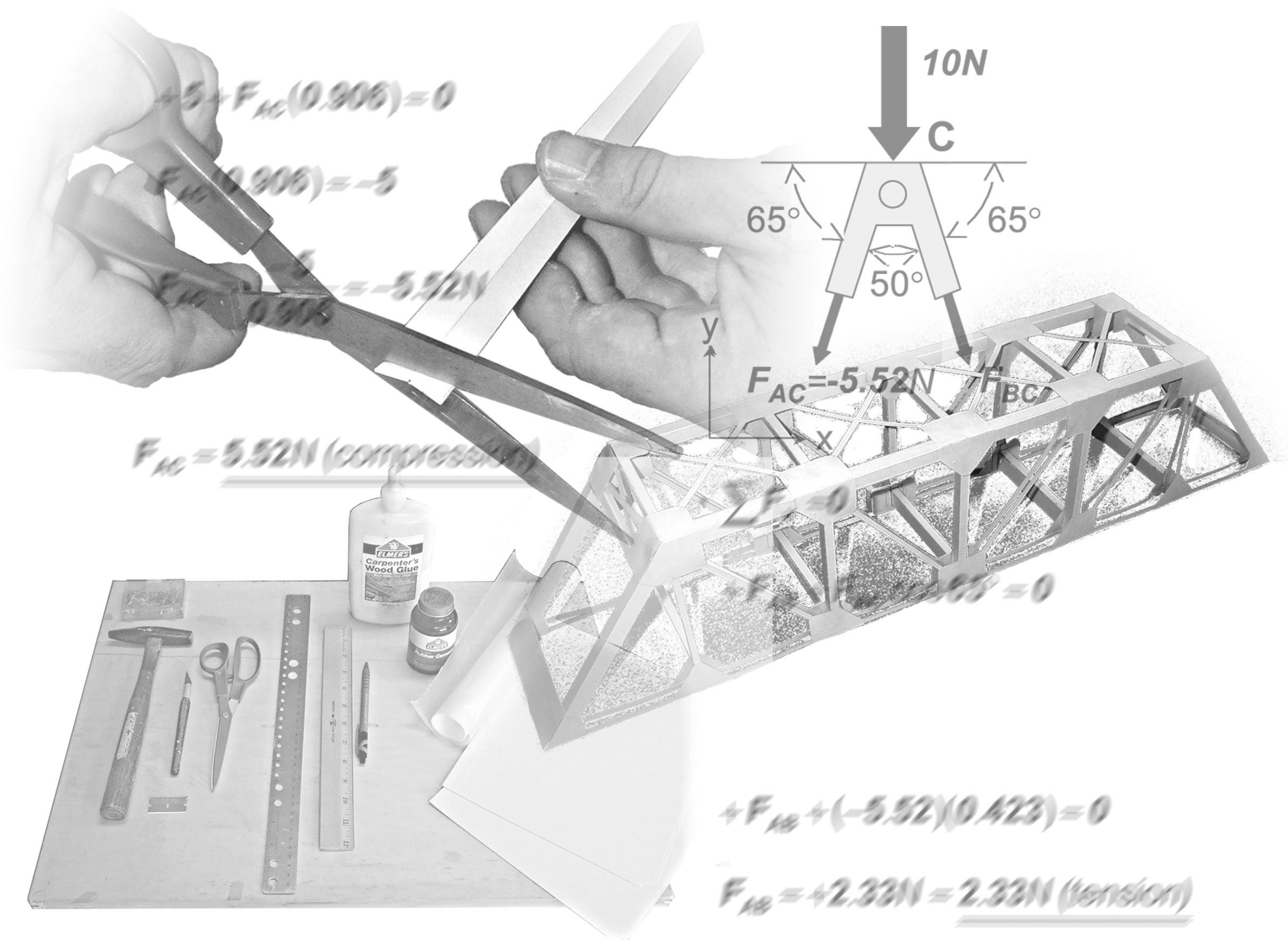
Designing and Building File-Folder Bridges

A Problem-Based Introduction to Engineering



Stephen J. Ressler, P.E., Ph.D.
United States Military Academy

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Every bridge begins in the mind of an engineer.

