PENNSTATE

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October 30, 2015

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. Local flooding from a recent 100-year flood event completely destroyed a structurally deficient vehicle bridge located over 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. The destroyed bridge is along a heavily traveled local road and is designated as a vital lifeline for vehicle access to the Mount Nittany Medical Center located in State College, PA. All traffic must now be re-routed more than 10 miles around the destroyed bridge, thereby disrupting residential traffic flow, local commerce, and exposing State College residents to considerable risk, since police and emergency vehicles do not have easy access to that area of College Township. The damaged bridge also severely restricts general regional vehicle access to the Mount Nittany Medical Center.

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

Design Criteria. As a preliminary PennDOT District 2-0 engineering report found that the previous bridge failed due to scour of its pier, it was recommended that the replacement bridge only have a single span and no piers placed in Spring Creek, so that similar bridge failure will not be repeated in any future extreme flooding events in Spring Creek. Since a truss bridge is economical to construct owing to its efficient use of materials, PennDOT District 2-0 recommended that a new through-type steel truss bridge would be the best choice for the replacement bridge. Two types of truss bridges were to be investigated further: the Howe truss and the Warren truss. The design criteria for the replacement bridge included: standard abutments, no piers (one span), deck material of medium strength concrete (0.23 meters thick), no cable anchorages, and that it be designed for the load of two AASHTO H20-44 trucks

(225kN) with one in each traffic lane. The bridge deck elevation was set at 20 meters and the deck span at 40 meters.

Technical Approach.

Phase 1: Economic Efficiency. Economic efficiency (cost) was determined using the Engineering Encounters Bridge Design 2015 (EEBD 2015) software based on the requirements, constraints, and performance criteria specified herein. The design objective was to use EEBD 2015 to perform a systematic and iterative analysis to design a stable Warren and Howe through truss bridge, optimized to keep the cost of the replacement bridge as low as possible; as well as to ensure that 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 was designed and built for both a Warren through truss bridge and a Howe through truss bridge. Each prototype bridge was load tested in the lab to catastrophic failure. The truss bridge type that exhibits the best structural efficiency when tested to failure in prototype was determined based on these results. The prototypes, which were built with standard Popsicle sticks, Elmer's white glue, and hot glue, were tested by loading the top cord of the truss with a loading block attached to a load suspended from the block.

Results.

Phase 1: Economic Efficiency. The Howe truss design, with an overall cost of $228,595.39, and the Warren truss design, at $213,282.00, were both fairly cost-efficient. In both cases, the designs used only one type of steel to minimize costs incurred by needing to make many different types and strengths. Smaller members and hollow tubes were also utilized when possible to balance structural integrity and lower cost. However, the total price of the Warren truss was lower than the Howe by $15,313.39 (Tables 1 and 4). The Warren truss design seemed a clear choice from an economic perspective.

Phase 2: Structural Efficiency. Under load testing, the Howe design held 77.9 lbs, for a structural efficiency of 452.4 (Table 7). This was above the Howe, Warren, and class averages. The Warren design held 32.7 lbs, for a structural efficiency of 202.6 (Table 8). While the Howe bridges had the higher average and contained the single highest structural efficiency of all bridges tested, they also contained the single lowest, resulting in a large range of values. The Warren bridges had a more concentrated spread but a lower average. Considering only the structural efficiency data, the Howe truss seemed to be stronger and more durable. However, this conclusion was tentative, as it was possible that the qualities of the better-performing Howe bridges might not be shared by the rest. In that case, it might be better to choose the more reliably performing Warren truss. The structural efficiency testing therefore resulted in the assertion that the Howe truss can be more structurally efficient, but in some instances, very high structural efficiency might be sacrificed for consistency and dependability.

Best Solution. The design team took into account both the economic efficiency and the structural efficiency of the bridge designs (Tables 1, 4, 7, 8). Financially, the Warren was the clear winner, as it would be cheaper to build by $15,313.39. On the other hand, this specific

Warren design was weaker and less structurally efficient than the Howe. Taking into account the structural efficiencies from the entire class, however, the Howe efficiencies had a large range and seemed less reliable; they could be very structurally efficient or not very much. The Warren average, while slightly lower, represented a smaller range of values. This seemed to indicate that the Warren truss is more consistent in quality. Therefore, it is recommended, based on these factors, that the Spring Creek bridge be built as a Warren truss. This design will be less expensive to build, which will be very positive for the project. It will also be dependably structurally efficient with a small range of efficiencies and an average not much different than that of the Howe.

Conclusions and Recommendations. The final recommendation was that the Spring Creek bridge be a Warren truss, due to financial and structural factors; the Warren design will be more economically efficient and more reliably structurally efficient. The next step for advancing the project should be to finalize the theoretical design and begin investigating the practical aspects of the project. The physical site of the bridge should be examined, and if any discrepancies arise between the current design and the realities of its implementation, the design should then be revised and edited according to the engineering design process.

Respectfully,

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ATTACHMENT 1

Phase 1: Economic Efficiency

Howe Truss.

Tables 1 – 3, Figure 1.

The Howe Truss bridge design, created in Engineering Encounters Bridge Design 2015 (EEBD 2015), is constructed entirely from carbon steel, avoiding additional expenses incurred by using different varieties of steel. Carbon steel is popularly chosen for bridge-building thanks to its strength and relatively low cost. This design incorporates a range of sizes and types of carbon steel structural members in order to balance cost efficiency and durability; thinner members are used where possible, and there are also hollow tubes to mitigate the effects of strain due to compression. The structure, according to the EEBD software, has an overall cost of $228,595.39 (Table 1). The structural members experiencing the most compression force are located on the top chord, particularly toward the center (Table 2, Figure 1). Structural Member 22 has the highest compression force-to-compression strength ratio (Table 3). The members making up the bottom chord experience the most tension force. Overall, this design minimizes cost and maximizes structural stability at that particular price.

Warren Truss.

Tables 4 – 6, Figure 2.

