THE TOHICKON AQUEDUCT:
Rehabilitating a Historic State Park Artefact

Authors: **William J. Collins, RLA, V.P., Principal Landscape Architect**
Simone Collins Landscape Architecture, Berwyn, PA, USA
wcollins@simonecollins.com
William Collins, RLA is a principal at Simone Collins Landscape Architecture of Norristown, Pennsylvania. He earned his BSLA from Ohio State University, and has practiced as a traditional timber framer, and served as bridge designer for the Tohickon Aqueduct rehabilitation.

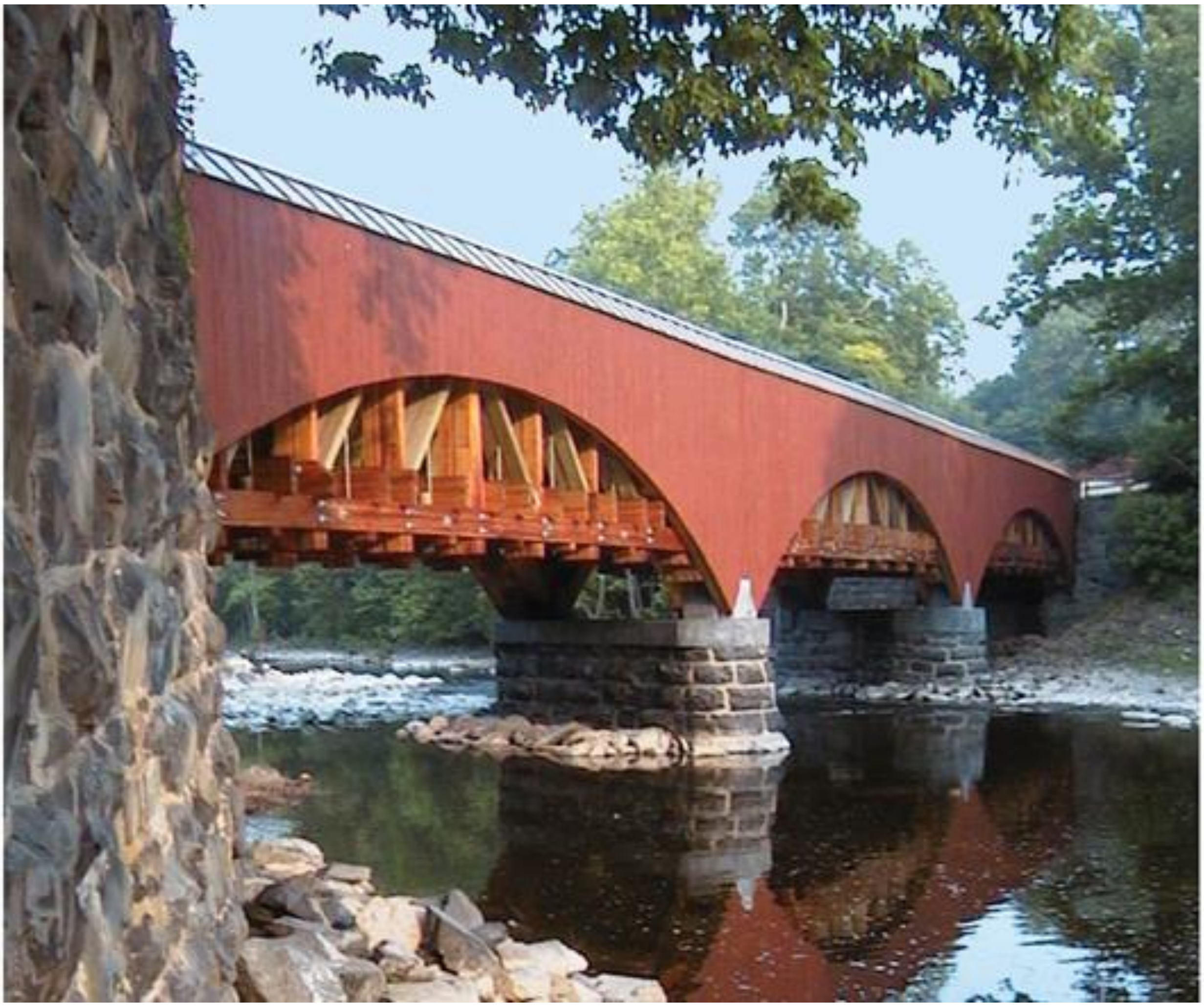

Fig. 1 The western elevation (upstream) of the rehabilitated Tohickon Aqueduct

Summary

The Tohickon Aqueduct is a heritage structure in Bucks County, Pennsylvania that was rebuilt to carry the historic Delaware Canal over the Tohickon Creek *(Fig.1).* The rehabilitation project was completed in June 2001 as a local-state-federal partnership to re-establish water flow; reopen the national Delaware and Lehigh Trail; improve infrastructure aesthetics; and extend the life of a heritage investment in a state park bridge. The Tohickon Aqueduct is the largest structure contributing to the 60-mile Delaware Canal National Landmark in Bucks and Northampton Counties, Pennsylvania. The rehabilitation design combines a traditional Burr Arch Truss system with modern wood materials and treatments to create a new 3-span, 220-foot timber bridge that carries the historic "water road" and towpath trail on rehabilitated stone foundations.

The design imperative was to protect investments in the wood superstructure by synthesizing traditional forms, techniques, and materials with modern timber treatments. Specifications included a hidden impermeable liner to contain the waterway and traditional cedar bridge sheathing and copper caps to create a complete “covered bridge” system. Mechanical detailing was equally important to protect timber materials as the preservative treatments that were specified, based on member location, size, lamination, and species. A canted trunk wall design was borrowed from the historic Roebling Aqueduct to reduce water load, maintain canal boat clearances, and brace the trusses laterally. Aesthetics were considered integral to the attributes of the structural timber and the design echoes the context of the historic commercial waterway and surrounding natural environment. Signature architectural treatments include coping the bridge siding concentric to the arches to expose the primary trusses to greater air circulation; relieve flood obstructions; and feature the monumental superstructure behind the drip lines.