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Preface:

For the Teacher

About Bridge-Building Projects

A few years ago, I worked with a group of our undergraduate engineering students to run a popsicle stick bridge-building contest for 11^{th} and 12^{th} graders from several local schools. Our purpose was to introduce the high school students to engineering and to stimulate their interest in engineering careers. We also hoped to motivate them to work hard in their math and science courses—to acquire the background necessary to study engineering at the college level.

The format of our contest was typical of the bridge-building projects that have become so popular in secondary school science and technology programs in recent years. We organized the students into teams, and each team received a pile of popsicle sticks and a hot glue gun. Within a specified period of time, each team built a model bridge to span a specified distance. At the end of the construction period, we placed each bridge into a hydraulic testing machine and loaded it to failure, to determine its strength. The bridge with the highest strength-to-weight ratio was declared the winner, and the students who created the winning structure received a nice trophy.

By all accounts, the event was a great success. A large number of students from several different high schools participated, and the inter-school rivalry helped to generate the sort of excitement I normally associate with a championship basketball game. The students certainly enjoyed themselves, and their teachers praised both the content and organization of the contest. Based on the unanimously positive feedback, we concluded that we had accomplished our goal. We had indeed introduced participants to the exciting, creative world of engineering.

Only after the event was over did I begin to question the value of our bridge-building contest. What had the students actually *learned* about engineering from the contest? After much soul-searching, I had to admit that the answer was "not much." Based on what our student participants actually *did* in the contest, they could only have learned three things:

- Engineers build bridges.
- Engineers test structures by loading them to failure.
- Engineers design bridges for maximum strength-to weight ratio.

Unfortunately, all three of these notions are quite wrong; yet they are perpetuated by virtually every model bridge-building project I have ever seen.

The essence of engineering is *design*. Engineering design entails the application of math, science, and technology to create something that meets a human need. The engineering design process is, at the same time, both systematic and creative. And the engineering design process is always iterative: engineers must explore many different alternatives before they can hope to achieve an optimum solution. These are the essential characteristics of engineering; yet our bridge-building contest communicated *none* of these characteristics to the student participants.

- Our students never actually *designed* their bridges. Some simply glued popsicle sticks together without forethought. Others drew sketches before they started building, but their sketches were based on nothing more than vague ideas of what a bridge should look like. We gave participants no basis to decide what might make a bridge design effective or efficient.
- Our students did not apply math or science, nor did we show them any evidence that math and science could have been used to design their bridges more effectively.
- Our students never experienced the iterative nature of design. They built a bridge and broke it—precisely one iteration. They had no opportunity to assess how well the design worked, make appropriate modifications, and test the validity of those modifications in subsequent design iterations.
- We gave our students a totally unrealistic standard for success—maximum strength-to-weight ratio, determined by testing the structure to failure. Engineers design actual structures to *stand up*, not to fail. Actual structures are generally designed to carry a *specified loading* safely, at minimum cost. Actual structures are *never* designed for maximum strength-to-weight ratio. If they were, then a 10-ton bridge that can safely carry a 10-ton load would be just as good as a 50-ton bridge that can carry a 50-ton load. But these two bridges are not equally safe. If you don't believe me, try driving a 20-ton truck across each one.

At the end of the day, our bridge-building contest provided little or no opportunity for students to learn what engineering is or what engineers do. However, it did have one positive impact: it convinced me that there must be a better way.

