PENNSTATE

School of Engineering Design, Technology and Professional Programs
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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.

A recent 100-year flood event has resulted in the collapse of a structurally deficient bridge in Spring Creek along Puddintown Road in College Township, Centre County, PA. This bridge is located in Pennsylvania Department of Transportation (PennDOT) Engineering District 2-0. Due to failure of the bridge, reaching important places in State College such as the Mount Nittany Medical Center is cumbersome and leaves citizens to risk as it is a 10 mile re-route around the bridge.

Objective.

Pennsylvania Department of Transportation of (PennDOT) Engineering District 2-0 has initiated an emergency project to accelerate the design of a new vehicle bridge over Spring Creek to replace the bridge destroyed by the recent extreme flood event.

Design Criteria.

The design criteria as laid out by PennDOT District 2-0 includes standard abutments, no piers (one span), deck material shall be medium strength concrete (0.23 meters thick), no cable anchorages and designed for the load of two AASHTO H20-44 trucks (225kN) with one in each traffic lane. The bridge deck elevation shall be set at 20 meters and the deck span shall be exactly 40 meters. Both a Warren through truss bridge and a Howe through truss bridge shall be analyzed. All other design components is in the control of the EDesign 100 team.

Technical Approach.

Phase 1: Economic Efficiency.

The Economic Efficiency of both the Warren and Howe truss bridges was determined by first creating bridges that could support both the dead load and live load of each bridge. From there, the materials and dimensions of the members in each bridge were altered to lower the

bridge cost. At the point where members could no longer be altered while maintaining the dead load and live load, each bridge was determined to be as economically efficient as possible.

Phase 2: Structural Efficiency.

To determine Structural Efficiency of the Warren and Howe Truss Bridges, a Warren and Howe prototype bridge were constructed with specific dimension guidelines and then weighed. After each bridge's weight was determined, each bridge was load tested to failure. The load was then weighed and by dividing the test load by the bridge weight (all in lbs.) the Structural Efficiency of each bridge was determined.

Results.

Phase 1: Economic Efficiency.

The economic efficiency of each bridge was determined by using the Engineering Encounters Bridge Designer 2016 program. Attachment 1 analyzes the data created from the program and explains the process required to arrive at a final bridge price. Also found in Attachment 1 is the process of reducing the price of the bridge to its minimum value while maintaining the ability to hold its dead load and the load tested. The output generated by the program showed that the Howe truss bridge design had a greater economic efficiency than the Warren truss bridge design.

Phase 2: Structural Efficiency

Attachment 2 contains the data of the load testing of the bridges. It also explains the process of designing and building the bridges. Each bridge was built using elmer's glue and popsicle stick. The most unique design implemented in each bridge design was the process of sanding half of a Popsicle stick allowing them to fit onto one plane. After the bridge prototype was finished, a load was placed at the center of the bridge to test the structural efficiency. The structural efficiency was calculated by dividing the load at failure by the weight of the bridge. All data can be found and explained in Attachment 2.

Best Solution.

(i) When comparing the two types of bridges, the Howe truss bridge has a greater economic efficiency. The overall cost of the Howe Bridge is $240,332.22. The price of the Warren truss bridge is approximately $9,000.00 more expensive than the Howe truss bridge with a total cost of $249,468.24.

(ii) The structural efficiency of each bridge type can be compared by looking at the average, geometric mean, maximum, minimum and range of the calculated structural efficiency collected after load testing. In each category, the Warren truss bridge has a greater value for structural efficiency. The two most important values to examine are the averages and the geometric means. They represent the data as a whole instead of just individual values. The geometric mean of the Warren truss bridge is 393 and the Howe truss bridge is 318. The averages of the structural efficiencies are 416 and 335 respectively. Team 6 had the most structurally efficient bridge using a Warren truss with a value of 734.

(iii) Another method used to determine the most suitable bridge is design efficiency. This is calculated by dividing the total cost of a bridge design with the structural efficiency of that bridge. Four values were calculated. The price of the Howe truss bridge was divided by the structural efficiency average and geometric mean generating values 718 and 755 respectively.

Similarly, the Warren truss bridge generated values of 599 and 635 respectively. Although the Warren truss bridge had a greater value for the average and geometric mean, the Howe's design cost was less than that of the Warren design, causing the design efficiency for the Howe truss bridge to be greater.

(iv) In order to determine the best constructability between the two bridge designs the material, production and connection costs will be compared. The design of the Howe truss bridge has 37 members and 20 joints per truss. The Warren design requires two extra members per truss which also means adding one more joint to the truss. This leads to a $2,400.00 increase in price in the Warren truss design. The material cost of the Howe truss bridge was less than the Warren truss bridge. This is due to the fact that the Howe truss bridge implements three different types of materials. This reduced the price because some of the materials cost less than the others.

The goal of this design project was to design the most structurally and economically efficient bridge. After evaluating the results and analyzing the data the design team reached the conclusion that the Warren truss bridge is the best solution for the replacement bridge in Centre County, PA. The most influential data gathered was the design efficiency. This data compared the price and the structural efficiency. It proved that the ratio of price to strength was less than that of the Howe truss bridge meaning less money is spent per structural efficiency. Even though the Warren truss bridge was more expensive, it is worth spending the extra $9,000.00 to make a more structurally efficient bridge.

Conclusions and Recommendations.

The design team has come to the conclusion that the Warren truss bridge should be the bridge to replace the fallen bridge in Centre County, PA. The next step needed to be implemented in this design process is to seek professional engineers. Their professional input can help this bridge design approach the construction process. After the final professional revisions are completed the bridge is ready to be built. The design for the bridge should also be presented to the residents of College Township, Centre County, PA in order for them to prepare themselves for the future renovations.

Respectfully,

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ATTACHMENT 1

Phase 1: Economic Efficiency

Howe Truss.

Using the Engineering Encounters Bridge Designer 2016 program, the Howe Truss constructed would cost approximately $240,332.22, consisting of material costs ($128,932.22), connection costs ($16,000.00), product costs ($18,000.00), and site costs ($77,400.00). Specifically, the material costs consisted of using carbon steel solid bar, carbon steel hollow tube, and quenched and tempered steel solid bar at varying prices, the connection costs consisted of connecting 20 joints for two trusses at $400 per joint, the product costs consisted of using multiple bars and tubes of varying dimensions and prices, and site costs consisted of deck costs, excavation costs, and abutment costs. All specific costs can be viewed within Table 1.

To make the Howe Truss as economically efficient as possible, the truss was initially constructed to just be structurally efficient. Once deemed as stable, the materials used in each member of the truss as well as the dimensions of each member were altered. Through a trial-and-error process in the Bridge Designer program, each member of the truss had its dimensions reduced and/or had its material changed to lower the overall cost of the truss. The process of reducing the truss' cost was done until each member of the truss could no longer have either its dimensions reduced or material changed while continuing to be structurally efficient.

Warren Truss.

The primary goal for this bridge was to be functional. The design was aimed for the bridge to hold the required weight without failing, while also being as cost effective as possible. This was accomplished through trial and error to determine the most effective construction materials, size of components, and hollow or solid tubing. It was determined that structural components with a tension force were more efficient when solid bars were used, while structural components with a compression force were more efficient when hollow tubes were used. Determining the size of each component was also trial and error, continuously making every beam smaller until just before failure, by keeping the compression and tension forces below 1.00, to maximize the amount of material needed and keep the beams as small as possible. The entire bridge was constructed of carbon steel bars, as an attempt to keep costs downs, because it was the cheapest material available. The final cost of the warren bridge was $249,468.24.

