

STRUCTURES

Second Edition

Daniel L. Schodek

Harvard University



PRENTICE-HALL, INC., *Englewood Cliffs, New Jersey 07632*

Library of Congress Cataloging-in-Publication Data

Schodek, Daniel L.,
Structures / Daniel L. Schodek. — 2nd ed.
p. cm.
Includes bibliographical references and index.
ISBN 0-13-855313-0
1. Structural analysis (Engineering) 2. Structural design.
I. Title.
TA645.S37 1992
624.1'7—dc20

91-31941
CIP

Editorial/production supervision and interior design: **Marcia Krefetz**
Manufacturing buyer: **Ed O'Dougherty**
Prepress Buyer: **Ilene Levy**
Acquisitions Editor: **Rob Koehler**
Managing Editor: **Mary Carnis**
Senior Managing Editor: **Barbara Cassel**
Production Assistant: **Bunnie Neuman**



© 1992 by Prentice-Hall, Inc.
A Simon & Schuster Company
Englewood Cliffs, New Jersey 07632

All rights reserved. No part of this book may be reproduced, in any form or by any means, without permission in writing from the publisher.

Printed in the United States of America
10 9 8 7 6 5 4 3 2 1

ISBN 0-13-855313-0

ISBN 0-13-855313-0



Prentice-Hall International (UK) Limited, *London*
Prentice-Hall of Australia Pty, Limited, *Sydney*
Prentice-Hall Canada Inc., *Toronto*
Prentice-Hall Hispanoamericana, S.A., *Mexico*
Prentice-Hall of India Private Limited, *New Delhi*
Prentice-Hall of Japan, Inc., *Tokyo*
Simon & Schuster Asia Pte. Ltd., *Singapore*
Editora Prentice-Hall do Brasil, Ltda., *Rio de Janeiro*

STRUCTURES

PREFACE

There exist an invariant set of physical principles founded in the field of mechanics that can be used by designers as aids to understanding the behavior of existing structural forms and in devising new approaches. The development of these principles has flowered during the past three centuries to the extent that they are amazingly well established and documented. Some new understandings, of course, are continuing to occur and will hopefully always occur. Still, the analytical tools already available to the designer are extensive and enormously powerful. This is true to the extent that the real challenge in the field of structures lies not so much in developing new analytical tools but in bringing those currently in existence to bear in the designing and formulation of creative structural solutions with the intent of making better buildings.

In this book we discuss in an introductory way the nature of the invariant physical principles that underlie the behavior of structures under load. The primary goal of the book, however, is not simply to teach analytical techniques but more generally, to explore their role in the design of structures in a building context. Because of this larger goal, the book covers material discussed not only in specialized engineering curricula but also, to some extent, that covered in architectural curricula as well. The traditional hard boundaries between subdisciplines in engineering, (e.g., statics and strength of materials) have also been deliberately softened and a more integrative approach taken.

The book is divided into three major parts. Part I is an introduction to the subject and to fundamental concepts of analysis and design. Part II introduces the reader to most of the primary structural elements used in buildings and discusses their analysis and design. Each of the chapters in this part is divided into sections that (1) introduce the element considered and explain its role in building, (2) discuss its behavior under load in qualitative terms (an “intuitive” approach), (3) examine its behavior under load in quantitative terms, and (4) discuss methods for designing (rather than just analyzing) the element. Part III contains a unique discussion of the logic of structural design, as it is a part of the larger building design process. The Appendix generally discusses more advanced principles of structural analysis.

The book is intended largely as a resource for students and instructors wishing to design their own curriculum. For those wanting to adopt a strictly qualitative approach to the subject, for example, it is possible to read only Chapter 1 in Part I, the sections entitled “Introduction” and “General Principles” in each of the chapters in Part II, and all of Part III. This coverage will provide a brief qualitative overview of the field with a special emphasis on design rather than analysis. For those students who already have a background in the analytical aspects of structures, Part III contains summary information useful in a design context. Part III can be read independently by such students.

Within Parts I, II, and III there is a certain redundancy in the way analytical topics are covered so that students or instructors can integrate the material in the order seen best fit. Shear and moment diagrams, for example, are first introduced in an abstract way in chapter 2. They are reintroduced in connection with the analysis of a specific structural element—the truss. *Where* the different presentations are introduced, if at all, may be varied by the instructor. The author, for example, typically chooses to introduce shear and moment diagrams initially as a part of truss analysis and then follow up with the more abstract development of shear and moment diagrams in Chapter 2 before going into beam analysis and design. Other instructors may choose to approach the subject material differently. The book is designed to have sufficient flexibility to support different approaches. In any event the material is presented in such a way that a direct cover-to-cover reading is also appropriate.

