Learning with 18th Century Engineers

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Abstract

Learning traditional engineering coursework within an historical context can be both interesting and instructive for students. In addition it offers some educational opportunities for students to broaden their view of where engineering fits into the overall spectrum of human activity. Mechanical engineering seniors at Bucknell have been learning engineering and design from some engineers who practiced in the 1700's. Two of these engineers (artists, patriots, etc.), Charles Willson Peale and Thomas Paine, were bridge designers, and another, Johann Christopher Christensen designed and supervised construction of America's first powered waterworks. Engineering student teams at Bucknell have studied these early designs and used them as a basis for senior design projects. Based upon their evaluation of the historic designs, the teams produced their own designs of replicas of the early works, and then they built and tested them. Because of the relative simplicity of the 18th Century designs, students applied engineering principles to them and saw new meaning in the fundamental concepts that they employed. They also came to appreciate the talents and skills of these early engineers, who did not have the benefit of modern engineering theory and computational methods.

I. Engineering within an Historical Context

Some of the most fascinating stories of human creativity, ingenuity, perseverance and accomplishment can be found in the history of engineering. As such this history can serve as a source of inspiration, motivation and good, technical content for engineering students. Identification of suitable historical examples and the incorporation of them into engineering courses present a pleasurable challenge and some surprising educational benefits.

* Students learn about the human dimension of engineering and about the engineers of the past as people, who have made contributions to their societies.
* Students learn about the significance of engineering accomplishments and the corresponding impact upon different aspects of civilization.
* Students gain an appreciation for how their subjects have developed with respect to content and time.
* Students learn the application of fundamental engineering principles upon easily understood systems because of the relative simplicity of old, historical engineering processes and equipment.

Most of the majors within a university curriculum are taught within a conscious, historical framework. This is true across the spectrum from the liberal arts through the sciences. The major historical figures within each field are identified and celebrated along with their works. Each student readily identifies himself or herself as one of a long line of people learning and possibly contributing later to their field. It humanizes their major and their activities within it. Engineering has not placed as much emphasis upon an historical context for its subjects and the engineers who have come before. Some educators such as Billington (1) and Petroski (2) have made significant contributions to this area. But for the most part, the incorporation of an historical perspective within engineering curricula is sporadic and spotty at best.

An area within the mechanical engineering curriculum at Bucknell that has proven to be a good outlet for historical connections is the senior design projects. The typical sequence of events in senior design courses (MECH 401 and MECH 402) is given in the Appendix. One historically based topic has been presented within the list of choices for student selection in each of the most recent three years. Each time, a team of three or four seniors has chosen to undertake the historical topic and build its designs around it. The following two examples present the nature of the projects.

II. 1998-99 Project: Designing an 18th Century Bridge

Questions:

* What ever happened to Thomas Paine after the American Revolution?
* Who wrote the first American book on bridge design?

These are two of the many questions that faced the senior design team of John Belding, Christina Johnson and Mary Megee. While many people can recall quickly some facts about the post-revolution lives of Washington, Jefferson, Adams and Franklin, few know anything about what happened to Thomas Paine. The answer in part may explain this situation. He became an engineer! Another interesting fact is that he moved back to Europe in 1787 and lived in England and France for fifteen years. More on Paine will follow.

To introduce the 1998-99 project, the senior design team was presented with the following statement.

> *The Schuylkill River formed a significant barrier to the growth of Philadelphia in the 1700's. The city leaders were determined to overcome this obstacle, and they solicited proposals for the design and construction of a bridge. Two early design concepts were recorded and have been passed down over the years. One was by Charles Willson Peale, who gained lasting fame as a painter of portraits (Washington, Franklin, Adams, Rittenhouse, etc.) as well as landscapes. Thomas Paine, revolutionary war patriot and author of "Common Sense" developed another.*

The purpose of this senior design project is to use today's engineering knowledge to analyze Peale's and Paine's designs. Based upon its assessment, the team will produce its own design for an 18th century bridge across the Schuylkill using the approach of either Peale or Paine. Finally a scale model will be built and tested to a design load deemed reasonable for 18th century use.