The Warren Truss bridge design, created in Engineering Encounters Bridge Design 2015 (EEBD 2015), is constructed entirely from high-strength low-alloy steel, avoiding additional expenses incurred by using different varieties of steel. High-strength low-alloy steel is a very strong variety of steel. While it may look more expensive than carbon steel, judicious use of this stronger steel can result in a lower cost overall. This design incorporates a range of sizes and types of carbon steel structural members in order to balance cost efficiency and durability; thinner members are used where possible, and there are also hollow tubes to mitigate the effects of strain due to compression. The structure, according to the EEBD software, has an overall cost of $213,282.00 (Table 4). The structural members experiencing the most tension force are located on the bottom chord, particularly toward the center (Table 5, Figure 2). Structural Member 4 has the highest tension force-to-tension strength ratio (Table 6). The members making up the top chord experience the most compressive force. Overall, this design minimizes cost and maximizes structural stability at that particular price, which is lower than the total price of the Howe truss.

ATTACHMENT 2

Phase 2: Structural Efficiency

Howe Truss.

Table 7, Figures 3, 4, 7.

Prototype Bridge. The prototype of the Howe truss bridge was built with Popsicle sticks, Elmer's glue, and hot glue. Constructed from 56 sticks, the design included 4 struts and 4 floor beams, with 5 verticals on each side. The top and bottom chords were created in a "sandwich" design that allowed several end posts and outer verticals to slip between the two layers in the chord. The structural members in the trusses were sanded smooth, glued together with undiluted Elmer's glue, held in place with binder clips, and left to dry for at least a week. The struts and floor beams were attached later with a hot glue gun. The verticals were cut shorter using a bandsaw to fit within the project specifications.

Load Testing. This design held 77.9 lbs under load testing with a structural efficiency of 452.4, which was less than only one other Howe bridge and one Warren bridge (Tables 7 and 8). The load testing was conducted by placing a loading block across the top of the bridge and hanging a weight underneath it, starting at 30 lbs. The highest structural efficiency of the bridges tested belonged to a Howe bridge (603.4); however, the Howe trusses also had the lowest, at 195.2. This resulted in a large range of values of structural efficiency. The average structural efficiency for the Howe bridges was calculated at 353.3.

Forensic Analysis. As can be seen in Figure 3, the Howe design featured eight horizontal struts connecting the trusses. These struts and floor beams were connected to the trusses with hot glue, whereas the trusses themselves were constructed using Elmer's glue, a polyvinyl acetate compound (PVA). Since the trusses were lined up fairly well and the bridge sat evenly on the testing area, it was able to hold a heavy load. When the bridge failed at 77.9 lbs of weight, it was due to the joints where the struts and floor beams connected to the trusses (Figure 4). These were the joints that had been created with hot glue. The Popsicle sticks themselves were largely intact after the failure, suggesting that the glue was the cause. A tentative conclusion can be drawn that hot glue is not as strong as PVA glue, and perhaps a stronger bridge could be made using solely PVA glue. About half of these joints failed, averaging one per horizontal strut. The bridge was then able to "unfold," failing completely. The first joint to fail was likely near the center, where the most stress occurred.

Results. This design performed better than most other Howe bridges and most of the Warren trusses as well. Its structural efficiency, calculated at 452.4, was above the Howe and Warren averages and the class average of 341.2. It is debatable whether this design's success can be broadly applied to Howe designs as a whole, as the Howe group had the largest range and also contained the single lowest structural efficiency.

Warren Truss.

Table 8, Figures 5, 6, 8.

Prototype Bridge. The prototype of the Warren truss bridge was built with Popsicle sticks, Elmer's glue, and hot glue. Constructed from 52 sticks, the design included 4 struts and 4 floor beams (Figure 5). The structural members in the trusses were sanded smooth, glued together with Elmer's glue diluted with water, held in place with binder clips, and left to dry for at least a week. The glue was diluted so that it would permeate the wood more deeply before drying and creating a strong bond. The struts and floor beams were attached later with a hot glue gun.

Load Testing. This design held 32.7 lbs under load testing with a structural efficiency of 202.6, which was the second-lowest of all bridges tested and the lowest in the Warren group (Tables 7 and 8). The load testing was conducted by placing a loading block across the top of the bridge and hanging a weight underneath it, starting at 30 lbs. The average structural efficiency for the Warren bridges was calculated at 329.1, lower than the Howe average by 24.2. However, the Warren bridges had a much smaller spread of structural efficiencies, with a range of 291.1.

Forensic Analysis. The Warren prototype's trusses were not completely parallel with each other, resulting in a slight wobble when set on a flat surface. This caused the bridge to lean to one side when the bucket and 30 lb weights were added. The prototype was then overcome by torsional forces and failed. The trusses, which were constructed in two "layers" each, separated from each other, and the resulting collision separated the layers of each truss (Figure 6). The main cause of failure was the torsional strain due to the prototype's uneven seating, which put an unusually high amount of force on the prototype.

Results. This design performed lower than average with a structural efficiency of 202.6. However, it is not clear whether this efficiency is indicative of Warren trusses as a whole; the Warren group had a smaller range of structural efficiencies, though the average was slightly lower than the Howe group.

