Engineering Iron and Stone

Understanding Structural Analysis and Design Methods of the Late 19th Century

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This book is affectionately dedicated to
Colin Bertram Brown
1929–2013

But O for the touch of a vanish'd hand,
And the sound of a voice that is still!
Alfred, Lord Tennyson

Preface

This book stems from a career-long interest in understanding how structural engineers worked in the past. Although we admire the great works of Roman engineering and the medieval cathedrals of Europe, we tend to think that modern engineering is somehow superior to the engineering that produced these structures. The premise of this book is that, for all its evident differences, modern engineering cannot claim superiority to the engineering of any period in the history of civilization. That contemporary engineering is based on a different mindset and a different set of values from the work of any of these other periods is evident. But the works that appeared in the engineering of other periods are not reproducible by contemporary methodology: each age defines its own artifacts and its own ways of producing these artifacts.

The late nineteenth century is a particularly significant time for understanding contemporary engineering: Although nineteenth-century engineering is different from modern engineering in the sense described, this period is closely related to the present time. Although Roman and medieval engineering are defined primarily by experience-based procedures, they are somewhat informed by emerging ideas from speculative science. By the nineteenth century, however, ideas of science were sufficiently advanced, and ideas about the role of science in society, such as positivism, were sufficiently widespread that engineers began to think of themselves as scientists of a sort and began to think that they were responsible for applying scientific procedures to constructed works.

A particularly interesting feature that emerged from the study of nineteenth-century engineering methods was the efficiency and accuracy of some of the procedures employed, as compared with the way we accomplish these tasks in the present age. Particularly in truss design, both analytical and graphical, most of the procedures employed in the nineteenth century appear to be more efficient than those that we teach to students in contemporary engineering programs. The reliance on graphical methods, especially for trusses and arches, is particularly revealing of the late nineteenth-century mindset and does influence the actual form of the structures.

In preparing this book I tried to focus on ordinary procedures used to design and construct ordinary works without placing emphasis on the exceptional engineering works that mark this period. Thus, although the reader can find references to the design of major works, most of the discussions in this book describe smaller works and the significant body of engineering design that went into their construction.

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Contents

Introduction

This book concerns the methods used for structural engineering design in the late nineteenth century. Even as the opportunities for business, industry, and transportation were expanding during this time, the methods of the civil engineering and the structural engineering professions were also expanding, in part to meet the demands of the expansion of industry. The intent of the present book is to capture, through investigation of writings, archival evidence, and examination of built works, the methods of structural design of bridges and buildings in the period from 1870 through 1900, roughly, the period known to historians as the Gilded Age (1865–1893). The value of this exercise is three-fold. First, understanding the intent of the designer is the key to a successful rehabilitation, whether architectural or structural. Second, the preservation of design methods for historic structures is at least as important as the preservation of the structures themselves. Third, many of the methods used in structural design in the late 1800s are valuable in their own right—quick, computationally efficient, understanding of the behavior of the structure, and often giving special insight into the actual performance of the structure.

In undertaking the historic preservation of structures from the late nineteenth century, understanding design intent is important—the way that a bridge or building was designed and the way that the elements of the structure were intended to function. Too often in historic preservation projects, we overlook the designer's conception of the structure and impose a modern outlook on the structure, with the result that significant historic fabric is removed unnecessarily. One of the most widespread misunderstandings concerning historic structures is the idea that the older structures were designed for lighter loading than modern-day structures. In fact, road bridges were designed for deck loads of up to 100 lbs/ft^2 (see, for instance, Waddell 1894); the 1,000 lb/ft on a 10-ft lane dictated by this loading is well above the lane loading requirements of AASHTO HS-20 (AASHTO 2013). Extraordinary vehicles, such as freight drays and road rollers, imposed very heavy loads on bridges. A passage of a steamroller is illustrated in the photo of the circa 1890 opening of the St. Mary's Street Bridge in San Antonio, TX (Figure I-1). Equally important is understanding in exactly what way nineteenth-century bridge design may have differed from modern design. Although most bridge decks do meet the AASHTO uniformly distributed lane load requirement, few nineteenth-century bridge designers imposed limits on the concentrated loads that the bridge could resist. A distributed load of 100 lbs/ft^2 placed to create maximum force in each member was usually the only loading requirement. As a result, focusing attention on the floor system of a bridge under rehabilitation is more important than on the main load-carrying system, such as truss, girder, or suspension cable.

