toric, strictly from a chronological standpoint, they become much more difficult to understand and interpret as a significant cultural resource. Evidence of significant events or technologies are consumed by newer technologies and processes. Progress and innovation are the keys to success in these fields. However, these priorities are contradictory to conservation and preservation efforts. Although HAER's focus is on documentation and interpretation, we are keenly aware of the delicate balance between preservation and progress in the engineering fields. Practical considerations of efficiency, productivity, and the need to remain competitive, coupled with advancements in technology, often overshadow concerns of preserving our cultural heritage. Through our documentation we try to raise the level of awareness and sensitivity to our technological heritage, hopefully inspiring efforts in which conservation and advancement coexist.

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Justin M. Spivey

Engineering Methods in Historical Research

How does it work? This is a question frequently asked in preparing HAER documentation, especially when a site or structure derives its historical significance from function rather than form. Historians and delineators consult technical literature and solicit expert advice to bolster their understanding of unfamiliar technological artifacts. But what if the artifact is equally unfamiliar to an expert in that technology? When researching the Lower Bridge at English Center, Pennsylvania, built in 1891, historian Mark M. Brown noted that its appearance resembled both a suspension bridge and a truss. Upon asking three engineers to characterize its behavior, surprisingly, he received three different answers. Taking an unusual opportunity for in-depth engineering study, HAER solved this mystery. During the summer of 1998, Dario A. Gasparini, Thomas E. Boothby, Stephen G. Buonopane, and I analyzed and load-tested the Lower Bridge.[1] Our work shows how quantitative analysis can enhance documentation by providing information to reveal the designer's intentions, evaluate the success of the design, and place it in a context of engineering technology and creativity.

The Lower Bridge's design was appropriate to methods and materials available in 1891, and therefore foreign to the different circumstances of modern engineering and construction. According to Donald Friedman, structural engineer and author of *Historical Building Construction,* "Advances in analysis and design were so rapid, especially before the 20th century, that a few years' difference in the date of construction could make a tremendous difference in a building's structure."[2] This is no less true of bridges. Modern analysis, while capable of determining an older structure's behavior, must be informed by the original designer's knowledge and intentions. Period textbooks and design manuals tell only what the academic community thought about structures, but the question remains how much of this information was incorporated into actual conceptualization and design.

In the case of the Lower Bridge, records identifying the designer or describing the design process have yet to be found. Without direct documentary evidence, we had to "reverse engineer," or infer the designer's thoughts from physical evidence offered by the structure itself. Engineering is a subjective art, influenced by such inconsistent human aspects as skill, judgment, and creativity. While engineers use precise mathematical tools and objective scientific laws, they also make assumptions and approximations in predicting the behavior of complex systems. The effort of shaping a structure, like tool paths on a metal part's surface, is often visible in the product. Reverse engineering makes it possible, and desirable, to critique a structure and evaluate its designer's knowledge and sophistication.

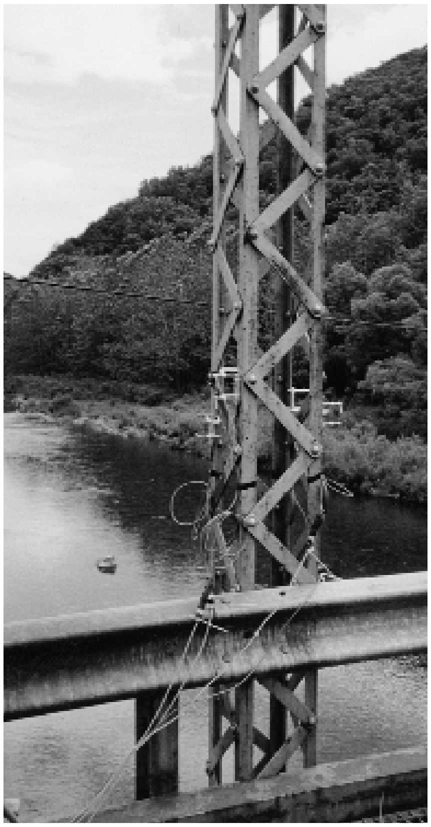
Engineers must make compromises among competing factors to produce an attractive, economical, functional, and safe design. The design process often begins with a listing of constraints. For the Lower Bridge, historical research identified some possible constraints. English Center, once a logging and tanning town, is located in north central Pennsylvania's Little Pine Creek valley. Spring floods on the creek transported logs downstream 30 miles to Williamsport. A particularly violent flood, however, destroyed English Center's Upper and Lower bridges in June 1889. Lycoming County commissioners selected Dean & Westbrook, New York engineers and contractors, to design and build new spans.[3] Records of the commissioners' quibbling over the number and cost of bridges, and the contractor's repeated requests for payment, indicate that budget was a controlling factor in the design. High material costs at that time pushed design toward material efficiency, even at the expense of complex fabrication. Rough terrain between English Center and the railroad in neighboring Pine Creek valley imposed another constraint, in the way of material transportation costs. Finally, because replacement bridges without piers in the creek bed would more likely survive future floods, the Lower Bridge needed to span 300 feet.

