Bridge Design and Construction

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Overview

Traveling in Pittsburgh, whether by automobile, train, boat, or on foot, there is a high probability of crossing over or under a bridge. With many physical obstacles such as hills, valleys, streams, and of course the Allegheny, Monongahela, and Ohio rivers, it's no wonder that some people claim Pittsburgh has more bridges than any other city in the world. Although often overlooked, these bridges have become a part of our heritage and have shaped our communities as much if not more than the three rivers themselves. Not only seen as connectors, bridges can be architectural works of art as well. With their detailed stonework, massive cabling, or majestic archways, bridges can simultaneously be practical and beautiful, skewing the truism that form follows function.

While bridges of all shapes and sizes are looked upon as works of art, most people take them for granted and either aren't concerned with or fail to realize the amount of knowledge necessary to properly design and construct a bridge. This knowledge, at least its rudimentary concepts, can be taught through any high school construction and/or technology education course since the majority of the principles are related to the corresponding fields of study in mathematics and science.

Rationale

It seems that the modern educational class structure leaves little room for alternative lesson planning. The core subjects including mathematics, English, history, and science are taught singularly without much interconnection. In contrast, Technology Education, which is the modern label for industrial arts, has the ability to be interdisciplinary with many possible vehicles to teach its concepts. In the case of this high school construction curriculum, bridges will be the vehicle used to teach mathematical and scientific principles in addition to the applied skills normally taught in a traditional industrial arts classroom.

Although the mathematical and scientific principles mentioned above can be taught individually, teaching them through bridge design and construction not only provides a refreshing and exciting way of learning, but also can provide a concrete object through which analysis, evaluation, and synthesis can be fully achieved. A closer look at the content can also offer the integration of historical perspective and critical writing skills, not to mention a newfound appreciation for the concepts and their impact on daily life.

While traditional high school industrial arts and construction curriculum focus more on applied skills, these lessons will concentrate more-so on these math and science concepts while remaining hands-on.

Because the traditional industrial arts student has been historically recognized to lack in other academic areas, this curriculum is structured so even the students with a low mathematical and scientific comprehension level can succeed. This can be achieved throughout the unit via a comprehensive review of the skills that may not have been retained by the student in the past, but will be critical to their future success. Even if select students have never been exposed to the material, the lessons will act as an introduction preparing them for the same information they will receive in their core classes. Again, teaching these skills through a vehicle such as bridges and supporting it through an authentic activity will help the student visualize the lesson and ultimately retain the knowledge. These skills will range from the most remedial, such as measurement and fractions, to the more challenging, such as functions in trigonometry.

In recent years, the Pittsburgh Public School District has drastically reduced the number of vocational and technology education classes. To my knowledge, there is currently no existing curriculum in the district that combines science, technology, engineering, and mathematics also known as the STEM model. Because technological advances in the past and present day are impacting the modern workforce, students must be better prepared for careers that involve science and mathematics. STEM curriculum alleviates the growing concerns that we are not preparing enough students for careers in technology.

Although few are skeptical, I believe that most students, if given the proper motivation and taught through the proper vehicle, can comprehend even the most difficult concepts, even if they have failed attempts in the past. This curriculum offers a second attempt or a solid introduction to the material related to the STEM initiative.

Objectives

To fully understand what goes into the conception, design, planning, construction, and completion of a bridge takes not only a strong background in science and mathematics but also years of study in engineering practices. And even with these years of study, it takes a team of minds to successfully bring a project to fruition not including the skilled labor of many people. The main objective of this curriculum unit is not to produce experts in the field of bridges but rather to use bridges as a medium to strengthen fundamentals, explore the purposes and aspects of design, and to present enough information so that the students can analyze and synthesize challenges when dealing with bridges. To accomplish this goal, I have divided the lessons into four major sections: measurement and scale; bridge types, materials, and components; planning and communication (technical drawing); and construction and modeling.

Measurement and Scale

Through not only Pennsylvania System of School Assessment testing but also personal experience, it has been shown that many high school students lack the ability to measure accurately and perform simple operations when dealing with fractions. This is the basis for the first section of this curriculum, measurement and scale. Because these simple skills are not only crucial in bridge construction but also in daily life, I felt it was an ideal place to begin. Although more lessons can be added, I have broken this section down into four lectures. The first addresses simple numbers and fractions. For some students this may seem elementary while for others it may be a much-needed refresher. Basic computations such as addition, subtraction, multiplication, and division will follow when the first lesson is grasped. Only when fractions and their computations are fully comprehended can measurement and ultimately scale be introduced, which are the third and fourth lessons respectively. Scale will be used when constructing models in the fourth section of this curriculum.

