Salvadori’s STRUCTURE IN ARCHITECTURE
The Building of Buildings

Fourth Edition

Robert A. Heller, PhD., PE
Deborah J. Oakley, AIA, PE

Editor-in-Chief: Andrew Gillfillan
Product Manager: Anthony Webster
Program Manager: Holly Shufeldt
Project Manager: Rex Davidson
Editorial Assistant: Nancy Kesterson
Team Lead Project Manager: Bryan Pirmann
Team Lead Program Manager: Laura Weaver
Director of Marketing: David Gesell
Senior Product Marketing Manager: Darcy Betts
Field Marketing Manager: Thomas Hayward
Procurement Specialist: Deidra M. Skahill

Creative Director: Andrea Nix
Art Director: Diane Y. Emberger
Cover Designer: Deborah Oakley
Cover Imagery: Deborah Oakley
Full-Service Project Management: George Jacob, Integra Software Services
Composition: Integra Software Services
Printer/Bindable: R. R. Donnelley/Menasha
Cover Printer: Phoenix Color
Text Font: 10/12 Times LT Pro

Unless otherwise indicated herein, any third-party trademarks that may appear in this work are the property of their respective owners and any references to third-party trademarks, logos or other trade dress are for demonstrative or descriptive purposes only. Such references are not intended to imply any sponsorship, endorsement, authorization, or promotion of Pearson’s products by the owners of such marks, or any relationship between the owner and Pearson Education, Inc. or its affiliates, authors, licensees or distributors.

Copyright © 2017 by Pearson Education, Inc. or its affiliates. All Rights Reserved. Printed in the United States of America. This publication is protected by copyright, and permission should be obtained from the publisher prior to any prohibited reproduction, storage in a retrieval system, or transmission in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise. For information regarding permissions, request forms and the appropriate contacts within the Pearson Education Global Rights & Permissions department, please visit www.pearsoned.com/permissions/

Library of Congress Cataloging-in-Publication Data
Names: Salvadori, Mario, author. | Oakley, Deborah, author.
| Heller, Robert A., author.
Title: Salvadori’s structure in architecture : the building of buildings / Deborah Oakley, Robert Heller, Mario Salvadori.
Other titles: Structure in architecture | Structure in architecture
Classification: LCC TA646 .533 2017 | DDC 729—dc23 LC record available at http://lccn.loc.gov/2015028454

10 9 8 7 6 5 4 3 2 1

ISBN 10: 0-13-280320-8
# Table of Contents

## PART I: The Basics

### 7 Beams 88

<table>
<thead>
<tr>
<th>7.1 Cantilevered Beams 88</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.2 Simply Supported Beams 96</td>
</tr>
<tr>
<td>7.3 Fixed Beams and Continuous Beams 100</td>
</tr>
<tr>
<td>7.4 Secondary Bending Stresses 103</td>
</tr>
<tr>
<td><strong>Key Ideas Developed in This Chapter</strong> 105</td>
</tr>
<tr>
<td>Questions and Exercises 106</td>
</tr>
<tr>
<td>Further Reading 106</td>
</tr>
</tbody>
</table>

### 8 Frames and Arches 107

<table>
<thead>
<tr>
<th>8.1 Post and Lintel 107</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.2 The Simple Frame 107</td>
</tr>
<tr>
<td>8.3 Multiple Frames 113</td>
</tr>
<tr>
<td>8.4 Gabled Frames and Arches 119</td>
</tr>
<tr>
<td>8.5 Arched Roofs 123</td>
</tr>
<tr>
<td><strong>Key Ideas Developed in This Chapter</strong> 125</td>
</tr>
<tr>
<td>Questions and Exercises 125</td>
</tr>
<tr>
<td>Further Reading 125</td>
</tr>
</tbody>
</table>

### 9 Some Fine Points of Structural Behavior 126

<table>
<thead>
<tr>
<th>9.1 How Simple is Simple Stress 126</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.2 The Largest Stress 127</td>
</tr>
<tr>
<td>9.3 The Importance of Plastic Flow 131</td>
</tr>
<tr>
<td><strong>Key Ideas Developed in This Chapter</strong> 134</td>
</tr>
<tr>
<td>Questions and Exercises 134</td>
</tr>
<tr>
<td>Further Reading 134</td>
</tr>
</tbody>
</table>

