Preface

The first edition considered only linear elastic behavior of structures. This assumption is reasonable for assessing the structural response in the early stage of design where one is attempting to estimate design details. As a design progresses, other critical behavioral issues need to be addressed.

The first issue concerns geometric nonlinearity which results when a flexible member is subjected to axial compression loading as well as transverse loading. This combination causes a loss in axial stiffness for the member, which may result in a loss in stability for the structural system. Euler buckling is an example of this type of nonlinear behavior.

The second issue is related to the behavior of the material used to fabricate structural members. Steel and concrete are the most popular materials for structural applications. These materials have a finite elastic range, i.e., they behave elastically up to a certain stress level. Beyond this level, their stiffness decreases dramatically and they experience significant deformation that remains when the specimen is unloaded. This deformation is referred to as "inelastic deformation." The result of this type of member behavior is the fact that the member has a finite load carrying capacity. From a structural system perspective, it follows that the structure has a finite load capacity. Given the experience with recent structural failures, structural engineers are now being required to estimate the "limit" capacity of their design using inelastic analysis procedures. Computer-based analysis is essential for this task.

We have addressed both issues in this edition. Geometric nonlinearity is basically a displacement issue, so it is incorporated in Chap. 10. We derive the nonlinear equations for a member; develop the general solution, specialize the solutions for various boundary conditions; and finally present the generalized nonlinear "member" equations which are used in computer-based analysis methods. Examples illustrating the effect of coupling between compressive axial load and lateral displacement (P-delta effect) are included. This treatment provides sufficient exposure to geometric nonlinearity that we feel is necessary to prepare the student for professional practice.

Inelastic analysis is included in Part III which deals with professional practice; we have added an additional chapter focused exclusively on inelastic analysis. We start by reviewing the basic properties of structural steel and concrete and then establish the expressions for the moment capacity of beams. We use these results together with some simple analytical methods to establish the limit loading for some simple beam and frames. For complex structures, one needs to resort to computer-based procedures. We describe a finite element-based method that allows one to treat the nonlinear load displacement behavior and to estimate the limiting load. This approach is referred to as a "pushover" analysis. Examples illustrating pushover analyses of frames subjected to combined gravity and seismic loadings are included. Just as for the geometric nonlinear case, our objective is to provide sufficient exposure to the material so that the student is "informed" about the nonlinear issues. One can gain a deeper background from more advanced specialized references.

Aside from these two major additions, the overall organization of the second edition is similar to the first edition. Some material that we feel is obsolete has been deleted (e.g., conjugate beam), and other materials such as force envelopes have been expanded. In general, we have tried to place more emphasis on computer base approaches since professional practice is moving in that direction. However, we still place the primary emphasis on developing a fundamental understanding of structural behavior through analytical solutions and computer-based computations.

Audience

The intended audience of this book is that of students majoring in civil engineering or architecture who have been exposed to the basic concepts of engineering mechanics and mechanics of materials. The book is sufficiently comprehensive to be used for both undergraduate and higher level structures subjects. In addition, it can serve students as a valuable resource as they study for the engineering certification examination and as a reference later in their careers. Practicing professionals will also find the book useful for self-study, for review for the professional registration examination, and as a reference book.

Motivation

The availability of inexpensive digital computers and user-friendly structural engineering software has revolutionized the practice of structural engineering. Engineers now routinely employ computer-based procedures throughout the various phases of the analysis and design detailing processes. As a result, with these tools engineers can now deal with more complex structures than in the past. Given that these tools are now essential in engineering practice, the critical question facing faculty involved in the teaching of structural engineering is "How the traditional teaching paradigm should be modified for the computer age?" We believe that more exposure to computer-based analysis is needed at an early stage in the course development. However, since the phrase "garbage in garbage out" is especially relevant for computer-based analysis, we also believe that the student needs to develop, through formal training in analysis methodology, the ability to estimate qualitatively the behavior of a structure subjected to a given loading and to confirm qualitative estimates with some simple manual computations.

Based on a review of the current structural engineering academic literature, it appears that the current set of undergraduate textbooks are focused mainly on either (1) teaching manual analysis methods and applying them to simple idealized structures or (2) reformulating structural analysis methods in terms of matrix notation. The first approach is based on the premise that intuition about structural behavior is developed as one works through the manual computations, which, at times, may seem exhaustive. The second approach provides the basis for developing and understanding computer software codes but does not contribute toward developing intuition about structural behavior.