When teaching fractions, measurement, and scale, I feel that traditional activities such as worksheets have fallen short. Although it once more may seem elementary, the use of teaching aids such as colored blocks, board games, or money may help the students visualize lessons centered on fractions and measurement. For example, when measuring, students will measure physical blocks of wood cut to specific lengths instead of lines on a worksheet or when learning fractions, they must put together an incomplete puzzle that has been broken into equal parts and determine what proportion is missing. I believe it is unconventional exercises such as these that will ultimately improve skills in these areas.

Bridge Types, Materials, and Components

Subsequent to the comprehension of measurement and scale comes the second section of the curriculum, bridge types, components, and materials. This builds upon the lessons learned in the first section by covering simple geometry shapes with the addition of concepts in physics. These concepts will be taught through the different bridge types. This portion of the unit consists of two major sections; the first, bridge types and second, materials.

The beginning set of lectures in the first section covers the basic bridge types including the truss, cantilever, cable stay, and suspension bridges. Models of these bridges will be on hand to specify the different components of each design. One way tension and compression will be investigated is through these models by pointing out what members are under which stress. Both physics and geometrical concepts can be introduced at this juncture including static and dynamic loading, weight distribution, and structural integrity.

The idea the different shapes hold different properties when constructing structures will be explored.

The second lecture will cover materials and their properties. Although I will briefly mention wood and its place in bridge building, because modern bridge design primarily uses steel and its alloys, an introduction to iron and steel manufacturing and its history is a good place to begin. The inception of the blast furnace to make pig iron and Abraham Darby's discovery to remove impurities with coke was the birth of modern metals. But because of its high carbon content, which made it rather brittle, iron was replaced by steel. With its reduced carbon content, steel is harder that iron yet flexible and more malleable making it a better choice for structures and other products. The mass production of steel became possible only after the introduction of the Bessemer Converter which by blowing air through the molten iron, reduced the carbon and allowed the addition of other minerals. A rival to the Bessemer Process was the Open-Hearth Process in which iron was transformed into steel in a broad shallow furnace as opposed to a tall pear shaped receptacle. Other topics can include electric arc furnaces and other modern steel manufacturing techniques.

The properties of steel will be introduced next with an explanation why it is ideal for bridge construction. Tensile strength, hardness, and thermal expansion will be covered along with what factors can determine or change these properties, the percentage of carbon being the main factor. Other materials such as plastics, glass, and synthetic materials will be used not only to contrast their characteristics to steel, but to also present other types of mechanical properties such as ductility and elasticity. Other material properties can also be introduced such as chemical, electrical, and acoustical.

After the introduction of steel, other metals such as aluminum, its alloys, magnesium, and titanium will be covered along with their properties. The question of why these metals are not used in certain applications such as bridge building will be the focus with the main points being the high cost and relatively low production volume being the reason they are not suitable for large structures.

One of the main tools used for this section will be The West Point Bridge Designer software. This educational program is very visual in nature and allows the student to modify test any structure type and test it against a structural load. The movement of the load, a truck in this case, causes each member to show its stress level, illustrating compression, tension, and other forces. Geometric shapes and angles can be substituted confirming why certain structures are used.

Constructing paper bridges is another activity designed to help students discover how different shapes and angles determine structural strength. Using one or multiple sheets of standard printer paper, students fold the paper into different shapes. The folded paper is then placed across a span, such as two books positioned apart and tested by placing weight on the paper. Overall strength is determined by the amount of weight the bridge can hold. Performing this activity in groups will also add a competitive element that can facilitate learning.

