ANGUS J. MACDONALD

Structure & Architecture

THIRD EDITION

ROUTLEDGE

Structure and Architecture

This thoroughly updated edition of Angus J. Macdonald's insightful book *Structure and Architecture* offers an in depth analysis of structural design and its relationship with architecture. It draws on clear explanations of the connections between structural form, structural performance and architectural design to explore the interface between the technical and the visual in architecture. Additional chapters in this new edition cover the fields of structural theory, structural philosophy, the contributions of prominent engineers to the evolution of Modern architecture, and the concept and practice of sustainable design. Fully illustrated, this critical appraisal of structures is a core-curriculum text for students of architecture, structural engineering and architectural history, and is also a valuable resource for practitioners of these disciplines.

Angus J. Macdonald is currently Professor Emeritus of Architectural Structures at the Edinburgh School of Architecture and Landscape Architecture, University of Edinburgh. He has served as Head of the Department of Architecture at the University of Edinburgh, as a Commissioner on the Royal Commission on the Ancient and Historical Monuments of Scotland and as a member of the Board of Governors of Edinburgh College of Art. He is the author or co-author of ten books, including: *Structural Design for Architecture*; *Anthony Hunt: The Engineer's Contribution to Contemporary Architecture*; and *John Fowler and Benjamin Baker: The Forth Bridge* (with I. B. Whyte); as well as book chapters, including 'Structure and Architecture: Tectonics of Form', in Kanaani, M. and Kopec, D. (eds), *The Routledge Companion for Architectural Design and Practice*; and numerous articles on the relationship between structure and architecture.

"This new expanded edition is a welcome update of Professor Macdonald's classic book introducing the principles and application of structural engineering to young architects and engineers. Using both historical and recent examples, with drawings and excellent photographs, he brings the subject alive and provides an invaluable resource. Best of all, he offers readers the material to develop a good understanding of the subject which will serve as a source of inspiration to all designers."

Bill Addis, *author of* Building: 3000 Years of Design Engineering and Construction

"Architecture and engineering are perfectly merged into one, both sensitive and sensible, subject in this splendid new edition of Angus Macdonald's admirable *Structure and Architecture*. Superbly written and precisely pin-pointing the most crucial and essential issues regarding both structural science and structural form and space-making, the present book spans topics ranging from basic structural behaviour to sustainability questions and the history of engineering theory and development in architecture. Angus Macdonald explores this wide field with profound understanding – and genuine love."

Bjørn Normann Sandaker, *Professor of Architectural Technology, The Oslo School of Architecture and Design; Adjunct Professor, Norwegian University of Science and Technology*

"This well-illustrated, fully revised and extended third edition of Angus Macdonald's book should be obligatory reading for those interested in exploring the often complex relationship between structure and architecture. I was impressed by the new reflective chapters deliberating on the philosophy of structures, the influence of engineers on the development of Modern architecture and, in particular, that drawing attention to the significant contribution that appropriate selection of low embodied energy materials and efficient structural systems can make in minimising a structure's impact on global climate change."

John Chilton, *Emeritus Professor, Architecture & Tectonics, University of Nottingham, UK*

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Third edition

Angus J. Macdonald

Routledge
Taylor & Francis Group
LONDON AND NEW YORK

Third edition published 2019
by Routledge
2 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN

and by Routledge
52 Vanderbilt Avenue, New York, NY 10017

Routledge is an imprint of the Taylor & Francis Group, an informa business

First edition published by Architectural Press 1994

Second edition published by Elsevier 2001

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data
Names: Macdonald, Angus, 1945– author.
Title: Structure and architecture / Angus J. Macdonald.
Description: Third edition. | New York : Routledge, 2018. |
Includes bibliographical references and index.
Identifiers: LCCN 2018000717| ISBN 9781138629226 (hardback) |
ISBN 9781138629240 (pbk.) | ISBN 9781315210513 (ebook)
Subjects: LCSH: Structural design. | Architectural design.
Classification: LCC TA658.2 .M32 2018 | DDC 624.1/77—dc23
LC record available at https://lccn.loc.gov/2018000717