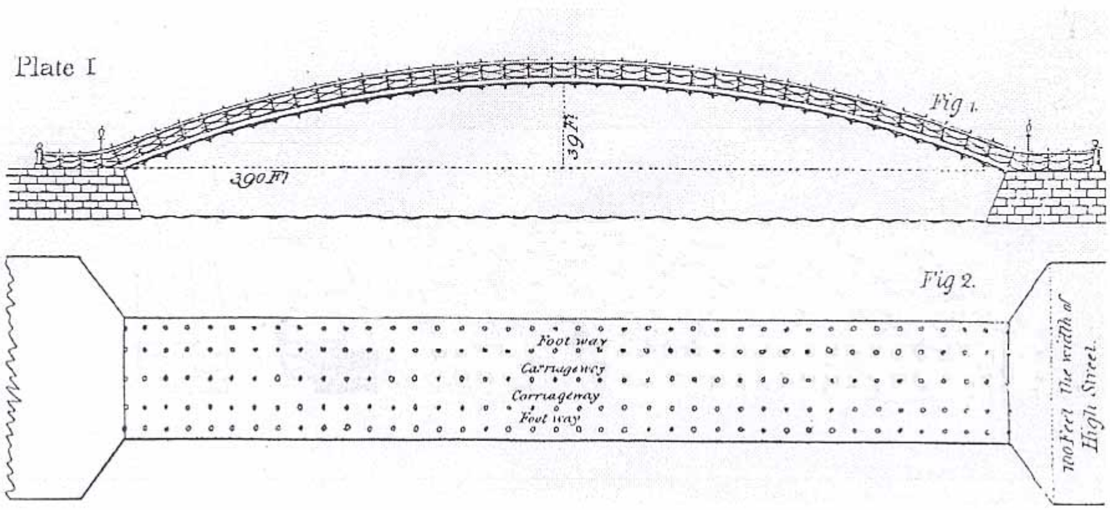
Here the students were confronted with a significant societal problem that was amenable to a technical solution. For the city of Philadelphia to grow, a means to span the Schuylkill River was needed. The gap at High Street was 390 feet wide. Two "new" design concepts had emerged during the 1700's from the creative minds of Paine and Peale. Paine's was developed independently of the Schuylkill project while he lived in England and was documented in his patent description of 1788 (3). Peale's was presented in a formal proposal to address the stated Philadelphia need, and its documentation exists in what appears to be the first American book on bridge design (4). His design is shown in Figure 1 on the next page.

Through their research the students learned about two engineers who were complex men and at times contradictory human beings. For example, the following was taken from the specifications in Paine's patent description.