Building floor loads used in the nineteenth century were similar to those used today. However, the approach to wind loads on buildings was very different. Because much heavier roof structures were present, uplift of the roof structure generally was not considered to be a design issue, although the possibility of wind loads causing a force reversal in a web member of a truss was considered by applying wind pressure to the windward side of a roof and by removing all load from the lee side.

Although the primary intent of this book is simply to present the methods of late nineteenth-century structural design and to recognize the inherent truth, simplicity, and value

Figure I-1. Opening of St. Mary's Street Bridge, San Antonio, TX, circa 1890.
Source: Reproduced by permission of the Huntington Library, San Marino, CA.

of these methods, greater sympathy and understanding for the methods by which a structure was designed may follow directly from the review of these methods. For all the merit of contemporary engineering analysis, it is worth considering from the outset that the designers of the original structure probably knew what they were doing. In evaluating the notion that many shorter span masonry bridges were designed empirically, understanding the success of this design method for structures of this type is important. Some of the most admired and most enduring masonry structures in the world also were designed empirically, whereas, conversely, contemporary structural analysis is not always able to explain the behavior of these structures. A frequent response of contemporary engineers in rehabilitation projects involving masonry bridges is to find the structure deficient by some form of modern structural analysis or to declare it "unrateable" and in need of reinforcement by saddling the arch or installing internal anchors. This response may be appropriate in a few cases, but it needs to result from a positive determination of why the structure is deficient, including the contradiction of the original designers' findings that this was an appropriate design, for instance, clear evidence of scour or formation of hinges in the arch ring. To say that the bridge was designed for horses and buggies is incorrect; bridge decks in urban settings usually were designed for loads of 100 lbs/ft^2, a load appropriate to the heavy vehicles that were in use at the time.

Similar arguments apply to building structures. An examination of contemporary documents reveals that the live loads in widespread use were greater than the loads used in design in contemporary codes and that the safety factors generally were greater. The underlying assumption of a rehabilitation effort could be that the original designers had it right.

Although significant recent attention has been directed toward the preservation of bridges and buildings, the ideas that are reflected in the design of a historic structure also merit preservation. For the reasons described herein, it is important that we retain the ability to understand a structure from the same viewpoint as a nineteenth-century engineer. The methods presented in this book have intrinsic value, that is, they are interesting on their own account. The methods also have comparative value: comparing the methods presented here with contemporary methods is a useful exercise. As an example, consider the Rankine-Gordon formula for column capacity (Chapter 9). This formula has a firm basis in reason, calculating the residual axial force capacity for an eccentrically loaded column. As such, it considers eccentricities without introducing the idealization of a perfectly straight, perfectly concentrically loaded column and the three curves (yield, Euler Buckling Theory, and interpolation) necessary to draw a complete column curve according to either the AISC (2011) specification for steel or the *National Design Specification for Wood Construction* (American Wood Council 2006). The methods presented in this book also have pedagogical value as an accompaniment to the current building codes and standards: it is useful to provide students with alternative means of achieving the same ultimate objective, which is to build worthy structures. This book is intended as an initial step toward the preservation of these ideas, in addition to preserving the structures themselves.