Planning and Communication

When designing and constructing not only large structures but small projects as well, students need to understand proper planning and communication is necessary to ensure money, time, and effort will not be wasted. The engineering design process is a philosophy that outlines the different stages of creation. Without this process in mind, designs may not reach their maximum potential or even see completion and always starts with a problem. In the case of this curriculum, a span needs to be bridged for transportation purposes. In stage one, the problem is analyzed and broken down so that all aspects are understood. Questions such as length, present conditions, variables, and what the present solution is should be answered. The goals for the project should also be outlined. Once the goals are determined, stage two, research, can begin. Because many bridge examples currently exist, the investigation of similar designs is a good place to start. In stage three, the requirements or specifications are compiled. Without specifications, engineers and designers have no limitations and if given the opportunity will over-construct the structure, which in most cases would not be economical. Just imagine a one of a kind cable-stayed bridge crossing Plum creek! Because there is normally more than one way of doing a job correctly, multiple solutions are conceived, which is stage four. Rough sketches are normally used as to not waste time. When multiple designs are created, new perspectives can emerge which should bring the best possible design to light. In stage five, the best solution is selected and further developed. In this stage, engineers and drafters modify the original design producing the final blueprints. With the use of prototyping, designs in stages four and five can be visualized and tested before the actual structure is erected. In stage six, these models are made and destroyed to determining their limits. In the final stage, evaluation, all data and information is reviewed to confirm that either the final solution meets the specifications or that the designers need to re-examine the problem to find further solutions.

When designing any object that many people will take part in constructing, such as a bridge with a large team of engineers, surveyors, general contractors, and laborers, everyone must have a clear understanding of the end result. The only way this can be communicated to all is through the technical drawing. These drawings contain the information such as the dimensions, materials, and fitment to clearly define the requirements for the structure or item. These drawings are unambiguous and must capture all of the geometric figures of the item so it can be accurately produced. Scale will be reviewed in this section.

Before the use of computers, drafters manually drew these drawings with a T-square, triangles, compasses, protractors, french curves, and other tools. Today, CADD, or computer aided drafting and design is used. This software makes their job much easier when fixing mistakes and re-draws are necessary. When drawing, there are two key ways one can illustrate the item. The first is the isometric view of the object. An isometric drawing is a 3-dimentional representation of the item along the x, y, and z axis. The second is known as a multi-view drawing which objects are represented by three projected views at right angles. Exploded views and cutaway drawings are also used.

Activities in both manual drawing and computer aided drafting and design will be employed to help illustrate the importance of planning and communication. Beginning with manual drafting, students will gain a greater appreciation for today's technology by experiencing the effort needed in the past to create a complete drawing. Because a majority of the skills used in manual drafting are carried over to CADD, learning the basic software functions should be relatively straightforward. In addition, because the goal of this section is not to become a professional drafter but instead offer an introduction to the subject, a less intense program such as Autodesk Illustrator will be used.

Construction and Modeling

As the final section in this unit, the students will learn about different construction techniques and build a model bridge to scale with those techniques. The skills learned in this section are similar to that of a traditional industrial arts class. Because many dangerous pieces of equipment will be used, safety will be the first lesson and of primary concern. Along with general shop and machine safety, individual lessons on the components, proper technique, and regular maintenance of the machines including but not limited to the table saw, band saw, scroll saw, miter saw, belt sander, drill press, plainer/surfacer, and jointer. Hand tools such as screw drivers, squares, and braces will also be reviewed. Basic construction techniques such as the proper way to square rough lumber and lessons on mechanical fasteners will conclude the first segment of this section. After safety tests are passed with 100 percent completion in addition to all students having a parent or guardian sign a machine operator's permit, instruction and constraints can be given to build a scale model bridge.

The final project of this curriculum will be a design challenge combining all of the skills learned throughout the unit to build a model bridge to scale using the materials provided. A quick review of bridge types, components, measurement, and scale will begin the assignment. Because this unit is based in a traditional industrial arts classroom, wood will be the material of choice with an option for students to bring in any other material they deem appropriate. Either in groups or unaccompanied, the students will choose what type of bridge they will be constructing. After the model is completed, a written report will supplement the model with information about the physical characteristics, geometric characteristics, present examples, historical references, and future modifications.

Strategies

Because of the unique structure and the diverse activities in the above lessons, there will be many different strategies utilized. Lectures combined with cooperative learning in addition to problem-based learning can best describe the approach needed to effectively teach this curriculum.