## PART II: Beyond the Basics 135

### 10 Grids, Plates, Folded Plates, and Space-Frames 136

<table>
<thead>
<tr>
<th>10.1 Load Transfer in Two Directions 136</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.2 Rectangular Beam Grids 136</td>
</tr>
<tr>
<td>10.3 Skew Grids 139</td>
</tr>
<tr>
<td>10.4 Plate Action 140</td>
</tr>
<tr>
<td>10.5 Plate Structures 143</td>
</tr>
<tr>
<td>10.6 Ribbed Plates 146</td>
</tr>
<tr>
<td>10.7 Strength Reserve in Plates 149</td>
</tr>
<tr>
<td>10.8 Folded Plates 150</td>
</tr>
<tr>
<td>10.9 Space Frames 152</td>
</tr>
<tr>
<td><strong>Key Ideas Developed in This Chapter</strong> 155</td>
</tr>
<tr>
<td>Questions and Exercises 156</td>
</tr>
<tr>
<td>Further Reading 157</td>
</tr>
</tbody>
</table>

## Structural Failures 196

<table>
<thead>
<tr>
<th>13.1 Historical Failures 196</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.2 Main Causes of Structural Failure 196</td>
</tr>
<tr>
<td>13.3 Faults in Structural Design 196</td>
</tr>
<tr>
<td>13.4 Faults in Coordination and Supervision 205</td>
</tr>
<tr>
<td>13.5 Faults in Materials 206</td>
</tr>
<tr>
<td>13.6 Consequences of Structural Failures 208</td>
</tr>
<tr>
<td><strong>Key Ideas Developed in This Chapter</strong> 208</td>
</tr>
<tr>
<td>Questions and Exercises 209</td>
</tr>
<tr>
<td>Further Reading 209</td>
</tr>
</tbody>
</table>

## Structural Aesthetics 210

<table>
<thead>
<tr>
<th>14.1 Aesthetics and Structures 210</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.2 Semiotic Messages 211</td>
</tr>
<tr>
<td>14.3 Origins of the Structural Message 211</td>
</tr>
<tr>
<td>14.4 Scale and the Structural Message 214</td>
</tr>
<tr>
<td>14.5 Aesthetics and Structural &quot;Correctness&quot; 216</td>
</tr>
<tr>
<td>14.6 The Message of Structure 218</td>
</tr>
<tr>
<td><strong>Key Ideas Developed in This Chapter</strong> 219</td>
</tr>
<tr>
<td>Questions and Exercises 220</td>
</tr>
<tr>
<td>Further Reading 220</td>
</tr>
</tbody>
</table>

## Conclusion: Understanding of Structural Principles 221

<table>
<thead>
<tr>
<th>15.1 Intuition and Knowledge 221</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.2 Qualitative and Quantitative Knowledge 221</td>
</tr>
<tr>
<td>15.3 The Future of Architectural Structures 222</td>
</tr>
<tr>
<td><strong>Key Ideas Developed in This Chapter</strong> 223</td>
</tr>
</tbody>
</table>

## Index 226

## Structures Bibliography 224
FOREWORD

When *Structure in Architecture* first appeared in 1963, it awakened architects to a qualitative, conceptual understanding of structures that was lacking, as engineers had always described structures clouded with mathematics. Here was an important new path that showed how structures work rather than how they are computed. Not only architects but engineers themselves and the general public were able for the first time to learn from this innovative approach. A strength of this book is that it demonstrates that an architectural structure itself can be deconstructed to reveal its elementary roots: beams, columns, frames, trusses, and shells, whose actions can be conceptually understood, clarifying the way in which the whole structure works.

In the 50 years since the first edition of this book was published, a vastly expanded catalog of available structural types has appeared; new materials have been developed, new shapes have been introduced, and, above all, advances in computing technology have allowed architects and engineers the freedom to conceive designs never before possible. A new edition was therefore inevitable.

Mario Salvadori was my teacher, my mentor, and then my partner in Weidlinger Associates. Together, we wrote four books on structural design, failures, and seismicity. All were drawn from the approach Mario conceived in *Structure in Architecture* to explain technical concepts using simplified language, making them accessible to readers of any age. I am honored, and it gives me great pleasure to introduce both new readers and readers of previous editions of *Structure in Architecture* to this new edition. The classic work has now been greatly improved to bring the original into the twenty-first century with updated graphics and structural examples, as well as a revised text to reflect recent advances in structural typology. This new edition will undoubtedly stand for the next decades as the go-to reference to understanding how structures work.