Fig. 2 The previous concrete and steel version of the Tohickon Aqueduct, built after WWII

The Tohickon Aqueduct is a milestone product of a decade-long partnership between the US Forest Service; Pennsylvania Department of Conservation and Natural Resources (DCNR); the local community; research institutions and private industry. The Forest Service provided financial and technical support over five phases of timber design development, including value-engineering of the final design to achieve a $1M cost reduction by replacing most solid timbers with glued-laminated (glulam) members while maintaining the integrity of the true Burr Arch Truss design. UMaine Advanced Wood Engineering Center (AWEC) designed and field-tested fiber-reinforced polymers (FRPs) on glued-lam transverse beams under the unique uniform live load conditions of a watered aqueduct. The Tohickon Aqueduct received four national, state and local design awards.

Keywords: *Theodore Burr, Arch, Truss, Roebling Aqueduct, Delaware Canal, State Park, covered bridge, DCF Engineering Inc., FRP, Fiber-reinforced polymer, Glued-laminated timber, glulam, Ithiel Town, Pennsylvania Department of Conservation and Natural Resources (DCNR), J.D. Eckman Inc., Simone Collins Inc., timber bridge, Tohickon, University of Maine Advanced Wood Engineering Composites Center (AWEC), USDA Forest Service, Economic Action Program (EAP) and Wood in Transportation Program (WIT).*

1. Brief History of the Delaware Canal

The 60-mile Delaware Canal was originally built in two years between Easton and Bristol, Pennsylvania, however craftsmanship was so poor in some sections that it took two more years to reconstruct the system so that that it would hold water. Commercial navigation began in 1834 and operated for nearly 100 years before a steel truss version of the Tohickon Aqueduct failed in 1931, ending the canal era in Pennsylvania *(Fig 3).* After World War II, the canal was acquired to serve as a Pennsylvania state park, and soon thereafter the Tohickon Aqueduct was rebuilt as a concrete and steel superstructure that remained functional until the early 1990s *(Fig 2).*