About the West Point Bridge Designer

I developed the West Point Bridge Designer software in direct response to the inherent limitations of the traditional model bridge-building project. When a student uses the Bridge Designer, he or she designs a real bridge, not a model. The design uses real structural materials, not Popsicle sticks, balsa wood, or pasta. The "simulated load test" is based on a realistic truck loading and actual principles of structural mechanics. More important, the basic design paradigm is realistic. With the West Point Bridge Designer, a bridge must be designed to carry a fixed, code-specified loading safely and at minimum cost. No more maximum strength-to-weight ratio! And the computer simulation provides a reasonably accurate representation of the iterative nature of design. The student is free to explore a nearly limitless range of alternative designs and to observe the cause-effect relationships between design changes and subsequent structural performance. A student who designs a bridge with this software experiences a reasonably authentic simulation of the engineering design process.

Since I first made the West Point Bridge Designer available on the worldwide web three years ago, the response from teachers, students, and engineering practitioners has been overwhelmingly positive and enormously valuable. Many teachers, in particular, have provided insightful suggestion for making the Bridge Designer a more valuable educational tool. I have incorporated these recommendations into subsequent software releases whenever it was feasible to do so.

It is important for me to acknowledge up front that the West Point Bridge Designer also has some serious limitations as an educational tool. It can easily contribute to an unhealthy reliance on the computer as the unquestioned source of the Right Answer. In a sense, it is a "black box"—a computer tool that students can use without really understanding the principles on which the tool is based. Most importantly, the Bridge Designer is only a simulation. Civil engineering involves lots of physical things, like steel, concrete, and soil; and lots of physical concepts, like force, load, and strength. Yet the Bridge Designer provides no opportunity for students to work with any physical object beyond the computer mouse.

These limitations are significant; yet I believe they can be largely overcome by providing appropriate context—by integrating the software into math, science, or technology instruction in a rigorous and meaningful way. This book is intended to help you do it.

About this Book

Many teachers saw the need for this book long before I did. Soon after the West Point Bridge Designer was released, they began asking for information to help integrate the software into their math, science, and technology curricula. With amazing consistency, they asked these two questions:

- How does the software actually analyze a bridge, and how can I teach these mathematical and scientific principles to my students?
- How can my students use the West Point Bridge Designer in conjunction with a hands-on model bridge-building activity?

These requests reflect admirable educational goals. The first seeks to use a practical application as the basis for teaching fundamental principles, the second to connect the design process to the creation of a physical product. These requests provided the inspiration for this book and have guided its development from start to finish.

The purpose of this book is to provide students with an opportunity to learn how engineers use math, science, and technology to design real structures. The book is composed of five separate but closely integrated learning activities. Students who do all five will:

- design, build, and test model bridges;
- use an authentic engineering design process to develop their designs;
- apply math, science, and computer technology as problem-solving tools;
- learn how real bridges are designed and built; and
- learn how real truss bridges work.

This book is necessarily rigorous. Consistent with its purpose, it includes many of the mathematical and scientific concepts that engineers use to analyze and design real structures. I have attempted to present these concepts in their simplest possible form; nonetheless, many students will find them to be quite challenging. And that's good! In my own experience, presenting students with a tough challenge is a powerful way to motivate them to learn.

Many books that introduce students to engineering contain no math at all. A number of these books are wonderfully written, and they all serve an important purpose. Nonetheless, I sometimes wonder if the total exclusion of math from an introductory engineering book doesn't send some students an unhealthy message: *engineering is interesting, but the math behind it is too hard for you to understand*. In this book I have tried to send a different message: *engineering is interesting, and the math behind it is challenging but achievable*.

I should add that every math and science concept presented herein has a direct, practical application in one or more of the five learning activities. Thus, students who do the learning activities in a thoughtful way will also receive an important message about the relevance of math and science in our world.