ATTACHMENT 2

Phase 2: Structural Efficiency

Howe Truss.

Prototype Bridge.

To construct the Howe Truss, all 60 Popsicle sticks provided for construction along with both Elmer's and hot glue were used. The truss is a direct downscaled model of the Howe Truss constructed using the Bridge Designer program. To construct the truss, the ends of specific Popsicle sticks were sanded to be flush with other sticks at the truss' joints, eventually being stagnated with Elmer's glue. Each joint was kept immobile using clips immediately after gluing until completely dry. To connect the two sides of the truss, eight Popsicle sticks (four on top, four on bottom) were glued to each side using hot glue. After construction, the bridge dimensions were 13.5 in x 4.25 in x 3.75 in.

Load Testing.

The Howe Truss constructed was determined to have a structural efficiency of 375, a figure higher than the design team average of 335. Overall, the truss constructed placed second in structural efficiency, only behind design team six's truss that had an efficiency of 556. In terms of all design teams, the minimum structural efficiency was 201 while the maximum was 556, the range of efficiencies was 355, and the geometric mean was 318. For statistics specific to design team four's truss, the truss weighted 80.8 grams (.1778 lbs.) and carried a load at failure of 66.7 lbs.

Forensic Analysis.

The Howe Truss inevitably failed not due to a joint failure, but due to the truss being slightly slanted and not completely vertical. Ultimately, as weight was added to the load, an increasing torque was applied to the truss until it fell over onto its side. Essentially, the truss failed where the Popsicle sticks were hot glued to connect the two sides and not at any specific joint. This conclusion is difficult to tell merely by looking at the photos of the truss after the test, but can clearly be seen in a slow-motion video of the load test.

Results. Like previously stated, the Howe Truss was calculated to have a structural efficiency of 375, making it the second most efficient in the class. For specific numbers about each design team's Howe Truss, please refer to Table 7.

Warren Truss.

Prototype Bridge.

The prototype bridge was designed to be as stable as possible. Having every beam completely straight seemed ideal, to avoid any bending and uneven distribution of weight and support. This was accomplished by shaving down the Popsicle sticks to half their depth at the locations where they would normally overlap another stick. In doing this, the sticks would be flush with each other, leaving no curvature to the beams and even lightening the bridge. The

bridge was constructed using Q-tips to Elmer's glue to every intersecting joint, and binder clips to hold them in place until dry.

Load Testing.

The prototype bridge weighed 57.6 grams (0.1270 lbs), which was the lightest in the class, and the load failure was 54.1 pounds, leaving it with a structural efficiency of 427, the third best in the class. The maximum structural efficiency was 734, and the range was 496. The median structural efficiency was 403, the average was 416, and geometric mean was 393. A more detailed analysis can be found under table 8.

Forensic Analysis.

The Warren Truss bridge failed due to weak connecting beams. This was determined because both sides remained completely intact. This could have been due to insufficient glue on the beams connecting the two sides, or that only one layer of Popsicle sticks as the loading mechanism was simply not enough to withstand more weight. As observed in the video of its failure, the weight bucket pulled straight down and destroying the load beams.

Results.

An EXCEL bar chart is included as Figure 8 comparing Structural Efficiencies as presented in Table 8.

TABLES

TABLE 1
Howe Truss Bridge
Cost Calculation Report from Bridge Designer 2015

Type of Cost	Item	Cost Calculation	Cost
Material Cost (M)	Carbon Steel Solid Bar	(5643.4 kg) x ($4.30 per kg) x (2 Trusses) =	$48,532.94
	Carbon Steel Hollow Tube	(4637.4 kg) x ($6.30 per kg) x (2 Trusses) =	$58,431.84
	Quenched & Tempered Steel Solid Bar	(1830.6 kg) x ($6.00 per kg) x (2 Trusses) =	$21,967.44
Connection Cost (C)		(20 Joints) x (400.0 per joint) x (2 Trusses) =	$16,000.00
Product Cost (P)	1 – 50x50 mm Carbon Steel Bar	(1,000.00 per Product) =	$1,000.00
	2 – 55x55 mm Carbon Steel Bar	(1,000.00 per Product) =	$2,000.00
	2 – 65x65 mm Carbon Steel Bar	(1,000.00 per Product) =	$2,000.00
	1 – 70x70 mm Carbon Steel Bar	(1,000.00 per Product) =	$1,000.00
	1 – 75x75 mm Carbon Steel Bar	(1,000.00 per Product) =	$1,000.00
	4 – 80x80 mm Carbon Steel Bar	(1,000.00 per Product) =	$4,000.00
	2 – 90x90 mm Quenched & Tempered Steel Bar	(1,000.00 per Product) =	$2,000.00
	3 – 100x100 mm Quenched & Tempered Steel Bar	(1,000.00 per Product) =	$2,000.00
	2 – 110x110 mm Carbon Steel Bar	(1,000.00 per Product) =	$2,000.00
	1 – 110x110 mm Quenched & Tempered Steel Bar	(1,000.00 per Product) =	$1,000.00

	1 – 140x140x7 mm Carbon Steel Tube	(1,000.00 per Product) =	$1,000.00
	1 – 150x150x7 mm Carbon Steel Tube	(1,000.00 per Product) =	$1,000.00
	4 – 160x160 mm Carbon Steel Bar	(1,000.00 per Product) =	$4,000.00
	2 – 180x180x9 mm Carbon Steel Tube	(1,000.00 per Product) =	$2,000.00
	4 – 200x200x10 mm Carbon Steel Tube	(1,000.00 per Product) =	$4,000.00
	2 – 220x220x11 mm Carbon Steel Tube	(1,000.00 per Product) =	$2,000.00
	2 – 240x240x12 mm Carbon Steel Tube	(1,000.00 per Product) =	$2,000.00
	2 – 260x260x13 mm Carbon Steel Tube	(1,000.00 per Product) =	$2,000.00
Site Cost (S)	Deck Cost	(10 4-meter panels) x ($4,700.00 per panel) =	$47,000.00
	Excavation Cost	(19,400 cubic meters0 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**	**$128,932.22 + $16,000.00 + $18,000.00 + $77,400.00 =**	**$240,332.22**

TABLE 2
Howe Truss Bridge
Load Test Results Report from Bridge Designer 2015

#	Material Type	Cross Section	Size (mm)	Length (m)	Slenderness	Compression Force/Strength	Tension Force/Strength
1	CS	Bar	80	4.00	173.21	0.00	0.93
2	CS	Bar	110	4.00	125.97	0.00	0.88
3	QTS	Bar	90	4.00	153.96	0.00	0.89
4	QTS	Bar	110	4.00	125.97	0.00	0.68
5	QTS	Bar	100	4.00	138.56	0.00	0.85
6	QTS	Bar	100	4.00	138.56	0.00	0.85
7	QTS	Bar	100	4.00	138.56	0.00	0.81
8	QTS	Bar	90	4.00	153.96	0.00	0.87
9	CS	Bar	110	4.00	125.97	0.00	0.85
10	CS	Bar	80	4.00	173.21	0.00	0.91
11	CS	Tube	200	4.00	51.50	0.95	0.00
12	CS	Tube	260	4.00	39.61	0.95	0.00
13	CS	Bar	160	4.00	86.60	0.85	0.00
14	CS	Bar	160	4.00	86.60	0.97	0.00
15	CS	Bar	160	4.00	86.60	0.97	0.00
16	CS	Bar	160	4.00	86.60	0.84	0.00
17	CS	Tube	260	4.00	39.61	0.92	0.00
18	CS	Tube	200	4.00	51.50	0.93	0.00
19	CS	Tube	240	5.66	60.69	0.96	0.00
20	CS	Tube	240	5.66	60.69	0.99	0.00
21	CS	Bar	80	4.00	173.21	0.00	0.93
22	CS	Tube	220	5.66	66.21	0.99	0.00
23	CS	Bar	75	4.00	184.75	0.00	0.86