TABLES

Table 1
Cost Calculation Report from Bridge Designer 2015

Type of Cost	Item	Cost Calculation	Cost
Material Cost (M)	Carbon Steel Solid Bar	(4922.0 kg) x ($4.30 per kg) x (2 Trusses) =	$42,328.77
	Carbon Steel Hollow Tube	(6179.9 kg) x ($6.30 per kg) x (2 Trusses) =	$77,866.62
Connection Cost (C)		(20 Joints) x (500.0 per joint) x (2 Trusses) =	$20,000.00
Product Cost (P)	2 - 60x60 mm Carbon Steel Bar	(%s per Product) =	$1,000.00
	7 - 70x70 mm Carbon Steel Bar	(%s per Product) =	$1,000.00
	2 - 80x80 mm Carbon Steel Bar	(%s per Product) =	$1,000.00
	4 - 100x100 mm Carbon Steel Bar	(%s per Product) =	$1,000.00
	4 - 110x110 mm Carbon Steel Bar	(%s per Product) =	$1,000.00
	1 - 150x150x7 mm Carbon Steel Tube	(%s per Product) =	$1,000.00
	3 - 160x160x8 mm Carbon Steel Tube	(%s per Product) =	$1,000.00
	2 - 180x180x9 mm Carbon Steel Tube	(%s per Product) =	$1,000.00
	4 - 200x200x10 mm Carbon Steel Tube	(%s per Product) =	$1,000.00
	6 - 240x240x12 mm Carbon Steel Tube	(%s per Product) =	$1,000.00
	2 - 260x260x13 mm Carbon 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	(19,900 cubic meters) x ($1.00 per cubic meter) =	$19,900.00
	Abutment Cost	(2 standard abutments) x ($5,250.00 per abutment) =	$10,500.00
	Pier Cost	No pier =	$0.00
	Cable Anchorage Cost	No anchorages =	$0.00
Total Cost	M + C + P + S	$120,195.39 + $20,000.00 + $11,000.00 + $77,400.00 =	$228,595.39

Table 2
Load Test Results Report from Bridge Designer 2015

#	Mater-ial Type	Cross Section	Size (mm)	Length (m)	Compress-ion Force	Compress-ion Strength	Compress-ion Status	Tension Force	Tension Strength	Tension Status
1	CS	Solid Bar	80x80	4.00	0.00	333.51	OK	1409.60	1520.00	OK
2	CS	Solid Bar	100x100	4.00	0.00	814.24	OK	2004.95	2375.00	OK
3	CS	Solid Bar	100x100	4.00	0.00	814.24	OK	2192.15	2375.00	OK
4	CS	Solid Bar	110x110	4.00	0.00	1181.16	OK	2502.45	2873.75	OK
5	CS	Solid Bar	110x110	4.00	0.00	1181.16	OK	2601.18	2873.75	OK
6	CS	Solid Bar	110x110	4.00	0.00	1181.16	OK	2601.18	2873.75	OK
7	CS	Solid Bar	110x110	4.00	0.00	1181.16	OK	2488.62	2873.75	OK
8	CS	Solid Bar	100x100	4.00	0.00	814.24	OK	2164.71	2375.00	OK
9	CS	Solid Bar	100x100	4.00	0.00	814.24	OK	1955.69	2375.00	OK
10	CS	Solid Bar	80x80	4.00	0.00	333.51	OK	1377.65	1520.00	OK
11	CS	Hollow Tube	240x240 x12	5.66	1993.47	2028.51	OK	0.00	2599.20	OK
12	CS	Hollow Tube	240x240 x12	5.66	1948.29	2028.51	OK	0.00	2599.20	OK
13	CS	Hollow Tube	150x150 x7	7.21	391.74	404.39	OK	111.78	950.95	OK
14	CS	Hollow Tube	160x160 x8	7.21	429.75	538.75	OK	73.76	1155.20	OK
15	CS	Solid Bar	70x70	6.00	0.00	86.89	OK	623.29	1163.75	OK
16	CS	Solid Bar	70x70	6.00	0.00	86.89	OK	846.86	1163.75	OK
17	CS	Hollow Tube	160x160 x8	7.21	465.50	538.75	OK	63.75	1155.20	OK
18	CS	Solid Bar	70x70	4.00	0.00	195.50	OK	1027.37	1163.75	OK
19	CS	Solid Bar	70x70	6.00	0.00	86.89	OK	878.81	1163.75	OK
20	CS	Hollow Tube	160x160 x8	7.21	488.54	538.75	OK	0.00	1155.20	OK
21	CS	Solid	70x70	4.00	0.00	195.50	OK	1051.33	1163.75	OK

		Bar								
22	CS	Hollow Tube	200x200 x10	4.12	1452.98	1474.34	OK	0.00	1805.00	OK
23	CS	Hollow Tube	240x240 x12	4.12	2066.65	2221.46	OK	0.00	2599.20	OK
24	CS	Hollow Tube	240x240 x12	4.00	2192.15	2234.95	OK	0.00	2599.20	OK
25	CS	Hollow Tube	260x260 x13	4.00	2502.45	2660.84	OK	0.00	3050.45	OK
26	CS	Hollow Tube	260x260 x13	4.00	2488.62	2660.84	OK	0.00	3050.45	OK
27	CS	Hollow Tube	240x240 x12	4.00	2164.71	2234.95	OK	0.00	2599.20	OK
28	CS	Hollow Tube	240x240 x12	4.12	2015.88	2221.46	OK	0.00	2599.20	OK
29	CS	Hollow Tube	200x200 x10	4.12	1420.05	1474.34	OK	0.00	1805.00	OK
30	CS	Hollow Tube	200x200 x10	6.40	1036.85	1195.87	OK	0.00	1805.00	OK
31	CS	Hollow Tube	180x180 x9	7.21	748.22	791.21	OK	0.00	1462.05	OK
32	CS	Hollow Tube	180x180 x9	7.21	709.82	791.21	OK	0.00	1462.05	OK
33	CS	Hollow Tube	200x200 x10	6.40	1006.17	1195.87	OK	0.00	1805.00	OK
34	CS	Solid Bar	70x70	6.00	0.00	86.89	OK	613.78	1163.75	OK
35	CS	Solid Bar	60x60	5.00	0.00	67.54	OK	640.28	855.00	OK
36	CS	Solid Bar	70x70	6.00	0.00	86.89	OK	581.83	1163.75	OK
37	CS	Solid Bar	60x60	5.00	0.00	67.54	OK	621.11	855.00	OK

Table 3
Member with Highest Compression Force-to-Strength Ratio Details

Member 22

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	200x200x10
Area	0.0076 sq. meters
Moment of Inertia	4.59E-05 meters⁴
Member Length	4.12 meters

Section (mm):

Cost:

Unit Cost	$375.86 per meter
Member Cost	$1549.70

Strength vs. Length: Graph all tabs Member:

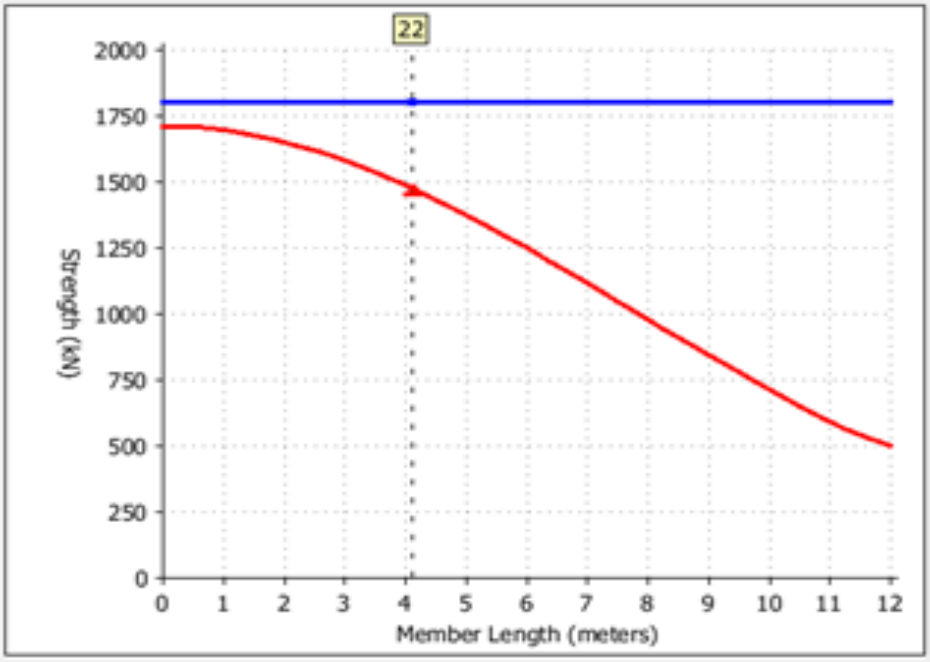


Table 4
Cost Calculation Report from Bridge Designer 2015

Type of Cost	Item	Cost Calculation	Cost
Material Cost (M)	High-Strength Low-Alloy Steel Solid Bar	(8822.5 kg) x ($5.00 per kg) x (2 Trusses) =	$88,224.75
	High-Strength Low-Alloy Steel Hollow Tube	(1611.2 kg) x ($7.00 per kg) x (2 Trusses) =	$22,557.25
Connection Cost (C)		(21 Joints) x (500.0 per joint) x (2 Trusses) =	$21,000.00
Product Cost (P)	2 - 65x65 mm High-Strength Low-Alloy Steel Bar	(%s per Product) =	$1,000.00
	4 - 90x90 mm High-Strength Low-Alloy Steel Bar	(%s per Product) =	$1,000.00
	4 - 100x100 mm High-Strength Low-Alloy Steel Bar	(%s per Product) =	$1,000.00
	2 - 110x110 mm High-Strength Low-Alloy Steel Bar	(%s per Product) =	$1,000.00
	11 - 110x110x5 mm High-Strength Low-Alloy Steel Tube	(%s per Product) =	$1,000.00
	3 - 130x130x6 mm High-Strength Low-Alloy Steel Tube	(%s per Product) =	$1,000.00
	8 - 140x140 mm High-Strength Low-Alloy Steel Bar	(%s per Product) =	$1,000.00
	4 - 140x140x7 mm High-Strength Low-Alloy Steel Tube	(%s per Product) =	$1,000.00
	1 - 150x150 mm High-Strength Low-Alloy 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	(15,000 cubic meters) x ($1.00 per cubic meter) =	$15,000.00
	Abutment Cost	(2 standard abutments) x ($5,250.00 per abutment) =	$10,500.00
	Pier Cost	No pier =	$0.00
	Cable Anchorage Cost	No anchorages =	$0.00
Total Cost	M + C + P + S	$110,782.00 + $21,000.00 + $9,000.00 + $72,500.00 =	$213,282.00

Table 5
Load Test Results Report from Bridge Designer 2015

#	Mat-erial Type	Cross Section	Size (mm)	Length (m)	Compres-sion Force	Compres-sion Strength	Compres-sion Status	Tension Force	Tension Strength	Tension Status
1	HSS	Solid Bar	65x65	4.00	0.00	145.35	OK	1348.28	1384.74	OK
2	HSS	Solid Bar	90x90	4.00	0.00	534.22	OK	2459.13	2654.77	OK
3	HSS	Solid Bar	100x100	4.00	0.00	814.24	OK	2713.70	3277.50	OK
4	HSS	Solid Bar	90x90	4.00	0.00	534.22	OK	2624.99	2654.77	OK
5	HSS	Solid Bar	100x100	4.00	0.00	814.24	OK	2857.05	3277.50	OK
6	HSS	Solid Bar	100x100	4.00	0.00	814.24	OK	2869.40	3277.50	OK
7	HSS	Solid Bar	90x90	4.00	0.00	534.22	OK	2640.22	2654.77	OK
8	HSS	Solid Bar	100x100	4.00	0.00	814.24	OK	2712.26	3277.50	OK
9	HSS	Solid Bar	90x90	4.00	0.00	534.22	OK	2430.68	2654.77	OK
10	HSS	Solid Bar	65x65	4.00	0.00	145.35	OK	1315.82	1384.74	OK
11	HSS	Solid Bar	110x110	2.83	1906.76	2111.61	OK	0.00	3965.78	OK
12	HSS	Solid Bar	140x140	4.12	2218.66	2857.89	OK	0.00	6423.90	OK
13	HSS	Solid Bar	140x140	4.00	2862.97	2987.82	OK	0.00	6423.90	OK
14	HSS	Solid Bar	140x140	4.00	2845.76	2987.82	OK	0.00	6423.90	OK
15	HSS	Solid Bar	140x140	4.12	2743.42	2857.89	OK	0.00	6423.90	OK
16	HSS	Solid Bar	140x140	4.12	2165.13	2857.89	OK	0.00	6423.90	OK
17	HSS	Solid Bar	110x110	2.83	1860.85	2111.61	OK	0.00	3965.78	OK
18	HSS	Hollow Tube	140x140 x7	2.83	0.00	950.00	OK	1137.22	1220.54	OK
19	HSS	Hollow Tube	140x140 x7	3.61	704.00	840.19	OK	0.00	1220.54	OK
20	HSS	Hollow Tube	110x110 x5	3.61	0.00	390.52	OK	493.80	688.28	OK
21	HSS	Hollow	110x110	4.47	224.39	296.32	OK	221.52	688.28	OK