The author is, of course, indebted to a vast number of people in either a direct or an indirect way for the approach taken in this book. Professor Spiro Pollalis contributed his time and help in revising the manuscript from the first edition. He directly contributed the new sections on reinforced concrete in Chapter 9 and on computer-based structural analysis methods in Chapter 4 and Appendix 12. David Thal, John Leeke, and Joe Kennard helped in preparing illustrations for the second edition. Especially important are Kay, Ned, and Ben Schodek, who provided their own special form of support. The endless patience and contributions of several years of students in the Graduate School of Design at Harvard who have taken courses involving the material contained herein is also greatly appreciated.

Daniel L. Schodek
Cambridge, Massachusetts

CONTENTS

PREFACE	xv
part I INTRODUCTORY CONCEPTS	1
chapter 1 STRUCTURES: AN OVERVIEW	2
1.1 Introduction, 2	
1.2 General Types of Structures, 4	
1.2.1 <i>Primary Classifications, 4</i>	
1.2.2 <i>Primary Structural Elements, 4</i>	
1.2.3 <i>Primary Structural Units and Aggregations, 12</i>	
1.3 Basic Issues in the Analysis and Design of Structures, 14	
1.3.1 <i>Fundamental Structural Phenomena, 14</i>	
1.3.2 <i>Structural Stability, 16</i>	
1.3.3 <i>Members in Tension, Compression, Bending, Shear, Torsion, and Bearing: an Introduction, 18</i>	

1.4	Funicular Structures: Arches, Cables, and Related Forms, 20	
1.4.1	<i>Basic Characteristics, 20</i>	
1.4.2	<i>Structural Behavior, 21</i>	
1.5	Other Classifications, 27	
chapter 2	PRINCIPLES OF MECHANICS	30
2.1	Introduction, 30	
2.2	Forces and Moments, 31	
2.2.1	<i>Forces, 31</i>	
2.2.2	<i>Scalar and Vector Quantities, 31</i>	
2.2.3	<i>Parallelogram of Forces, 32</i>	
2.2.4	<i>Resolution and Composition of Forces, 35</i>	
2.2.5	<i>Moments, 35</i>	
2.2.6	<i>Statically, Equivalent Systems, 37</i>	
2.3	Equilibrium, 40	
2.3.1	<i>Equilibrium of a Particle, 40</i>	
2.3.2	<i>Equilibrium of a Rigid Body, 40</i>	
2.4	External and Internal Forces and Moments, 44	
2.4.1	<i>External Force Systems, 44</i>	
2.4.2	<i>Internal Stresses, Forces, and Moments, 48</i>	
2.4.3	<i>Shear and Moment, 53</i>	
2.4.4	<i>Distribution of Shears and Moments, 57</i>	
2.4.5	<i>Relations Among Load, Shear, and Moment in Structures, 64</i>	
2.5	Mechanical Properties of Materials, 66	
2.5.1	<i>Introduction, 66</i>	
2.5.2	<i>General Load-Deformation Properties of Materials, 66</i>	
2.5.3	<i>Elasticity, 66</i>	
2.5.4	<i>Strength, 70</i>	
2.5.5	<i>Other Material Properties, 70</i>	
chapter 3	INTRODUCTION TO STRUCTURAL ANALYSIS AND DESIGN	78
3.1	Analysis and Design Criteria, 78	
3.2	Loads on Structures, 80	
3.2.1	<i>Introduction, 80</i>	
3.2.2	<i>Static Forces, 81</i>	
3.2.3	<i>Wind Loads, 84</i>	
3.2.4	<i>Earthquake Forces, 86</i>	
3.2.5	<i>Load Combinations, 92</i>	

