In-Depth Analysis of the Arrigoni Bridge: an Exemplary Model of a Through Arch Truss and Suspension Combination

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ABSTRACT

Bridges have been an integral part of human transportation networks for thousands of years. The Arrigoni Bridge in Middlesex County, Connecticut, is a great example of the ingenuity of engineering design; the structural combination of through-arch trusses and vertical, helical wire suspender components are an ingenious and iconic application of multiple design approaches. The purpose of this project was to create a replica of the Arrigoni Bridge, which allowed the creators to visualize the different components and forces interacting with and within the bridge. A scale model of the bridge was constructed; a truss manifold and high gauge suspension wires composed the basis of the model. A theoretical analysis of the internal forces of the bridge among its individual components was completed with respect to the model. The model was subjected to high and particular forces to verify the results of the analysis; especially, the estimated point of failure inferred from the highest strain. The extrapolated information is then compared with the actual bridge verifying the validity of the concepts used, and the representativeness of the scale model to larger, non-arbitrary structures.

1 INTRODUCTION

By claiming a handful of fair assumptions about a structure, an illuminating analysis can be completed, verifiable by model load testing: Identification and calculation of a structure's internal members' forces provides an intuitive analogous, if simplified, framework for identifying the structure's greatest points of stress and so potential failure. Hence, a general theory arises for a substantive heuristic approach for identifying regions of particular structural interest, such as those that may be experiencing the greatest load and thus requiring reinforcement.

Thus, it seemed natural to examine the example such a neatly complex, invaluable and integral piece of infrastructure as the Arrigoni Bridge, nestled in the heart of the heavily populated regions of Middletown and Portland. That it has quietly and steadfastly served well through decades of heavy usage reflects the masterful execution of the mechanics of statics. Evidently, it is an ideal and extraordinarily appropriate vessel upon which to attempt to validate the heuristic approach outlined herein.

2 MODELLING AND ASSEMBLY

The actual bridge is comprised of two identical arches, each supporting a deck with 34 cables across a symmetrical span of 200 meters. [3]

For prudence we modelled one arch [Fig 1], or half of the bridge.

Figure 1: Aerial photo of a single Arrigoni Arch

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2.1 Through Arch Truss

A complete blueprint of the bridge was inaccessible, so the reference data was compiled from an assembly of public records. An assortment of assumptions were necessary to complete the design, so the model is vastly simplified, inherently imperfect and regrettably only carries a likeness to the true design.

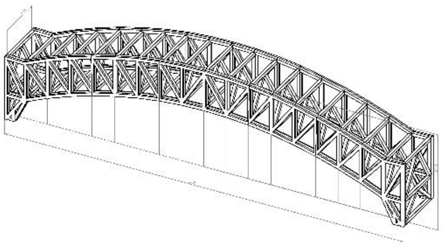

Figure 2: Isometric Drawing of Design, Solidworks

Span and cable lengths were appropriated from a report of the bridge sanctioned by Connecticut's DoT [2]. The lengths of the cables were used to derive the general contours of the arch. We assumed the cables were equidistant from each other, and that the base section was equally separated. To facilitate production we assumed the bases were also identical. The height from the bottom arch and the top arch was inferred from various pictures of the bridge at different angles, and we assumed, to facilitate design and construction, that it is identical across the entire span of an arch. Ultimately, we figured a general 1:140 scale would be an appropriate balance between the practicality of production and the ideal of presentation. We exemplified the application of the scale in Table 1.

Table 1: Length of Cables in Scale

Cables	**L3/L17**	**L4/L16**	**L5/L15**	**L6/L14**	**L7/L13**	**L8/L12**	**L9/L11**	**L10**
(m)	7.93	11.9	15.2	17.9	20.1	21.6	22.6	22.9
scale	0.057	0.085	0.108	0.128	0.144	0.155	0.161	0.163

Naturally, the design of the truss was iterative. None of us had any true experience with CAD software, which made what might have been a simple design arduous. The first iteration was crude, but by the 5th version we had a fully itemized 3D assembly of the truss within SolidWorks™. The final design was developed with the laser cutting of plywood parts in mind; a 2D scalable vector graphic print set was arranged for the laser cutter containing every individually labelled part. The 6th version came together with rigorous respect to design specificity, but near completion, a glaring design flaw became apparent. The bridge was to be joined at the center, but the weight of the bridge and cumulative minor mistakes prohibited full adherence and no support; since the bases weren't fixed it collapsed under its own weight. It wasn't necessary to scuttle the bridge as the 7th and final version of the design merely included an additional outer frame.