24	CS	Tube	200	5.66	72.83	0.97	0.00
25	CS	Bar	65	4.00	218.18	0.00	0.88
26	CS	Tube	180	5.66	80.92	0.90	0.00
27	CS	Bar	55	4.00	251.93	0.00	0.85
28	CS	Tube	150	5.66	96.78	0.92	0.09
29	CS	Bar	55	4.00	251.93	0.00	0.87
30	CS	Tube	140	5.66	104.04	0.98	0.15
31	CS	Bar	50	4.00	277.13	0.00	0.98
32	CS	Tube	180	5.66	80.92	0.86	0.00
33	CS	Bar	65	4.00	213.18	0.00	0.85
34	CS	Tube	200	5.66	72.83	0.94	0.00
35	CS	Bar	70	4.00	197.95	0.00	0.96
36	CS	Tube	220	5.66	66.21	0.97	0.00
37	CS	Bar	80	4.00	173.21	0.00	0.91

TABLE 3
Howe Truss Bridge from Bridge Designer 2015
Member with Highest Compression Force/Strength Ratio

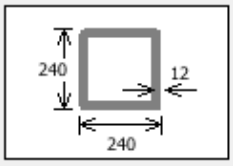
Material Properties:

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	Hollow Tube
Cross-Section Size	240x240x12
Area	0.0109 sq. meters
Moment of Inertia	9.51E-05 meters^4
Member Length	5.66 meters

Section (mm):



Cost:

Unit Cost	$541.24 per meter
Member Cost	$3061.69

Strength vs. Length: Graph all tabs Member:

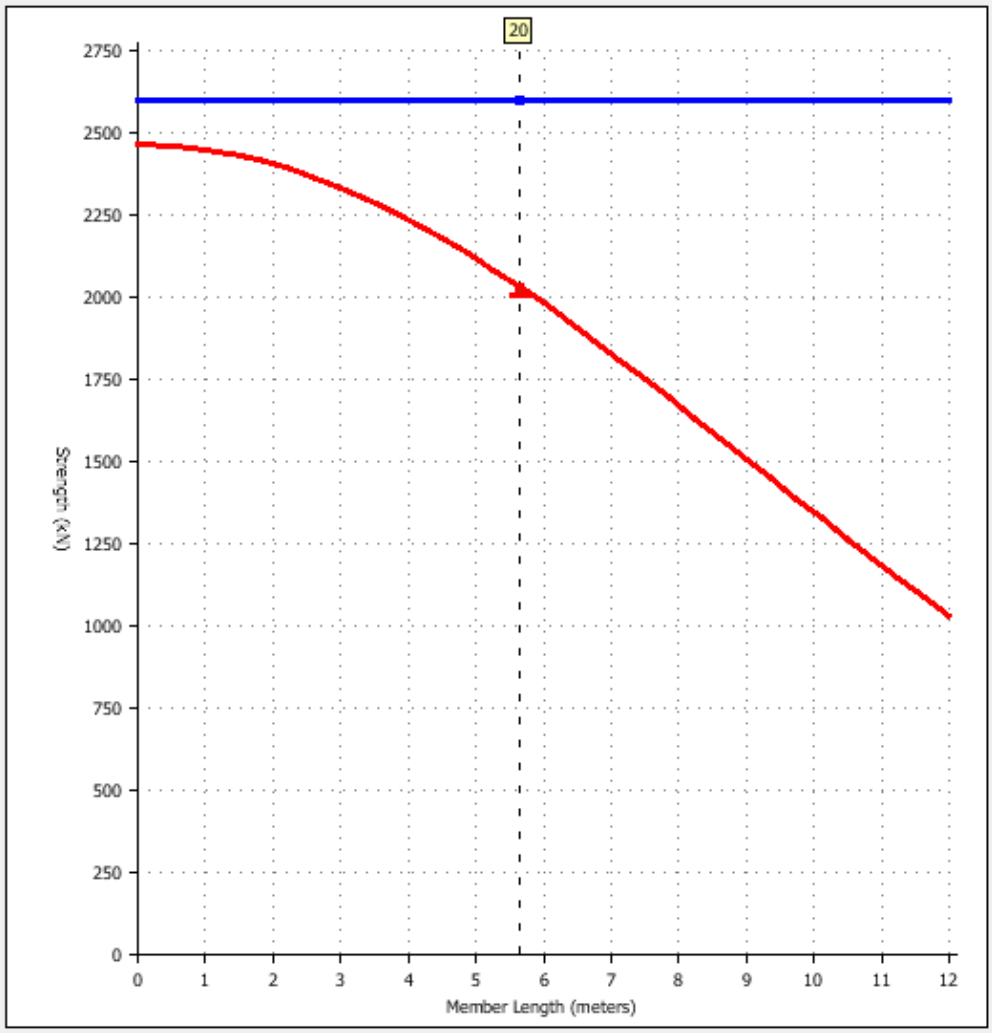


TABLE 4
Warren Truss Bridge
Cost Calculation Report from Bridge Designer 2015

Type of Cost	Item	Cost Calculation	Cost
Material Cost (M)	High-Strength Low-Alloy Steel Solid Bar	(16542.8 kg) x ($4.30/kg) x (2 Trusses)=	$142,268.24
Connection Cost (C)		(21 Joints) x (400.0/joint) x (2 Trusses)=	$16,800.00
Product Cost (P)	3 - 55x55 mm Carbon Steel Bar 2 - 60x60 mm Carbon Steel Bar 1 – 65x65 mm Carbon Steel Bar 2 – 70x70 mm Carbon Steel Bar 2 – 75x75 mm Carbon Steel Bar 4 – 90x90 mm Carbon Steel Bar 2 – 100x100 mm Carbon Steel Bar 2 – 110x110 mm Carbon Steel Bar 8 – 120x120 mm Carbon Steel Bar 6 – 130x130 mm Carbon Steel Bar 2 – 140x140 mm Carbon Steel Bar 4 – 160x160 mm Carbon Steel Bar 1 – 170x170 mm Carbon Steel Bar	(%s per product)=	$1,000.00
Site Cost (S)	Deck Cost	(10 4-meter panels) x ($4,700.00/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/ abutment)=	$11,000.00
	Pier Cost	No pier=	$0.00
	Cable Anchorage Cost	No Anchorages=	$0.00
Total Cost	**M+C+P+S**	**$142,268.24 + $16,800.00 + $13,000.00 +$77,400.00=**	**$249,468.24**