3.3	The General Analysis Process, 93	
3.3.1	<i>Basic Steps, 93</i>	
3.3.2	<i>Modeling the Structure, 95</i>	
3.3.3	<i>Modeling the External Loads, 99</i>	
part II	ANALYSIS AND DESIGN OF STRUCTURAL ELEMENTS	111
chapter 4	TRUSSES	112
4.1	Introduction, 112	
4.2	General Principles, 113	
4.2.1	<i>Triangulation, 113</i>	
4.2.2	<i>Member Forces: Qualitative Analyses, 115</i>	
4.3	Analysis of Trusses, 118	
4.3.1	<i>Stability, 118</i>	
4.3.2	<i>Member Forces: General, 121</i>	
4.3.3	<i>Equilibrium of Joints, 123</i>	
4.3.4	<i>Equilibrium of Sections, 130</i>	
4.3.5	<i>Shears and Moments in Trusses, 136</i>	
4.3.6	<i>Statically Indeterminate Trusses, 138</i>	
4.3.7	<i>Use of Special Tensile Members: Cables, 139</i>	
4.3.8	<i>Space Trusses, 141</i>	
4.3.9	<i>Joint Rigidity, 142</i>	
4.3.10	<i>Other Methods of Analysis, 143</i>	
4.4	Design of Trusses, 145	
4.4.1	<i>Objectives, 145</i>	
4.4.2	<i>Configurations, 146</i>	
4.4.3	<i>Depths of Trusses, 156</i>	
4.4.4	<i>Member Design Issues, 156</i>	
4.4.5	<i>Planar versus Three-Dimensional Trusses, 162</i>	
chapter 5	FUNICULAR STRUCTURES: CABLES AND ARCHES	164
5.1	Introduction to Funicular Structures, 164	
5.2	General Principles of Funicular Shapes, 165	
5.3	Analysis and Design of Cable Structures, 168	
5.3.1	<i>Introduction, 168</i>	
5.3.2	<i>Suspended Cable Structures: Concentrated Loads, 164</i>	
5.3.3	<i>Suspended Cables: Uniformly Distributed Loads, 175</i>	
5.3.4	<i>General Funicular Equation, 178</i>	
5.3.5	<i>Cable Lengths, 179</i>	
5.3.6	<i>Wind Effects, 179</i>	

5.4	Design of Cable Structures, 181	
5.4.1	<i>Simple Suspension Cables, 181</i>	
5.4.2	<i>Double-Cable Systems, 183</i>	
5.4.3	<i>Cable-Stayed Structures, 186</i>	
5.5	Analysis and Design of Arches, 187	
5.5.1	<i>Masonry Arches, 187</i>	
5.5.2	<i>Parabolic Rigid Arches: Uniformly Distributed Loadings, 189</i>	
5.5.3	<i>Funicular Arches: Point Loadings, 191</i>	
5.5.4	<i>Three-Hinged Arches, 192</i>	
5.5.5	<i>Design of Arch Structures, 198</i>	
chapter 6	MEMBERS IN BENDING: SIMPLE BEAMS	210
6.1	Introduction, 210	
6.2	General Principles, 211	
6.2.1	<i>Beams in Buildings, 211</i>	
6.2.2	<i>Basic Stress Distributions, 212</i>	
6.3	Analysis of Beams, 219	
6.3.1	<i>Bending Stresses, 219</i>	
6.3.2	<i>Lateral Buckling of Beams, 228</i>	
6.3.3	<i>Shear Stresses, 231</i>	
6.3.4	<i>Bearing Stresses, 237</i>	
6.3.5	<i>Torsion, 238</i>	
6.3.6	<i>Shear Center, 240</i>	
6.3.7	<i>Deflections, 241</i>	
6.3.8	<i>Principal Stresses, 244</i>	
6.4	Design of Beams, 246	
6.4.1	<i>General Design Principles, 246</i>	
6.4.2	<i>Design of Timber Beams, 253</i>	
6.4.3	<i>Steel Beams, 257</i>	
6.4.4	<i>Reinforced Concrete Beams, 262</i>	
chapter 7	MEMBERS IN COMPRESSION: COLUMNS	278
7.1	Introduction, 278	
7.2	General Principles, 279	
7.3	Analysis of Compression Members, 281	
7.3.1	<i>Short Columns, 281</i>	
7.3.2	<i>Long Columns, 283</i>	
7.4	Design of Compression Members, 293	
7.4.1	<i>General Design Principles, 293</i>	
7.4.2	<i>Column Sizes, 299</i>	

- 7.4.3 *Timber Columns, 299*
- 7.4.4 *Steel Columns, 300*
- 7.4.5 *Reinforced Concrete Columns, 301*

chapter 8 CONTINUOUS STRUCTURES: BEAMS

304

- 8.1 Introduction, 304
- 8.2 General Principles, 305
 - 8.2.1 *Rigidity, 307*
 - 8.2.2 *Force Distributions, 307*
- 8.3 Analysis of Indeterminate Beams, 308
 - 8.3.1 *Approximate Methods of Analysis, 308*
 - 8.3.2 *Effects of Variations in Member Stiffness, 311*
 - 8.3.3 *Effects of Support Settlements, 314*
 - 8.3.4 *Effects of Partial-Loading Conditions, 315*
- 8.4 Design of Indeterminate Beams, 318
 - 8.4.1 *Introduction, 318*
 - 8.4.2 *Design Moments, 319*
 - 8.4.3 *Shaping Continuous Beams, 319*
 - 8.4.4 *Use of Construction Joints, 321*
 - 8.4.5 *Controlling Moment Distributions, 324*
 - 8.4.6 *Continuous Beams Made of Reinforced Concrete, 326*