Clearly there is a need for a text that provides a balanced treatment of both classical and modern computer-based analysis methods in a seamless way and also stresses the development of an intuitive understanding of structural behavior. Engineers reason about behavior using simple models and intuition that they have acquired through problem-solving experience. The approach adopted in this text is to develop this type of intuition through computer simulation which allows one to rapidly explore how the structure responds to changes in geometry and physical parameters. We believe this approach better prepares the reader for the practice of structural engineering.

Objectives

Structural engineers have two major responsibilities during the design process. First, they must synthesize the structural system, i.e., select the geometry and the type of structural members that make up the structure. Second, they must size the members such that the structure can comfortably support the design loading. Creating a structural concept requires a deep knowledge of structural behavior. Sizing the members requires information about the internal forces resulting from the loading. These data are acquired through intelligent application of analysis methods, mainly computer-based methods. With these responsibilities in mind, we have selected the following objectives for this book:

- *Develop the reader's ability to analyze structures using manual computational procedures.*
- *Educate the reader about structural behavior*. We believe that a strong analytical background based on classical analysis methodology combined with computer simulation facilitates the development of an understanding of structural behavior.
- *Provide the reader with an in-depth exposure to computer-based analysis methods*. Show how computer-based methods can be used to determine, with minimal effort, how structures respond to loads and also how to establish the extreme values of design variables required for design detailing.

- *Develop the reader's ability to validate computer-based predictions of structural response.*
- *Provide the reader with idealization strategies for reducing complex structures to simple structural models.*
- *Develop an appreciation for and an awareness of the limitations of using simple structural models to predict structural behavior through examples which illustrate behavioral trends as structures become more complex.*

Organization

We have organized this text into three parts. Parts I and II are intended to provide the student with the necessary computational tools and also to develop an understanding of structural behavior by covering analysis methodologies, ranging from traditional classical methods through computer-based methods, for skeletal-type structures, i.e., structures composed of one-dimensional slender members. Part I deals with statically determinate structures; statically indeterminate structures are covered in Part II. Certain classical methods which we consider redundant have been omitted. Some approximate methods which are useful for estimating the response using hand computations have been included. Part III is devoted to structural engineering issues for a range of structures frequently encountered in practice. Emphasis is placed on structural idealization, how one identifies critical loading patterns, and how one generates the extreme values of design variables corresponding to a combination of gravity, live, wind, earthquake loading, and support settlement using computer software systems.

Brief descriptions of the subject content for each part are presented below.

Part I discusses statically determinate structures. We start with an introduction to structural engineering. Statically determinate structures are introduced next. The treatment is limited to linear elastic behavior and static loading. Separate chapters are devoted to different skeletal structural types such as trusses, beams, frames, cables, curved members, footings, and retaining walls. Each chapter is self-contained in that all the related analysis issues for the particular structural type are discussed and illustrated. For example, the chapter on beams deals with constructing shear and moment diagrams, methods for computing the deflection due to bending, influence lines, force envelopes, and symmetry properties. We find it convenient from a pedagogical perspective to concentrate the related material in one location. It is also convenient for the reader since now there is a single source point for knowledge about each structural type rather than having the knowledge distributed throughout the text. We start with trusses since they involve the least amount of theory. The material on frames is based on beam theory, so it is logical to present it directly after beam theory. Cables and curved members are special structural types that generally receive a lower priority, due to time constraints, when selecting a syllabus. We have included these topics here, as well as a treatment of footings and retaining walls, because they are statically determinate structures. We revisit these structures later in Part III.

Part II presents methods for analyzing statically indeterminate structures and applies these methods to a broad range of structural types. Two classical analysis methods are described, namely, the force (also referred to as the flexibility) method and the displacement (or stiffness) method. We also present some approximate analysis methods that are based on various types of force and stiffness assumptions. These methods are useful for estimating the structural response due to lateral loads using simple hand computations. Lastly, we reformulate the traditional displacement method as a finite element method using matrix notation. The finite element formulation (FEM) is the basis of most existing structural analysis software packages. Our objectives here are twofold: first, we want to enable the reader to be able to use FEM methods in an *intelligent* way, and second, we want the reader to develop an understanding of structural behavior by applying analysis methods to a broad range of determinate and indeterminate skeletal structures. *We believe that using computer analysis software as a simulation tool to explore structural behavior is a very effective way of building up a knowledge base of behavioral modes*, *especially for the types of structures commonly employed in practice*.

