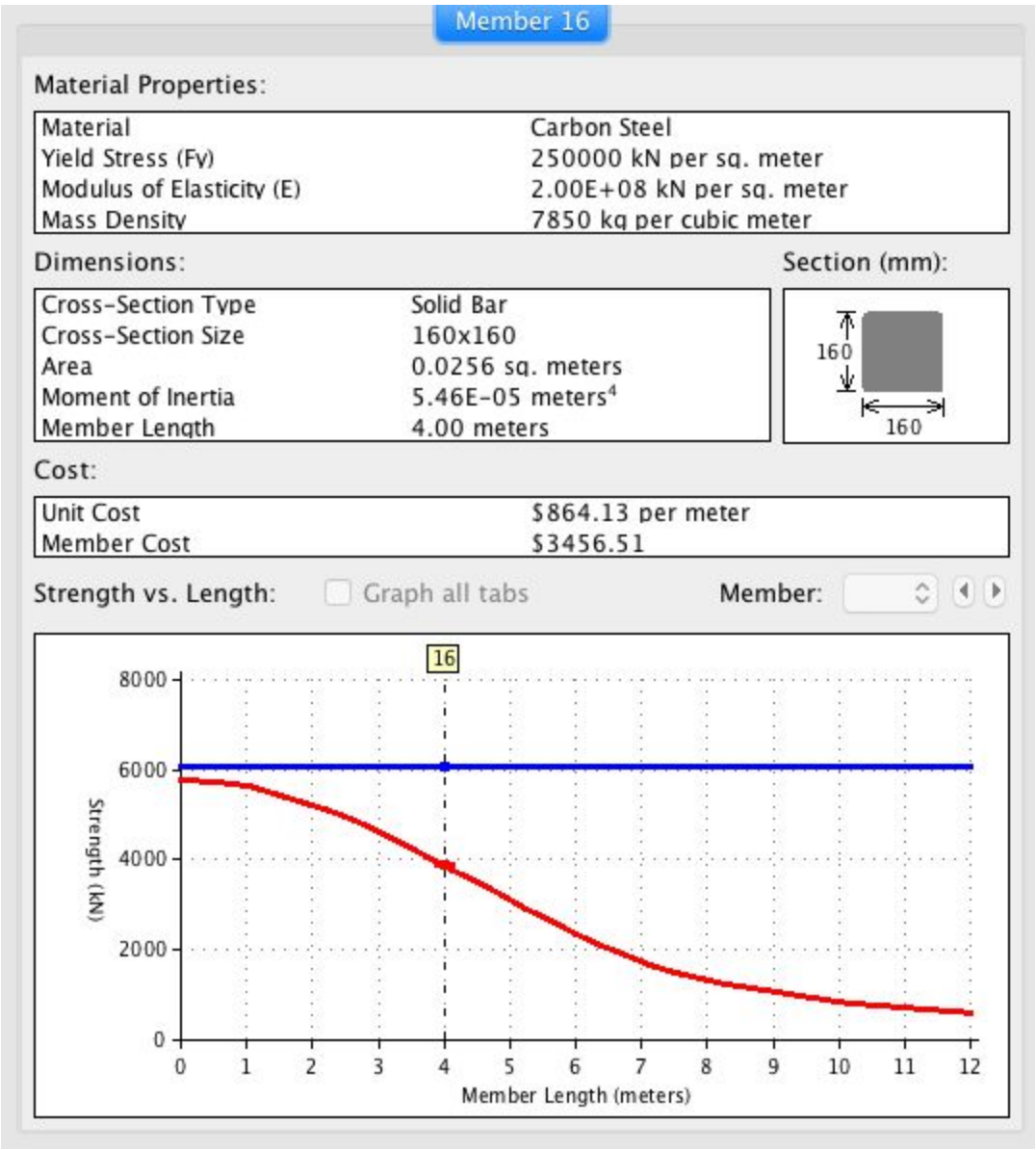


TABLE No. 4
Warren Truss Bridge
Member Details Report from Bridge Designer 2016

Cost Calculation Report from Bridge Designer 2016

Type of Cost	Item	Cost Calculation	Cost
Material Cost (M)	Carbon Steel Solid Bar	(3362.4 kg) x ($4.30 per kg) x (2 Trusses) =	$28,916.43
	Carbon Steel Hollow Tube	(386.6 kg) x ($6.30 per kg) x (2 Trusses) =	$4,871.12
	High-Strength Low-Alloy Steel Solid Bar	(1256.0 kg) x ($5.60 per kg) x (2 Trusses) =	$14,067.20
	High-Strength Low-Alloy Steel Hollow Tube	(2549.2 kg) x ($7.00 per kg) x (2 Trusses) =	$35,689.30
	Quenched & Tempered Steel Hollow Tube	(1975.9 kg) x ($7.70 per kg) x (2 Trusses) =	$30,429.46
Connection Cost (C)		(21 Joints) x (400.0 per joint) x (2 Trusses) =	$16,800.00
Product Cost (P)	10 - 100x100 mm Carbon Steel Bar	(%s per Product) =	$1,000.00
	4 - 100x100 mm High-Strength Low-Alloy Steel Bar	(%s per Product) =	$1,000.00
	6 - 100x100x5 mm High-Strength Low-Alloy Steel Tube	(%s per Product) =	$1,000.00
	4 - 150x150x7 mm High-Strength Low-Alloy Steel Tube	(%s per Product) =	$1,000.00
	2 - 180x180x9 mm Carbon Steel Tube	(%s per Product) =	$1,000.00
	6 - 200x200x10 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
	4 - 220x220x11 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	1 - 240x240x12 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
Site Cost (S)	Deck Cost	(10 4-meter panels) x ($5,100.00 per panel) =	$51,000.00
	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	$113,973.51 + $16,800.00 + $9,000.00 + $81,400.00 =	$221,173.51