Overview of the Learning Activities

The five learning activities are as follows:

- ***Learning Activity #1: Build a model of a truss bridge.*** In this activity, we will build a model bridge from cardboard file folders. The bridge has already been designed, and accurate drawings and fabrication instructions are provided. Through this activity, students will learn bridge terminology, construction techniques, and some basic concepts in physics and structural engineering. Students do not need any special knowledge of math or science to do this activity.
- ***Learning Activity #2: Test the strength of structural members.*** In this activity, we will use experimental testing to determine the strength of structural members made of file folder cardboard—the same stuff we used to build our bridge model in Learning Activity #1. The data obtained from these tests will be used extensively in Learning Activities #3 and #5. Students will learn some basic concepts from engineering mechanics, as well as procedures for designing and conducting experiments. To do this activity, students need only basic arithmetic skills and the ability to create a graph. The ability to use a spreadsheet program is helpful but not required. This activity requires the use of a simple wooden testing device. Instructions for building the device are included in Appendix C.
- ***Learning Activity #3: Analyze and evaluate a truss.*** Here we will calculate the internal member forces in our model truss bridge. We will then evaluate the structural safety of the truss by comparing these calculated forces to the member strengths we determined experimentally in Learning Activity #2. Through this activity, students will learn more advanced concepts from physics and engineering mechanics. Students need to apply geometry, algebra, and trigonometry to do the activity successfully. A review of key concepts from trigonometry is included; however, students who have not yet learned geometry or algebra will not be able to do this project.
- ***Learning Activity #4: Design a truss bridge with a computer.*** In this activity, we will design a full-scale highway truss bridge using the West Point Bridge Designer software. The design process includes working through multiple iterations to ensure that the structure will carry the prescribed loads safely and at minimum cost. Through this activity, students will learn the engineering design process and will have an opportunity to reinforce many of the basic structural engineering concepts learned in earlier activities. This activity also includes an overview of how actual bridges are designed and built. Students do not need any special knowledge of math or science to use the West Point Bridge Designer.

Why cardboard?

At first glance, cardboard from manila file folders might seem an odd material to use for bridge-building projects. But in fact, I have found it to be far superior to the more traditional model bridge-building materials—balsa wood, popsicle sticks, toothpicks, and pasta.

Here's why:

- File folders are readily available and very inexpensive.
- Cardboard is easy to work with. It can be easily folded, cut with a scissors, and glued with common household adhesives.
- The behavior of cardboard as a structural material is surprisingly predictable.
- Cardboard provides the capability to build two fundamentally different kinds of structural members—hollow tubes and solid bars. Understanding how these two types of members work is an important part of understanding structural engineering.
- Cardboard provides the capability to build connections that are stronger than the members they join together. I can't overstate the importance of this characteristic. Throughout this book, we will learn how to design structural members so that they are strong enough to carry load safely. But a well-designed member is of little use if its connections fail before the member itself does. A chain is only as strong as its weakest link. If you've ever built and tested a truss bridge made of balsa wood or Popsicle sticks, you know that these structures almost always fail at the connections. As a result, their load-carrying capacity is less than it could be and, more importantly, is almost impossible to predict analytically.

So head for the supply closet; grab a stack of file folders; and let's build some bridges.

- ***Learning Activity #5: Design and build a model truss bridge.*** Here we will apply what we have learned in the previous four activities to design, build, and test a model truss bridge. Students should have completed Learning Activities #1, #2, and #3 to do this project successfully; however, if they do not have adequate math background to complete Learning Activity #3, they can bypass the mathematical structural analysis by using the Gallery of Structural Analysis Results provided in Appendix B. The gallery presents a complete set of computed analysis results for a variety of different truss configurations.

A Gallery of Truss Bridges—a compendium of photographs showing actual truss bridges from all over the United States—is also provided in Appendix A. The gallery is used as part of several learning activities and is also intended to provide students with a resource for ideas about their own bridge designs.

Also included is a Glossary (Appendix D), which provides definitions for mathematical, scientific, and engineering terms used throughout the book. The first appearance of any Glossary term in the text is highlighted in **bold** type.

Organization of Each Activity

This book is organized in a *problem-based learning* format. Each learning activity is presented as a problem to be solved. Information pertinent to the problem solution is provided "just in time"—mathematical, scientific, and technological concepts are included within the specific learning activities in which they are applied. Each activity has a set of learning objectives, which students achieve by (1) working through the problem solution and (2) answering questions that are intended to stimulate critical thought about key concepts.