Fig. 3 The western elevation of the steel truss version of the Tohickon Aqueduct with cascade overflows

2. The Community Partnership Design Process

By 1990, the State was planning to replace the deteriorating concrete aqueduct with a new concrete superstructure. Members of the Point Pleasant Community Association (PPCA) began discussing the possibility of reconstructing the aqueduct "the way they originally built it, with wood." A local landscape architect with timber framing experience prepared concept plans for a timber aqueduct. The concepts were presented at a meeting in 1992 of community, with local and the state park officials. DCNR offered to partner with the community outside of the normal engineering selection process – asking the PPCA to deliver engineering plans for a timber aqueduct superstructure. DCNR would be responsible for all other project engineering and administration.

The PPCA received assistance from the Forest Service in 1992 – beginning a 10-year partnership with the first of five Forest Service grants needed to retained Simone Collins landscape architecture and DCF Engineering as the timber superstructure design team. The project design advanced slowly between 1992 and 1999 as phases of funding became available to develop engineering analyses; pre-final design; final engineering; and the timber construction documentation that married with DCNR substructure engineering.

3. Engineering a Modern Burr Arch Truss Timber Aqueduct

3.1 Geometric constraints of the historic waterway

Multiple design constraints controlled how a new timber structure would fit within the existing features and conditions. Critical original elevations needed to be maintained at bottom of the superstructure to prevent stream encroachment, and at the trunk inverts to preserve the hydraulics within the canal. The new structure was limited in width by the two existing stone piers that were to be preserved and re-used. The "centers" between piers were not identical and the substructures were skewed 30 degrees from the bridge transverse.

3.2 Selecting a structural truss system

The landscape architect researched the Delaware Canal historic documents at the National Canal Museum archives in Easton, and DCNR searched its own archives – neither yielding any plans of the four previous versions of the Tohickon Aqueduct. The lack of historic data freed the new structural system to be selected based on other considerations. All extant timber bridges in Bucks County are Town lattice trusses – making the Town the local preference. DCF questioned whether a Town truss would be stiff enough to carry the water load, but Town trusses also posed other issues.

Town lattices are known for their toughness, but they are created from many lighter built-up members, making the system more susceptible to potential decay on hidden surfaces. The Town lattice is also difficult to repair or reinforce in place because of its vast array of members. A Town lattice can be coupled with an arch to increase stiffness, but practical problems arise in constructing a Town lattice truss from pressure treated materials due to the amount of field boring required for timber "trunnels" (pins) that must be driven tightly through the members. Controlling moisture content within such pressure treated materials would have posed a problem. Additionally, a Town lattice truss would have needed to be constructed continuous over three spans and extend beyond the end supports for a distance equal to its depth – a structural reality that would increase the length of the Tohickon Aqueduct approximately 24 feet.

DCF modelled both Town lattice and a Burr trusses, and concluded that a Burr truss system would provide the stiffest traditional timber structure, and be more suitable for an aqueduct structure than a Town truss. The Burr truss-arch is known to be statically indeterminate, but has been demonstrated that the arch provides great stiffness to the system and the truss affords stability. DCF designed the Burr trusses *(Fig 4)* for the Tohickon Aqueduct as a redundant system so that either the trusses <u>or</u> the arches could carry the loads independently. In the 19th Century, builders would simply proportion each to carry the load, and then "yoke the two together." Arch and truss were analysed separately and together by DCF, and each section of Burr Truss was designed to support 4000 plf or a total of 8000 plf per span.