Table 5
Warren Truss Bridge

Load Test Results Report from Bridge Designer 2016

#	Material Type	Cross Section	Size (mm)	Length (m)	Slenderness	Compression Force/Strength	Tension Force/Strength
1	HSS	Tube	100	4.00	102.99	0.00	0.94
2	HSS	Tube	100	4.47	115.15	0.00	0.96
3	HSS	Tube	100	4.47	115.15	0.46	0.59
4	HSS	Tube	100	4.47	115.15	0.62	0.53
5	HSS	Tube	100	4.47	115.15	0.00	0.90
6	HSS	Tube	100	4.00	102.99	0.00	0.92
7	CS	Bar	100	4.00	138.56	0.00	0.67
8	CS	Bar	100	4.00	138.56	0.00	0.99
9	CS	Bar	100	4.00	138.56	0.00	0.99
10	CS	Bar	100	4.00	138.56	0.00	0.66
11	CS	Bar	100	4.47	154.92	0.00	0.35
12	CS	Bar	100	4.47	154.92	0.00	0.45
13	CS	Bar	100	4.47	154.92	0.00	0.55
14	CS	Bar	100	4.47	154.92	0.00	0.34
15	CS	Bar	100	4.47	154.92	0.00	0.44
16	CS	Bar	100	4.47	154.92	0.00	0.53
17	HSS	Bar	100	4.00	138.56	0.00	0.86
18	HSS	Bar	100	4.00	138.56	0.00	0.94
19	HSS	Bar	100	4.00	138.56	0.00	0.95
20	HSS	Bar	100	4.00	138.56	0.00	0.87
21	HSS	Tube	150	4.47	76.51	0.74	0.00
22	HSS	Tube	150	4.47	76.51	0.46	0.07
23	HSS	Tube	150	4.47	76.51	0.41	0.10
24	HSS	Tube	150	4.47	76.51	0.70	0.00
25	HSS	Tube	200	4.47	57.58	0.43	0.00
26	HSS	Tube	200	4.47	57.58	0.71	0.00
27	HSS	Tube	200	4.47	57.58	0.58	0.00
28	HSS	Tube	200	4.47	57.58	0.45	0.00
29	HSS	Tube	200	4.47	57.58	0.56	0.00
30	HSS	Tube	200	4.47	57.58	0.69	0.00
31	QTS	Tube	200	4.00	51.50	0.82	0.00
32	QTS	Tube	200	4.00	51.50	0.80	0.00
33	QTS	Tube	220	4.00	46.82	0.85	0.00
34	QTS	Tube	220	4.00	46.82	0.97	0.00
35	QTS	Tube	220	4.00	46.82	0.96	0.00
36	QTS	Tube	220	4.00	46.82	0.84	0.00

37	QTS	Tube	240	4.00	42.91	0.81	0.00
38	CS	Tube	180	4.00	57.22	0.98	0.00
39	CS	Tube	180	4.00	57.22	1.00	0.00

Table 6

Warren Truss Bridge

Member Details Report from Bridge Designer 2016

Member with the Highest Tension Force/Strength Ratio

Member List | Member Details

Members 8,9

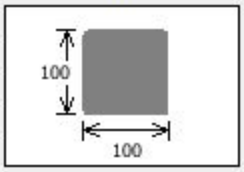
Material Properties:

Material	Carbon Steel
Yield Stress (Fy)	250000 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	Solid Bar
Cross-Section Size	100x100
Area	0.0100 sq. meters
Moment of Inertia	8.33E-06 meters^4
Member Length	--

Section (mm):



Cost:

Unit Cost	$337.55 per meter
Member Cost	--

Strength vs. Length: Graph all tabs Member: 8

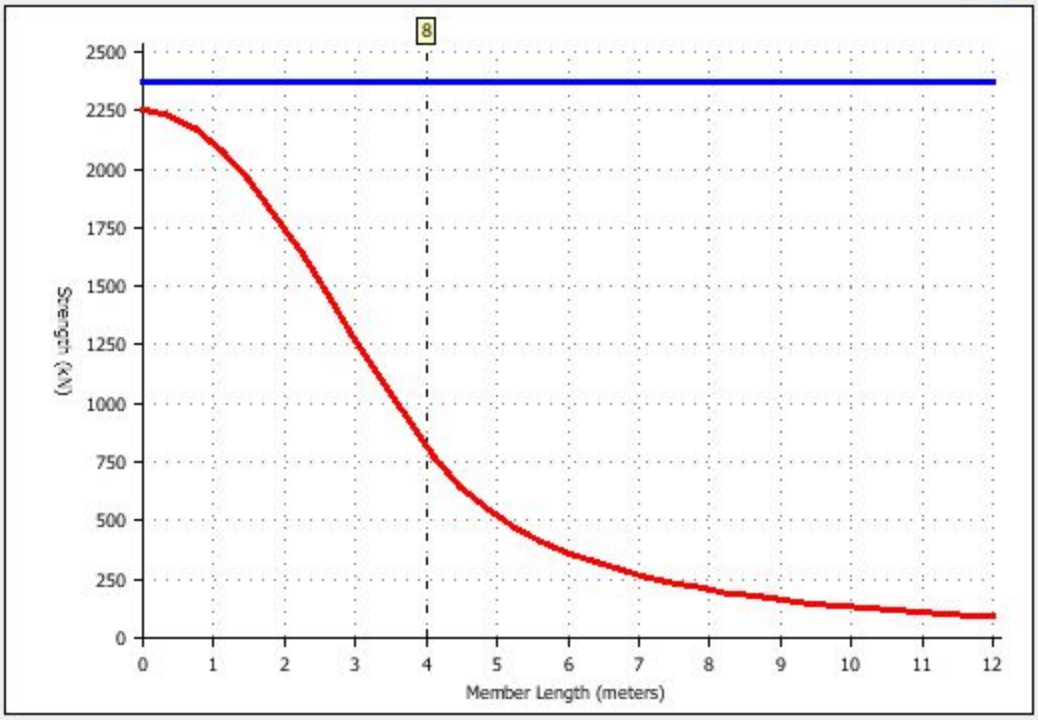


Table 7.
Structural Efficiency of Howe Truss Bridges between different design teams

Number	Structural Efficiency	Weight (g)	Load (lbs)	Weight (lbs)
1	366.4522869	78.6	63.5	0.173283132
2	269.0114559	77.9	46.2	0.171739898
3	418.8918125	73.2	67.6	0.161378184
4	631.7693283	77.9	108.5	0.171739898
5	208.6404292	73.7	33.9	0.162480494
6	203.3992964	72.7	32.6	0.160275874
7	194.0162386	85.1	36.4	0.187613162

Minimum: 194.016
Maximum: 631.769
Range: 437.723
Average: 327.45
Geomean:299.22

Table 8.
Structural Efficiencies of Warren Bridges between Different design teams

Team #	SE	Weight (g)	Load (lbs)	Weight (lbs)
1	410.2113091	71.1	64.3	0.156748482
2	430.9408884	82.1	78	0.180999302
3	648.1514641	80.2	114.6	0.176810524
4	311.5698868	82.4	56.6	0.181660688
5	188.3896385	80.9	33.6	0.178353758
6	234.691268	63.2	32.7	0.139331984
7	337.0994451	80.6	59.9	0.177692372

Minimum: 199.389
Maximum: 648.1514
Range: 448.7624
Average: 365.864
Geomean: 434.674

