Design Paradigms

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Case Histories of Error and Judgment in Engineering

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To
William Petroski, P.E.,
brother engineer

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Preface

Possibly the greatest tragedy underlying design errors and the resultant failures is that many of them do indeed seem to be avoidable, yet one of the potentially most effective means of improving reliability in engineering appears to be the most neglected. Historical case studies contain a wealth of wisdom about the nature of design and the engineering method, but they are largely absent from engineering curricula, perhaps because the state of the art always seems so clearly advanced beyond that of decades, let alone centuries or millennia, past. However, the state of the art is often only a superficial manifestation, arrived at principally through analytical and calculational tools, of what is understood about the substance and behavior of the products of engineering. Anyone who doubts this assertion need only look to the design errors and failures that occur in the climate of confidence, if not hubris, known as the state of the art.

The fundamental nature of engineering design transcends the state of the art. Thus it follows that historical case studies that illuminate those aspects of conceptualization, judgment, and error that are timeless constants of the design process can be as important and valuable for understanding technology and its objects as are the cal-

culus or the latest computer software. The lessons of the past are not only brimming with caveats about what mistakes should not be repeated but also are full of models of good engineering judgment.

This book argues for a more pervasive use of historical case studies in the engineering curriculum. There are several direct benefits and cultural byproducts to be derived from such use: the patterns of success and failure that have manifested themselves in engineering for centuries are made explicit and readily available for extrapolation; the lessons learned by our professional ancestors can be kept high in the consciousness of succeeding engineering generations; an awareness of the timeless elements of the engineering method and their commonality across ostensibly disparate specialties can give a theoretical foundation to the engineering curriculum that students often find wanting; a common store of case histories and anecdotes can serve as a lingua franca among the various engineering fields that will emphasize their similarities; and, finally, engineering students can be made more aware of the roots of their profession and its relationship to society.

The objective of this book is not only to present a model for explaining how errors are introduced into the design process but also to provide a means by which practicing designers may avoid making similar errors in their own designs. The use of pithy and classic anecdotes set in familiar design situations is an excellent means for abstracting general principles while at the same time providing unifying themes and useful lessons that will be remembered. But it would not serve the intention of this work merely to relate a long list of familiar and hackneyed stories about classic engineering failures, such as the Leaning Tower of Pisa or the Tacoma Narrows Bridge. Already well-known case studies cannot in themselves necessarily help us to reach new conclusions about design or to eliminate errors in design generally.

What can both teach us about design and improve our practice of it is a carefully selected group of case histories or studies that illuminate different, even if often overlapping, aspects of the design

process and that thus serve as paradigms for both theory and practice. To be effective as a paradigm of error, a particular case study not only must be capable of being presented as a fresh and memorable story (or at least a familiar story told from a fresh perspective) but also must be capable of evoking a host of related case studies or horror stories in a wide variety of engineering contexts and disciplines, thus demonstrating how over time the same or similar mistakes have led to repeated failures of design. If a paradigmatic case study can do this, then it is likely to embody a general principle of design error that can also arise in new design situations. Thus the paradigm will have the dual value of providing a guide for understanding the design process as well as presenting a means of improving it by alerting the designer to common pitfalls in design logic.

The anecdotal nature of the paradigms presented in this book is intended to evoke associations with the real situations in which human designers necessarily find themselves every day. The guiding principle has been to select, explicate, and validate a group of paradigms that illustrate forcefully how certain types of errors can be introduced into or avoided in various aspects of the design process. However, this collection of paradigms is not intended to constitute a unique, distinct, exhaustive, or definitive classification of design errors, but rather to show the efficacy of the approach.

Some more recent examples of engineering failures have been included to emphasize that the construction of a historically based paradigm is not just a scholarly exercise, but one that is relevant today and will remain relevant for avoiding error in engineering designs of the twenty-first century. If persuasive paradigms and instructive case histories can be multiplied and disseminated in an effective way, there is reason to believe that they can become as important a part of the designer's intellectual tool kit as are laws of mechanics, rules of thumb, and computer models.

This book is intended not only for engineering students; practicing engineers may find it a different perspective on their profession, and general readers interested in gaining some insight into the en-

gineering method might find it a painless introduction to the subject. Since the book's concrete case histories and lessons are intended to be accessible to engineering students and practitioners from all fields and at all levels, as well as to the general reader, jargon has been eschewed and equations have been all but eliminated. Thus the reader need bring no prerequisites to the book other than a mind open to the idea that what engineers were doing in times past has some relevance to what engineers do today.

The work leading up to this book was made possible in part by a grant from the National Science Foundation, for which I am grateful. Several of the chapters have been adapted from refereed articles, which I have published in the following journals: *Journal of Engineering Design* (Chapter 1), *Research in Engineering Design* (Chapter 2), *Journal of Mechanical Design* (Chapter 3), *Structural Safety* (Chapter 4), *Civil Engineering Systems* (Chapter 5), *Structural Engineering Review* (Chapter 7), and *Journal of Performance of Constructed Facilities* (Chapter 8). Much of Chapter 6 is scheduled to appear in *Civil Engineering,* and most of the ideas in Chapter 10 appeared first in my engineering column in *American Scientist.* Helpful comments of anonymous reviewers and the editors of these publications have often made these chapters more focused, but any errors that remain are naturally artifacts of my own humanity.

This manuscript, like most of my recent work, was first drafted in the carrel kindly assigned to me by Albert Nelius in the William R. Perkins Library of Duke University. While I am, as always, indebted to many librarians, both at Duke and throughout the interlibrary loan network, I must once again single out for special acknowledgment and praise Eric Smith of Duke's Aleksandar S. Vesić Engineering Library. His knowledge and help have been indispensable. As always, my wife, Catherine, has understood my need to retreat to my study at home and remains my fairest reader.