TABLE 5
Warren Truss Bridge
Load Test Report Results from Bridge Designer 2015

					Load Test Results		
#	Material Type	Cross Section	Size (mm)	Length (m)	Slender-ness	Compression Force/Strength	Tension Force/Strength
1	CS	Bar	60	4.47	258.20	0.86	0.46
2	CS	Bar	65	4.47	238.34	0.93	0.36
3	CS	Bar	55	4.47	281.67	0.00	0.97
4	CS	Bar	90	4.47	172.13	0.96	0.03
5	CS	Bar	70	4.47	221.31	0.00	0.86
6	CS	Bar	110	4.47	140.84	0.75	0.00
7	CS	Bar	75	4.47	206.56	0.00	0.98
8	CS	Bar	120	4.47	129.10	0.76	0.00
9	CS	Bar	140	4.00	98.97	0.97	0.00
10	CS	Bar	90	4.47	172.13	0.88	0.05
11	CS	Bar	55	4.47	281.67	0.00	0.92
12	CS	Bar	110	4.47	140.84	0.71	0.00
13	CS	Bar	70	4.47	221.31	0.00	0.83
14	CS	Bar	120	4.47	129.10	0.73	0.00
15	CS	Bar	75	4.47	206.56	0.00	0.95
16	CS	Bar	120	4.47	129.10	0.95	0.00
17	CS	Bar	90	4.47	172.13	0.00	0.82
18	CS	Bar	130	4.47	119.17	0.88	0.00
19	CS	Bar	90	4.47	172.13	0.00	0.84
20	CS	Bar	130	4.47	119.17	0.90	0.00
21	CS	Bar	120	4.47	129.10	0.98	0.00
22	CS	Bar	60	4.00	230.94	0.00	0.85
23	CS	Bar	100	4.00	138.56	0.00	0.83
24	CS	Bar	120	4.00	115.47	0.00	0.85
25	CS	Bar	130	4.00	106.59	0.00	0.88
26	CS	Bar	130	4.00	106.59	0.00	0.96
27	CS	Bar	130	4.00	106.59	0.00	0.96
28	CS	Bar	130	4.00	106.59	0.00	0.88
29	CS	Bar	120	4.00	115.47	0.00	0.85
30	CS	Bar	100	4.00	138.56	0.00	0.82
31	CS	Bar	55	4.00	251.93	0.00	0.98
32	CS	Bar	120	4.00	115.47	0.88	0.00
33	CS	Bar	140	4.00	98.97	0.95	0.00
34	CS	Bar	160	4.00	86.60	0.86	0.00
35	CS	Bar	160	4.00	86.60	0.98	0.00
36	CS	Bar	170	4.00	81.51	0.87	0.00
37	CS	Bar	160	4.00	86.60	0.99	0.00
38	CS	Bar	160	4.00	86.60	0.87	0.00
39	CS	Bar	120	4.00	115.47	0.90	0.00

TABLE 6
Warren Truss Bridge from Bridge Designer 2015
Member with Highest Tension Force/Strength Ratio

Member 37

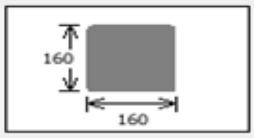
Material Properties:

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	160x160
Area	0.0256 sq. meters
Moment of Inertia	5.46E-05 meters^4
Member Length	4.00 meters

Section (mm):



Cost:

Unit Cost	$864.13 per meter
Member Cost	$3456.51

Strength vs. Length: Graph all tabs Member:

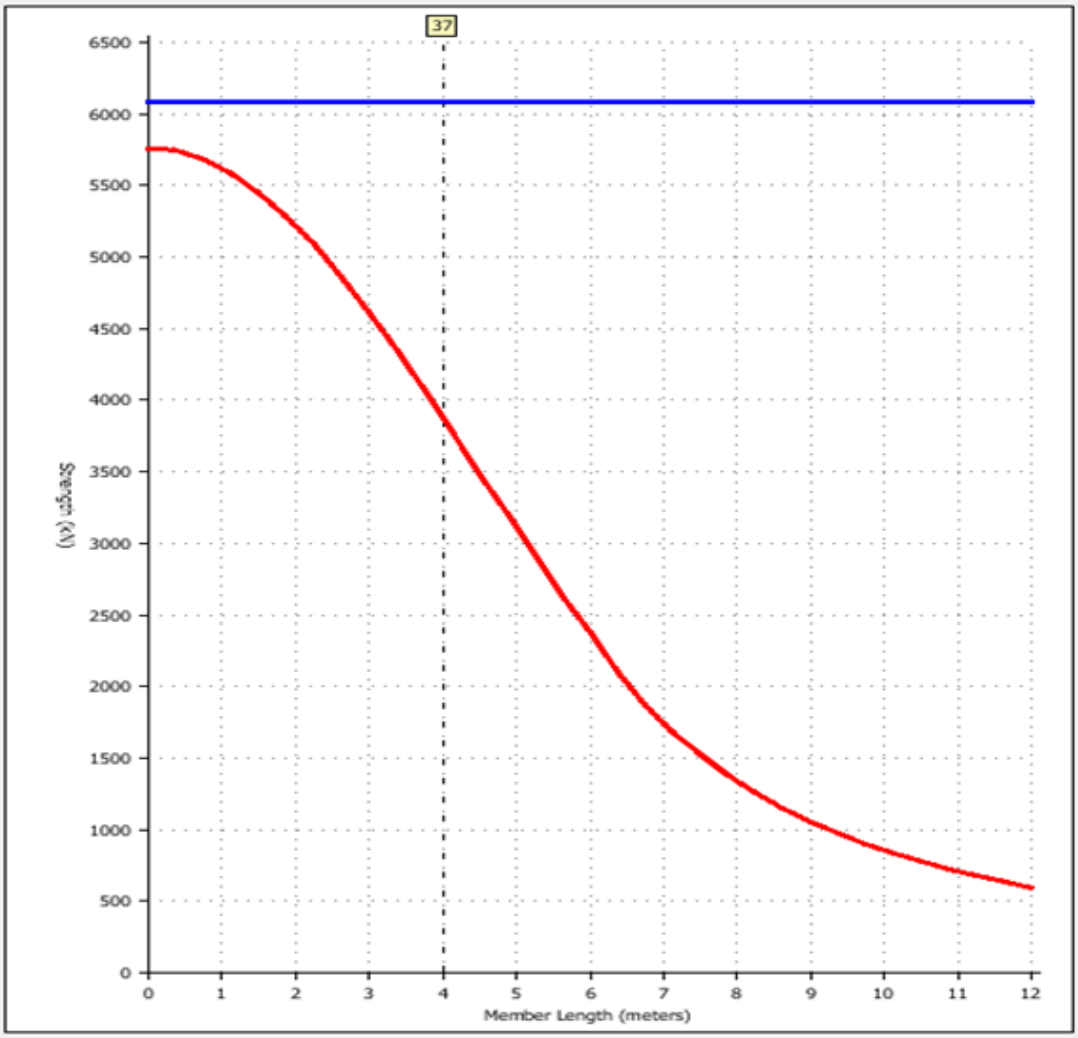


TABLE 7
Howe Truss Bridge Load Failure/Structural Efficiency

EDSGN 100 Design Team #	Howe Truss Bridge Weight (grams)	Bridge Weight (lbs.)	Load at Failure (lbs.)	Structural Efficiency
1	83.8	0.1844	65.3	354
2	80.8	0.1778	57.4	323
3	66.6	0.1465	32.6	222
4	80.8	0.1778	66.7	375
5	76.4	0.1681	52.3	311
6	82.6	0.1817	101.1	556
8	73.7	0.1621	32.6	201
			minimum	**201**
			maximum	**556**
			range	**355**
			average	**335**
			geomean	**318**