These constraints motivated the designer to produce a design that combines a suspension bridge's efficiency with a truss's stability. Catenary eye-bar chains, the defining feature of a suspension bridge, efficiently carry loads in tension. This part of the structure, while capable of supporting its own weight (dead load), is not stable under moving loads or wind (live loads). Stout vertical members and slender diagonal rods, resembling a truss, add stiffness and stability. The combination of suspension and truss systems is an indeterminate structure, meaning that the force carried by each member depends on the properties of all members. Exact analysis would be infeasible without a computer.[4] We set out to determine how, then, the designer might have conceptualized, designed, and devised an erection sequence for the Lower Bridge.

Lower Bridge at English Center, Pennsylvania, showing prominent catenary eye-bar chain and diagonal truss members. Photo by Joseph E. B. Elliott, 1997.

Our work began with a study of suspension bridge forms.[5] Suspension bridges are capable of spanning great distances because tension is a more efficient use of metal than compression or bending. But while a suspended chain or cable is stable for downward loads, upward loads are problematic. Observing that moving loads and wind tend to oscillate suspension bridges, engineers have long recognized a need for additional stiffening. Deck-stiffening trusses or girders have dominated popular and technical literature during the 20th century, obscuring a number of viable alternatives developed previously. Pittsburgh's Point Bridge, the country's fourth-longest span when completed in 1876, had stiffening trusses attached to its catenary chain. Alternately, the truss could run the entire depth between catenary and deck, a system used on the Lower Bridge. These two spans are reminders of alternatives to the conventional, deck-stiffened suspension bridge form.

In June 1998, we created a computer model of the Lower Bridge and conducted load testing of the actual bridge to verify the model. Using strain gauges installed on various members of the bridge, we collected data as a truck of known weight traveled across the span. We converted strain gauge data to force results, and these compared favorably against results from the computer model. We then analyzed the model with some of its members removed, to gain insight into how an engineer might have approached the structure in 1891. Late-19th-century textbooks suggested analyzing indeterminate structures as a combination of two parallel, determinate structures. This procedure is approximate at best, but entirely plausible for the Lower Bridge.



Detail of vertical member (labeled U11-L11 in drawing on next page), with strain gauges installed for load testing. Photo by author, 1998.

The Lower Bridge's designer likely first considered the bridge, without diagonal members, under dead load. Construction during the summer of 1891, when the creek was low, could have proceeded on temporary wooden scaffolding in the creek bed. If built from the deck up, the stocky vertical members would support the eye-bar links. Once connected to the towers, this system could support its own weight. Without the diagonals connected, it would be a determinate structure, free from stresses caused by members slightly too long or too short. The designer could have specified an erection procedure to take advantage of this. The next step is less certain because the diagonal rods were designed to allow tension adjustment.[6] If tightened while scaffolding supported the bridge, the diagonals would help carry forces from the bridge's own weight. It would have been safer to assume that the diagonals would not remain tight enough to help, however, leaving the vertical members to carry the entire dead load. Our analysis of the model without any diagonals shows that the force in the chain is fairly uniform along its length. This is characteristic suspension bridge behavior, which the designer seems to have recognized. Consistent with the uniform force carried under dead load, the chain has a constant size (and strength) across the span.