Matthys Levy

PREFACE

It has been 30 years since Mario Salvadori updated the last edition of *Structure in Architecture*. On its initial publication in 1963, it was one of the first and only books of its kind to introduce the principles of structures to architectural students in a largely nonmathematical manner. The variety of textbooks of this genre has grown and changed dramatically since that time, and contemporary publishing practices have dramatically evolved as well. Now long out of print and superseded by many newer books presenting rich graphic content, *Structure in Architecture* has not been surpassed in popularity by other texts, but the presentation may also seem dated or unappealing to contemporary students. Nevertheless, it remains an outstanding work of one of the most influential individuals in the area of architectural structures education. Rather than relegate it to the bin of history, a new edition to perpetuate its legacy was called for. This edition thus presents a substantial revision of the graphic presentation, while retaining the clarity of, and expanding on, the original text.

ON MARIO SALVADORI

To better understand the history, place, and authority of this text, it is helpful to understand briefly something about Mario Salvadori. Throughout his career, he wrote voluminously and taught extensively on the topic of architectural structures, as well as engaging in a number of conference discussions about the nature of the dialog between architects and engineers. Holding Italian doctorate degrees in mathematics and civil engineering, for nearly 50 years he taught in both schools of civil engineering and architecture at Columbia University in New York, rising to be one of the most distinguished faculty members of that era.

Fourteen years into his teaching career, while continuing his academic appointment, he joined the practice of the brilliant Hungarian engineer Paul Weidlinger. There, too, Dr. Salvadori distinguished himself by becoming a partner in 1963 and later chairman of Weidlinger Associates, thus impacting the design of many important structures, conducting numerous forensic structural investigations, as well as shaping the careers of generations of young engineering practitioners. For his lifetime of contributions, he was widely honored by engineering, architecture, and academic societies alike.

Of all the achievements of an illustrious career, however, Mario Salvadori was most proud of his work teaching science and math to inner-city children in the New York City region, using buildings and bridge structures as a springboard. The last three decades of his life were increasingly dedicated to this personal educational mission. The legacy of this work lives on today in the form of the Salvadori Center (or STEM Center for short), a center that he established in 1987—an organization dedicated to the mission of educating children in what is now referred to as STEM, for Science, Technology, Engineering, and Math. Clearly decades ahead of his time, Mario was active with the Center until the very end of his life, passing away in 1997 at the age of 90.

ABOUT STRUCTURE IN ARCHITECTURE

Along with the works produced in his dual careers of academia and practice, Mario Salvadori wrote also for the lay audience. His most popular books such as *Why Buildings Stand Up* and *Why Buildings Fall Down* (coauthored with Matthys Levy) have been in print continuously since their first publication in 1980 and 1992, respectively. These can be seen as later-career books very much influenced by his work with children, written in a manner accessible to anyone with no formal training beyond basic schooling.

The first edition of *Structure in Architecture*, in contrast, came much earlier (1963), yet Dr. Salvadori had at this point been teaching at Columbia for nearly twenty-five years and this was already his fourth published book. Two subsequent editions in 1975 and 1986, plus ten foreign-language translations, attest to the interest and worldwide popularity of the book. Unlike the later popular texts, however, *Structure in Architecture* went deeply into principles that are important for architects to understand, though never with much mathematics.

The issue of just how technical an engineering education an architectural student requires has been a matter of debate for decades. A polarity exists even within the community of educators who teach and research in architectural structures: On the one hand, there are those who firmly believe that all calculations are the basis for the study while, on the other hand, there are also those who feel quite the opposite. With his unique talents, Mario Salvadori was able to successfully bridge these two disparate worlds and recognize the commonality between the two. He was able to translate arcane principles of mathematics and science into simple language that—quite literally—even young children could understand.

Dr. Salvadori believed that the conceptual approach was a vital starting point for (or at least concurrent study with) a more technical study. He was thus able to engage many architecture students who would otherwise have had no interest in the more technical aspects of architectural design.
THE INTENT OF THE FOURTH EDITION

Deborah Oakley was approached by Pearson Education to undertake the project as a new coauthor, joining with Robert Heller to revisit and update the text for a new edition of this book. As noted previously, the objective was to appeal to a new audience, while retaining all of the strong points of the earlier edition. The fourth edition of this book has been extensively rewritten and revised. This edition presents a cohesive and thoroughly current treatment of the topics presented in this book. The text reflects the current state of the field, incorporating recent developments and emerging trends in the field of architectural engineering. The new edition includes updated graphics, examples, and case studies to reflect the latest advances in the field. The fourth edition is designed to provide a comprehensive introduction to the field of architectural engineering, suitable for undergraduate students in architectural engineering programs.
FOREWORD TO PREVIOUS EDITIONS

In this thoughtfully written book, Professor Salvadori endeavored to eliminate one of the most serious gaps between theory and practice in the field of structures. His aim is to build a bridge between the more or less conscious intuition about structure, which is common to all mankind, and the scientific knowledge of structure, which gives a fair representation of physical reality on the basis of mathematical postulates.