Part III discusses typical structural engineering problems. Our objective here is to expose the reader to a select set of activities that are now routinely carried out by structural engineers using structural engineering software. These activities are related to the approach followed to establish the "values" for the design variables. Defining these values is the key step in the engineering design process; once they are known, one can proceed to the design detailing phase. Specific chapters deal with horizontal structures such as multi-span girder, arch, and cable-stayed bridge systems, modeling of three-dimensional vertical structures subjected to lateral loading, and vertical structures such as low- and high-rise buildings subjected to gravity loading. The topics cover constructing idealized structural models, establishing the critical design loading patterns for a combination of gravity and live loading, using analysis software to compute the corresponding design values for the idealized structures, defining the lateral loading due to wind and earthquake excitation for buildings, and estimating the three-dimensional response of low-rise buildings subjected to seismic and wind loadings.

Course Suggestions

The following suggestions apply for students majoring in either civil engineering or architecture. Depending on the time available, we suggest organizing the material into either a two-semester or a three-semester sequence of subjects.

Our recommendations for the three-semester sequence are as follows:

Structures I

The goal of this subject is to provide the skills for the analysis of statically determinate trusses, beams, frames, and cables and to introduce some computer-based analysis methods.

Chapters 1, 2, part of 3, part of 4, and the first part of 5

Structures II

The objectives of this subject are to present both classical and computer-based analysis methods for statically indeterminate structures such as multi-span beams, gable frames, arches, and cable-stayed structures subjected to various loadings. The emphasis is on using analysis methods to develop an understanding of the behavior of structures.

Chapters 9, 10, 11, 12, 6, and the last part of 5

Structures III

This subject is intended to serve as an introduction to the practice of structural engineering. The material is presented as case studies for the two most common types of structures, bridges, and buildings. Issues such as geometrical configurations, idealized structural models, types and distribution of loadings, determination of the values of the design variables such as the peak moment in a beam, force envelopes, and inelastic behavior are discussed. Both the superstructure and the substructure components are considered. Extensive use of computer software is made throughout the subject. Recitation classes dealing with the design detailing of steel and concrete elements can be taught in parallel with the lectures.

Chapters 13, 14, 15, 16, 7, and 8

The makeup of the two-semester sequence depends on how much background in mechanics and elementary structures the typical student has and the goal of the undergraduate program. One possibility is to teach Structures I and II described above. Another possible option is to combine Structures I and II into a single subject offering together with Structures III. A suggested combined subject is listed below.

Structures (Combined I + II)

Chapters 3, 4 (partial), 9 (partial), 10, 11, and 12

Features of the Text

Organization by Structural Type

The chapters are organized such that an individual chapter contains all the information pertaining to a particular structural type. We believe this organization facilitates access to information. Since the basic principles are generic, it also reinforces these principles throughout the development of successive chapters.

Classical Analysis Methods

In-depth coverage of classical analysis methods with numerous examples helps students learn fundamental concepts and develop a “feel” and context for structural behavior.

Analysis by Hand Computation

The book helps teach students to do simple hand computing, so that as they move into doing more complex computational analysis, they can quickly check that their computer-generated results make sense.

Gradual Introduction of Computer Analysis

The text provides students with a gradual transition from classical methods to computational methods, with examples and homework problems designed to bring students along by incorporating computational methods when most appropriate to in-depth coverage of finite element methods for skeletal structures.

Example Problems

Example problems in each chapter illustrate solutions to structural analysis problems, including some problems illustrating computer analysis. Most of the example problems are based on real scenarios that students will encounter in professional practice.

Units

Both SI and customary US units are used in the examples and homework problems.

Homework Problems that Build Students’ Skills

An extensive set of homework problems for each chapter provides students with more exposure to the concepts and skills developed in the chapters. The difficulty level is varied so that students can build confidence by starting with simple problems and advancing toward more complex problems.

Comprehensive Breadth and Depth, Practical Topics

The comprehensive breadth and depth of this text means it may be used for two or more courses, so it is useful to students for their courses and as a professional reference. Special topics such as the simplifications associated with symmetry and antisymmetry, arch-type structures, and cable-stayed structures are topics that a practicing structural engineer needs to be familiar with.

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