chapter 9 CONTINUOUS STRUCTURES: RIGID FRAMES

328

- 9.1 Introduction, 328
- 9.2 General Principles, 329
- 9.3 Analysis of Rigid Frames, 332
 - 9.3.1 *Approximate Methods of Analysis, 332*
 - 9.3.2 *Importance of Relative Beam and Column Stiffnesses, 338*
 - 9.3.3 *Sidesway, 341*
 - 9.3.4 *Support Settlements, 343*
 - 9.3.5 *Effects of Partial Loading Conditions, 343*
 - 9.3.6 *Multistory Frames, 344*
 - 9.3.7 *Vierendeel Frames, 345*
- 9.4 Design of Rigid Frames, 347
 - 9.4.1 *Introduction, 347*
 - 9.4.2 *Selection of Frame Type, 347*
 - 9.4.3 *Design Moments, 350*
 - 9.4.4 *Shaping of Frames, 352*
 - 9.4.5 *Member and Connection Design, 355*
 - 9.4.6 *General Considerations, 355*

chapter 10 PLATE AND GRID STRUCTURES**357**

- 10.1 Introduction, 357
- 10.2 Grid Structures, 358
- 10.3 Plate Structures, 361
 - 10.3.1 *One-Way Plate Structures, 361*
 - 10.3.2 *Two-Way Plate Structures, 362*
- 10.4 Design of Two-Way Systems: General Objectives for Plate, Grid, and Space-Frame Structures, 372
- 10.5 Design of Reinforced Concrete Plates, 374
- 10.6 Space-Frame Structures, 383
- 10.7 Folded Plate Structures, 386

chapter 11 MEMBRANE STRUCTURES**392**

- 11.1 Introduction, 392
- 11.2 Pneumatic Structures, 393
 - 11.2.1 *Background, 393*
 - 11.2.2 *Air-Supported Structures, 397*
 - 11.2.3 *Air-Inflated Structures, 401*
 - 11.2.4 *Other Considerations, 402*
- 11.3 Analysis and Design of Net and Tent Structures, 403
 - 11.3.1 *Curvatures, 404*
 - 11.3.2 *Support Conditions, 405*
 - 11.3.3 *Other Considerations, 406*

chapter 12 SHELL STRUCTURES**407**

- 12.1 Introduction, 407
- 12.2 Spherical Shell Structures, 409
 - 12.2.1 *Membrane Action, 409*
 - 12.2.2 *Types of Forces in Spherical Shells, 410*
 - 12.2.3 *Meridional Forces in Spherical Shells, 412*
 - 12.2.4 *Hoop Forces in Spherical Shells, 413*
 - 12.2.5 *Distribution of Forces, 414*
 - 12.2.6 *Concentrated Forces, 415*
 - 12.2.7 *Support Conditions: Tension and Compression Rings, 415*
 - 12.2.8 *Other Considerations, 419*
- 12.3 Cylindrical Shells, 420
- 12.4 Hyperbolic Paraboloid Shells, 422

part III	PRINCIPLES OF STRUCTURAL DESIGN	425
chapter 13	STRUCTURAL GRIDS AND PATTERNS: GENERAL PLANNING AND DESIGN	427
13.1	Introduction, 427	
13.2	Common Grids, 428	
13.3	General Characteristics of Structural Hierarchies, 429	
	13.3.1 One-Way Systems, 429	
	13.3.2 Two-Way Systems, 434	
	13.3.3 Relation to Roof Shape, 436	
	13.3.4 Relations Between Span Length and Structure Type, 438	
	13.3.5 Relations Between Loading Type and Structure Type, 443	
	13.3.6 Concentrated Versus Distributed Structures, 443	
	13.3.7 Imposed Constraints: Fire Safety Requirements, 444	
13.4	Design Issues, 445	
	13.4.1 Relation of Structure to Functional Spaces, 445	
	13.4.2 Space-forming Characteristics, 448	
	13.4.3 One-Way Versus Two-Way Systems: Impact of Grid Geometry and Dimensions, 449	
	13.4.4 Effects of Local Geometrical Conditions, 454	
	13.4.5 Varying Support Locations, 457	
	13.4.6 Nonuniform Grids, 457	
	13.4.7 Accommodating Large Spaces, 458	
	13.4.8 Accommodating Special Conditions, 460	
	13.4.9 Meeting of Structural Grids, 463	
chapter 14	STRUCTURAL SYSTEMS: DESIGN FOR LATERAL LOADINGS	468
14.1	Lateral Forces: Effects on the Design of Structures, 468	
	14.1.1 Basic Design Issues: Low- and Medium-Rise Structures, 468	
	14.1.2 Multistory Construction, 476	
14.2	Earthquake Design Considerations, 481	
	14.2.1 General Principles, 481	
	14.2.2 General Design and Planning Considerations, 482	
	14.2.3 General Characteristics of Earthquake-Resistant Structures, 486	
	14.2.4 Stiff or Flexible Structures, 489	
	14.2.5 Materials, 490	
	14.2.6 Nonstructural Elements, 491	