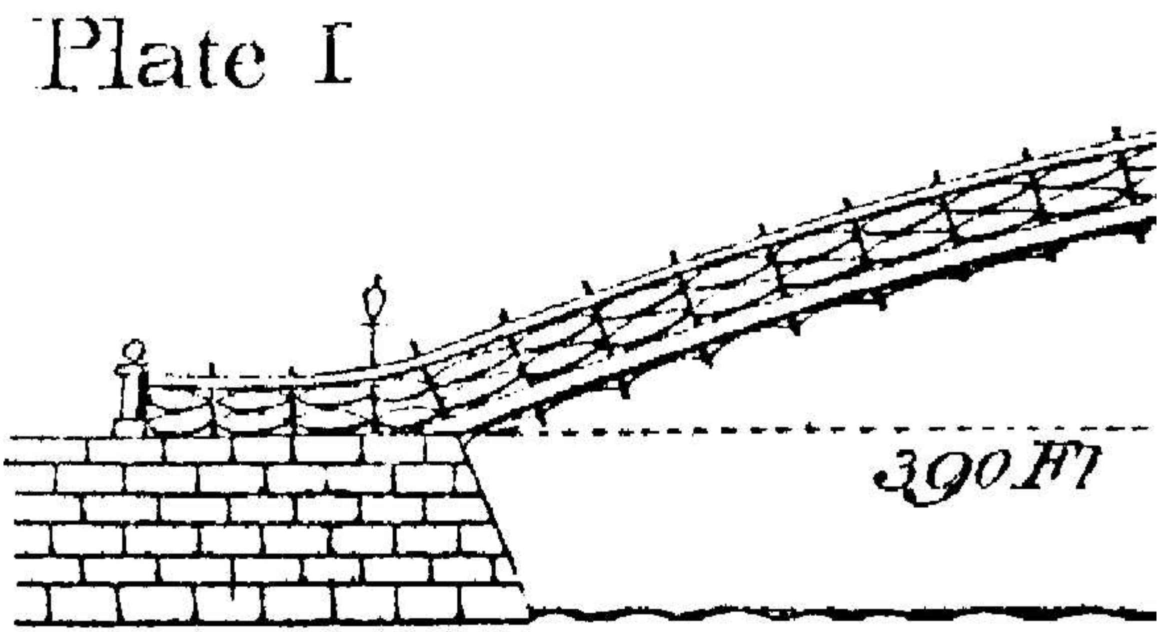
Whereas His most Excellent Majesty King George the Third, by His Letters patent under the Great Seal of Great Britain, bearing date the twenty-sixth day of August, in the twenty-eighth year of his reign, did give unto me, the said Thomas Paine, His special licence that I, the said Thomas Paine, during the term of fourteen years therein expressed, should and lawfully might make, use, exercise, and vend, within England, Wales, and the Town of Berwick-upon-Tweed, my invention of "A METHOD OF CONSTRUCTING OF ARCHES, VAULTED ROOFS, AND CEILINGS, EITHER IN IRON OR WOOD. ON PRINCIPLES NEW AND DIFFERENT TO ANYTHING HITHERTO PRACTICED, BY MEANS OF WHICH CONSTRUCTION ARCHES, VAULTED ROOFS, AND CEILINGS MAY BE ERECTED TO THE EXTENT OF SEVERAL HUNDRED FEET BEYOND WHAT CAN BE PERFORMED IN THE PRESENT PRACTICE OF ARCHITECTURE;"

... this from the "Firebrand" of the American Revolution.

Along with the human side of their project and the historical significance of this 18th century engineering to the development of structural design, the project posed educational opportunities for the students to apply engineering principles and methods to some simple structural arches. This aided them in the analysis, design, construction, and testing of their own scaled bridge arch Specific tasks are given in Table 1. In the end, they took great pride in their work and showed an appreciation for its relationship to history.



Peale's Original Drawing



Enlargement of Left Side of Bridge

Figure 1

Table 1 Technical Tasks for 18th Century Bridge Design Project	
Project Element	Methods & Principles Used
Loading	The students estimated the kinds of loadings the 18th century bridge might have experienced. They settled on 48 inches of snow equating to about 500,000 pounds distributed across the bridge. They read that Peale had assumed 200,000 pounds.
Peale's Design	The students analyzed Peale's shallow, wooden arch using the finite element method. They concluded that it was too shallow and too thin to support the assumed loading. (Interestingly, the Philadelphia town leaders rejected Peale's design as well.)
Paine's Design	The students analyzed Paine's semi-circular, cast iron arch design using finite elements and verified the suitability of a greater aspect ratio for the bridge and the desirability of Paine's idea of "multiple arches" with the overall arch.
Students' Design	The students incorporated elements of Peale's and Paine's designs into their own custom bridge design to span the 390-foot gap. They verified their design using both finite element analysis and their own MathCad model using the method of joints to determine forces and stresses.
Students' Testing	The students developed the size, material and loading specifications for a a 1/10 scale, wooden arch for eventual testing in the Bucknell Structures Laboratory. The completed arch exceeded their design load under actual testing to failure. (See Figure 2.)

