

DESIGN OF HIGHWAY BRIDGES

An LRFD Approach

THIRD EDITION



Richard M. Barker and Jay A. Puckett

Up-to-date coverage of bridge design and analysis— revised to reflect the fifth edition of the AASHTO LRFD specifications

Design of Highway Bridges, Third Edition offers detailed coverage of engineering basics for the design of short- and medium-span bridges. Revised to conform with the latest fifth edition of the American Association of State Highway and Transportation Officials (AASHTO) LRFD Bridge Design Specifications, it is an excellent engineering resource for both professionals and students. This updated edition has been reorganized throughout, spreading the material into twenty shorter, more focused chapters that make information even easier to find and navigate. It also features:

- Expanded coverage of computer modeling, calibration of service limit states, rigid method system analysis, and concrete shear
- Information on key bridge types, selection principles, and aesthetic issues
- Dozens of worked problems that allow techniques to be applied to real-world problems and design specifications
- A new color insert of bridge photographs, including examples of historical and aesthetic significance
- New coverage of the “green” aspects of recycled steel
- Selected references for further study

From gaining a quick familiarity with the AASHTO LRFD specifications to seeking broader guidance on highway bridge design—*Design of Highway Bridges* is the one-stop, ready reference that puts information at your fingertips, while also serving as an excellent study guide and reference for the U.S. Professional Engineering Examination.

The late **RICHARD M. BARKER, PhD, PE**, was Professor Emeritus of Civil and Environmental Engineering at Virginia Polytechnic Institute and State University. Dr. Barker spent more than fifty years as a structural designer, project engineer, researcher, and teacher.

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Richard M. Barker
Jay A. Puckett

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PREFACE

The objective of the third edition is the same as the first two editions, that is, to provide the student or practitioner a meaningful introduction to the design of medium-and short-span girder bridges. However, the manner in which the material is presented has changed. Instead of the eight chapters of the second edition, the content has been spread out over twenty shorter chapters. This organization should lead to easier reading and simpler organization of classroom assignments.

To help understand how these changes have come about, it is informative to see how the process all started. It was in August 1990 that the two authors were at an International Conference on Short and Medium Span Bridges in Toronto, Canada, where both were presenting papers. They had often met at these bridge conferences and were familiar with each other's work—Puckett's on analysis and software development and Barker's fundamental application of LRFD to geotechnical materials. Both were classroom teachers in structural engineering.

At the time, a number of major changes were taking place in the design of highway bridges. Philosophically the most dramatic was the change from a deterministic (allowable stress) design approach to a probabilistic (limit state) design concepts. The other big change was a government edict that highway bridges that were built with federal dollars had to be constructed and designed in the metric system starting in 1997.

The timing was right for a comprehensive textbook on the design of highway bridges. The American Association of State Highway and Transportation Officials (AASHTO) were in the midst of a complete rewriting of their Bridge Design Specifications in a LRFD format. Finite-element analysis tools had matured, truck loads were better understood through weigh-in-motion studies, material behavior was being unified for prestressed and non-prestressed concrete by the American Concrete Institute (ACI), post-buckling strength of plate girder webs and fatigue strength of weld details were better understood.

The two professors decided that someone needed to write a textbook to present these changes to students and practicing

civil engineers. So over dinner and a major league baseball game, they realized they could be the ones to do the writing. Puckett took his sabbatical with Barker at Virginia Tech in 1993, they wrote trial chapters, prepared a proposal that was accepted by John Wiley & Sons, and the first edition with ten chapters was published in 1997.

It was not long before the metric system requirement was dropped and the highway bridge designers needed a textbook written in U.S. Customary Units. Therefore, it became necessary to make revisions and to prepare a second edition of the book. Besides the units change, the LRFD specifications were in their third edition and the textbook needed to be updated. As new material was added, the number of pages was deemed too large and two chapters were dropped—Wood Bridges and Substructure Design. These two topics are found only in the metric system units of the first edition.