No one doubts that the bridging of this gap is possible and that, if achieved, it would be extremely useful.

In order to invent a structure and to give it exact proportions, one must follow both the intuitive and the mathematical paths.

The great works of the distant past, built at a time when scientific theories were nonexistent, bear witness to the efficiency and power of intuition.

Modern theories are incessantly and progressively developed, and their refinement is illustrated by the construction of ever greater and more daring structures. If structural invention is to allow the efficient solution of the new problems offered daily by the ever-growing activity in the field of construction, it must become a harmonious combination of our personal intuition and of an impersonal, objective, realistic and rigorous structural science.

In other words, theory must find in intuition a force capable of making formulas alive, more human and understandable, and of lessening their impersonal technical brittleness. On the other hand, formulas must give us the exact results necessary to obtain "the most with the least," since this is the ultimate goal of all human activities.

Through always clear and, at times, most elementary examples, Professor Salvadori’s book tends to unify these two viewpoints (I was almost going to say, these two mentalities), which must be cast into a unique synthesis if they are to give birth to the essential unity of all great structures.

Future architects will find it particularly useful to study this book in depth and to meditate upon it, since even if they cannot entrust the final calculation of a structure to a specialist, they must then be able to invent it and to give it correct proportions. Only then will a structure be born healthy, vital and, possibly, beautiful.

I feel that we must be particularly grateful to Professor Salvadori for undertaking this anything but easy task.

Pier Luigi Nervi

PREFACE TO THIRD EDITION

As stated in the preface to the first edition, this book has been written for those
- who love beautiful buildings and would like to know why they stand up;
- who dream of designing beautiful buildings and would like them to stand up;
- who have designed beautiful buildings and would like to better know why they stand up.

The principles of structure are eternal, but new developments in structural materials, methods of design, and construction techniques constantly change the application of such principles to the building of buildings, and require frequent reassessment of the field of construction.

As one starts revising a book such as this it becomes obvious that virtually every page requires clarifications, additions, and updating. Besides innumerable changes of this nature this edition contains:
- A new chapter on structural failures, a topic of increasing concern in our society.
- A new chapter on structural aesthetics, a subject of growing awareness to architects and engineers, that has interested me for many years.
- A new treatment of space-frames for large roofs that have become, because of their economy and beauty, the most popular structures of our time, the world over.
- The first presentation of new techniques for the erection of membrane roofs unsupported by air pressure.
- An updating of structural material properties and construction methods.
- A record of new limits reached in the field of architectural structures.
- Over eighty new or modified figures by the original illustrator, Felix Cooper.

The intuitive and descriptive presentation is unchanged from that used in previous editions; irrespective of background, the book can be understood by anyone interested in why buildings stand up.

The structural concepts presented here were formerly introduced mathematically to graduate students of the School of Architecture at Princeton University and, later, to students of the graduate School of Architecture at Columbia University. The same concepts have been presented without mathematics to freshmen in architecture at Columbia, with the help of the models and motion pictures of my friend Robert Heller. Professor Heller did not participate in the preparation of this edition, and the changes and new material are solely my responsibility.

I hope that my latest efforts will meet with the same favor accorded previous editions throughout the world.

My deep gratitude goes to
- my former collaborator, Dr. Robert Heller, for his help in conceiving the original illustrations and for his constructive suggestions;
- my teachers at the Faculty of Pure Mathematics of the University of Rome, who made mathematics part of my mental makeup and allowed me to move beyond it;
- Charles R. Colbert, the former dean of the School of Architecture at Columbia, for encouraging me to try this intuitive approach to structures;
- to Felix Cooper for drawing the illustrations;
- to Tim McEwen of Prentice-Hall for suggesting that I prepare this revised edition;
- to all my friends for their interest and support during the relatively brief but intense period when the thoughts accumulated in years of study became this book;
- to my wife, Carol, who stood by me from the time this book was first conceived to the day I corrected the proofs of this present edition.

