Bill Addis (Ed.)

CONSTRUCTION HISTORY SERIES

PHYSICAL MODELS

Their historical and current use in civil and building engineering design

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in civil and building engineering design

Edited by Bill Addis

Ernst & Sohn
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edited by Karl-Eugen Kurrer and Werner Lorenz

Coverphotos (clockwise order):
Model, 1:30 scale, of the 15-storey Alexander Building, made by John Blume and Harry Hesselmeyer, 1932-33. (Image: John A. Blume Earthquake Engineering Center, reproduced by permission)

Soap-film model for the sports hall, Jeddah (end view, using parallel light). (Image: Courtesy of Institute of Lightweight Structures, Stuttgart)

Model test for a proposed monocable suspension bridge for a bridge over the Rhine at Emmerich, 1961. Designed by Fritz Leonhardt and tested at MPA Stuttgart. (Image: Südwestdeutsches Archiv für Architektur und Ingenieurbau, Karlsruhe; Fritz Leonhardt collection)

Water-bath model for Aldwyck Housing Group HQ, Houghton Regis, UK. (Image: Breathing Buildings)

Study of wall profiles in cinemas, 1930. (Image Archive, ETH Library Zurich)

University Library, Basel, 1964. 1:20 scale model in acrylic resin. (Image: Heinz Hossdorf)

1:37.5 scale celluloid model of the reinforced-concrete hangars (first version) designed by Pier Luigi Nervi, tested at the Politecnico di Milano, 1935-36. (Image: ISMES Historical Archive)

1:50 scale acoustic model for the concert hall in the Krakow Congress Centre, Poland. (Image: Ingarden and Ewy Architects)

1:50 scale model of the Thames Surge barrier to study the effectiveness of measures for protecting the river bed. (Image: Courtesy of HR Wallingford).

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Foreword of the series editors

Construction history has experienced amazing momentum over the past decades. It has become a highly vibrant, independent discipline attracting much attention through its international networks. Although research projects at national level focus on different themes, they are united through the knowledge that their diversity in terms of content and methods, and hence the associated synthesizing potential, are precisely the strengths that shape this new field of research. Construction history opens up new ways of understanding construction between engineering and architecture, between the history of building and history of art, between the history of technology and history of science.

Since Galileo's time, engineers and architects have been using physical models to build bridges between the conceptual design of engineering structures on the one hand and their detailed design on the other. As editor and one of the authors of the present volume of the *Construction History Series/Edition Bautechnikgeschichte*, Bill Addis has gathered together contributions by authors from very diverse backgrounds, different countries, to demonstrate the vital role that physical models play in the design of engineering structures. The authors' multi-method approach not only offers a fascinating and comprehensive insight into the historical development of building and civil engineering, but also enhances our perception of the changing relationship between experiment and theory in times of paradigm shifts in the aforementioned fields of historical research.

Karl-Eugen Kurrer and Werner Lorenz
Series editors

Foreword

The art of devising and capturing geometrical parameters is an essential part of architects' and engineers' daily working lives. In fact, no structures can be designed without it. The problem is that the individual components of many modern structures are subject to complicated internal stresses triggered by external loads from the wind, earthquakes and a range of other potentially complex phenomena. Building up a precise, scientifically rigorous picture of these loads and the internal stresses and deformations that arise as a result (such as the deflection of a bridge when a train travels over it) is certainly no easy task. Indeed, predicting the stresses and deformations experienced by structures and their components via purely theoretical means is, at best, only sufficient for anticipating general trends and cannot provide the precision necessary for reliable structural calculations. For this reason, both architects and engineers have long used models to help them with their plans. 'Models', in this context, are defined as physical or mathematical representations that demonstrate one or more specific properties of a structure. For example, a model of a load-bearing construction will display its structural and deformation characteristics, but not the acoustic qualities of the design in question.