		Tube	x5							
22	HSS	Hollow Tube	110x110 x5	4.47	181.49	296.32	OK	165.33	688.28	OK
23	HSS	Hollow Tube	110x110 x5	5.39	0.00	208.49	OK	496.85	688.28	OK
24	HSS	Hollow Tube	130x130 x6	5.39	0.00	407.02	OK	640.78	975.38	OK
25	HSS	Hollow Tube	130x130 x6	5.39	381.41	407.02	OK	69.81	975.38	OK
26	HSS	Hollow Tube	110x110 x5	5.39	79.36	208.49	OK	371.87	688.28	OK
27	HSS	Hollow Tube	110x110 x5	5.39	112.59	208.49	OK	338.63	688.28	OK
28	HSS	Hollow Tube	130x130 x6	5.39	348.18	407.02	OK	103.05	975.38	OK
29	HSS	Hollow Tube	110x110 x5	5.39	0.00	208.49	OK	607.31	688.28	OK
30	HSS	Hollow Tube	110x110 x5	5.39	0.00	208.49	OK	574.94	688.28	OK
31	HSS	Hollow Tube	110x110 x5	4.47	237.11	296.32	OK	153.80	688.28	OK
32	HSS	Hollow Tube	110x110 x5	4.47	208.83	296.32	OK	293.77	688.28	OK
33	HSS	Hollow Tube	110x110 x5	3.61	0.00	390.52	OK	477.08	688.28	OK
34	HSS	Hollow Tube	140x140 x7	3.61	680.59	840.19	OK	0.00	1220.54	OK
35	HSS	Hollow Tube	140x140 x7	2.83	0.00	950.00	OK	1109.68	1220.54	OK
36	HSS	Solid Bar	140x140	4.12	2817.16	2857.89	OK	0.00	6423.90	OK
37	HSS	Solid Bar	150x150	4.12	2873.43	3616.45	OK	0.00	7374.38	OK
38	HSS	Solid Bar	140x140	4.00	2975.15	2987.82	OK	0.00	6423.90	OK
39	HSS	Solid Bar	140x140	4.12	2834.58	2857.89	OK	0.00	6423.90	OK

Table 6
Member with Highest Tension Force-to-Strength Ratio Details

Member 4

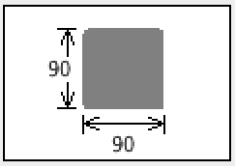
Material Properties:

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	Solid Bar
Cross-Section Size	90x90
Area	0.0081 sq. meters
Moment of Inertia	5.47E-06 meters^4
Member Length	4.00 meters

Section (mm):



Cost:

Unit Cost	$317.92 per meter
Member Cost	$1271.70

Strength vs. Length: Graph all tabs Member:

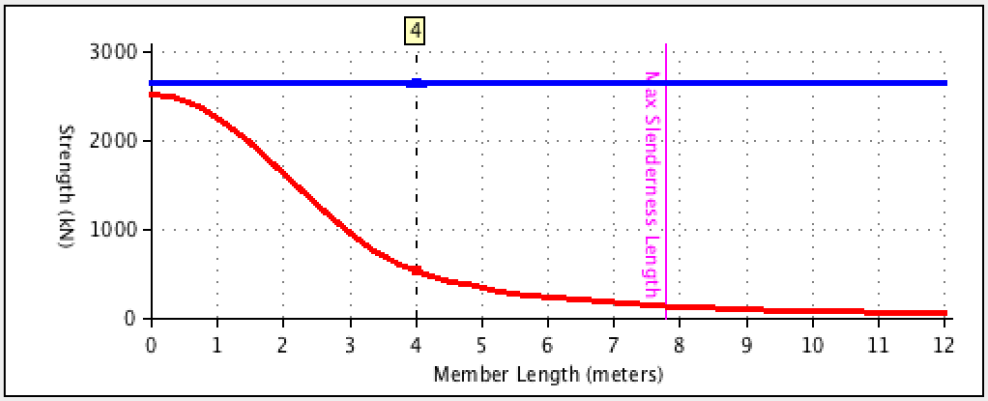


Table 7
Howe Truss Weights and Structural Efficiencies

	Estimated Bridge Weight (grams)	Actual Bridge Weight (grams)	Estimated Load at Failure (lbs)	Load at Failure (lbs)	Structural Efficiency (Load at Failure in lbs / Dead Load in lbs)
1	82.536	84.5	66	49.4	265.2
2	71.31	75.3	55	34.0	204.8
3	82.531	81.8	65	108.8	603.4
4	76.35	78.1	60	77.9	452.4
5	80.7	81.4	60	58.3	324.8
6	81.9707	85.2	50	72.1	383.9
7	79.8	79.7	75	34.3	195.2
8	77.03	80.0	65	70.0	396.8
				Minimum	195.2
				Maximum	603.4
				Range	408.2
				Mean	353.3

Table 8
Warren Truss Weights and Structural Efficiencies

	Estimated Bridge Weight (grams)	Actual Bridge Weight (grams)	Estimated Load at Failure (lbs)	Load at failure (lbs)	Structural Efficiency (Load at Failure in lbs / Dead Load in lbs)
1	82.776	85.2	66	39.0	207.7
2	73.61	80.3	105	55.1	311.3
3	82.536	83.4	65	90.8	493.7
4	70.0763	73.2	60	32.7	202.6
5	77.96	85.3	100	60.8	323.2
6	79.07	83.8	100	70.4	381.2
7	71.5312	75.5	60	55.6	334.1
8	79.78	81.9	65	68.4	378.7
				Minimum	202.6
				Maximum	493.7
				Range	291.1
				Mean	329.1