New York

Mario Salvadori

This book is joyfully dedicated to my architectural students who for thirty years taught me how to teach structures.
Like many disciplines, the knowledge base of structures is rooted in fundamental concepts that apply at all levels of understanding. The first five chapters of this book introduce those essential principles upon which all the later chapters are developed. Chapter 1 discusses the basic idea of structures and the relationship between architects and engineers, while Chapter 2 describes the types of forces (loads) that structures must resist, and the relationship to building codes that prescribe them. Chapters 3 and 4 present the basic properties of materials used in construction and the basic conditions required for structures to exist, while Chapter 5 illustrates the essential types of behavior that structural elements are subjected to.

1.1 WHAT IS STRUCTURE?
It can be argued that the essence of a building is structure, for no physical object, whether built or natural, can exist but for the structure that gives it form (Figure 1.1). Without the structural armature of our bones, we would be like jellyfish or octopi, slithering on the ground going about our daily business. It is the structure of its wood fibers that enables the tree to stand, just as it is the structure of the bridge that enables it to span a river. The difference between the two is merely that one developed from nature, the other by the will of a human creator. Over the centuries, humanity has come to understand many of the secrets of nature. We have learned how to employ that understanding to a desired end in the creation of structures that meet our specific needs for shelter, commerce, worship, recreation, and transportation.

The purpose of this book is to take the reader on a journey into both becoming aware of the wide variety of built structures in the world and developing an understanding for the key principles that underlie them. The complete engineering design of a structure is normally a complex undertaking, especially for larger structures. It requires an ability to mathematically model forces that exist in response to the loads that the structure may experience during its useful life, and the proportioning of materials to resist those forces. Nevertheless, it is entirely possible to arrive at a very strong intuitive understanding of structural behavior and materials with little or no math. This text presumes no formal training in advanced mathematics, and so it is well suited for beginning students of architecture, as well as practitioners who need a refresher, or the serious lay student seeking to understand more about the subject. As such it can serve as a good preparation for the undertaking of more advanced study in the principles of engineering structures.

1.2 STRUCTURE IN NATURE
The place where we first and most directly encounter structure is not in architecture but within nature herself. Every living thing, from the smallest cell to the tallest tree, has a structural form that is shaped in direct response to the forces of its environment, such as gravity, water pressure, and wind. Other natural structures serve the needs of their builders. The spider’s web is built of the arachnid’s own secretion. The bee’s geometrically precise honeycomb and the beaver’s dam could not be better constructed by humans.

Each of us therefore has an innate understanding of structures at a very subliminal level because our very bodies are structure. We physically sense the pull of gravity and intuitively know to widen our stance and lean into a strong wind, for example. Capitalizing on this, we can use our own bodily sense and a growing awareness of structural forms in nature to help understand how built structures are designed and constructed.

The shape and proportions of a structural form are significantly a matter of scale (Figure 1.2a-c). We can observe that the branching pattern of a dandelion stalk is far more
slender than if the plant were enlarged to the size of even a small bush, never mind a large tree. This is due to the fact that the amount of material increases by the cube of its size and yet the pull of gravity is essentially constant. This is to say that the doubling in size of an object or organism increases its volume by a factor of not two or four, but by eight times. An ant is known to be an organism that can carry a load many times its own body weight. Enlarge it to the size of an elephant, and the spindly legs of the ant, even if proportionally enlarged, would no longer be sturdy enough to even support itself despite how appropriate the form may be at its natural size (too much for 1930s science fiction films!).

We can therefore look to nature as an aid in our quest to understanding the behavior of human-created structures. Consider a tree branch (Figure 1.2c). It is essentially a cantilever, which is a beamlike element that is supported only at one end (see Chapter 7). Notice how the tree branch is thickest where it meets the tree trunk... this is also the place where the internal stresses of the wood fibers must resist at their highest value for the branch. As a consequence, more material is needed here to resist these stresses. We can similarly look to the behavior of natural materials, many of which, such as wood and stone, we use in our constructed buildings. Hair is an example of a material that can have a high degree of ductility—it can be pulled and stretched somewhat before it breaks. A blade of grass, though exhibiting some ductility, will snap much more readily when pulled. These are but a few of the engineering properties of materials that will be discussed at length in Chapter 3, Structural Materials.

1.3 THE ARCHITECT AND THE ENGINEER

Architects interact with numerous specialists in the creation of a building, many of whom are engineers. It is helpful to gain a perspective of the variety of engineering disciplines and understand the role that these professionals play in relation to architects. At its basis, engineering is the art of creation in the service of a desired end. By employing known principles of science and properties of materials, there are many branches of engineering that work with, and even within individual branches there are sub-specialties.