Mathematical models of selected slices of reality stand out thanks to the high, comprehensive levels of precision they achieve in the predictions they produce. This is one of their great strengths. Of course, the accuracy of these predictions is dependent on the quality of each model's design. In comparison with their physical counterparts, mathematical models are also at a disadvantage when it comes to clarity and intelligibility: they typically give their results in two-dimensions and, as such, lack the potential for tactile exploration offered by three-dimensional representations. This tangibility is one of the main benefits of physical models and – alongside the consideration that they are relatively quick and easy to make – is precisely the reason why they continue to play such a central role in design processes in all branches of building and civil engineering today. Indeed, physical models are still used to grasp the key behavioural properties of a construction or engineering system at speed and to make initial optimisations before mathematical models are brought in to help generate the final result.

For hundreds of years, architects and engineers have depended on physical models for developing optimal constructions and determining the stresses and deformations experienced by entire structures and their constituent parts.

Since the late nineteenth century physical models have also played a major role in hydraulic, seismic, acoustic and wind engineering. In fact, for a long time, physical models have ranked alongside empirical knowledge as cornerstones of the construction industry, especially when new structures and novel materials were being included in designs. As a consequence, a huge range of different modelling techniques were employed from the days of the mason's lodges at Gothic building sites right up to the mid-twentieth century. In spite of their tremendous significance for the development of construction as a discipline overall, however, these creations have never been comprehensively described, classified, categorised or placed in a historical sequence. That is, at least, not until the publication of this book, which represents the very first time such a feat has ever been achieved. Even this simple fact alone is enough to make it a crucial, foundational text that will doubtless soon become an essential reference work for students and professionals in the fields of architecture, building and civil engineering alike.

Professor Werner Sobek
Institute for Lightweight Structures & Conceptual Design (ILEK)
University of Stuttgart

Preface

Both historical and current civil and building engineering are often considered in terms of the practical skills of using materials to construct artefacts, and the theoretical tools used to calculate and predict their engineering behaviour before construction begins. So often one hears talk of the theory and practice of engineering. Yet there is more to engineering than this.

Many books have dealt with the historical development of the practical aspects of construction – the history of canals, of dams, of bridges, of masonry structures, of iron construction. Many others have dealt with the history of engineering science and theory – the equations of fluid flow, the statics and equilibrium of structures, the elasticity of materials, the curious behaviour of soil, the reverberation and absorption of sound in a room.

I have long argued that there is a crucial third strand of engineering skill that is equally deserving of historical study – the skill of design. I have argued that design comprises two main activities or outcomes: to convey the designer's ideas to the people who will build an engineering artefact; and to provide the confidence that the proposed design will perform as wished by the client, and as intended by the designer [1].

Over centuries, the first outcome has been achieved by means of drawings, geometrically-faithful models at reduced scale, material data, design rules and codes of practice, and various types of performance specification specific to particular engineering disciplines.

The second outcome, providing the confidence to build, one might call it, has been achieved in simple ways such as following precedent, or learning from the experience of what was not successful. It has also been achieved in more sophisticated ways including making and testing a full-size prototype structure[1] or a reduced-scale model of an engineering construction, and the use of theories of engineering science. Today this might be described as reducing risk to an acceptable level.

The history of engineering design, then, comprises histories of the various ways that engineers have communicated their designs, and how they have provided

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[1] In UK English it is always awkward to have to refer to a full-size, or full-scale, or actual or real structure. In American English, the word 'prototype' is used, which is much easier. However, in UK English this word means making the first few examples of a product that later goes into batch- or mass-production. In this book the UK English terms are used, despite their awkwardness.