FIGURES

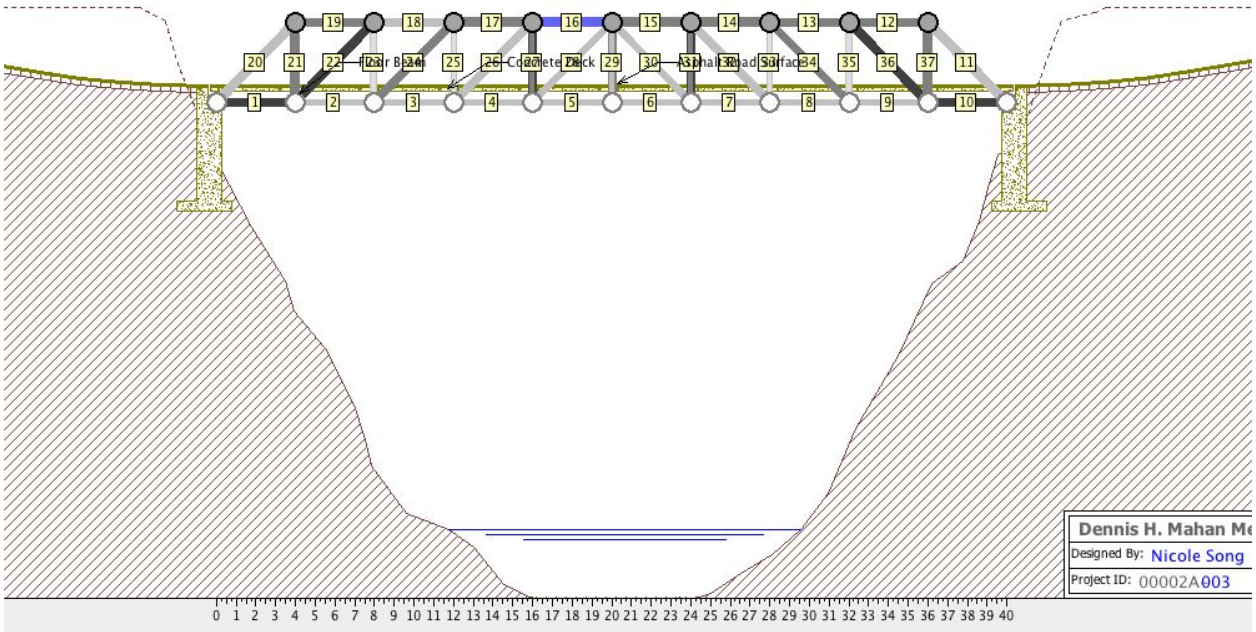


Figure 1. Howe Bridge Model from EEBD 2015

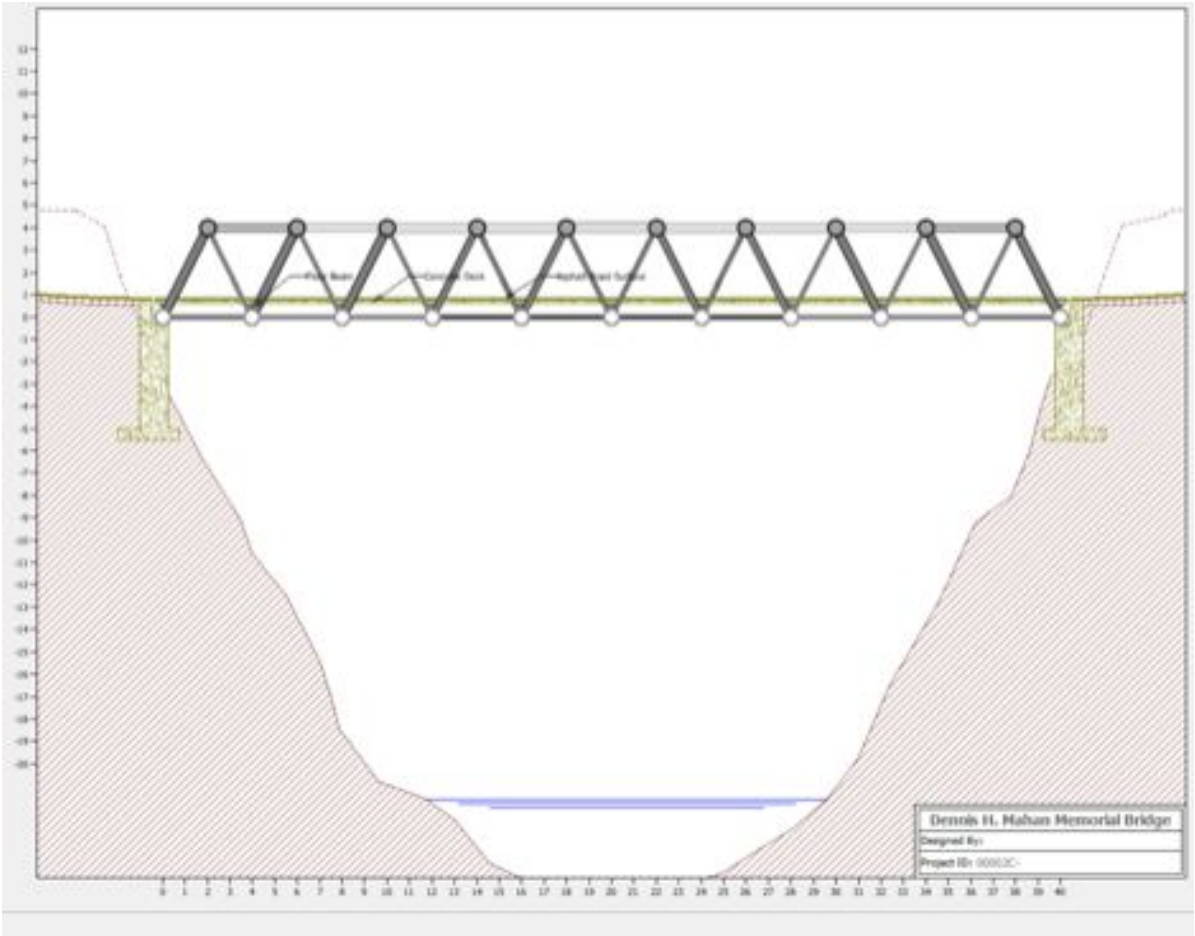