The designer would then have considered another determinate structure, adding only those diagonals that ascend outward from mid-span toward a tower. (Adding all diagonals would create an indeterminate structure. Although the remaining diagonals help carry asymmetrical loads, they would not be considered at this stage of design.) Regardless of when the diagonals were tightened, they would be responsible for the truss action that stiffens the bridge under live loads. Modern load-testing and analysis show that diagonals carry tension forces from a moving load up to the eye-bar chain, compressing some vertical members. Member sizes chosen by the designer are consistent with these forces, showing that he anticipated truss action. Diagonals increase in size (and strength) toward mid-span. Unlike the slender hangers on a conventional suspension bridge, which can take only tension, the Lower Bridge has stocky vertical members capable of taking compression.

This reconstruction of the design process illustrated the thought required to achieve this structure on a rural site in 1891. Rather than avoid structural indeterminacy, the designer used it to gain material efficiency. In its member sizes, this unique structure reflects its designer's sophisticated understanding of its behavior at various stages of completion. (Another round of modern analysis would determine the particular load cases and stress limits used to size members, and further assess the designer's knowledge and skill.) The Lower Bridge's stiffening system as built uses about 40 percent less material than would a conventional deck-stiffening truss of equivalent length and stiffness. Also, because the eye-bar chain carries tension, it does not need overhead lateral bracing as found on ordinary trusses. For a 300-foot span, this design creatively combines a suspension bridge's efficiency with a truss's stability.

Reverse engineering is a recent addition to HAER documentation, and it holds great promise for identifying and celebrating the human effort and insight behind America's historic engineered structures. Previous HAER engineering studies of bridges have involved structural analysis and micrographic analysis of metals.[7] This study is the first to include load-testing, and future studies might take advantage of technologies such as non-destructive evaluation of concrete reinforcement. These methods could enhance HAER documentation of other structures, including dams, canals, mills, and large buildings. Modern engineers could also help in documentary research, deciphering their predecessors' design notes or interpreting older methods such as graphic analysis of structures. Although engineering study can increase appreciation of structures as historic artifacts, many are still in active use, like the Lower Bridge. Hopefully engineering study will also increase understanding of how these structures work, leading to maintenance and rehabilitation with due respect for the original designer's intentions.

Notes

[1] U.S. Department of the Interior, HAER No. PA-461, "Lower Bridge at English Center," 1998, Prints and Photographs Division, Library of Congress, Washington, DC. HAER is grateful to the Pennsylvania Department of Transportation and the Pennsylvania Historical and Museum Commission for co-sponsoring this work. Gasparini is a professor of civil engineering at Case Western Reserve University; Boothby is an associate professor of architectural engineering at Pennsylvania State University; and Buonopane is a structural engineer with Simpson, Gumpertz & Heger in Arlington, Mass.

[2] Donald Friedman, *Historical Building Construction* (New York: Norton, 1995), 8.

[3] Dean & Westbrook replaced both Upper and Lower bridges in 1891. The Upper Bridge, demolished in 1932, resembled the Lower Bridge.

[4] Determinate structures are considerably easier to analyze, even without a computer, because forces do not depend on member properties.

[5] Gasparini, et al., "Stiffening Suspension Bridges," in *Proceedings of an International Conference on Historic Bridges* (Morgantown: West Virginia University Press, 1999).

[6] As the bridge stands today, some diagonals are tight and others are loose, with no regular pattern.

[7] The author knows of only three other HAER studies involving quantitative analysis: HAER No. IA-89, "Structural Study of Concrete Arch Bridges," 1996; No. IA-90, "Structural Study of Iron Bowstring Bridges," 1996; and No. PA-478, "Structural Study of Pennsylvania Historic Bridges," 1997. The last included the micrographic analysis.