TABLE 8
Warren Truss Bridge Load Failure/ Structural Efficiency

EDSGN 100 Design Team #	Warren Truss Bridge Weight (grams)	Bridge Weight (lbs.)	Load at Failure (lbs.)	Structural Efficiency
1	80.1	0.1762	59.7	339
2	78.6	0.1729	41.1	238
3	73.0	0.1606	48.2	300
4	57.6	0.1267	54.1	427
5	73.9	0.1626	76.8	472
6	82.5	0.1815	133.3	734
8	72.6	0.1597	64.4	403
			minimum	**238**
			maximum	**734**
			range	**497**
			average	**416**
			geomean	**393**

FIGURES

FIGURE 1
Howe Truss Bridge from Bridge Designer 2015

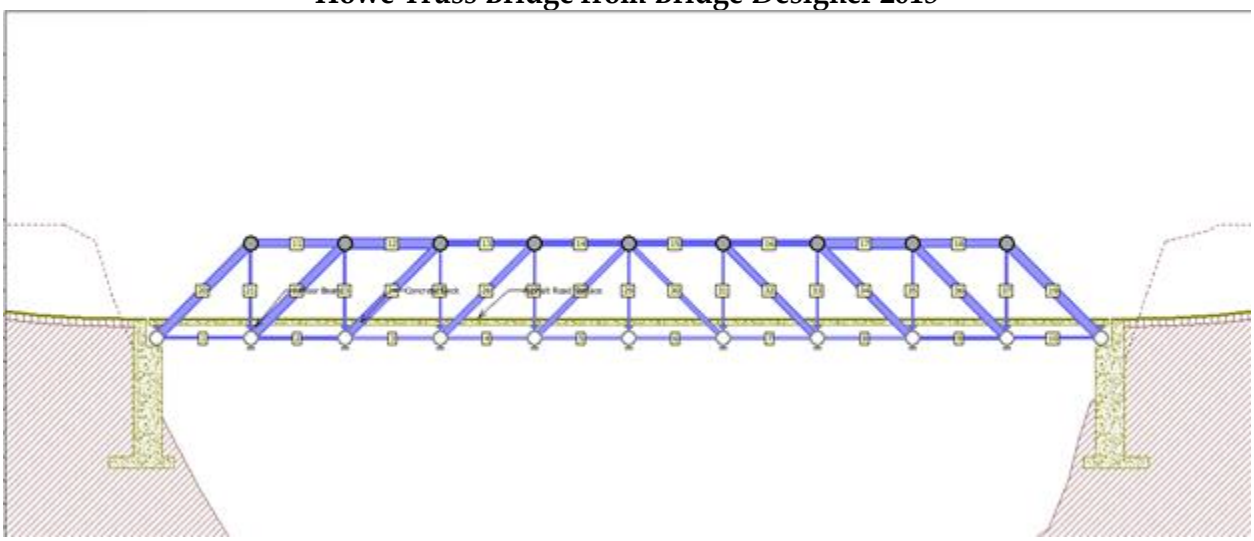


FIGURE 2
Warren Bridge from Bridge Designer 2015