ISBN: 978-1-138-62922-6 (hbk)
ISBN: 978-1-138-62924-0 (pbk)
ISBN: 978-1-315-21051-3 (ebk)

Typeset in Caslon
by Florence Production Ltd, Stoodleigh, Devon, UK

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Preface to the third edition

The theme of this book is the relationship between structural engineering and architecture. Its purposes are to provide insights into the role of structural design in architecture, and to offer the reader the key components of the knowledge required to make informed judgements about structure in the critical appraisal of buildings.

The preliminary Chapters (1 to 6) are similar to those in the previous editions and are concerned principally with explaining the properties and behaviour of structures, as a preliminary to the discussion of the types of relationship possible between structural design and architectural design. These chapters have been comprehensively revised and updated, with new illustrations.

Four new chapters have been added in this third edition; these widen the scope of the book to include coverage of the following important topics: structural theory; structural philosophy; the works of prominent engineers of the Modern period; and environmental sustainability.

The intention in these additional chapters is to give an indication of the contribution made by each of these specific topics to the subject as a whole. Each is also intended to demonstrate the breadth and depth of its respective topic, by exploring a limited number of aspects of it in detail. The new chapter on structural theory, for example, closely examines two areas only of this very large field, selected because these allow general conclusions to be drawn about the role and influence of theory on design, and to allow insights into the depth of the subject. Similarly, the chapter on engineers deals with only a very few of the many members of that profession who have made important contributions to the development of architecture in the Modern period, again selected for their particularly significant roles. The final chapter on environmental sustainability is intended to give a general view of this increasingly relevant topic on present and future relationships between structural engineering and architecture.

The book does not attempt to be comprehensive: no single-volume treatment could cover all aspects of this very large field in detail and space limitations have inevitably necessitated many omissions. I hope nevertheless that the book will provide a useful overview of the subject for students and practitioners of both structural engineering and architecture, and also for members of related professions such as urban planning, landscape architecture and architectural history.

Angus J. Macdonald, Edinburgh, July 2018

Acknowledgements

I would like to thank all those who have assisted in the making of this book, in its present and previous editions: colleagues and students, past and present, with whom interesting discussions have taken place over many years, in the stimulating and supportive context of the University of Edinburgh, as well as many other academic and practitioner collaborators on various projects; all those who have contributed, or assisted in locating photographs and illustrations, who are either mentioned below or individually credited where the images occur in the book; and also all those involved in various ways in the making of the book itself.

Special thanks are due to the following: Stephen Gibson for his carefully crafted line drawings for the first two editions, the majority of which are included in this third edition; Andrew Siddall for the additional complex line drawings which he generated for this third edition; Pat Hunt, Tony Hunt and the staff of the picture libraries of Ove Arup & Partners and Anthony Hunt Associates; Thérèse Duriez for picture research for the first edition; the staff of Architectural Press (formerly Butterworth-Heinemann) for their hard work and patience in initiating, editing and producing the earlier editions, particularly Neil Warnock-Smith, Hilary Norman, Diane Chandler, Angela Leopard, Sián Cryer and Sue Hamilton; and, for this third edition, Fran Ford and the teams at Routledge/Taylor & Francis and Florence Production.

Thanks are due most particularly to my partner in several senses of the word, Patricia Macdonald, for her continued encouragement and for her expert assistance and scrutiny of many aspects of the text and illustrations.

Introduction

This book on architectural structures seeks to provide the reader with both the technical background required to appreciate the role of structure in architecture and a discussion of all aspects of this role, including the contribution of structure to architectural form and style and its importance in relation to questions such as environmental sustainability. The intention is to give insights into both the methodology of structural engineering in relation to architecture and its historical development.