Civil engineering is a very broad discipline, which encompasses a wide range of sub-specialties. These include individuals responsible for site design (addressing land surveying, site grading, drainage, and parking); transportation engineers who design highways and other transit systems; environmental engineers who focus on the treatment processes to provide clean water and dispose of waste; fire protection engineers who focus on the safety of structures against fire hazard; and geotechnical engineers who specialize in the analysis of the soil and rock that buildings are built upon.

Electrical engineers are responsible for the design of systems to electrically power buildings, as well as the internal distribution of power to lighting, electrical outlets, and machinery. There are also electrical engineers with whom architects typically have little interaction, including those who are responsible for the large-scale generation of power and distribution through the "power grid" on a regional scale, and electronics and computer engineers who design the "high-tech" systems of the modern world.

Mechanical engineering is another particularly broad discipline. Some mechanical engineers design automobiles (automotive engineers) or airplanes (aerospace engineers), while others create the machinery that we are all familiar with in our daily lives, such as kitchen appliances and household utilities. The types of mechanical engineers that architects most frequently interact with are those who design the heating, ventilation, and cooling systems in buildings, as well as elevators and escalators.

The most important branch of engineering in relationship to the subject of this book is yet another sub-specialty of civil engineering, the structural engineer. Structural engineers, as the name implies, are responsible for the creation of safe structures. This includes those who design bridges and other highway structures, as well as those whose main focus is on the design of building structures. The subject of this book is fundamentally focused on the principles that underlie the profession of structural engineering.

What distinguishes engineers from architects? How do engineers think? The popular stereotypical image of an engineer is the introverted nerd lacking social skills with thick-rimmed glasses and a pocket protector. Although there may be some who fit this description, the truth is actually far from the reality. Engineering, in fact, is a very creative process and, fundamentally, engineers are problem solvers. It is actually rather difficult to lump engineers into one class, because there are so many branches of engineering. Many engineers are the types who enjoy logic puzzles, or the need to put together something work and other intellectual challenges. A good percentage are tinkerers who like to work with their hands. If any generalization can be made, it is that all good engineers excel at rational problem solving.

So how do architects think in contrast to engineers? In many regards, architecture is among the last of the great humanist fields of study. Whereas engineers are most often specialists within their given field, architects are generalists who learn to see the big picture. A good architect must have a basic understanding of each of the many disciplines needed to construct a building. Architecture spans across many levels, from the most sublime sculpting of form and manipulation of such intangibles as light and shadow, to the social responsibility of the project at an urban scale, to the physical realization of building construction. With the increasing complexity of the world, and increasing recognition of the role that buildings play in our environment, a good architect is called on like never before to be conversant in the supporting roles of an ever-growing number of disciplines including.

1.4 HISTORICAL DEVELOPMENT

As noted earlier, structure is an essential component of architecture, and has always been so. No matter whether man built a simple shelter for himself and his family or enclosed large spaces where he could worship, trade, discuss politics, or be entertained, humans had to shape certain materials and use them in certain quantities to make their architecture. And so, the gravitational pull of the earth and other powerful forces of nature.

Wind, snow, and rainstorms, earthquakes, and fires had to be resisted. If possible, this was accomplished with expenditures of labor and materials that were not unreasonable in relation to their availability and cost. And because from earliest times a sense of beauty has been innate in humans, all constructions by civilized peoples were also conceived according to certain aesthetic tenets. This often impose on the structure far more stringent requirements than those of strength and economy.

It may be thought, therefore, that structure was always considered important, and, in a sense, dictated architecture. This is simply not so. Magnificent buildings have been created in the past, and are created even today, with a notable disregard for the "correctness of structure." The Parthenon (Figure 1.3), divinely beautiful as it is, translates...
CHAPTER ONE  Structure in Architecture

structural forms typical of wood construction into marble and is, structurally speaking, "wrong." Since wood is a material capable of withstanding tension and compression, and long horizontal elements require both tensile and compressive resistance, they are well built out of wood but much less so of stone.

Stone withstands compression well, but has very little ability to carry tension. Thus, horizontal elements can be built in stone only by reducing their length and supporting them on heavy vertical elements, such as columns or piers. Hence, horizontal elements of stone are "incorrect" from a structural point of view. On the other hand, Gothic cathedrals could span up to one hundred feet (30 meters) and cover hundreds of square yards (hundreds of square meters) crowded with worshippers by making use of the arch—a curved structural element in which tension is not developed. Thus, stone is the correct material for a vaulted type of structure, and the beauty of the Gothic cathedrals satisfies both our aesthetic sense and our feeling for structural strength (Figure 1.4). This precept is echoed in the famous statement by architect Louis I. Kahn when he "asked" a brick, "What do you want to be?" And, metaphorically, the brick replied, "I like an arch," which is a pure compressive structure. Like stone, brick is a material weak in tension, and so structures in which it always remains in compression are the most appropriate form for such materials.