Finally, the methods outlined in this book may, in some cases, be superior to the methods used in contemporary practice. The rapidity of computation and the intimate relation between the structure and its analysis present in early methods of analysis have been lost by the numerically intensive analytical methods employed in the present. In the graphical analysis of a load-carrying structure, for instance, the forces acting on a structure, the bending moments, and a suitable shape for the structure can be inferred from a single diagram. The flow of forces through a truss under variable loading can be immediately understood using some of the analytical methods for trusses that the book will explore. Some of the historic computation methods also depend on an ability to visualize the transmission of forces through a structure that is not evident in the application of computer-based methods of analysis. In particular, graphic analysis is practically a concurrent method of analysis and design in which a diagram of the paths of load resistance in a structure is created.

Modern methods of analysis are based on increasingly precise computations, where efficiency is unnecessary because the computer is the primary calculating instrument. Because of the difficulty of computations in the late nineteenth century, methods from this period show an economy of calculation that could significantly benefit modern engineering. A few of these calculation methods are described in Chapter 5.

Sources of Information

The principal source of information for this book is the textbooks of the period. A very great number of very useful textbooks have been made available as free books on Google .com or HathiTrust.com. The most useful books have been the design manuals, such as Kidder's *Architects' and Builders' Pocket-Book*, or Trautwine's *The Civil Engineer's Pocket-Book*. Additionally, several catalogs have been consulted. Various other academic source materials are available and have been very useful to the development of this work. Engineering professors often mimeographed and bound their course notes, and some of these materials remain available in libraries throughout the country. Notable among these is George Fillmore Swain's notes, while the notes of Augustus Jay Du Bois and Charles Crandall also have been consulted. The records of the Berlin Iron Bridge Company, mostly available at the Huntington Library in San Marino, CA, also have been found to be very revealing of contemporary ideas of bridge and building design. Almost all of the published textbooks cited at the end of each chapter in this work are also available as free eBooks on Google .com or HathiTrust.com.

Many images have been obtained from the online material available in the Library of Congress's collection of Historic American Buildings Survey/Historic American Engineering Record (HABS/HAER) measured drawings and photographs. The catalog number is given in the caption for each of these images. The search box for this catalog can be found at http://www.loc.gov/pictures/collection/hh/.

Organization and Format of the Book

This book is divided into three major sections covering the three major types of design practiced in the nineteenth century: empirical, analytical, and graphical. Empirical rules for engineering fall generally into three classes. The first type of empirical rule is practice based, that is depending on precedent without further consideration. Contemporary examples of this type of rule include the application of span/depth rules. These methods particularly apply to the design of masonry arches, which is described in Chapter 2. A second class of empirical rule is a rational analysis that is abbreviated and used to develop rules to be applied to the design of specific structures. Examples of this practice are Hatfield's rules, described in Chapter 3. Chapter 4, describing the empirical design of metal structures, contains several results of column tests curve-fitted to the development of semiempirical formulas of the third class.

The following section of the book describes analytical procedures for design. Unlike the previous section, this section is divided by type of structure: the subject of Chapter 6 is the analysis of arches in masonry or iron and steel. Chapter 7 covers the analytical methods used for trusses in wood or iron, applied to building structures, highway bridges, and railroad bridges. The topic of Chapter 8 is analytical methods for the design of beams and girders, including continuous girders, whereas Chapter 10 describes the developed methods for the analysis of portal frames, which can be extended to more general frames.

Finally, the book describes the highly evolved methods of graphic analysis used during this time period. Chapter 11 is an introduction to graphical analysis to give the reader the opportunity to study the terms used and the general methods used in graphical analysis. The analysis method can be applied to arches, beams, and frames, and includes refined developments in geometry. Chapter 12 covers the graphical analysis of trusses, Chapter 13 is about the graphical analysis of arches, Chapter 14 concerns the graphical analysis of beams, and Chapter 15 describes the graphical analysis of portal frames and is comparable to the analytical methods presented in Chapter 10.

In the concluding Chapter 16, the influence of analysis and design methods on the design outcome is investigated. The remainder of the chapter consists of a case for the preservation of the methods of analysis of the late nineteenth century.

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