Lecture will most likely be the primary way information is instructed and cooperative learning will be used in group projects. But because most of the activities and lessons pose problems that are ill structured, can change with the addition of new information, and can have multiple correct answers, problem-based learning is the most effective strategy. Motivation, higher-order thinking, and authenticity describe problem-based learning. Essentially, students are faced with a real world problem that challenges them to think creatively to find a solution. It also prepares the students to think critically, analytically, and exhaust their resources effectively teaching them how to learn. This student-centered strategy puts the responsibility of learning on the student and puts the teacher in the role of a facilitator who asks questions and offers some guidance in order to keep frustration to a minimum.

Classroom Activities

Measurement and Scale
THE LINEAR FRACTION PUZZLE

The linear fraction puzzle is a 12" X 12" wooden puzzle with different fractional pieces that fit sequentially on the board. These pieces represent the different equal fractional parts of the board including ½, 1/3, ¼, 1/5, 1/6, 1/7, 1/8, 1/9, 1/10. For example, there are (2) ½ pieces that fit tight onto the board and there are (3) 1/3 pieces that fit tight against the board, etc… The object of the puzzle is to visually clarify that any object can be split into even segments and those segments are counted in a specific way, i.e. fractions. This is done by building "stairs" or completing the puzzle. Because the line is more often used that any other shape in construction, it provides the students with a better representation of fractions than a circle, which is more commonly used to describe fractions.

Directions for the puzzle

Stairs:

1. Separate all of the pieces into their respective groups and keep them in their own pile.
2. To build the steps, start with the biggest piece, ½, and place it onto the board. The student should notice that it takes up half of the space.
3. Place the next biggest piece onto the board, 1/3, above the ½. The student should notice that it is smaller than the ½ even though it has a 3 in the fraction (1/3).
4. Repeat this process until the 1/10 piece is stacked.

After the stairs have been completed, the students should understand fractional divisions are sequentially smaller.

Whole units:

1. Separate all of the pieces into their respective groups and keep them in their own pile.
2. Place the first ½ piece onto the board in its respective position. Place the second ½ piece so that it's end is touching the end of the first piece. These two pieces should fit tight against the two sides of the board. The student should notice that it took two pieces to span the length of the board.
3. Place the first 1/3 piece above the two ½ pieces on the board. Place the second 1/3 piece end to end next to the first piece. After the third 1/3 piece is in place, the student should see that it took three 1/3 pieces to span the length of the board.
4. After these steps are repeated, the student should come to the conclusion that the number on the bottom of a fraction, the denominator, equals the number of pieces needed to make a whole.

With this activity complete, the students should understand fractions and be ready to understand measurement.

PRACTICAL LUMBER MEASUREMENT

Although some students can grasp the concept of measurement through the use of worksheets, others need an alternative approach geared more toward visual learners. In this activity, students will use a special ruler to measure colored pre-cut lengths of wood to the nearest 1/8 inch. This special 4 foot long ruler is exploded at a scale of 24:1 meaning every 1/8" in reality is 3" for greater visibility. In addition, every other 1/8 segment is shaded to achieve the same goal of greater visibility. After the linear fraction puzzle, measuring the pre-cut pieces of wood with this large ruler should help grasp the concept that measurement is simply counting space. That space is divided into fractional units and by using a standard ruler, an exact number can be assigned to that space.

The pre-cut pieces of wood are as follows:

Black…..3”
Blue……9”
Red…….12”
Yellow…15”
Orange…18”
Green…..24”
White…..27”
Natural…39”

Bridge Types, Materials, and Components

WEST POINT BRIDGE DESIGNER

The West Point Bridge Designer software is an excellent tool to introduce students to an authentic hands-on bridge engineering experience. The essence of this activity is to explore the possibilities in bridge design through trial and error. This software is a part of the West Point Bridge Design Contest, which is a nationwide internet-based competition intended to promote math, science, and technology education in U. S. middle schools and high schools. The contest provides students with a realistic introduction to engineering through an engaging, hands on design experience. To make things more interesting, we will have an in-class competition that will adhere to the national competition’s goals and regulations. Because the competition is free and open to all who wish to participate, its resources are available through their web site and are complimentary for its lessons.

The principal teaching tool for this activity is the software tutorial, which is downloaded along with the software itself. This tutorial offers an ample amount of information on how to use the software and includes suggestions on how to create a better bridge. Beginning with the selection of the many variables such as abutments, length, and materials the deck is then laid. The structural members are then added at chosen points. When the bridge is completed, immediate feedback is then given via a simulated test run by a truck crossing the bridge. Compression and tension are highlighted as the stressed members are loaded. Once this activity is completed, students should have a clearer understanding of how bridges work.