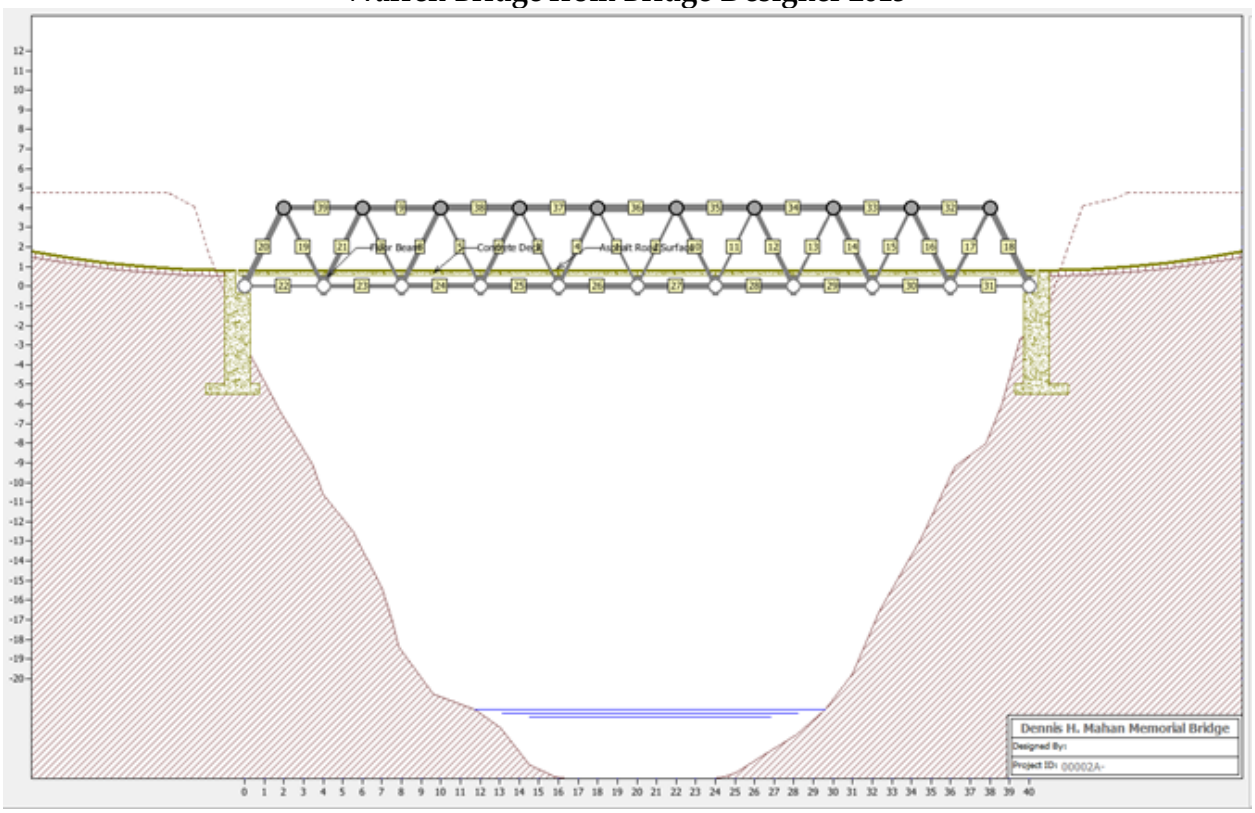


FIGURE 3
Howe Truss Bridge Prototype before Load Test

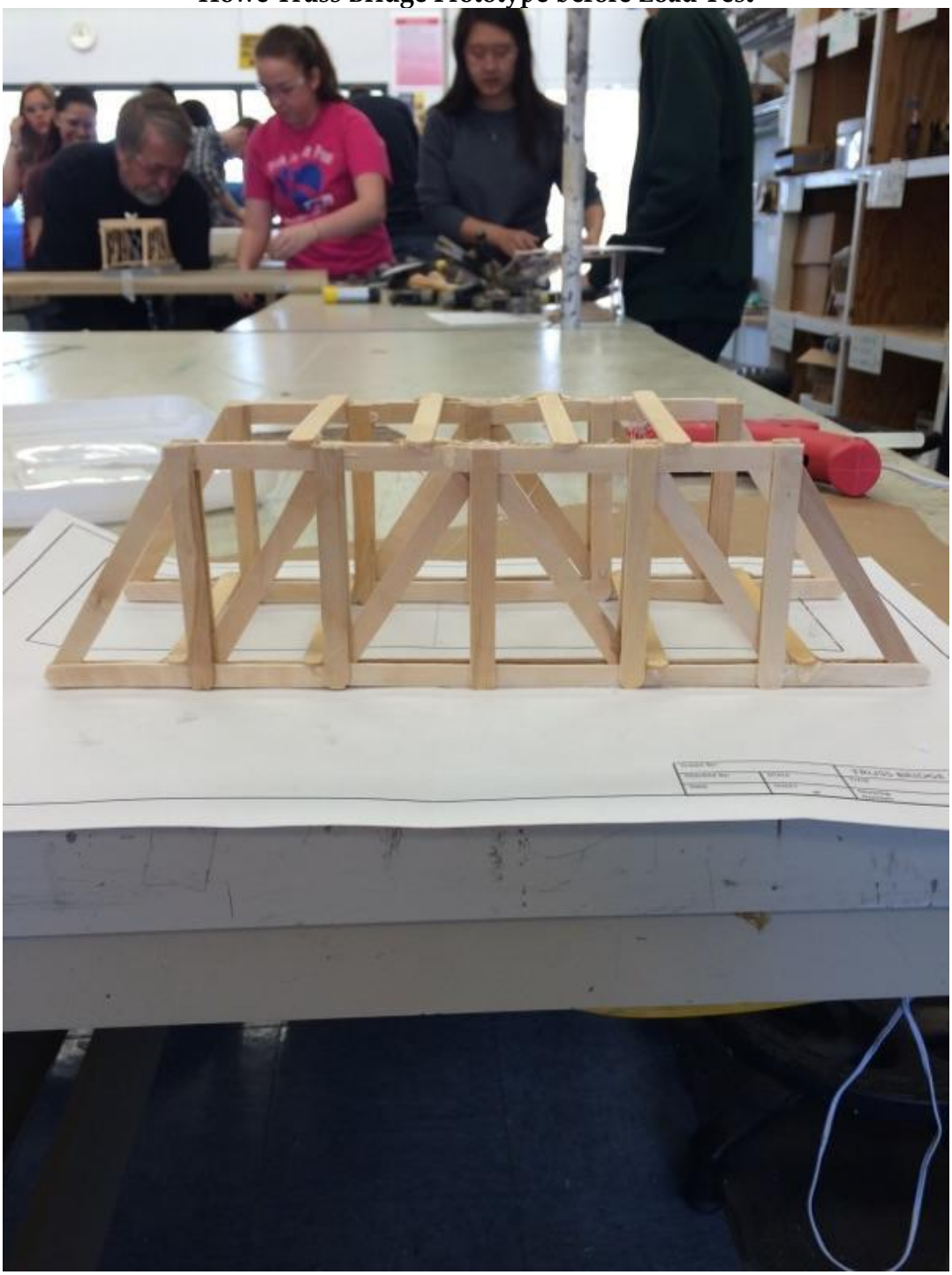


FIGURE 4
Howe Truss Bridge Prototype after Load Test

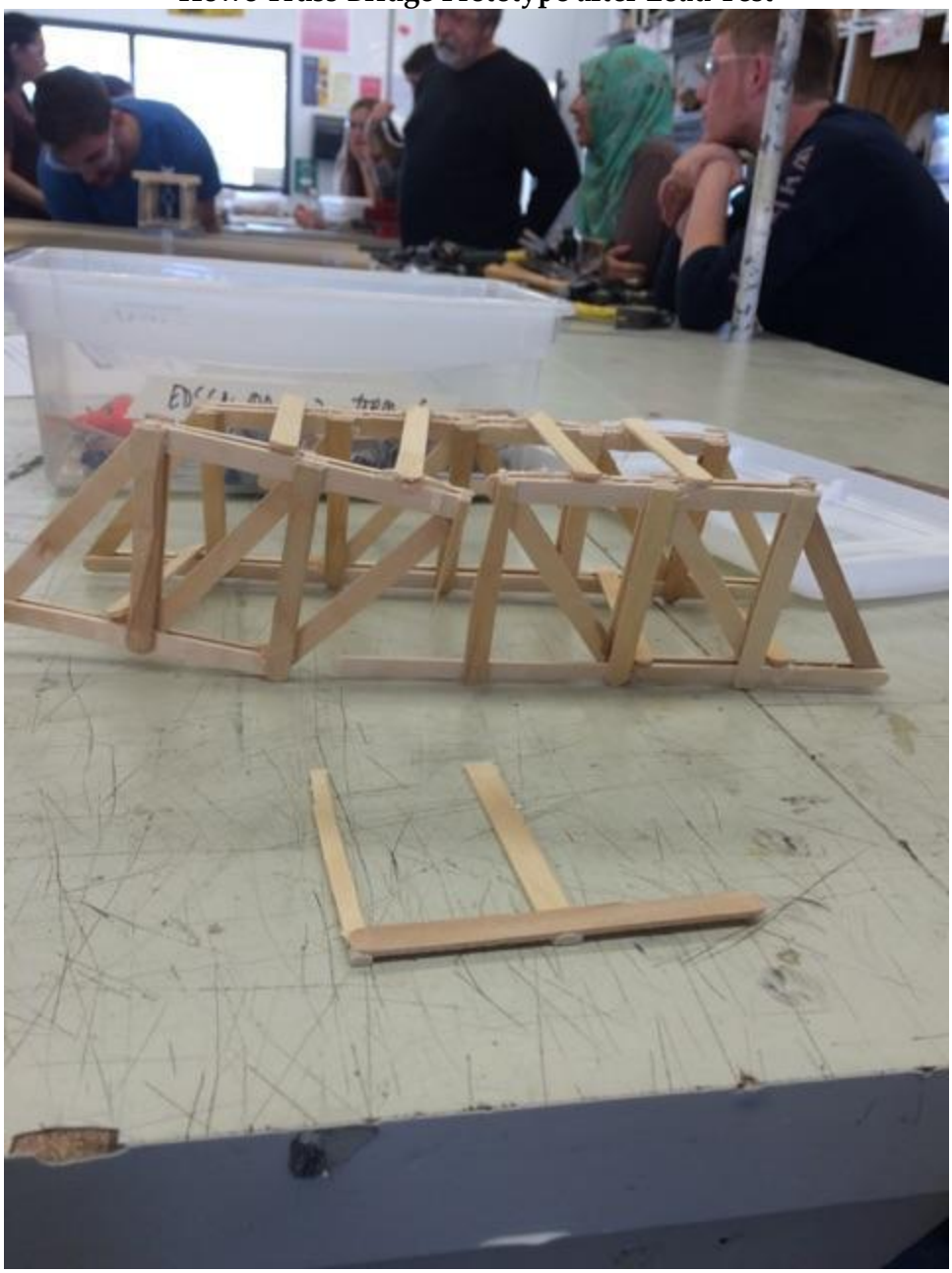


FIGURE 5
Warren Bridge Prototype before Load Test