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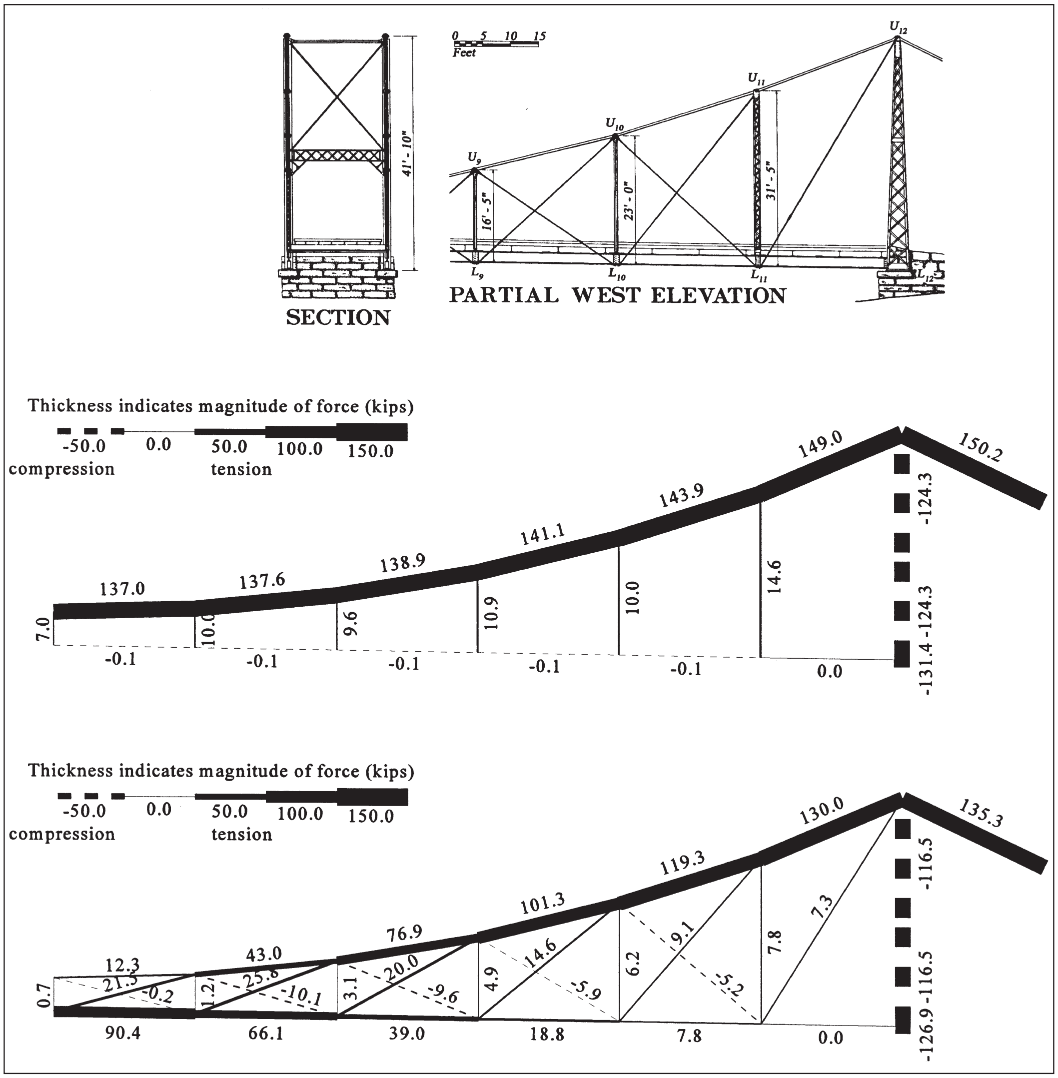

Top: Section and partial west elevation of Lower Bridge. Drawing by Jonathan Cherry and Michael Falser, 1997. Middle: Force results (kilopounds) from computer analysis of model without diagonal members, under dead load, showing nearly constant force in eye-bar chain. Drawing by author, 1998. Bottom: Force results (kilopounds) from computer analysis of model with diagonal members, under live load of 25 pounds per square foot, showing increasing forces in diagonals toward mid-span. Drawing by author, 1998.