The remaining eight chapters of the second edition have been divided into four parts: General Aspects of Bridge Design (Chapters 1–7), Loads and Analysis (Chapters 8–12), Concrete Bridges (Chapters 13–16), and Steel Bridges (Chapters 17–20). Another change in the layout of the third edition is the addition of an insert of mainly color bridge photos. These photos have been selected to illustrate bridges of historical significance; the ones most aesthetically pleasing that are most beautiful in their surroundings, and noteworthy as the longest, tallest, or highest bridges of their type.

We suggest that a first course in bridges be based on Chapters 1–7 with Chapters 5, 6, and 7 compulsory reading. Loads and analysis should follow with required reading in Chapter 8 and selected portions of Chapter 9 and 10 depending upon the students' background and instructor's interest.

Design can be addressed with either the chapters on concrete (Chapters 13–16) or those on steel (Chapters 17–20). Instructor guidance is required to lead the student through these chapters and to address the topics of most interest. For example, concrete bridges could be addressed with nonprestressed bridges which would simplify the topic. However, teaching prestressed concrete within a bridge context could be an excellent way for students to gain

broad-based knowledge in this area for both bridges and buildings. Similarly, teaching design using the steel chapter leads to a general knowledge of composite cross sections, staged construction, and plate girders. As the associated principles are common with buildings and bridges, again the bridge course can be used within a broader context.

How much of the material to present to a particular class is at the discretion of the professor, who is the best person to judge the background and maturity of the students. There is enough material in the book for more than one course in highway bridge design.

Practitioners who are entry level engineers will find the background material in Chapters 1–12 helpful in their new assignments and can use Chapters 13–16 and 17–20 for specific guidance on design of a particular bridge type. The same can be said for seasoned professionals, even though they would be familiar with the material in the loads chapter, they should find the other chapters of interest in providing background and design examples based on the AASHTO LRFD specifications.

Finally, those practitioners who just appreciate bridge history and aesthetics might find those chapters of interest from a personal enjoyment perspective. Bridges are art and so many are simply beautiful.

ACKNOWLEDGMENTS

We would like to recognize those who have made the production of the third edition possible. The first person to be acknowledged is the editorial assistant at John Wiley & Sons who prepared a twenty chapter manuscript from the contents of the eight chapters of the second edition. This reorganized manuscript became the working document that the authors could edit and assign correct numbers to equations, figures, and tables.

To accompany the description of the I-35W Bridge collapse, the new figures drafted by Philip Jennings, a structural engineering graduate student at Virginia Tech, are gratefully acknowledged. Thanks also to the following state departments of transportation who supplied photographs of their bridges: Arizona, Colorado, Washington State, and West Virginia. The authors appreciate the computer modeling and project photos provided by Julie Smith of the FIGG Engineering Group.

The patience, understanding, and support shown us by Jim Harper, Bob Argentieri, Dan Magers, and Bob Hilbert at John Wiley & Sons, especially during the time of the senior author's health issues, are greatly appreciated.

Finally, we wish to thank Marilyn Barker and Kathy Puckett for their continued patience and strong support during our time of writing.

The authors would appreciate it that if the reader should have questions or if errors are found you would contact us at puckett@uwyo.edu.

PERSONAL ACKNOWLEDGMENT TO RICHARD BARKER

I wish to recognize and thank Rich for his career of achievement in teaching, learning, research, and practice in bridge engineering, and most of all sharing it with me. Rich has made a tremendous difference to the professional lives of so many students and colleagues. I will be forever grateful for his friendship, guidance, selfless and thoughtful approach from which I have benefitted and learned so very much.

Rich was a professional in every sense of the term.

Happy trails, Rich.

Jay Puckett
Laramie, Wyoming

PREFACE TO THE SECOND EDITION

This book has the same intent as the first edition and is written for senior-level undergraduate or first-year graduate students in civil engineering. It is also written for practicing civil engineers who have an interest in the design of highway bridges. The objective is to provide the reader a meaningful introduction to the design of medium- and short-span girder bridges. This objective is achieved by providing fundamental theory and behavior, background on the development of the specifications, procedures for design, and design examples.