Figure 2. Warren Bridge Model from Bridge Designer 2015

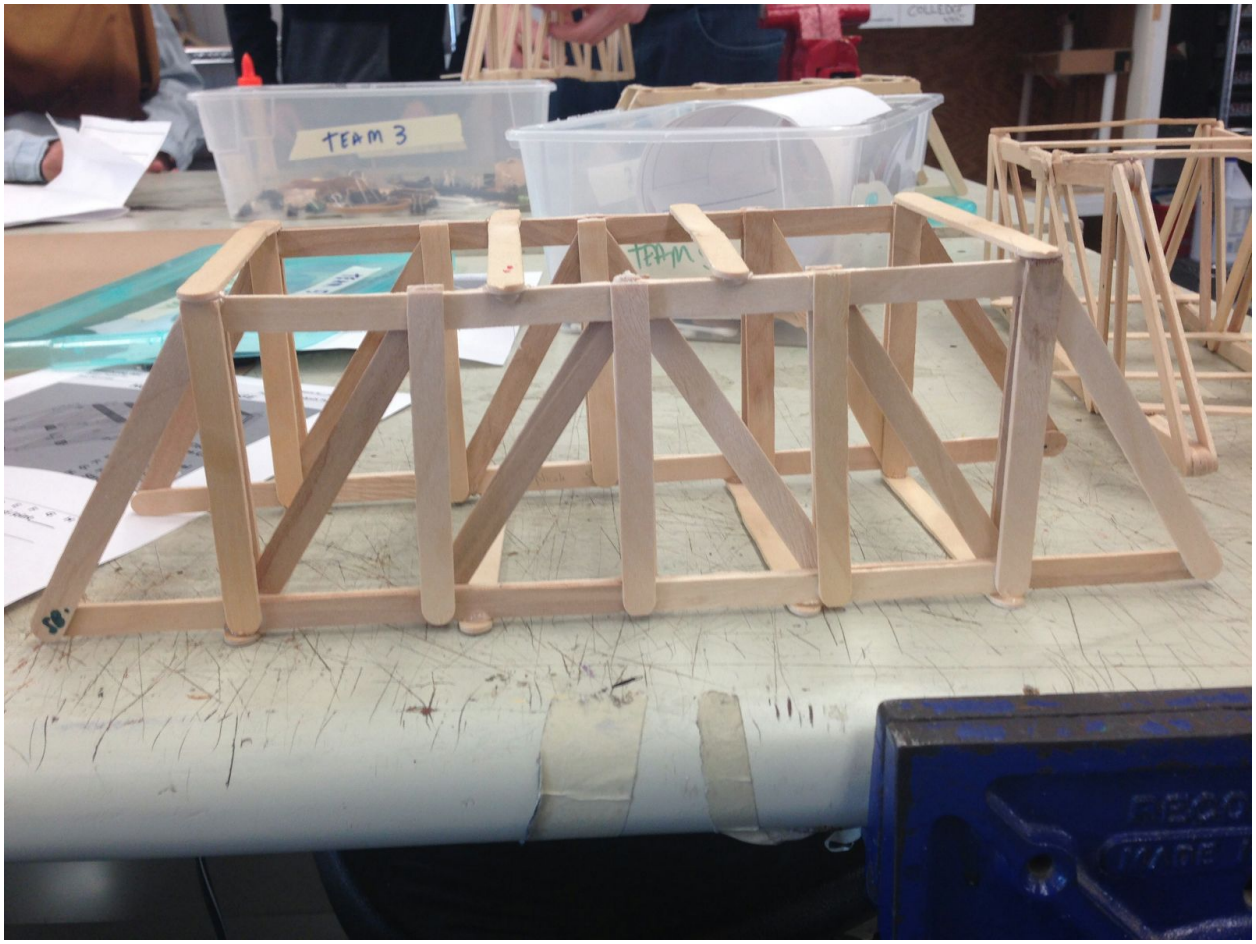


Figure 3. Prototype of Howe Bridge Prior to testing