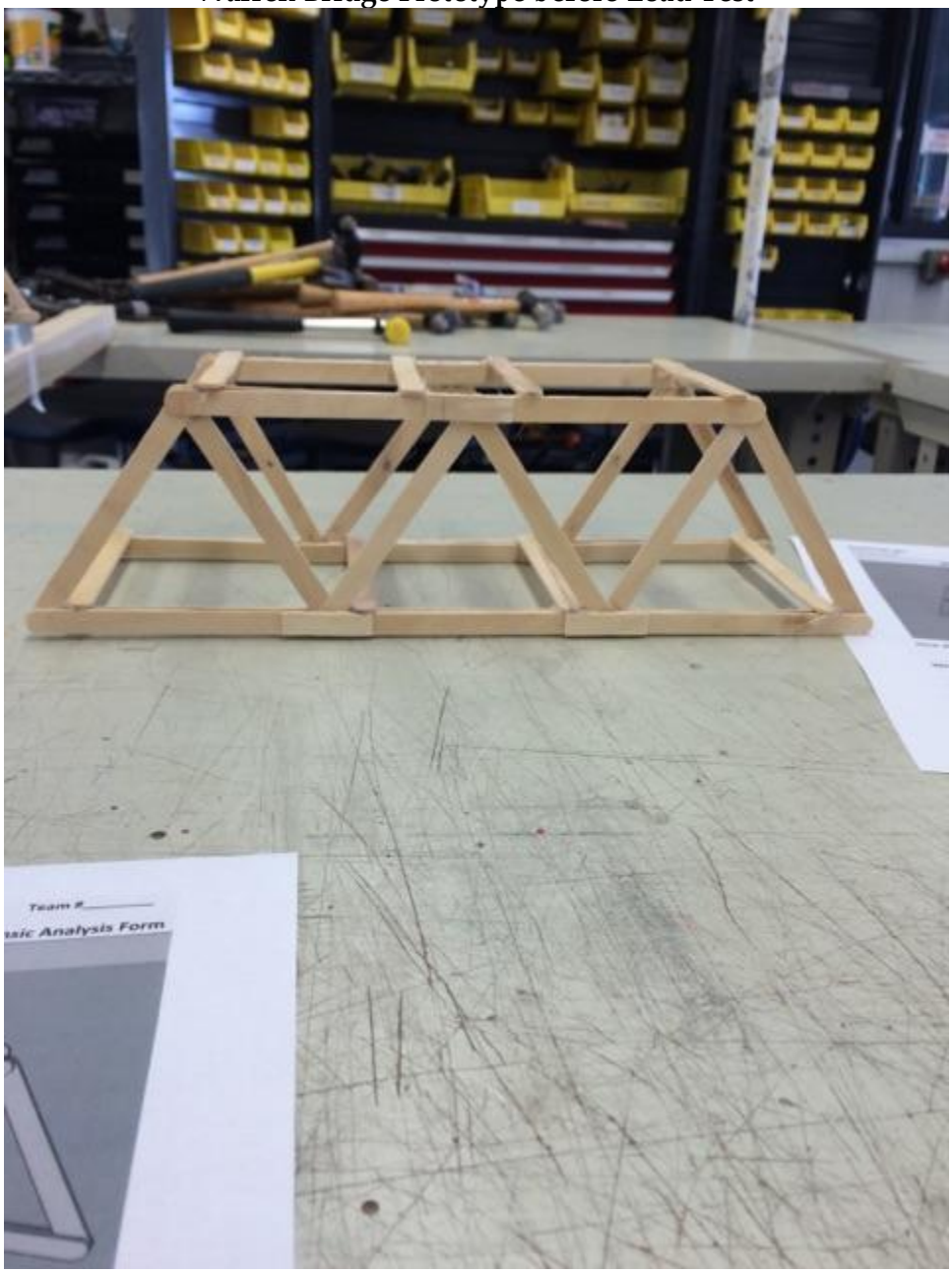


FIGURE 6
Warren Bridge Prototype after Load Test

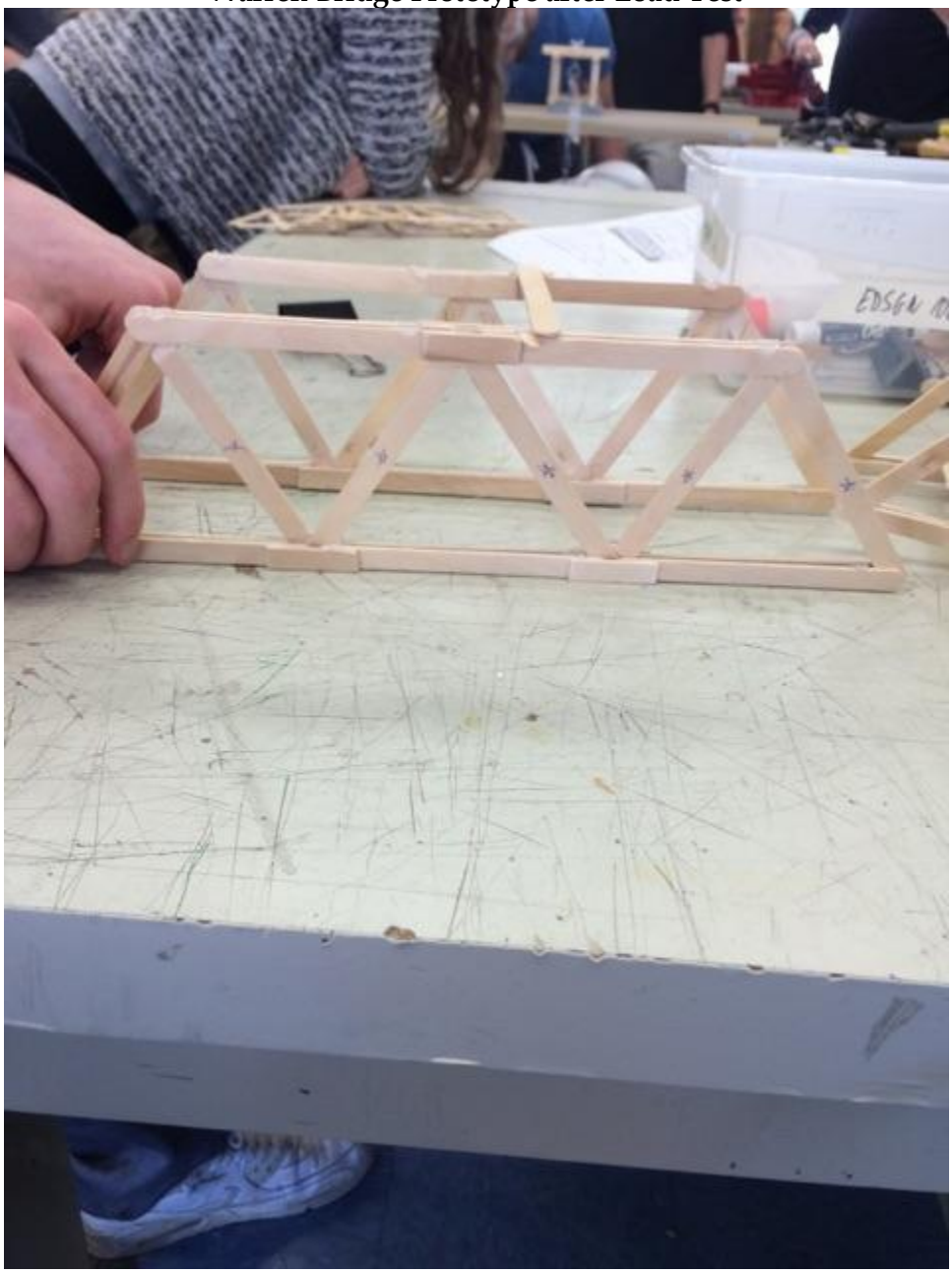


FIGURE 7
Howe Truss Bridge Structural Efficiencies

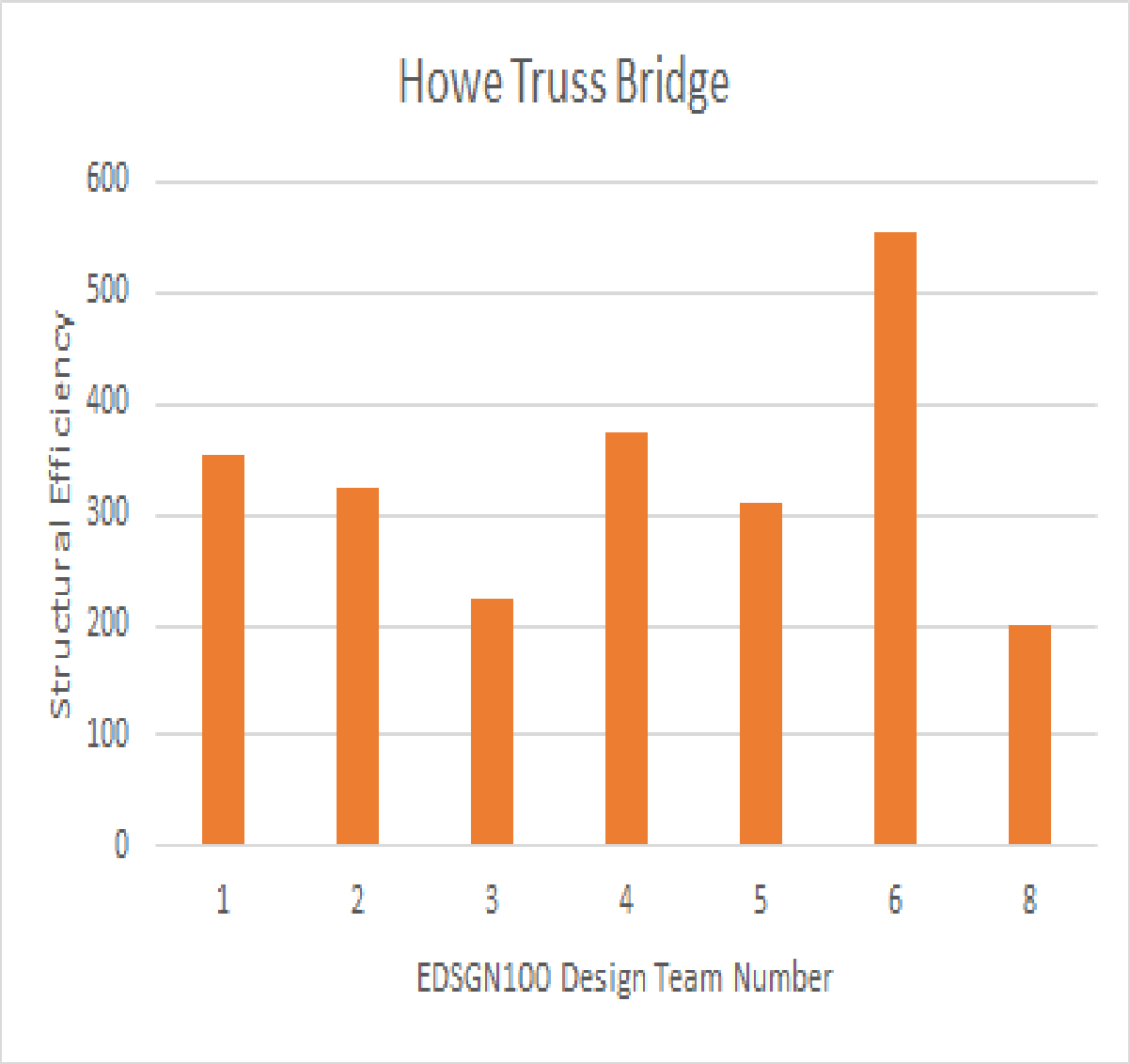
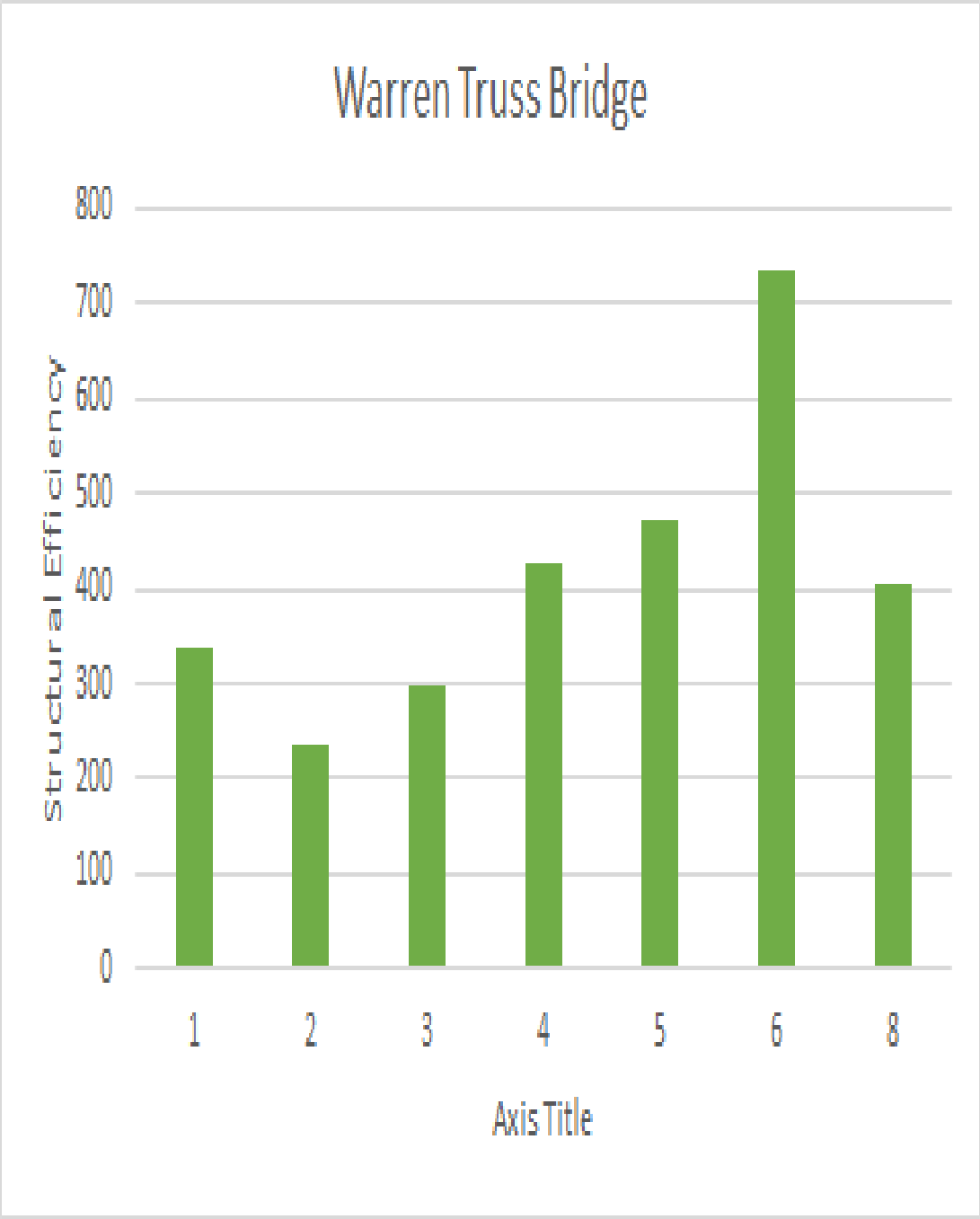



FIGURE 8
Warren Truss Bridge Structural Efficiencies