FIGURES

Figure 1
Howe Bridge Design

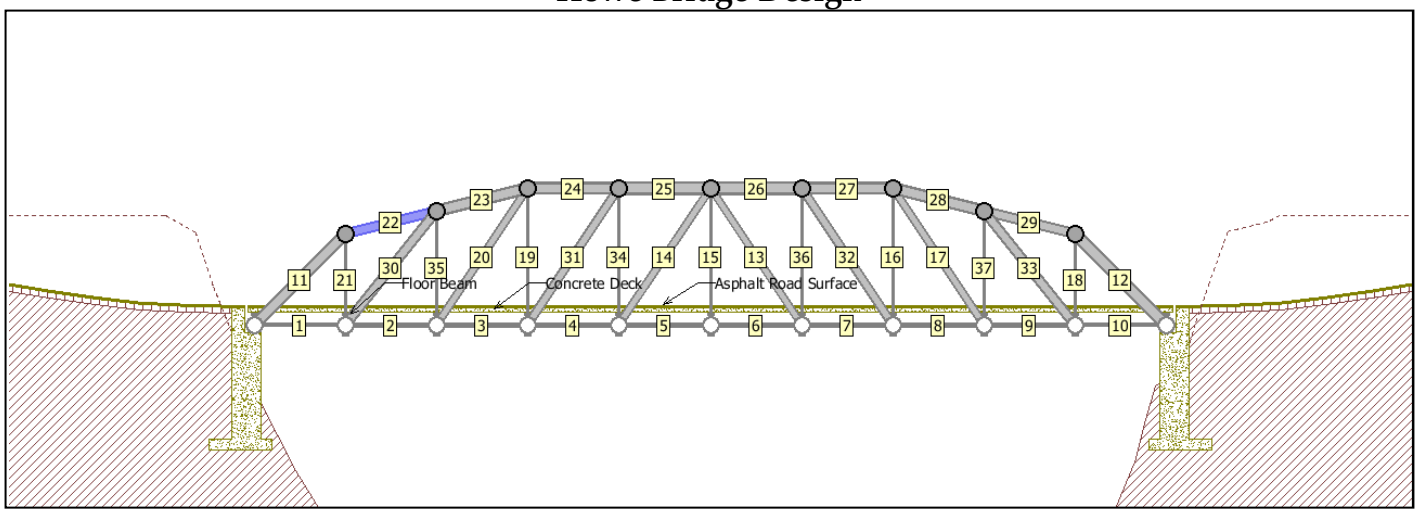


Figure 2
Warren Bridge Design

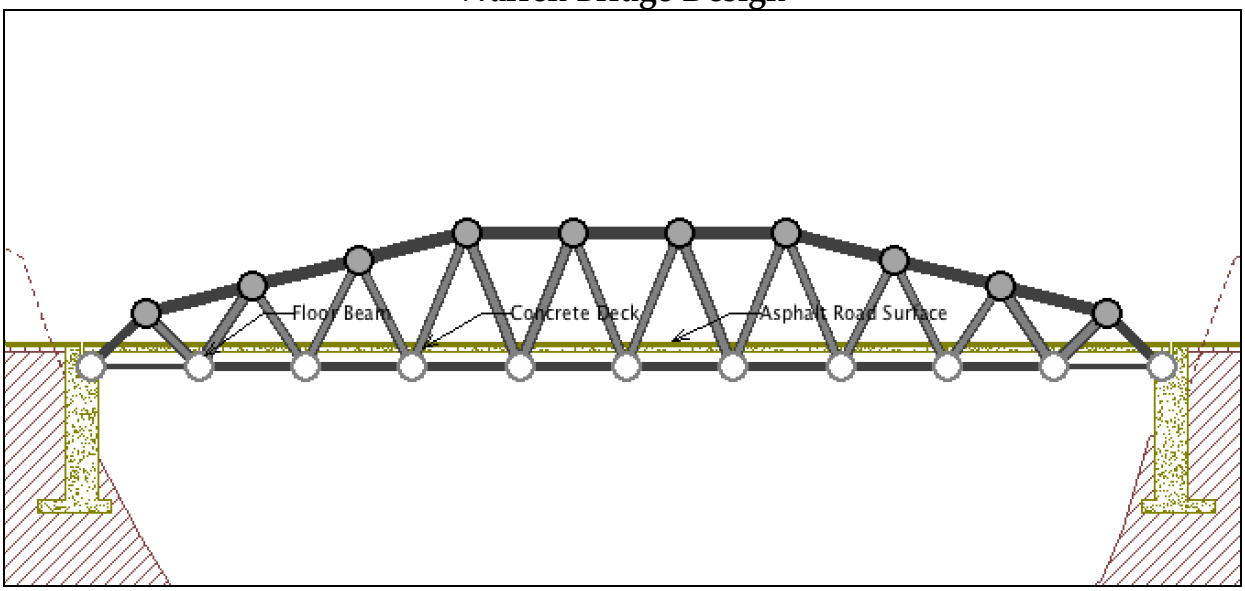


Figure 3
Prototype of the Howe Bridge

Figure 4a
Howe Truss Bridge After Failure Load Testing

Figure 4b