chapter 15	STRUCTURAL SYSTEMS: CONSTRUCTIONAL APPROACHES	493
15.1	Introduction, 493	
15.2	Wood Construction, 494	
15.3	Reinforced Concrete Construction, 498	
15.4	Steel Construction, 504	
chapter 16	STRUCTURAL CONNECTIONS	510
16.1	Introduction, 510	
16.2	Basic Geometries, 510	
16.3	Basic Types of Connectors, 513	
	16.3.1 Bolts and Rivets, 514	
	16.3.2 Welded Joints, 518	
	APPENDICES	520
appendix 1:	CONVERSIONS	520
appendix 2:	CENTROIDS	520
appendix 3:	MOMENTS OF INERTIA	522
	A.3.1 General Formulation, 522	
	A.3.2 Parallel-Axis Theorem, 524	
	A.3.3 Negative Areas, 525	
appendix 4:	BENDING STRESSES IN BEAMS	526
appendix 5:	SHEARING STRESSES IN BEAMS	527
appendix 6:	MOMENT-CURVATURE RELATIONS	529
appendix 7:	DEFLECTIONS	530
	A.7.1 General Differential Equation, 530	
	A.7.2 Deflections: Double-Integration Method, 531	
appendix 8:	MOMENT-AREA THEOREMS: SLOPES AND DEFLECTIONS	532
appendix 9:	DOUBLE-INTEGRATION METHODS OF ANALYZING INDETERMINATE STRUCTURES	535

appendix 10:	DEFLECTION METHODS OF ANALYZING INDETERMINATE STRUCTURES	536
appendix 11:	MATRIX DISPLACEMENT METHODS (OR STIFFNESS METHODS)	539
appendix 12:	FINITE ELEMENT TECHNIQUES	544
appendix 13:	CRITICAL BUCKLING LOADS FOR COMPRESSION MEMBERS	535
appendix 14:	MEMBER PROPERTIES	547
appendix 15:	TYPICAL MATERIAL PROPERTIES	548
	INDEX	549

part I

INTRODUCTORY CONCEPTS

The three chapters in Part I provide an overview and introduction to structures and their use in buildings. The first chapter is a self-contained overview of the field and discusses different ways of classifying structural elements and systems. The second chapter reviews certain fundamental principles of mechanics that are generally applicable to the analysis of any structure. The third chapter considers the loads that structures must be designed to carry and generally discusses the structural analysis and design process as it occurs in a building context.

chapter 1

STRUCTURES: AN OVERVIEW

1.1 INTRODUCTION

Definitions are a time-honored way of opening any book. A simple definition of a *structure* in a building context is that a structure is a device for channeling loads that result from the use and/or presence of the building to the ground. Important in the study of structures are many widely varying concerns. The study of structures certainly involves coming to understand the basic principles that define and characterize the behavior of physical objects subjected to forces. More fundamentally, it even involves defining what a force itself is, since this familiar term represents a fairly abstract concept. The study of structures in a building context also involves dealing with much broader issues of space and dimensionality. The words “size,” “scale,” “form,” “proportion,” and “morphology” are all terms commonly found in the vocabulary of a structural designer.

As a way of getting into the study of structures, it is useful to reconsider the first definition of a structure given above. Although valuable in the sense that it defines the purpose of a structure, the original definition unfortunately provides no insight into the makeup or characteristics of a structure: What *is* this device that channels loads to the ground? To adopt the complex and exacting style of a dictionary writer, a *structure* could be defined as a physical entity having a unitary character