Space does not permit that any of the topics be covered comprehensively. For example, the works of only a small number of the many engineers who have contributed prominently to Modern architecture have been included – chosen for their particular significance. Similarly, the discussion of structural theory covers only a few small aspects of that topic, again selected to allow broad conclusions to be drawn concerning the role of theory in the building process as a whole, and to give insights into its depths. The relationship between built form and environmental sustainability now influences every aspect of structural and architectural design and is discussed where relevant throughout the book. In addition, crucial aspects of the topic are considered in a separate chapter, but the coverage is necessarily limited and of a general nature. There are therefore many omissions, made necessary by the attempt to cover the full breadth and depth of a very large field. It is hoped that the book will nevertheless give the reader a wide appreciation of the particular contribution that structural engineering makes to architecture in all of its forms.

It has long been acknowledged that an appreciation of the role of structure is an attribute that is essential for the development of a proper understanding of architecture. It was Vitruvius, writing at the time of the founding of the Roman Empire, who identified the three basic requirements of architecture as *firmitas*, *utilitas* and *venustas* and Sir Henry Wotton (Wotton, 1624, 2013), in the seventeenth century, who translated these as 'firmness', 'commodity' and 'delight'. Subsequent theorists have proposed different systems by which buildings may be evaluated, their qualities discussed and their meanings understood but the Vitruvian ontology nevertheless still provides a valid basis for the examination and criticism of a building.

In the present day the question of which of the three Vitruvian qualities is the most important is controversial. For some, a building cannot be considered

Facing page:
L'Oceanogràfic, Valencia, Candela/Calatrava. Photo: Sebastian Weiss.

to be satisfactory unless it fulfils its utilitarian functions well in respect of firmness and commodity. From such a viewpoint, there cannot be delight without well-designed structure and a set of spaces that function well for the intended purpose of the building. For others, these mundane functions are of secondary importance in relation to the aesthetic agenda which is considered overwhelmingly to be the source of delight. For much of the Modern period the latter view has tended to dominate architectural discourse and, as a consequence, many of its best-regarded buildings perform poorly in respect of firmness and commodity.

It is not the intention of this book to enter into the controversy that surrounds the relative importance of the three Vitruvian virtues but simply to offer criteria by which the structural qualities of a building – the basis of 'firmness' – may be judged. To be in a position to make such judgements the critic or observer must know something of the structural make-up of the building. This requires an ability to read a building as a structural object, a skill that depends on a knowledge of the functional requirements of structure and an ability to distinguish between the structural and the non-structural parts of the building. These topics are discussed here in Chapters 1 to 6.

Traditionally, the primary consideration, so far as the purely technical performance of a structure is concerned, was that it should fulfil its function with maximum economy of means in three respects: efficiency in the use of material, ease of construction and long-term durability. In this view, a structure should contain no more material than is necessary; it should be no more difficult to design and construct than is necessary and it should not require that excessive amounts of maintenance be carried out in order that it can continue to function adequately for its intended purpose. A recent addition to these traditional objectives, which arises from the increasing need for buildings to be designed for sustainability, is the requirement that a structure should not unduly disrupt the ecosystem in which it is placed. It should, in other words, have some of the qualities of a living organism, particularly with respect to its consumption of energy and materials and its suitability for recycling or re-use. All of the above desirable qualities are affected by the form that is adopted for the structure.