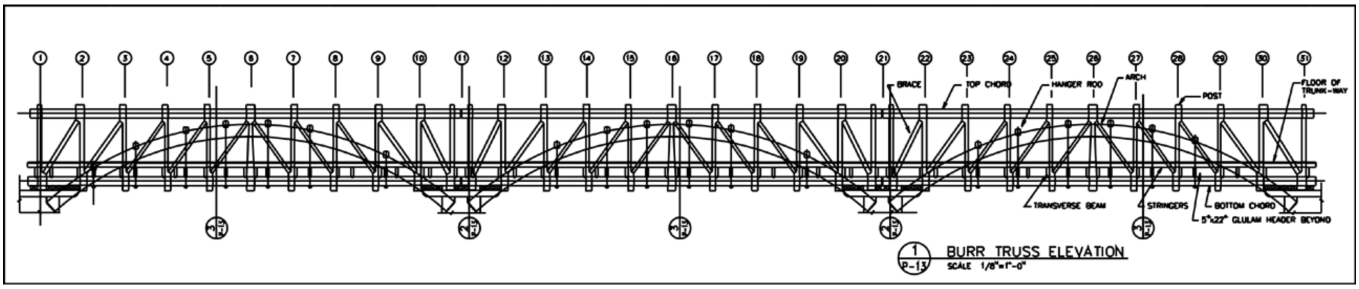

Fig.4 DCF construction drawing – elevation of the Burr Truss

3.3 Integrating engineering and bridge architecture

The bottom elevation of the new trusses was set at the bottom of structure elevation of the previous aqueduct structure. Tall trusses were needed to provide adequate stiffness in the superstructure and this reality required the new timber trusses to extend above the towpath elevation – physically separating the towpath from the waterway. The landscape architect designed the towpath as an