This book is based on the American Association of State Highway and Transportation Officials (AASHTO) LRFD Bridge Design Specifications, Third Edition, and Customary U.S. units are used throughout. The general approach is to present theory and behavior upon which a provision of the specifications is based, followed by appropriate procedures, either presented explicitly or in examples. The examples focus on the procedures involved for a particular structural material and give reference to the appropriate article in the specifications. It is, therefore, suggested that the reader have available a copy of the most recent edition of the AASHTO LRFD Bridge Design Specifications.

The scope is limited to a thorough treatment of medium- and short-span girder bridges with a maximum span length of about 250 ft. These bridge structures comprise approximately 80% of the U.S. bridge inventory and are the most common bridges designed by practitioners. Their design illustrates the basic principles used for the design of longer spans. Structure types included in this book are built of concrete and steel. Concrete cast-in-place slab, T-beam, and box-girder bridges and precast-prestressed systems are considered. Rolled steel beam and plate girder systems that are composite and noncomposite are included.

Civil engineers are identified as primary users of this book because their formal education includes topics important to a highway bridge designer. These topics include studies in transportation systems, hydrodynamics of streams and channels, geotechnical engineering, construction management, environmental engineering, structural analysis and

design, life-cycle costing, material testing, quality control, professional and legal problems, and the people issues associated with public construction projects. This reference to civil engineers is not meant to exclude others from utilizing this book. However, the reader is expected to have one undergraduate course in structural design for each structural material considered. For example, if only the design of steel bridges is of interest, then the reader should have at least one course in structural analysis and one course in structural steel design.

Chapter 1 introduces the topic of bridge engineering with a brief history of bridge building and the development of bridge specifications in the United States. Added to the second edition is an expanded treatment of bridge failure case histories that brought about changes in the bridge design specifications. Chapter 2 emphasizes the need to consider aesthetics from the beginning of the design process and gives examples of successful bridge projects. Added to the second edition are a discussion of integral abutment bridges and a section on the use of computer modeling in planning and design. Chapter 3 presents the basics on load and resistance factor design (LRFD) and indicates how these factors are chosen to obtain a desirable margin of safety. Included at the end of all the chapters in the second edition are problems that can be used as student exercises or homework assignments.

Chapter 4 describes the nature, magnitude, and placement of the various loads that act on a bridge structure. Chapter 5 presents influence function techniques for determining maximum and minimum force effects due to moving vehicle loads. Chapter 6 considers the entire bridge structure as a system and how it should be analyzed to obtain a realistic distribution of forces.

Chapters 7 and 8 are the design chapters for concrete and steel bridges. Both chapters have been significantly revised to accommodate the trend toward U.S. customary units within the United States and away from SI. New to the second edition of the concrete bridge design chapter are discussions of high-performance concrete and control of flexural cracking, changes to the calculation of creep

and shrinkage and its influence on prestress losses, and prediction of stress in unbonded tendons at ultimate.

Chapter 8 includes a major reorganization and rewrite of content based upon the new specifications whereby Articles 6.10 and 6.11 were completely rewritten by AASHTO. This specification rewrite is a significant simplification in the specifications from the previous editions/interims; however, the use of these articles is not simple, and hopefully Chapter 8 provides helpful guidance.

The organization of the design chapters is similar. A description of material properties is given first, followed by general design considerations. Then a discussion is given of the behavior and theory behind the member resistance expressions for the various limit states. Detailed design examples that illustrate the LRFD specification provisions conclude each chapter.