THE PAPER BRIDGE

Building with inherently weak materials like paper quickly leads to a close consideration of the structural elements and properties of materials. There is an element of surprise, which increases students' interest in the physics, when they discover just how strong they can make this seemingly flimsy material. This activity is easily set up and gives students a chance to explore the material as a lead-in to further building. Building bridges emphasizes the concepts involved in carrying weight at a distance from the supports.

This activity provides a good opportunity to ask students to talk about bridges and cantilevers that they know. There are many bridges around to talk about. They range from monuments like the Golden Gate or Brooklyn bridges to simple logs thrown across a creek. Examples of cantilevers include balconies, awnings hanging in front of buildings, branches on trees, or even our arms when we hold them out. Discussion of examples like these invites your students to bring their own experience into the understanding of building out.

Ask the students to take a sheet of paper and construct a bridge which will span an 8-inch gap between desks. They should not use any materials to anchor the bridge to the desks. When the students have achieved this first step, ask them to experiment by adding small weights, one at a time, to the center of the bridge. When their bridge collapses, have the students try to construct an even stronger bridge, using another sheet of paper.

Keep a record of the trials. Ask the students to draw the shape of their bridge and mark down how much weight each bridge held before collapsing. In addition to having them write down "five pennies" or "three paper clips," have the students measure the weights of the pennies, paper clips, or whatever, on a scale, and record the loads on the bridges. Have the students draw a cross-section of their bridges, as well as a silhouette, so that they will be able to look closely at which constructions were successful and which were not.

Have the students share their particularly strong or weak bridges with the rest of the class. Discuss and chart the shapes that were discovered to be successful. Ask the following questions:

What shape seemed to be the weakest/strongest?

What part of the bridge seemed to collapse first?

Where was the bridge weakest?

What would you use to make the paper bridge even stronger?

What do you think would happen if the desks were farther apart? Closer together? Why?

What do you think would happen if you could anchor the bridges to the desks? Why?

Bridges illustrate the effect of weight or another force at a distance from a pivot or support point (torque), and they also provide experience with beams.

In this activity, students experiment with a variety of shapes such as folded corrugations and rolled tubes that can make an inherently weak material such as paper much stronger. Paper is very weak under compression and is somewhat stronger under tension (i.e., it collapses when you push the ends together but it doesn't pull apart easily). When you put weight on a sheet of paper it tends to buckle because it is very thin. It has no strength along the thin direction. By folding or rolling the paper, you create a "thickness" which allows the paper to reinforce itself and not collapse so easily.

You can illustrate this property of paper in a simple demonstration with an 8-foot-long 2-by-4 piece of lumber. Support the beam on two short blocks at either end. Lay the beam flat and push down at the center. It gives easily. Now, turn the beam on its side (have helpers steady each end on the blocks for stability). In this case, when you push down at the center, the beam is much more rigid. When turned on its side, there is more wood further from the center line, in the areas where it can best counteract the tension on the top and compression on the bottom.

Building paper bridges with other kinds of paper can also extend this work. What can you do with a single sheet of newspaper? How about a sheet of tissue paper? What can you build with a sheet of cardboard?

Planning and Communication

MANUAL DRAFTING

Hand drafting has proven to be a great tool for learning concepts important to the drafting process. Students learn and retain concepts better when they have to physically manipulate the content. Even though most technical working drawings are now created using CAD; the individual who has developed a basic understanding of drafting presentation principles through hand drafting will ultimately be a more knowledgeable and skilled drafter.

Because most manual drafting textbook assignments are given sequentially from simple to difficult, replication of the drawings using the proper tools such as a T-square, compass, French curve, and various triangles will be sufficient for this activity. Because there is not a specific drawing that must be replicated, I am leaving the assignments and choice of textbook to the teacher's discretion.

Construction and Modeling

SCALE MODEL

For the culminating activity, the students will break into teams to use all of the skills they have learned throughout the unit to build a working scale model bridge of their design with the materials of their choice. They may use any piece of equipment in the shop that they have been properly trained to use. Submitted with their model will be a professional quality technical drawing of the bridge along with details describing the components and their functions. To finish the project, the students will present their model and information to the class on the day assigned. Although this is intended to be an open-ended design challenge, a size constraint of three feet long will be placed on the activity in the interest of time and materials.