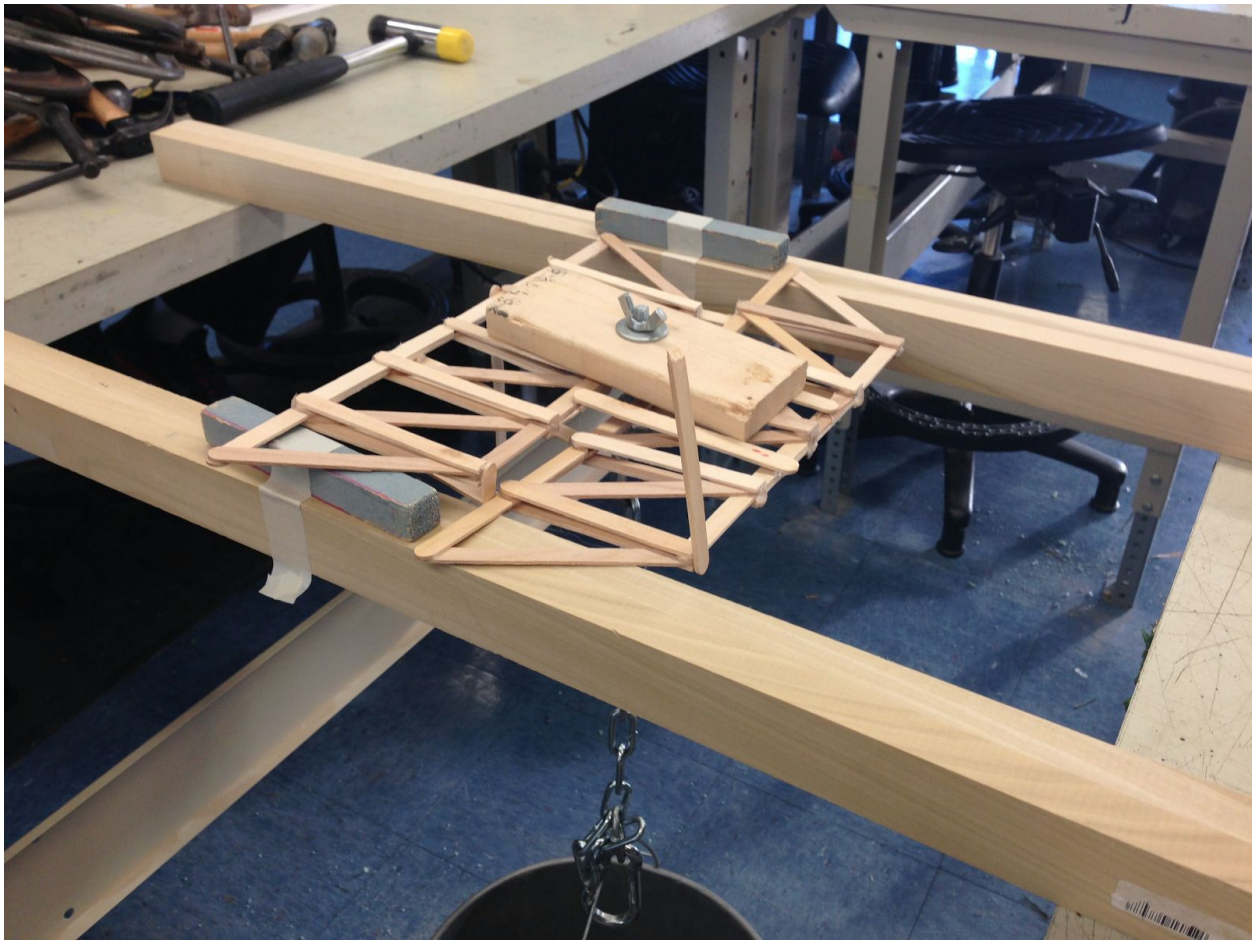


Figure 4. Howe Truss Bridge After Failure

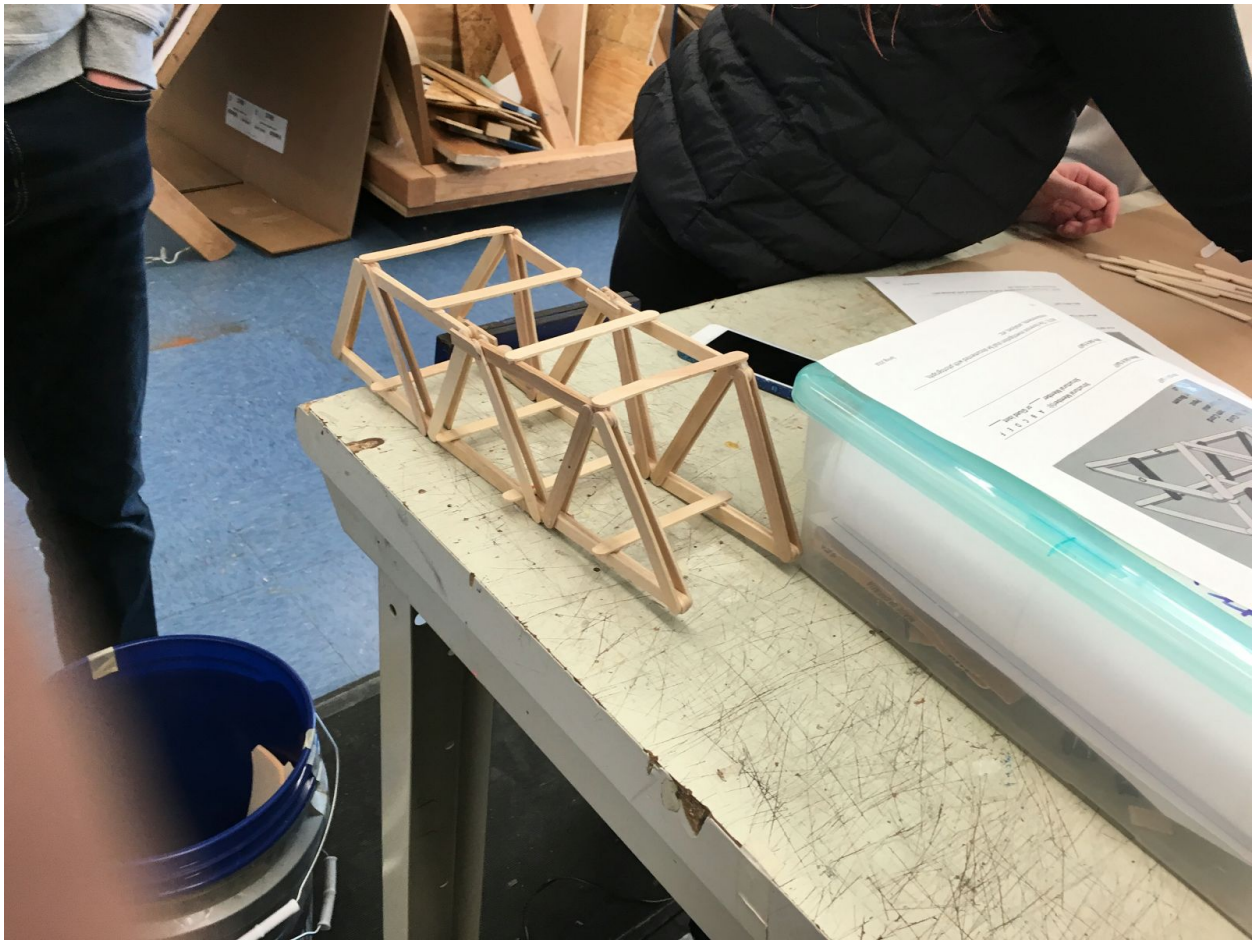


Figure 5. Warren Truss Bridge Before Failure