We suggest that a first course in bridges be based on Chapters 1–6, either Sections 7.1–7.6, 7.10.1, and 7.10.3 of Chapter 7 or Sections 8.1–8.4, 8.6–8.10, and 8.11.2. It is assumed that some of this material will have been addressed in prerequisite courses and can be referred to only as a reading assignment. How much of the material to present to a particular class is at the discretion of the professor, who is probably the best person to judge the background and maturity of the students. There is enough material in the book for more than one course in highway bridge design.

Practitioners who are entry-level engineers will find the background material in Chapters 1–6 helpful in their new assignments and can use Chapters 7 and 8 for specific guidance on design of a particular bridge type. The same can be said for seasoned professionals, even though they would be familiar with the material in the loads chapter, they should find the other chapters of interest in providing background and design examples based on the AASHTO LRFD specifications.

ACKNOWLEDGMENTS

In addition to the acknowledgements of those who contributed to the writing of the first edition, we would like

to recognize those who have helped make this second edition possible. Since the publication of the first edition in 1997, we have received numerous emails and personal communications from students and practitioners asking questions, pointing out mistakes, making suggestions, and encouraging us to revise the book. We thank this group for their feedback and for making it clear that a revision of the book in Customary U.S. units was necessary.

We wish to acknowledge those who have contributed directly to the production of the book. The most important person in this regard was Kerri Puckett, civil engineering student at the University of Wyoming, who changed the units on all figures to Customary U.S., drafted new figures, catalogued the figures and photos, performed clerical duties, and generally kept the authors on track. Also assisting in the conversion of units was H. R. (Trey) Hamilton from the University of Florida who reworked design examples from the first edition in Customary U.S. units.

We also appreciate the contributions of friends in the bridge engineering community. Colleagues at Virginia Tech providing background material were Carin Roberts-Wollmann on unbonded tendons and Tommy Cousins on prestress losses. Thanks to John Kulicki of Modjeski & Masters for his continuing leadership in the development of the LRFD Specifications and Dennis Mertz of the University of Delaware for responding to questions on the rationale of the specifications. The authors appreciate the computer modeling and project photos provided by Linda Figg, Cheryl Maze, and Amy Kohls Buehler of Figg Engineers.

The patience and understanding shown us by Jim Harper and Bob Hilbert at John Wiley & Sons is gratefully acknowledged.

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PREFACE TO THE FIRST EDITION

This book is written for senior level undergraduate or first year graduate students in civil engineering and for practicing civil engineers who have an interest in the design of highway bridges. The object of this book is to provide the student or practitioner a meaningful introduction to the design of medium- and short-span girder bridges. This objective is achieved by providing fundamental theory and behavior, background on the development of the specifications, procedures for design, and design examples.

This book is based on the American Association of State Highway and Transportation Officials (AASHTO) LRFD Bridge Design Specifications and System International (SI) units are used throughout. The general approach is to present theory and behavior upon which a provision of the specifications is based, followed by appropriate procedures, either presented explicitly or in examples. The examples focus on the procedures involved for a particular structural material and give reference to the appropriate article in the specifications. It is, therefore, essential that the reader have available a copy of the most recent edition of the AASHTO LRFD Bridge Design Specifications in SI units. (For those who have access to the World Wide Web, addendums to the specifications can be found at <http://www2.epix.net/~modjeski>.)

The scope of this book is limited to a thorough treatment of medium- and short-span girder bridges with a maximum span length of about 60 m. These bridge structures comprise approximately 80% of the U.S. bridge inventory and are the most common bridges designed by practitioners, illustrating the basic principles found in bridges of longer spans. Structure types included in this book are built of concrete, steel, and wood. Concrete cast-in-place slab, *T*-beam, and box-girder bridges and precast-prestressed systems are considered. Rolled steel beam and plate girder systems that are composite and non-composite are included, as well as wood systems. This book concludes with a chapter on substructure design, which is a common component for all the bridge types.