Perhaps the most fundamental consideration in relation to structural performance is with the relationship between structural form and structural efficiency. As is explained in Chapter 4, the principal single factor that affects this is the overall form of the structure in relation to the pattern of load that it supports, because it is the relationship between form and load distribution that determines the type of **internal force** that occurs in structures: axial-type internal forces can be resisted much more efficiently than those that derive from bending. In the case of architectural structures, which predominantly involve horizontal spans carrying distributed gravitational loads, the shapes that produce axial rather than bending-type internal forces are curvilinear – arches, domes, vaults, cable nets, fabric tents. These are the most efficient forms. The straight, horizontal spans of rectilinear frameworks produce predominantly bending-type internal forces that result in an inefficient use of structural material. Where, as is frequently the case, it is not practicable to adopt a curvilinear form, the efficiency of straight-sided arrangements can be improved by the use of complex cross-sections, such as the I-form or box beam, or by other devices such as triangulation of the internal geometry. The reasons for this are also explained in Chapter 4 where a classification system for structures is suggested. The fact that the performance of a structure is to a large extent determined by its form means that it is possible to make a meaningful assessment of its suitability from a purely visual inspection of its make-up. This technique of assessment is explained in detail in Chapters 4 and 6.

One of the most significant aspects of structural behaviour is that high efficiency requires high complexity: curvilinear forms are more efficient than those that are straight-sided; complex cross-sections are more efficient than solid circles or rectangles. Most structures involve a compromise between complexity of form, which improves efficiency, and simplicity of form, which makes design, construction and maintenance easier, and one of the most interesting aspects of the design of any structure is the nature of the compromise that has been achieved.

In making a judgement concerning the suitability of a chosen structural arrangement for a particular application, the important question is whether or not the level of complexity that is present is appropriate; whether or not the particular compromise that has been adopted is sensible, in other words. The various factors that influence this question are discussed in Chapter 6 where it is shown that the most important of these is *span*: the larger the span, the greater is the level of efficiency that is necessary and therefore of complexity that can be justified. Thus, large-scale enclosures usually involve the use of spectacular curvilinear forms or complex triangulated arrangements while those of modest scale are generally supported by simple, but inefficient, post-and-beam frames of various kinds. High complexity is rarely justified technically for structures of short or medium span. These, and other factors that influence the selection of structural form, are the subject of Chapter 8.

In the context of architecture, where the question of 'delight' becomes a major consideration, the relationship between structural design and architectural design can take many forms and the selection of structure type for a building is often influenced by the requirements of appearance and aesthetics rather than simply by technical performance. The role of structure can range from that of simply an agency that provides support for a building and whose visual qualities are of no particular significance, to one in which the structural elements contribute symbolic meaning and expression of various kinds to the architecture. This possible architectonic function of structure is discussed in Chapters 8, 9 and 10.

It is possible for an architect virtually to ignore structural considerations while inventing the form of a building and to conceal entirely the structural elements in the completed version of the building. Many buildings of the Modern period fall into this category, for example, the Walt Disney Concert Hall in Los Angeles (2003) by the architect Frank Gehry (Figures 0.1 and 0.2) and the Glasgow Transport Museum building (2012) by Zaha Hadid (Figures 1.9, 1.10, 10.25 and 10.26). Buildings such as these contain a structure but the technical requirements of the structure have not significantly influenced the form that has been adopted and the structural elements themselves are not direct or visible contributors to the aesthetics of the architecture. Structures that have been evolved in this way rarely perform well when judged by technical criteria. At the other extreme it is possible to produce a building that consists of little other than structure and where structural considerations

Figure 0.1 Walt Disney Concert Hall, Los Angeles; Frank Gehry (1929–), architect. An example of Late-Modern 'Digital Architecture'. The form of this building was little influenced by structural requirements.

Photo: Jon Sullivan/Wikimedia Commons.

have dominated the design. The masonry vaulted enclosure system that is under development by Afrotech and Foster & Partners for use in Africa as a terminal for a medical supply facility operated by drones is an example of this (Figure 0.3). Between these extremes many different approaches to the relationship between structure and architecture are possible. In the early Modern buildings of Walter Gropius, Ludwig Mies van der Rohe (Figure 0.4), Le Corbusier and others, the forms that were adopted were influenced by the types of geometry that were suitable for steel or reinforced concrete structural frameworks. In these cases structure and architecture were allowed to develop together. In another approach, structure can be allowed to dominate the appearance of a building for stylistic reasons and this often leads to the selection of a particular type of structure from consideration principally of its visual qualities rather than its technical performance – something that was common in the work of the so-called High-Tech architects of the late twentieth century (Figures 3.19, 9.28 and 10.7). As is discussed in Chapter 10, the relationship between structure and architecture can therefore take many forms and it is the purpose of this book to explore these against a background of information concerning the technical properties and requirements of structures.