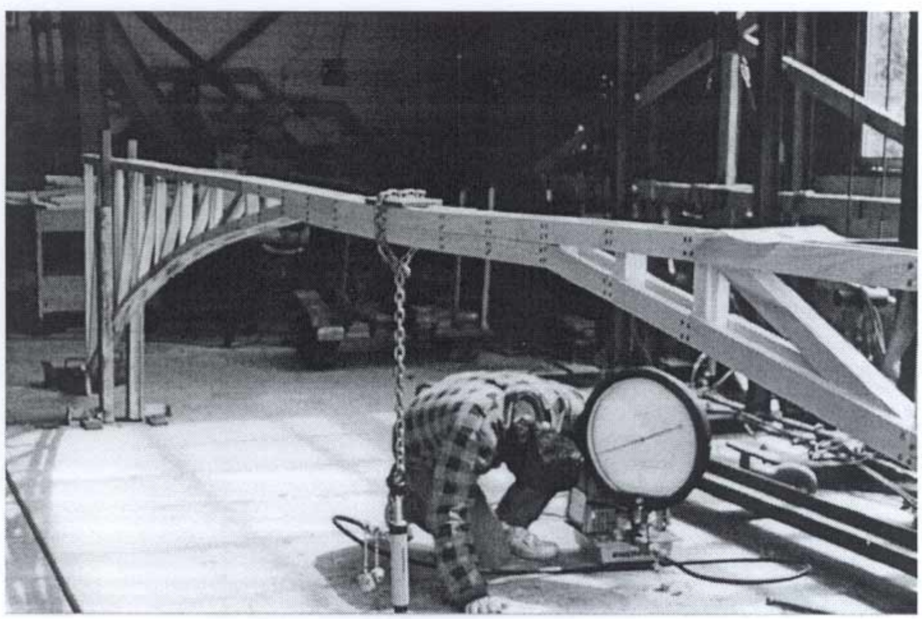


Figure 2 Testing to Failure of the 39-Foot Arch

III. 1999-00 Project: Re-Design America's First Water Powered Waterworks

Questions:

* Where was the first powered waterworks in America?
* Why wasn't it in Boston, New York or Philadelphia?

The answer to the first question is Bethlehem, Pennsylvania (5). The answer to the second question presented the team of Mark Csontos, Keith Donahue, Jerome Halluitte, and Andrea Kresge with a different perspective on technological development. In the mid-1700's Bethlehem was on the Pennsylvania frontier. It was not a center of knowledge, trade, industry or government. Nonetheless, the community did recruit a German-trained engineer, Johann Christopher Christensen, to design and build a public water system. However, it was not primarily the technical know-how that resulted in this historical achievement. The main reason was sociological/political. The town was founded in 1741 by Moravians, an industrious, religious sect, who came to the Quaker colony for the freedom to practice their faith. The church and its leader controlled their community strictly and tightly. When he decided that a waterworks was needed, the decision was done, resources were committed, and it was built. Even in the face of growing population and disease linked to poor water supply, the political haggling among factions in the larger cities of the country delayed similar decisions for about another half-century after the Moravians had their system operational.

The project statement as presented to the senior design team follows.

> *In 1754 the Moravians of Bethlehem, Pennsylvania designed and built the first powered waterworks in America. Interestingly they chose a water wheel to power the pumps for pumping water from the Monocacy Creek up to their settlement in Bethlehem. Your design team has been contracted to explore the feasibility and then build an actual, working scale model of this system for use by an historical preservation commission. This senior design project involves analyzing the early Moravian system using 20th century technology. Power requirements and water delivery rates must be evaluated. Estimates of the efficiency of the Moravian system are needed. Based upon this assessment, the design team must redesign the early Bethlehem system and build and test a scale model of a water wheel powered pumping station that will deliver water to the same relative elevation as the Moravians did in the 1700's. This will involve a detailed design of the water wheel to maximize power and efficiency. Materials used should be similar to those available in the late eighteenth century.*

Here again the initial research conducted by the design team placed their work within an historical context. They learned about Christensen and his educational and experiential preparation in Europe that enabled him to build in the wilderness. They learned about the

Moravian tradition and saw for themselves the original eighteenth century Moravian buildings during a visit to Bethlehem. They came to appreciate the value of good water for a community, and the role that technology plays in its delivery. With the relatively simple system that Christensen built to pump water, they applied many of the fundamental principles of mechanical engineering. Specific tasks are outlined in Table 2.