Howe Truss Bridge After Failure Load Testing

Figure 5
Prototype of the Warren Bridge

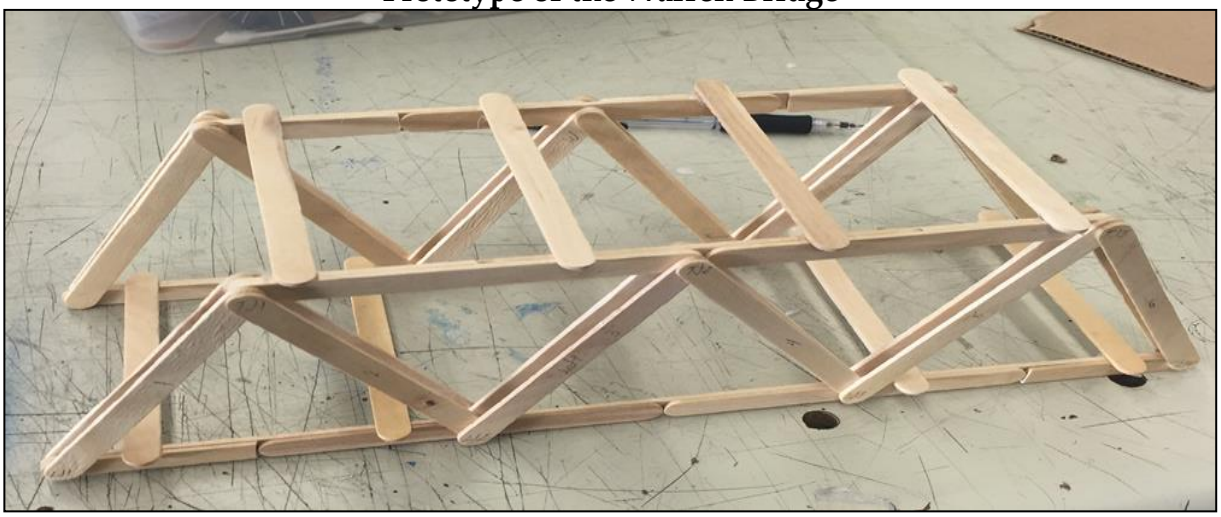


Figure 6a
Warren Truss Bridge After Failure Load Testing

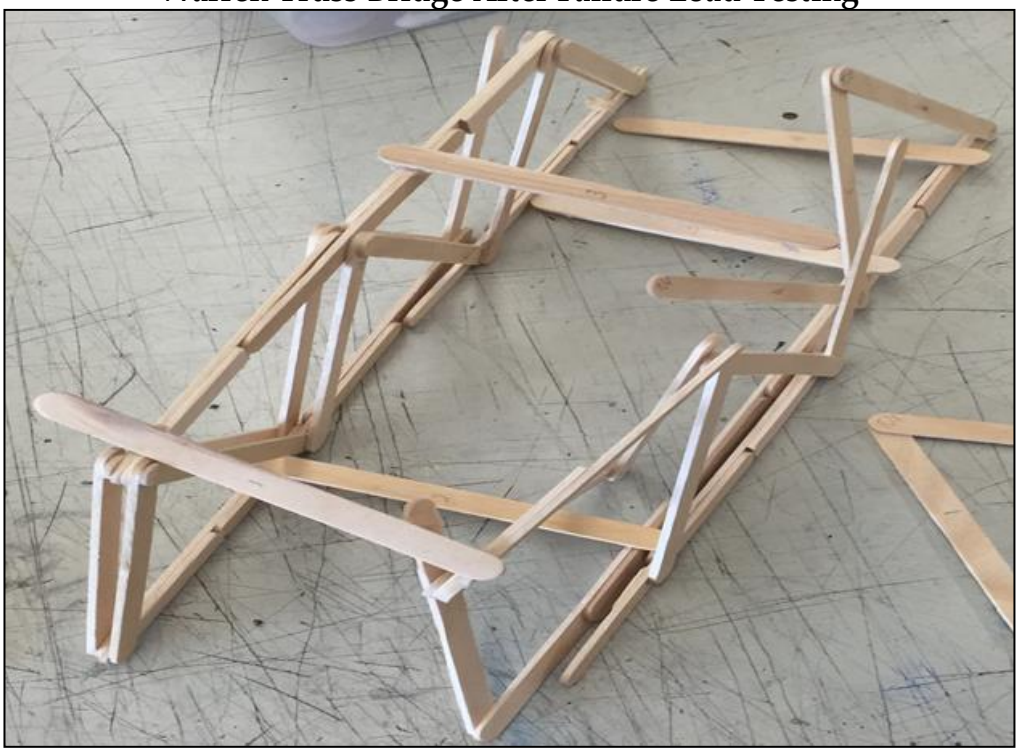


Figure 6b
Warren Truss Bridge After Failure Load Testing