Bibliography/Resources

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This book is an excellent text for non-science majors because of its in-depth but easily understandable explanations of the fundamentals of physics.

Kidney, W. *Pittsburgh Bridges: Architecture and Engineering.* Pittsburgh History and Landmarks Foundation. Pittsburgh, PA. 1999.
The author has photographed and explained the design of most major bridges in the Pittsburgh area. Several historic photographs are also included.

Regan, B. *Bridges of Pittsburgh.* Local History Company. Pittsburgh, PA. 2006.
Similar to Pittsburgh Bridges: Architecture and Engineering, this book has included descriptions and pictures of most major bridges in the Pittsburgh area. Several drawings are also included.

Tonias, D. Zhao, J. *Bridge Engineering: Rehabilitation, and Maintenance of Modern Highway Bridges.* McGraw-Hill. New York, NY. 2006
This resource presents clear information on the entire bridge design, engineering, and construction process.

Whitney, C. *Bridges of the World: Their Design and Construction.* Dover Publications.

New York, NY. 2003.
The author describes the fundamental principles involved in the design of bridges. All varieties are reviewed with the addition of their historical backgrounds.

Appendix A

STANDARDS FOR TECHNOLOGICAL LITERACY

The Nature of Technology

Std. 1: Students will develop an understanding of the characteristics and scope of technology.

Std. 2: Students will develop an understanding of the core concepts of technology.

Std. 3: Students will develop an understanding of the relationships among technologies and the connections between technology and other fields of study.

Technology and Society

Std. 4: Students will develop an understanding of the cultural, social, economic, and political effects of technology.

Std. 5: Students will develop an understanding of the effects of technology on the environment.

Std. 6: Students will develop an understanding of the role of society in the development and use of technology.

Std. 7: Students will develop an understanding of the influence of technology on history.

Design...

Std. 8: Students will develop an understanding of the attributes of design.

Std. 9: Students will develop an understanding of engineering design.

Std. 10: Students will develop an understanding of the role of troubleshooting, research and development, invention and innovation, and experimentation in problem solving.

Abilities for a Technological World

Std. 11: Students will develop the abilities to apply the design process.

Std. 12: Students will develop the abilities to use and maintain technological products and systems.

Std. 13: Students will develop the abilities to assess the impact of products and systems.

The Designed World...

Std. 14: Students will develop an understanding of and be able to select and use medical technologies.

Std. 15: Students will develop an understanding of and be able to select and use agricultural and related biotechnologies.

Std. 16: Students will develop an understanding of and be able to select and use energy and power technologies.

Std. 17: Students will develop an understanding of and be able to select and use information and communication technologies.

Std. 18: Students will develop an understanding of and be able to select and use transportation technologies.

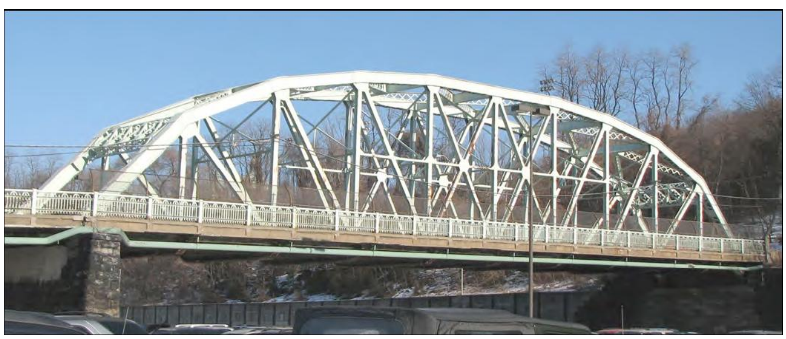
Std. 19: Students will develop an understanding of and be able to select and use manufacturing technologies.

Std. 20: Students will develop an understanding of and be able to select and use construction technologies.

Appendix B

COMMON BRIDGE DESIGNS IN PITTSBURGH

Suspension



Truss (Pratt)

Photos courtesy of Vagel Keller.

Deck Arch

Tied Arch

Deck Plate Girder