Photo courtesy of Mark Csontos

Figure 3

View of the Original Waterworks Building (at Right)
Up to the Location of the Town Water Tower
(Current Location of the Moravian Church Steeple)

Table 2 Technical Tasks for 18th Century Waterworks Design Project

Project Element	Methods & Principles Used
Water Demand	The students estimated the water flow requirement for Bethlehem in the 1700's based upon the known population.
Pressure Need	The students applied Bernoulli's Equation to the original piping system from the waterworks building up to the wooden water tower. They determined the pressure needed at the pump to deliver their estimated flow rate up the 94-foot rise. (See Figure 3.)
Pump Design	The students studied old drawings of eighteenth century pumps and analyzed the kinematics of the three cylinder pumps.
Gears	The students applied machine design concepts to analyze the power, torque and speed transmission through the Bethlehem system.
Power Source	The students analyzed the fluid mechanism for power generation by the undershot water wheel used in the waterworks.
Structural Analysis	The students applied principles of statics and stress analysis to estimate the forces present in the system and their influence on the materials and sizes of the parts.
Scaling	The students took their analysis of the Bethlehem system and developed the specifications for a 1/4 scale working replica. They built a complete 3D Pro/Engineer solids model of their replica and used it to generate a materials list and the engineering drawings for fabrication. (See Figure 4.)
Students' Testing	The students constructed their replica of the waterworks and tested it in the flume of the Bucknell Hydraulics Laboratory. Their system delivered a steady water flow up a 15-foot head in the lab.

This senior design team also took great pride in their accomplishment. Their replica worked perfectly. A video documentation was made that shows the entire system in operation in the flume. Some particularly interesting views are given of the water flow through the water wheel. It gives a good visual idea of the momentum transfer producing the power with the wheel. As a final reward for their efforts, the Historic Bethlehem Partnership, Inc. requested the donation of their replica for a working display at their museum within the original waterworks building. Preparations continue at this time to make that donation.

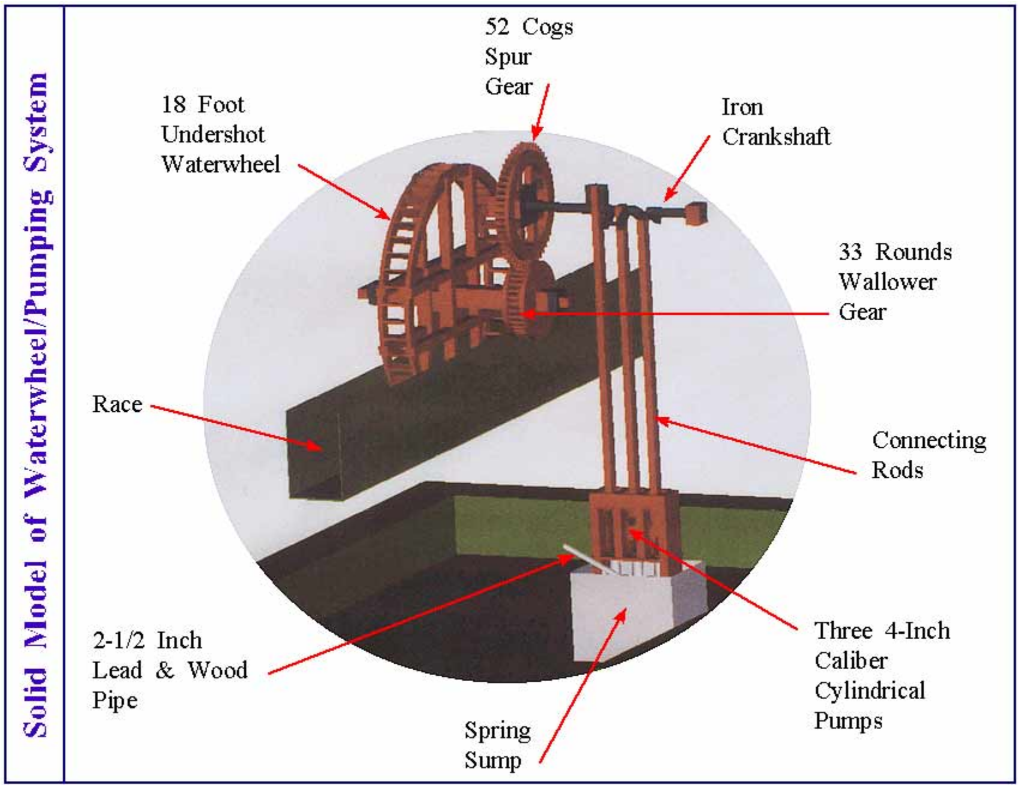


Figure 4 Pro/Engineer Model Produced by Senior Design Team

IV. Closing Remarks

These two examples from senior design projects demonstrate one way that engineering history can be integrated into a traditional curriculum. Not only did the projects provide students with an opportunity to learn, re-learn and apply fundamental engineering principles and methods, but they also enabled them to derive the benefits that come from placing their work within an historical context.