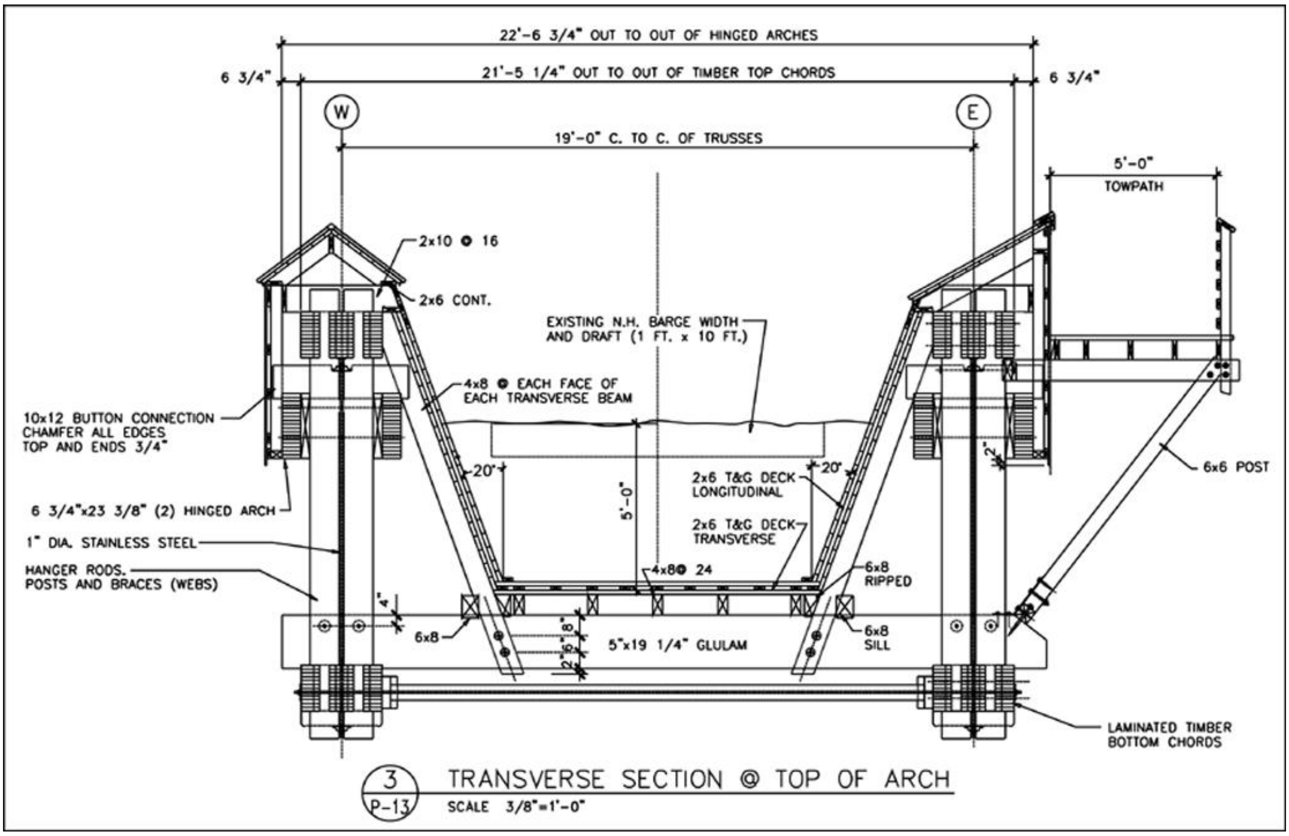

Fig.5 DCF construction drawing – transverse section through the superstructure

outrigger deck, supported by canted posts bearing on the downstream truss to allow canal boat towropes to slide over the truss top *(Fig. 5)*. DCF and SC collaborated on the trunk design that would bear on the transverse beams and conduct water across the bridge without leaking. The canted trunk post design that was documented and reconstructed by the National Park Service in the renowned Roebling Aqueduct over the Upper Delaware River was adapted for the Tohickon Aqueduct design. The trapezoid cross section of waterway reduced the design load, and the angled posts serve as transverse braces for the trusses.

3.4 Using modern materials within a traditional structure

DCF realized that glulam members would be required for the long truss chords and transverse beams to carry the water load to the trusses, however the first specifications for the truss posts and braces included several timber species, kiln drying, and preservative treatments to meet the particular demands for each member. Ultimately, only truss braces and the trunk/wall braces were constructed of solid timber. All partners envisioned that an impermeable liner system was absolutely essential to contain the canal water and protect the structural timbers below. The landscape architect designed the trunk system with a structural wood sheathing and wood façade liner to hide and protect the geotextile liner laid in between. The façade liner was designed as an interlocking, removable "pallet" system that was fixed in place without piercing the impermeable liner. The tops of the trunk liner system and the exterior sheathing were all covered by copper caps to create a completely "covered" bridge. Although covered and mechanically protected, all timber materials were also pressure treated to resist decay because moisture derived from leaks, condensation, floods, and splashing were judged to be unacceptable risks to an untreated structure. The landscape architect prepared the schematic plans for the stone and concrete abutments and piers to initiate the design interface between the community "superstructure" and State "substructure" engineering teams.

3.5 Value Engineering / Technology Transfer

The collaborative design-documentation process did not end in 1999 when the project partnership was faced with a $3.1 M construction bid as the lowest submitted by J.D. Eckman Inc.(JDE) of Chester County, PA. The State determined that a $3.1M timber aqueduct exceeded the budget available for the project, and directed DCNR to develop an alternative design for bid using concrete. The PPCA petitioned DCNR to consider a "value-engineered" timber aqueduct as an alternate bid. The Forest Service agreed to fund the value engineering tasks and suggested that Fiber-Reinforced Polymers (FRP) tensile material be considered as a cost savings measure to reduce the sizes of timber members. DCNR agreed to re-bid two alternates – timber and concrete.