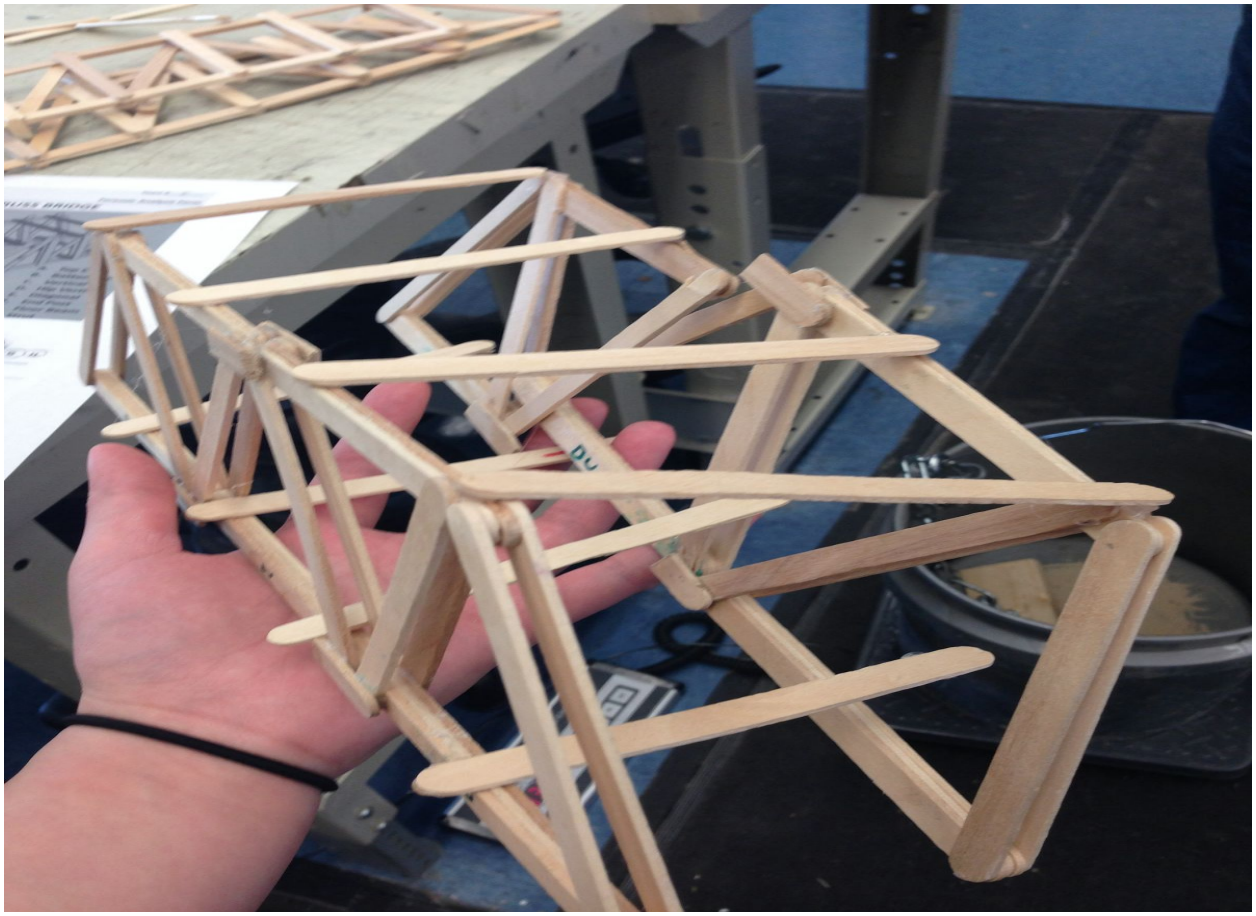


Figure 6. Warren Truss Bridge After Failure

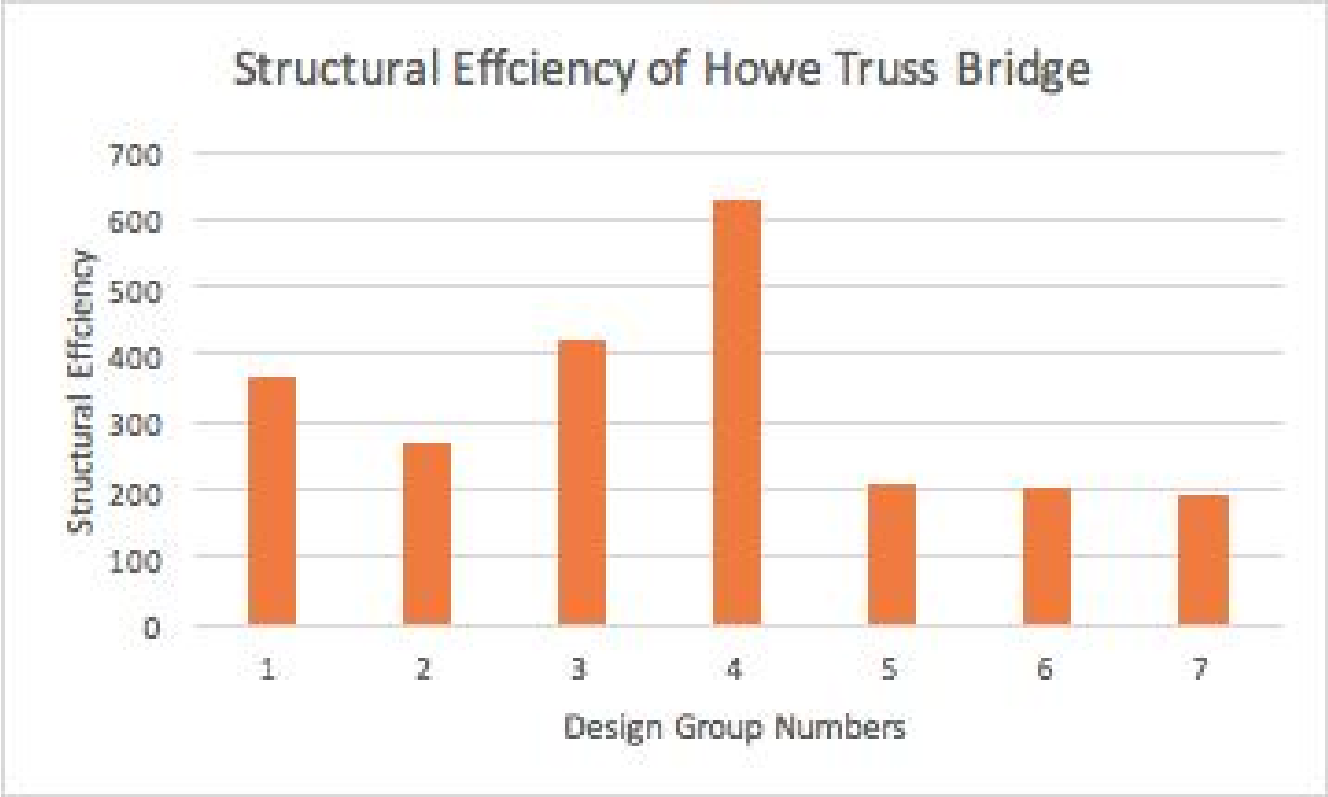