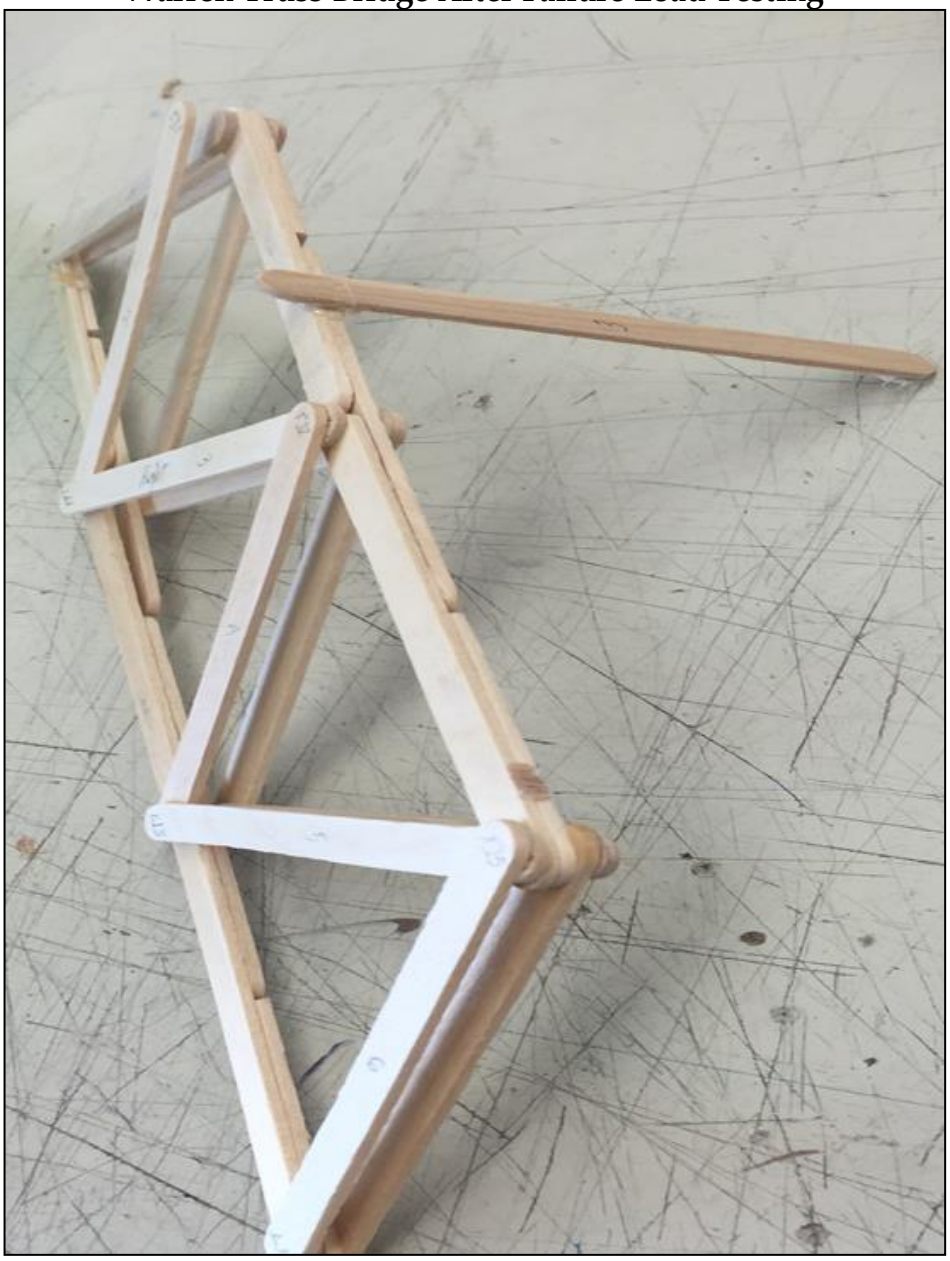


Figure 7
Comparative Structural Efficiency of Howe Bridges

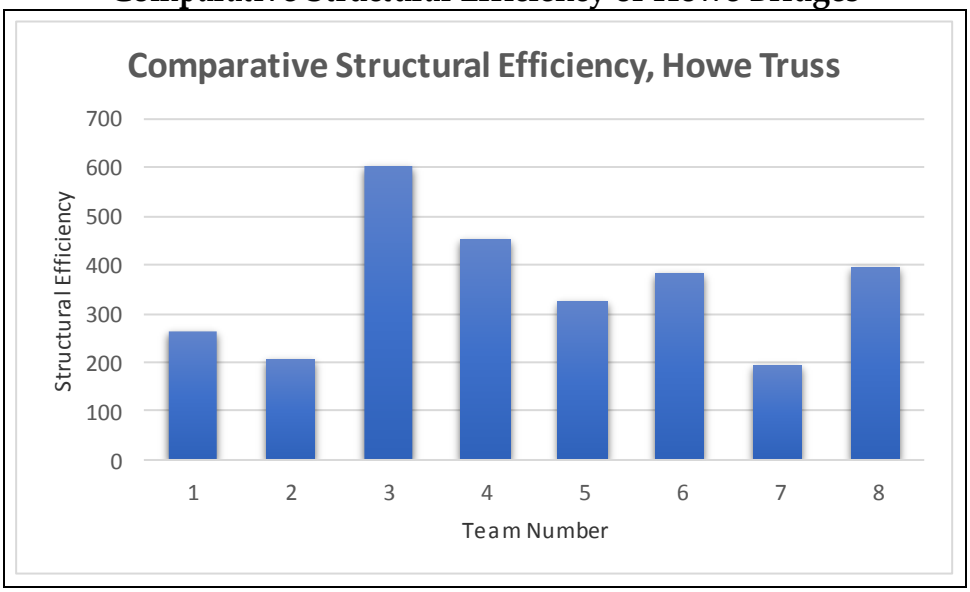
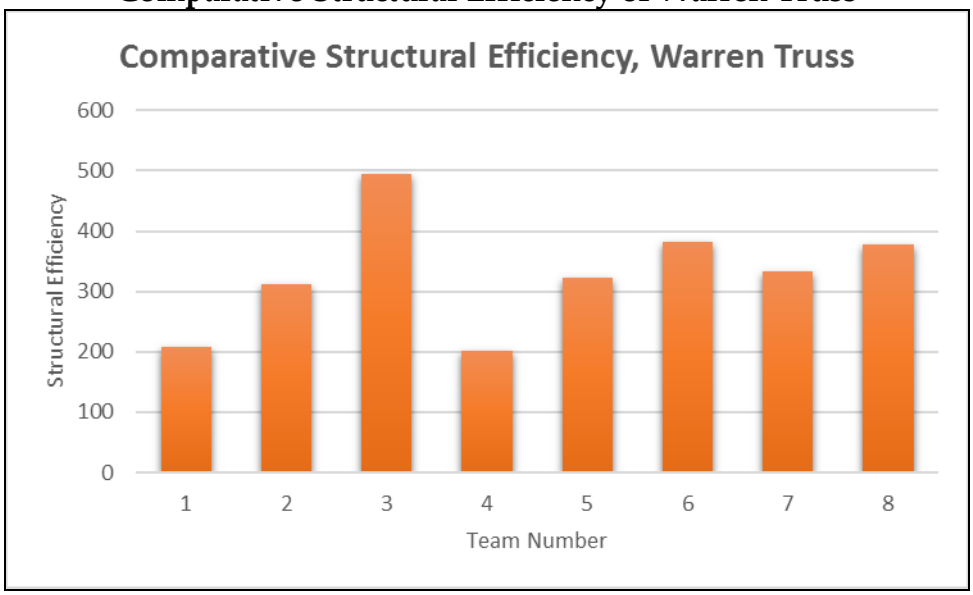



Figure 8
Comparative Structural Efficiency of Warren Truss