Value engineering included two tasks: cost-cutting design measures and technology transfer. The landscape architect coordinated the work and the team identified areas where the timber construction could be simplified and costs reduced. The traditional Burr truss form was accepted as the "character-defining" feature and was retained for the timber alternate. Using the same Burr truss structural plans, specifications and details were value-engineered as follows:

- All timber framing labor qualifications were eliminated.
- All traditional handcrafted mortise and tenon joinery (including lightning bolt splices) were eliminated and replaced with steel fasteners.
- Solid timbers were eliminated and replaced with glued-laminated (glulam) materials for major members. (This was extremely cost-effective for the shouldered truss posts to eliminate the problems of material supply, shrinkage, and cross-section tolerances.)
- Multiple species were eliminated and southern pine was specified.
- Arches were redesigned as glulam members (Shear blocks, stitch bolts, dual species, and special treatment of the bearing laminations were eliminated.)
- Pentachlorophenol (Penta) wood preservative was specified as the preservative treatment for all glulam members. (Except for the arches that were too large to treat after fabrication, so a Penta type C was used - which is a Penta in light petroleum solvent instead of oil - that allows gluing after treatment.)
- The State did not want creosote treatment in the structure, so bearing sills and sleepers were treated with CCA.
- The half-lap joints at the interfaces of the arches and trusses were eliminated.
- The different span lengths between existing foundations were made identical by re-engineering the concrete caps on the pier tops. Forming and placing the concrete thrust pads after the arches were suspended in place accommodated the remaining differences.
- The continuous 3-span truss of the original design was replaced by three separate and identical span trusses (to simplify fabrication.)
- The primary suspension rods and transverse rods remained as stainless steel, but some stainless steel hardware items were replaced with galvanized steel. The State requested that the decking hardware remain as stainless steel as a remedy to the local acid rain.
- Contractors were permitted to submit shop drawings for the superstructure and fasteners.
- FRPs were introduced as a potential new material

The landscape architect compiled and distributed the new technical specifications to potential general contractors, material suppliers, and fabricators in advance of the State rebid bid notice. PPCA mailings and phone conferences helped communicate the project simplifications to bidders. The design team goal was to remove contractor uncertainties and reduce construction costs by $.5M below the original $3.1M low bid. The second round of construction bids returned in 2000 with another low bid by JDE at $2.1M – one million dollars less than its previous low bid. The State selected JDE and construction began without the FRP-glulams included in the contract, because DCNR would not allow transverse beams to be downsized based upon new FRP-glulam technology that was yet to be field-tested. A compromise with DCNR allowed FRP-glulam specifications to be included in the construction documents prepared by DCF and AEWC, but only for transverse beams that were sized to bear the full load without FRP reinforcement. This created the opportunity to monitor field performance of FRP-glulam members in the Tohickon Aqueduct.

3.6 Introducing Fiber-Reinforced Polymers into the Project

An aqueduct is an unusual structure because it is uniformly loaded almost perpetually. The Tohickon Aqueduct supports 350 tons of water within its trunk. Any traversing vessel displaces an amount of water equal to its weight, resulting in a constant total uniform weight on the aqueduct. DCF and AEWC determined that the high bending moments in the transverse beams offered the best FRP testing opportunity. Approximately one third (24 total) of the transverse beam members within the bridge were fabricated with fiber-reinforced polymers (FRP) for the purpose of monitoring this application under extended duration of a "uniform load," as created by the unique field conditions of a working aqueduct filled with water. The monitoring regime was designed to measure "creep" of the FRP material as a function of deflection over time under the sustained loading of the water-filled aqueduct, in an environment where temperature and relative humidity are uncontrolled.