It has been argued by architectural historians, as well as by some structural engineers, that a deep concern for structure will unavoidably lead to beauty. It is undeniable that a "correct" structural system clarifies the eye of even the most unknowledgeable layman, and that a "wrong" structure is often aesthetically ugly. But it would be hard to prove that aesthetics is essentially dependent on structure. It is easy to show, instead, that some "incorrect" structures are lovely, while some "correct" ones are aesthetically unsatisfying. It may perhaps be wiser to say that correctness of structure is, most of the time, a necessary condition of beauty, but is not sufficient to guarantee beauty. Some contemporary architects and engineers, such as Santiago Calatrava and Christian de Portzamparc, or their equally famous predecessors, such as Felix Candela and Pier Luigi Nervi, are so imbued with artistic sense that their structures are beautiful (Figures 1.5a and 1.5b). But some grandiose buildings, recently erected, are full of evidence of lacking technique, undeniably lack beauty.

We may thus conclude that knowledge of structures on the part of the architect is highly desirable, and that correctness of structure cannot add but to the beauty of architecture. But considerations of beauty aside, no architecture can be effectively constructed without consideration of structure, and so the better an architect understands the principles of structure, the more empowered will he or she be to make a positive impact on the design from the earliest stages. Final engineering will then be a confirmation of earlier design decisions, as opposed to a determination of conflicts that must be resolved in order to ensure structural strength and stability, potentially with negative consequences to the original design intent.

FIGURE 1.4  The grain vaults of the magnificent Reims cathedral in northern France are an expression of a "correct" structure. Here, stone is used to its basic ability in compression, with little or no tensile stresses being developed. The stone arches of the grain vaults effectively channel the heavy load of the stone roof out and down to the exterior walls, where further structures on the exterior known as flying buttresses counteract the outward push.

Photo courtesy of Terri Meyer Boeke

1.5 The present interest in architecture

In the recent as well as the ancient past, the figure of the architect was unique: He or she was both an artist and a technologist, a designer, and a builder. Michelangelo could be a painter, a sculptor, an architect, and a master builder: The Vatican in Rome bears his imprint in all four fields. During the last century, however, specialization of knowledge has cut off the field of architecture, and the various functions—once entrusted to the same individual—are now frequently exercised by several different specialists. In the construction team of any important building: the architect and the structural engineer. Today, no architect would dare design a building of even modest size without consulting a structural engineer. The roots of this dependence are to be found in the increasing importance of economic factors, in the technological direction of our culture, and, above all, in our mass civilization's need for an increasing number of all types of structures.

As the number of human beings multiplied at an increasing rate during the last few centuries so as to create a "population explosion," civilized societies have also given each human more services, sharply increasing the "psychological density" of the population. Each one of us requires and is given more schooling, more travel, more medical care, more entertainment. Large numbers of people gather under the same roof for all the gregarious activities so typical of our era. Large stations and airports, large stadia, large theaters, large churches, large arenas appear in increasing numbers. Urban agglomerations require the sprawling of taller buildings. The large structure has become a symbol of our culture and a monument to governments, churches, or corporations. In addition, housing the millions and supplying them with schools and hospitals are among the basic goals of civilized societies.

The architect is challenged by these tremendous tasks; the layman becomes aware of the importance of architecture in his own life. Thus, the specialists meet to solve new, difficult problems in a climate of public interest. The general public whose monies are often used for these large projects takes a personal interest in their construction. This interaction between the specialists and the public may lead to better, and more correct, architecture, provided the layman understands the basic problems of the specialist, and the specialists themselves have a common bond of mutual understanding. This is the central theme of contemporary architectural education, including both the education of the architect and the popularization of architecture.

1.6 Structures and intuition

It is obvious that only the most serious training in mathematics and the physical sciences will allow a designer to analyze a complex structure to the degree of refinement required by modern technology. Today's structural engineer is a specialist among specialists, a subgroups among civil engineers. As new technologies develop, even structuralists specialize: At present some structural engineers specialize in reinforced concrete, others in reinforced concrete roofs only, and some in roofs, only, of a particular shape or even another material such as high-strength fabric. One goes to these specialists for advice on a particular type of structure as one would go to a medical specialist for advice on a rare type of disease.