Faculty members can find specific examples of engineering history in a number of sources. Along with publications such as Technology and Culture - The International Quarterly of the Society for the History of Technology, many interesting (and often almost forgotten) accounts of engineering achievements can be obtained from local historical societies, regional and state museums and archives around the country. The professional engineering societies have published many historical articles and books over the years. Students themselves often relate stories of their own ancestors who worked in America's early industries.

As a result of these two historically based senior design projects, the director of the Bucknell Library's Rare Book Collection and Archives asked if some mechanical engineering students could research, design and build a working replica of the Gutenberg style printing press for demonstration purposes. It was proposed as a senior design project this academic year, and a team of three students is now in the middle of their own engineering adventure in history.

Postscript

A reviewer of this paper suggested that a student's view of incorporating an historical perspective into engineering courses would be useful. One of the students who worked on the waterworks project offered the following thoughts.

> *I guess I could say some of the greatest things I got out of our project were a perspective and an appreciation. The perspective is to look at a structure, a road, a machine or even an empty field and be able to see an evolution. I feel I could decipher what the design intent was and how its usefulness changed with time or how its function was changed to keep up with the times. The appreciation is to see what people were able to accomplish with little resources compared to today.*
>
> *The thing that I took away and is a second nature to me now is to find what is under my nose. For example I work next to the Chesapeake Bay Bridge, built in the early '50s. Before the bay bridge there were ferries. I walk at lunchtime; I slowly picked up where the docks were and the four-lane road that led to them and also something intriguing. For months I walked past this pile of rocks cemented together with a nice sized anchor sitting on top of it. It is close to where the ferry docks were, so I began to think that perhaps this is some type of memorial to the ferries, which died when the bridge opened.*
>
> *This anchor monument is in plain sight at the gate where I work. Everyone who works were I do has to pass it every day. So I asked some people who have worked here for 20+ years, "What is the story behind the anchor?" The most common reply is " What Anchor?"*
>
> *Keith Donahue, B.S. - M.E. '00*
> *Northrop Grumman*
> *Oceanic Systems*
> *Annapolis, MD*

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Thomas P. Rich is a Professor of Mechanical Engineering at Bucknell University. Dr. Rich received a B.S.M.E. from Carnegie-Mellon University in 1965 and a M.S. and Ph.D. in Mechanical Engineering from Lehigh University in 1967 and 1969 respectively. He has held teaching positions at Texas A&M University and the University of Southampton, U.K. Dr. Rich served as Dean of the College of Engineering at Bucknell from 1986 to 1997. He has research interests in computer-based mechanics, fracture mechanics and the history of engineering. He is currently writing an electronic book documenting the history of engineering and technology of the Commonwealth of Pennsylvania. He is a Teaching Fellow for the Society and Technology Residential College at Bucknell.

Appendix - Bucknell Senior Design Project Agenda

The senior design projects at Bucknell span both semesters of the final undergraduate year. The typical sequence of events in the courses follows.

Fall Semester

* Faculty members submit brief descriptions of potential project topics, which they offer to advise.
* Students individually select and rank the projects that they prefer to pursue.
* The course coordinator forms teams balancing students' interests and project topics.
* A student team works with the course coordinator and project advisor (often in a client role) to define and layout a yearlong plan for completion.
* The team conducts appropriate research into subjects needed to formulate their design.
* Student team members conduct required engineering analyses and preliminary tests in formulating their design.
* The student team produces a complete "paper" design that meets the project's requirements.
* Paper designs include all specifications needed to build and test the system.
* A formal presentation is made, and a report is submitted.

Spring Semester

* Student team procures all the materials and equipment needed to build the designed system.
* Student team tests the performance of their fabricated system and evaluates their design.
* If time permits, some iteration and improvements are made to the original system.
* A formal presentation is made, and a complete, formal report is submitted.