Each learning activity is organized into the following sections:

- **Overview of the Activity.** This section provides a brief description of the learning activity.
- **Why?** This section explains why the activity is worth doing and how it relates to previous and subsequent learning activities.
- **Learning Objectives.** This section lists the specific knowledge and skills that students can be expected to gain from thoughtful completion of the activity.
- **Information.** This section provides background information pertinent to the activity. In most cases, students would probably be able to complete the activity successfully without this information; however, it is unlikely that they will really learn from the activity without the context that this information provides. For example, a student can certainly build a model bridge without understanding the terms *tension* and *compression*; however, it is highly unlikely that the student will really learn anything meaningful about how structures are designed without some appreciation for these terms.
- **The Problem.** This section presents a fictitious scenario describing a *need* and the student's role in devising a solution that satisfies the need.
- **The Solution.** This section guides the student through the planning and conduct of the problem solution, step by step. At appropriate points throughout the solution, questions are posed, as a means of stimulating critical thinking about important aspects of the project.
- **Answers to the Questions.** Here answers to the critical thinking questions from the preceding section are provided. This section always starts on a new page, so that the teacher can conveniently provide students with copies of the preceding six sections, without revealing the answers to the critical thinking questions.
- **Ideas for Enhancing the Activity.** This final section provides suggestions for enriching or extending the students' learning experience in the activity.

Of these eight sections, the first six should be provided to the students to guide their participation in the learning activity. The seventh—Answers to the Questions—can be provided to students at the end of the activity, if the teacher chooses to do so. The eighth section is intended solely for the teacher.

Some Simpler Bridge-Building Activities

For the teacher who would prefer to do simpler, more qualitative structural engineering activities, there are a number of excellent references available. These include:

Johmann, Carol A. and Elizabeth J. Rieth. ***Bridges! Amazing Structures to Design, Build, and Test.*** Charlotte, Vermont: Williamson Publishing, 1999. *(For ages 7-14.)*

Kaner, Etta. ***Bridges.*** Toronto: Kids Can Press, 1997. *(For ages 8-12.)*

Pollard, Jeanne. ***Building Toothpick Bridges.*** Palo Alto: Dale Seymour Publications, 1985. *(For ages 5-8.)*

Salvadori, Mario. ***The Art of Construction.*** Chicago: Chicago Review Press, 1990. *(For ages 10 and up.)*

WGBH Educational Foundation. ***Building Big Activity Guide.*** Boston: WGBH Educational Foundation, 2000.

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I am deeply indebted to many people for their invaluable contributions to this book. Colonel Kip Nygren, Head of the Department of Civil and Mechanical Engineering at the U. S. Military Academy, first suggested that a book of learning activities might be an appropriate way to reinforce the educational value of the West Point Bridge Designer software. Mr. Brian Brenner, Dr. Mark Evans, and a team of civil engineers from Parsons Brinckerhoff provided invaluable input to the description of bridge design in Learning Activity #4. Ms. Cathy Bale reviewed the manuscript, provided insightful recommendations for improvement, and did the myriad coordination tasks necessary to get the book into production. The American Society of Civil Engineers (ASCE) provided funding to support the development of the book, and ASCE's Managing Director of Education, Dr. Tom Lenox, was a constant source of guidance, encouragement, and feedback throughout the project. While the book was still being written, Dr. Doug Schmucker used draft versions of Learning Activities #1 and #2 as the basis for a project in his Materials Engineering course at Valparaiso University. Doug and his students provided thoughtful feedback about the book at a very critical time in its development. Many of the photographs in Learning Activity #1 were taken by Mr. Mike Doyle. Finally, the bridge photographs used for each chapter heading were provided by Mr. Jet Lowe of the National Park Service.

Colonel Stephen J. Ressler
West Point, New York
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For Claire and Anne.