But it is just as obvious that, once the basic principles of structural analysis have been established, it does not take a specialist to understand them on a purely physical basis. As previously noted, we all have some familiarity with structures in our daily lives: we know at what angle to set a ladder so that it will carry our weight without sliding on the floor; we can have a good sense of how thick a board must be to function as a bookshelf between two supports. We instinctively lean into the wind and widen our stance on a gusty day. It is a fairly easy step to capitalize on these experiences, to systematize such knowledge, and to reach a basic understanding of how and why a modern structure works.
While the layman may find this inquiry fascinating, the architect should find it mandatory: Without it he or she will soon be out of the field of contemporary architecture. For the interested public, it may be one more hobby; for the architectural student and the practicing architect, it is one of the basic requirements of the profession.

Once he or she has grasped the fundamentals, the architect must become conversant with the more refined points of the theory of structures. This will allow the intelligent application of a wealth of new ideas and methods unavailable until a few years ago even to the greatest architects (Figure 1.6). Architecture at its finest incorporates an understanding of structure from the earliest planning stages rather than something that comes after the architectural design is complete. This is only truly accomplished in close collaboration with skilled engineers who understand and share a common vision with the architect.

There is an obvious danger in this new availability and freedom. Art is enhanced by limitations, and freedom may easily lead to anarchy. Since, today, almost any structure can be built, the important question is: "Should it be built?" instead of: "Can it be built?" The architect is less hampered by technological difficulties and may be led astray into the world to the most unjustifiable structures. It is true that the average contemporary architect can aspire to greater achievements in the field of structures than even those of the exceptional practitioner of only a hundred years ago, but such achievements, the fruit of technology, are also obtained through blood, sweat, and tears. In the early decades of the twenty-first century, technological advances have enabled increasingly daring structures (Figure 1.7) that make even the tremendous technological leaps of a few decades ago seem pale (Figure 1.8).

What follows in the subsequent chapters of this book is an attempt to introduce the reader to the field of structures without appealing to a formal knowledge of mathematics or physics. This does not imply that structures will be treated in an elementary, incomplete, or simplified manner. On the contrary, some of the structural concepts presented in the last chapters of this book are refined and complex. Nevertheless, they can be grasped by the reader and recognized in general architectural constructions on a purely intuitive basis. It is hoped that this better knowledge of structural action may lead the interested student to a deeper understanding of the finer points of structural design, and architects to a better facility in embracing structure as a fundamental concept of architectural planning and aesthetic opportunity.

FIGURE 1.6 Contemporary structural analysis software enables visualization of forces in a structure in ways not previously possible. Such technologies enable both the practicing structural engineer and aspiring architect better understand the behavior of increasingly complex structures. The colors in the image are a visual depiction of deformations or stress levels in a structure under load. Photo courtesy of Autodesk, Inc. © 2012

FIGURE 1.7 The Central China Television headquarters tower (CCTV) in Beijing. A stunning example of a gravity-defying structure impossible to construct even a few decades ago, but made possible through contemporary developments in computer-aided structural analysis and advancement in materials and fabrication capabilities. But is it an example of structure built simply because we can? Photo: yun2008/Shutterstock

FIGURE 1.8 The John Hancock Tower in Chicago, Illinois, regarded as an exemplary model of structural efficiency and simple elegance, was designed in an era before advanced computational methods were widely available. Photo courtesy of Deborah Oakley

KEY IDEAS DEVELOPED IN THIS CHAPTER

- Structure is the external or internal armature that gives physical objects form and resistance to external forces.
- Structure may be human-made or natural.
- Built structures frequently imitate nature.

QUESTIONS AND EXERCISES

1. Look around you at the world of your immediate experience. Everything you can see and touch is some form of structure: from the smallest mineral crystal to the largest high-rise building or the longest spanning bridge. Notice what types of materials they are made of, and the different patterns they take. Begin to develop a questioning mind of how and why a structure is made the way that it is. Take notes and draw sketches. Keep a record of these observations.

2. You’ve been living in and around built structures all your life, but have you ever stepped back to really look at the variety of systems comprising this built world? How many different systems and materials do you note in the buildings and structures you interact with every day? Do you see patterns in the types of systems? Are some of them more supportive of the architecture while others seem more utilitarian? The first step in learning structures is to begin to develop this type of awareness.

FURTHER READING