Figure 7. Howe Truss Bridge Structural Effciencies

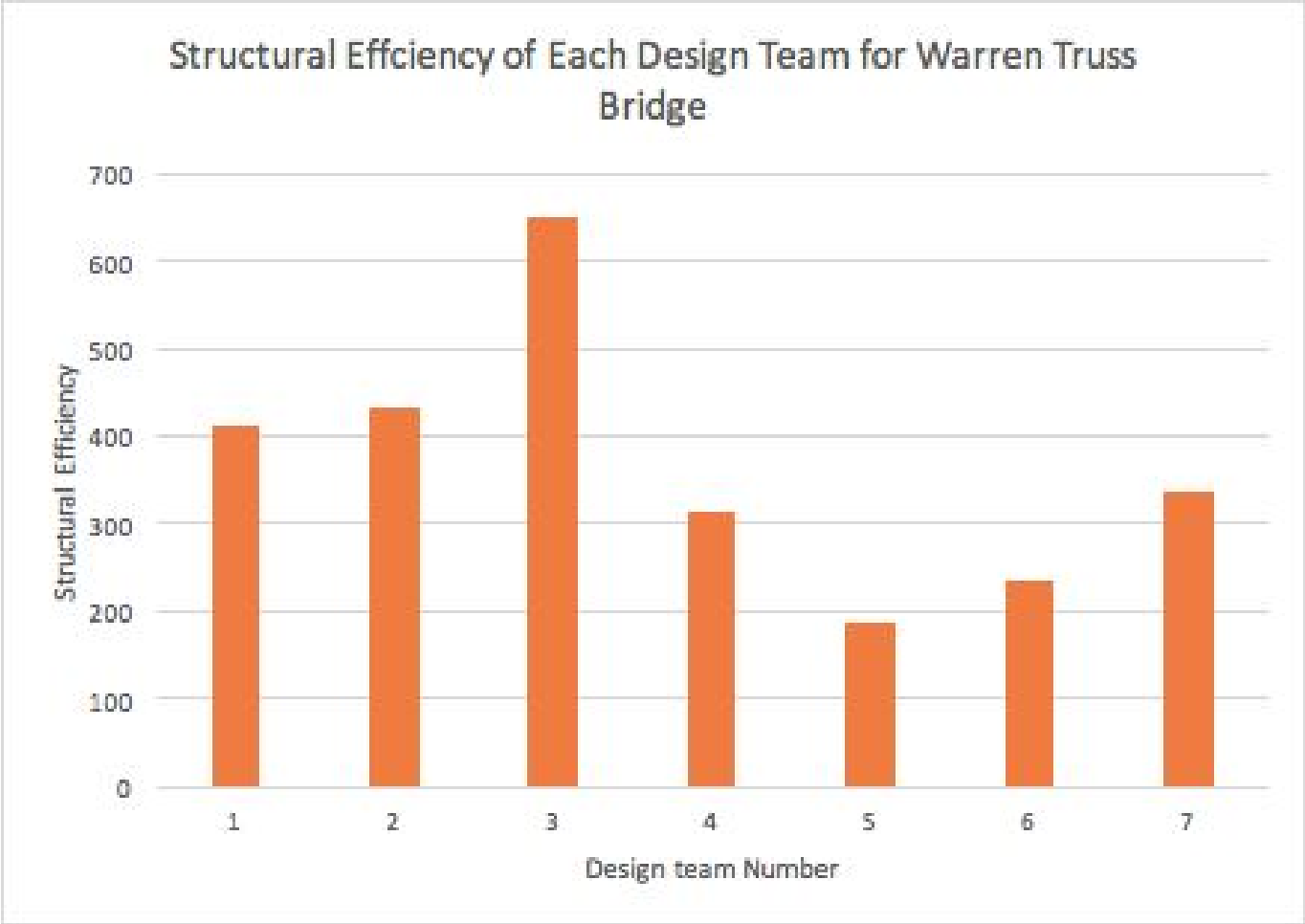


Figure 8. Warren Truss Bridge Structural Efficiencies