4. Constructing the Timber Aqueduct

Fig.6: The eastern elevation of the Tohickon Aqueduct during construction

DCNR agreed to allow FRPs to be used in the structure with the following stipulations:

1. The project construction schedule would not be delayed.
2. The contractor was voluntarily willing to participate.

The FRP-glulam work did not fall in the critical path and the contractor agreed to participate with the cooperation of the glulam manufacturer and supplier. The contractor determined that he could build two of the spans while waiting for FRP-glulam beams for the third span. FRP reinforcement was applied to 24 of the transverse beams, and to an additional six (6) floor beams for laboratory testing at AEWC. It was thought the FRP reinforcement could be applied to the beams at the manufacturing plant of Alamco Inc., in Minnesota. Unfortunately, the fabricator could not secure a

Fig. 7 View to north between trusses with transverse beams in place and trunk framing under construction

commercially available supply of pre-made layers of FRP, as specified by AEWC. Instead, the glulams designated for reinforcement, plus six extra test beams were shipped to Maine where AEWC manufactured and applied the FRP reinforcement. Meanwhile, the remaining two-thirds of the unreinforced glulam beams were shipped to the project site for assembly.

After the FRP reinforcement was applied, the six extra beams remained at AEWC for testing and the twenty-four FRP-glulams were sent for preservative treatment and then delivered to the project site. The beams arrived at the site in time for the contractor to install them without adversely affecting the construction schedule. When the structure was essentially completed, staff from AEWC arrived on site to attach instrumentation to eight of the FRP-glulam beams and eight of the unreinforced glulams. AEWC worked with JDE to install catwalks beneath the structure to make reading the instruments easier by data collection volunteers

4.1 FRP Field Monitoring and Data Analysis

Most deflection monitoring conducted in a laboratory setting uses digital (e.g. electronic data acquisition) or analog (e.g. dial gage) equipment. In using analog dial gauges, there needs to be a non-moving surface below the object onto which the gauge is mounted. With digital equipment, there needs to be a power supply, or solar panels to provide power to the equipment and data acquisition system. In the case of the aqueduct, there was not a suitable surface onto which a dial gauge could be mounted, and there was not a power supply available. As an alternative, “string and ruler” deflection gages were developed. This entails mounting a ruler to the neutral axis of the beam at mid-span and stringing a thin wire along the length of the beam from the neutral axis at each support. As the beam deflects, the mid-span “ruler” gauge deflects with the supports (line) remaining fixed, allowing for a deflection reading to be taken *(Fig. 8).*

Fig. 8 Field instrumentation on the Aqueduct (rods and rope are the catwalk system)

4.2 Conclusion

The Tohickon Aqueduct is both a cultural heritage structure and a modern timber structure. It continues Theodore Burr's brilliant 19th Century design legacy that combined the multiple king post truss with a two-hinged arch, as it showcases the possibilities to synthesize traditional construction methods with modern technology by featuring an array of hybrid details to suit unusual demands. As a demonstration project, it provided a real world laboratory for timber technology. The 10-year project satisfied the visions of community organizations, elected officials, heritage development promoters, historians, federal forestry administrators by employing the multi-disciplinary technical expertise of landscape architects, structural engineers, state agency engineers, and timber research engineers to create a compellingly beautiful structure as the next chapter in a remarkable historic structural genealogy. The Tohickon Aqueduct received the following awards:

- 1st Place – National Timber Bridge Award – Rehabilitation, 2002
- Honorable Mention – National Rail-Trail Design Recognition Awards, 2001
- Honor Award – ASLA, Pennsylvania/Delaware Chapter, 2001
- Excellence In Design, Franklin Wood Award – Bucks County AIA, 2002

4.3 Acknowledgements

- The late David C. Fischetti, P.E., engineer of record Tohickon Aqueduct superstructure
- The late Eugene Comoss. P.E., engineer of record Tohickon Aqueduct substructure
- Point Pleasant Community Association
- US Forest Service
- Pennsylvania Department of Conservation and Natural Resources
- Pennsylvania Department of Environmental Protection
- Pennsylvania Rural Development Council
- Pennsylvania Forestry Association
- UMaine AWEC
- National Canal Museum

Fig. 9 View north of the Tohickon Aqueduct prior to 1931. Note the boat and mules in operation.

Figure 10   View north of the new Tohickon Aqueduct, partially watered