Civil engineers are identified as primary users of this book because their formal education includes topics important to a highway bridge designer. These topics include studies in transportation systems, hydrodynamics of streams and channels, geotechnical engineering, construction management, environmental engineering, structural analysis and design, life-cycle costing, material testing, quality control, professional and legal problems, and the people issues associated with public construction projects. This reference to civil engineers is not meant to exclude others from utilizing this book. However, the reader is expected to have one undergraduate course in structural design for each structural material considered. For example, if only the design of steel bridges is of interest, then the reader should have at least one course in structural analysis and one course in structural steel design.

Chapter 1 introduces the topic of bridge engineering with a brief history of bridge building and the development of bridge specifications in the United States. Chapter 2 emphasizes the need to consider aesthetics from the beginning of the design process and gives examples of successful bridge projects. Chapter 3 presents the basics on load and resistance factor design (LRFD) and indicates how these factors are chosen to obtain a desirable margin of safety.

Chapter 4 describes the nature, magnitude, and placement of the various loads that act on a bridge structure. Chapter 5 presents influence function techniques for determining maximum and minimum force effects due to moving vehicle loads. Chapter 6 considers the entire bridge structure as a system and how it should be analyzed to obtain a realistic distribution of forces.

Chapters 7–9 are the design chapters for concrete, steel, and wood bridges. The organization of these three chapters is similar. A description of material properties is given first, followed by general design considerations. Then a discussion of the behavior and theory behind the member resistance expressions for the various limit states, and concluding with detailed design examples that illustrate the LRFD specification provisions.

Chapter 10 on substructure design completes the book. It includes general design considerations, an elastomeric bearing design example, and a stability analysis to check the geotechnical limit states for a typical abutment.

We suggest that a first course in bridges be based on Chapters 1–6, either Articles 7.1–7.6, 7.10.1, and 7.10.3 of Chapter 7 or Articles 8.1–8.4, 8.6–8.10, and 8.11.2, and conclude with Articles 10.1–10.3 of Chapter 10. It is assumed that some of this material will have been covered in prerequisite courses and can be referred to only as a reading assignment. How much of the material to present to a particular class is at the discretion of the professor, who is probably the best person to judge the background and maturity of the students. There is enough material in the book for more than one course in highway bridge design.

Practitioners who are entry level engineers will find the background material in Chapters 1–6 helpful in their new assignments and can use Chapters 7–10 for specific guidance on design of a particular bridge type. The same can be said for seasoned professionals, even though they would be familiar with the material in the loads chapter, they should find the other chapters of interest in providing background and design examples based on the AASHTO LRFD specifications.

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Acknowledgments to others who have contributed to the writing of this book is not an easy task because so many people have participated in the development of our engineering careers. To list them all is not possible, but we do recognize the contribution of our university professors at the University of Minnesota and Colorado State University; our engineering colleagues at Toltz, King, Duvall, Anderson & Associates, Moffatt & Nichol Engineers, and BridgeTech, Inc.; our faculty colleagues at Virginia Tech and the University of Wyoming; the government and industry sponsors of our research work; and the countless number of students who keep asking those interesting questions.

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Finally, on behalf of the bridge engineering community the authors wish to recognize John Kulicki of Modjeski & Masters and Dennis Mertz of the University of Delaware for their untiring leadership in the development of the LRFD Specification. The authors wish to thank these professionals for providing support and encouragement for the book and responding to many questions about the rationale and background of the specification. Others who contributed to the development of the LRFD Specification as members of the Code Coordinating Committee or as a Chair of a Task Group have also influenced the writing of this book. These include: John Ahlskog, Ralph Bishop, Ian Buckle, Robert Cassano, Paul Csagoly, J. Michael Duncan, Theodore Galambos, Andrzej Nowak, Charles Purkiss, Frank Sears, and James Withiam. A complete listing of the members of the task groups and the NCHRP panel that directed the project is given in Appendix D.

As with any new book, in spite of numerous proofreadings, errors do creep in and the authors would appreciate it if the reader would call them to their attention. You may write to us directly or, if you prefer, use our e-mail address: barker@vt.edu or puckett@uwyo.edu.

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