Figure 0.2 Walt Disney Concert Hall, Los Angeles; Frank Gehry (1929–), architect. The supporting structural steel framework is highly inefficient. The overall cost of the building was $274 million, compared to $190 (equivalent) for three other halls on the same site that were built in the 1960s with conventional post-and-beam structures.

Photo: Cygnusloop99/Wikimedia Commons.

Figure 0.3 Droneport Prototype Building; Norman Foster Foundation, architects; Ochsendorf, De Jong and Block, engineers. The principal element of this building is a self-supporting (and therefore structural) multi-bay vaulted enclosure constructed from compressed earth bricks. Structural requirements have strongly influenced the choice of form and materials.

Photo: Sonia Millat/Foster & Partners.

Figure 0.4 Farnsworth House, Illinois, 1951; Mies van der Rohe (1886–1969), architect. This building is supported by a rectilinear steel framework structure. The form is appropriate in the context of an industrialised society and for the span involved.

Photo: Victor Grigas/Wikimedia Commons.

Whatever the relationship between structure and architecture, the form of a structural armature is inevitably very closely related to that of the building that it supports and the act of designing a building – of determining its overall form – is therefore, consciously or unconsciously, also an act of structural design. The potential conflict between the visual aspects of a work of architecture and the purely technical performance of its structure is one of the most controversial aspects of the relationship between structure and architecture and is particularly relevant in the context of design for environmental sustainability. The debate is often diminished by a degree of misinformation, or even simply a lack of understanding of structural principles, by the participants and this is one of the problems of architectural interpretation that it is the intention of this book to address. The author hopes that the book will be found useful by architectural critics and historians as well as by students and practitioners of the professions concerned with building.


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CHAPTER 1

The relationship of structure to building

The simplest way of describing the function of an architectural structure is to say that it is the part of a building that resists the loads that are imposed on it. A building may be regarded as simply an envelope that encloses and subdivides space in order to create a protected environment. The surfaces that form the envelope, that is the walls, the floors and the roof of the building, are subjected to various types of loading: external surfaces are exposed to the climatic loads of snow, wind and rain; floors are subjected to the gravitational loads of the occupants and their effects; and most of the surfaces also have to carry their own weight (Figure 1.1). All of these loads tend to distort the building envelope and to induce it to collapse; it is to prevent this from happening that a structure is provided. The function of a structure may be

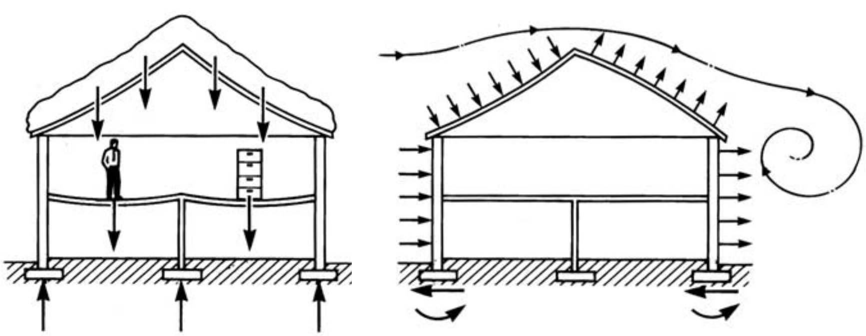

Figure 1.1 Loads on the building envelope. Gravitational loads due to snow and to the occupation of the building cause roof and floor structures to bend and induce compressive internal forces in walls. Wind causes pressure and suction loads to act on all external surfaces.

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Pantheon, Rome. Painting: Panini.