2.2 The Suspension Element

The suspension system involved 22AWG steel cables, crimps, and 60 eye-nuts. A platform of 15/16th in thick soft birch was requisitioned from scrap and repurposed to be our deck. 3/16th inch holes were drilled into the side of the bridge at the joints and directly below on the deck, accounting for the horizontal extrusion of the eye-nuts. 2 cables per side were omitted from the design due to constraints in the size of the nuts and wire crimps. Ultimately, we had 30 cables, instead of 34. The deck was raised slightly above the deck, levelled and then the cables were equally tensioned.

3 FUNDAMENTAL THEORY AND ASSUMPTIONS

Prior to surveying an approach to testing and analyzing, it was necessary to consider fundamental topics and assumptions in statics to constrain and define one.

3.1 Analysis of a Truss

Evidently, the scope of this project was limited to an undergraduate appreciation of structural analysis. Hence, for analytical purposes, certain assumptions were made and taken into consideration [1]:

- Members are perfectly joined at the end by fixed, smooth, frictionless pins.
- All forces are applied at the joints of the members.
- Structural members are all slender; of negligible weight.
- All members are ideal two force members; they maintain force pairs of equivalent magnitude acting in opposite directions along the same line of action.

Given these assumptions, the structure can be analyzed with regard to static determinacy [1] and the inherent principle of equilibrium. In the pursuit of thoroughness and completeness we decided to employ the method of joints.

3.2 The Method of Joints: Brief

A virtually isolated joint can yield additional information about internal forces if enough information is known about the magnitude and directions of the forces interacting with the body, such that there are enough determinate relationships to construct at least as many equilibrium equations as there are unknowns. A free body diagram can be summarily constructed. The principle of equilibrium at each joint is mathematically stated as the sum of forces and moments, respectively:

$$\sum F_{x,y,z} = 0 \tag{1}$$

$$\sum M_{x,y,z} = 0 \tag{2}$$

General convention states that a positive (+) value for a force indicates that the member is in tension, denoted Ⓣ, whereas a negative (-) value for a force indicates a compressive member, denoted Ⓒ. This is intuitive, as tensile forces leave the joint and compressive forces push upon it. [1]

4 EXPERIMENT AND ANALYSIS

The model was constructed with the intent of being pressure tested at the structural lab in UCF ENG2-116 under the 60-kip Satec Universal Loading Machine. Fittingly, it was dubbed “Hope”. We hypothesized that the point of failure would be analogous to the member or section experiencing the largest internal forces, and so, strains.

4.1 Testing Procedure

A load transferring apparatus was built with respect to the model, to ensure the vertical load of the ULM was distributed evenly onto the deck without pressing upon the truss itself. It was constructed out of dense hardwood oak and weighed 22.5 kg.

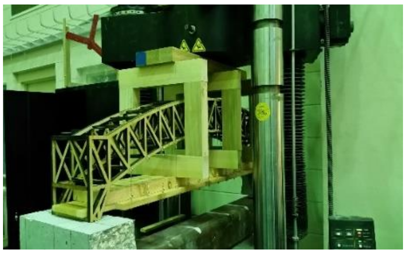

Figure 3: The model under the Satec ULM, prepared for load testing

The model and testing apparatus was centered on the crushing machine, supported by a steel beam. Cables were examined one last time for proper tension. The bases were not fixed. The lab operator engaged the machine and allowed it to increasingly exert a load on the structure until member OQ sheared from joint Q [Fig 5] at a maximum structural load of 6.67kN (1500lbs).

Load testing was completed to add context and render a statically determinate instant for our structure. Analysis of the bridge was done, joint by joint, to identify and evaluate the internal forces, support reactions and moments.

4.2 Additional Assumptions

In order to make calculations feasible, a few assumptions about the model itself were necessarily made:

- The bridge is of a single homogenous material.
- Assembly was perfect and the model is ideal; it is symmetric from and through the center.
- All suspension elements were equivalently and evenly tensioned.
- The base of the bridge comes to a single unfixed point, labelled A.
- The load is applied completely vertically (in “y”) and at the joints.
- There were no “z” forces; an “xy” plane analysis is sufficient.

4.3 Internal Force Analysis Results


Figure 4: Visible shearing at joint corresponding to Q in diagram.

The two lateral sides were combined into one; such that our virtual bridge was a single slender arch in the “xy” plane holding the entirety of the force. Similarly, given that the bridge was symmetrical and ideal, only a quarter section of the (total) bridge needed to be analyzed joint by joint, as the mirrored sections would theoretically prove identical.

Internal forces of the bridge are summarized by annotating the results in Table 2, and by visualizing it in Fig. 5. Clearly, members AE and BE are zero-force; they correspond to the three force joint with two opposite collinear forces rule [1]. However, the most notable members are OQ and SU, which are the two most highly stressed members in the truss. This section’s extremely high strain is consistent with the observed sight of failure at joint Q.
[Fig. 4, 5]

Table 2: Magnitude of the Internal Forces by Member

Member	Force (N)	T/C	M…	Force (N)	T/C	M…	Force (N)	T/C	M…	Force (N)	T/C
ST	73.08425	T	DG	3211.615	T	JL	7840.966	C	**SU**	**10711.31**	**T**
QP	154.6201	T	FI	2875.285	T	KM	7841.545	T	**QS**	**10493.22**	**T**
ON	417.0651	C	GF	2612.884	C	IK	6352.903	T	**OQ**	**9942.661**	**T**
RS	497.2665	T	HK	2496.074	T	DF	4607.199	C	**PR**	**9498.329**	**C**
UT	1009.346	T	EG	2304.356	T	GI	4504.179	T	**NP**	**9279.165**	**C**
NQ	1085.143	T	IH	2128.696	C	ED	4253.566	C	**MO**	**9083.087**	**T**
KJ	1500.963	C	CD	2113.127	C	CE	3949.085	T	**LN**	**8750.449**	**C**
LO	1620.175	T	JM	2108.145	T	AC	3336.165	C	**HJ**	**7977.171**	**C**

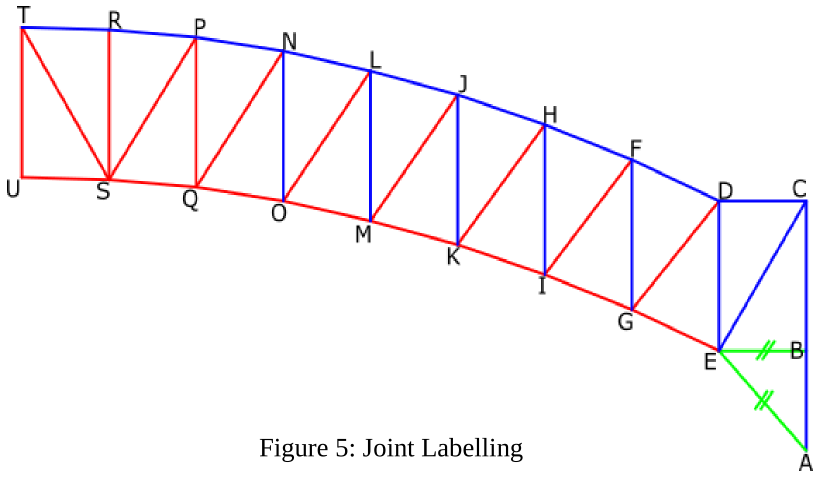

Figure 5: Joint Labelling
Compression (Blue) and Tension (Red) Visualization

Our assumptions were fairly reasonable, and though they were definitely gross misrepresentations of the physical reality, the analysis of the truss was yet substantive, conclusive and concurrent with the real world observations.

4.4 Example of Joint Analysis: at H

$$\sum F_x = 0; \qquad F_{HJ}\cos(17.53°) - F_{HK}\cos(51.63°) - 6057.28 = 0 \tag{1.1}$$

$$\sum F_y = 0; \qquad 4359.75 - F_{HJ}\sin(17.53°) - F_{HK}\sin(51.63°) = 0 \tag{1.2}$$

$$F_{HJ} = 7977.2\ \mathrm{N} \qquad F_{HK} = 2497.4\ \mathrm{N}$$

4.5 Sources of Error

Materially, the model constructed was far from ideal. Copious amounts of wood glue were used, and the plywood itself is inherently heterogeneous. There was a pre-existing curvature to the sheets of plywood used to laser cut the parts for the bridge. Additionally, there were countless mistakes in production. Even if each one was minor, they were cumulatively observable; one section of the outer frame required the ad lib addition of a modified Popsicle stick. It is important to note, the largest regrettable source of error resulted from the inability to perfectly reproduce the design of the Arrigoni Bridge itself.

5 CONCLUSION

The laborious construction of an intricate model was vindicated by the successful implementation of the analysis. As intuition suggested, the region experiencing the highest member forces represented the region most likely to fail. In fact, the model failed at precisely the point experiencing the largest forces. In addition, the model failed in the manner suggested by the type of forces (tensile) experienced at the point of failure (along QS, near joint Q) [Fig. 5], namely shearing. This implies that the heuristic approach to identifying regions of structural interest is potentially generally valid and could be assimilated into future projects.

Ultimately, the relationships explored in statics are inherent to the universe, and represent the manifestation of a practical, grander and more complete approach to understanding the fundamental nature of the physical world. This project, offered the chance to experience what it meant to be an engineer: to work in a team, to think quickly and critically, and to apply a masterful understanding of natural phenomena.

It was more than just an exercise in mechanics-statics.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

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