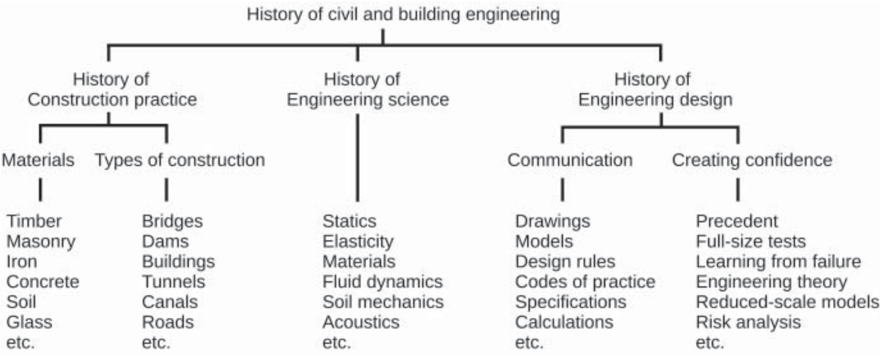

Figure 1 Diagram showing the scope of civil and building engineering history.

sufficient confidence in their designs to persuade clients to fund their projects and contractors to build them [2].

Using these ideas we can build up an overall picture of the history of civil and building engineering which also indicates where the subject of this book fits into the grand scheme (Figure 1). This diagram also provides an epistemological framework for engineering knowledge, applicable equally to the modern practice of civil and building engineering as to the history of the subject. For this reason, it also has consequences for the nature of progress in these fields. When considering the mechanism(s) by which progress is achieved, according to the idea that engineering is a matter of putting theory into practice, it is common to imply that progress occurs as a consequence of developments and progress in engineering science. However, this is patently wrong: there are no significant examples of progress in civil and building engineering construction that have arisen entirely as the result of progress in engineering science. Furthermore, there are countless examples of progress in engineering science that arose out of construction practice. Most progress has been symbiotic, with ideas and experience passing between the two with equal intensity in both directions. Reduced-scale models have often been the essential catalyst to the process, providing the only means by which the practical and theoretical worlds are brought together.

This book is devoted to the use of reduced-scale models, especially in the design process for civil and building engineering projects to help raise confidence in a proposed design. While the testing of full-scale prototypes is common in other engineering disciplines, the sheer size of construction projects generally prohibits full-scale testing. Faced with this constraint, making and testing a model is an intuitive thing to do, and surely goes back thousands of years for artefacts made from the traditional materials – timber, mud and masonry. One advantage of masonry construction is that the structural behaviour of a small model can be scaled up linearly to full size, and give reliable guidance. This is why masonry construction was able to make such dramatic progress from modest houses to the temples of Ancient Greece, the vaults and domes of Ancient Rome and then to the remarkable cathedrals of the Gothic era. However, most engineering phenomena cannot be scaled up linearly, and engineering theory is needed to transpose the results of small-scale tests to full-size behaviour. There was some understanding of this even in ancient Greece, and Vitruvius mentions that some aspects of model behaviour can be scaled up linearly, while others cannot (see Appendix A1).

This book has two main aims – to fill a gap in the history of construction by demonstrating the essential contribution to engineering progress made by physical models, and to give an overview of some uses of physical models in the twenty-first century. The greater part of the book looks at the history of using physical models and within this theme, the larger part is devoted to the use of models in structural and bridge engineering and some mechanical engineering fields such as pumping water. This partition largely reflects when and how models have been used in engineering design and also the availability of historical material. The first three sections look at mechanical and structural models from ancient times to around 1980, by which time their use was in decline as computers became more powerful and widely available. The next section deals with the use of models in engineering disciplines other than structural engineering – measuring the flow and forces associated with fluid flow in hydraulic engineering and wind tunnels, the loads and dynamic response cause by seismic events, the acoustical characteristics of buildings and the behaviour of soils under load. The final section takes a look at current practice in using physical models today in several branches of civil and building engineering.

The main focus of attention in the book is on physical models used by engineers to determine quantitative data – for example predicting wind loads on a building using a model in a wind tunnel. In German the word '*Messmodell*' is a convenient term that distinguishes this type of physical model from others that are merely mechanical or 'proof of concept' models or geometrically representative. Where appropriate, this book uses the term '*measurement model*' – a direct translation of the German word – for this purpose.

Despite being a large book, it has only scratched the surface of this enormous subject. Nearly every chapter would merit the more thorough attention of several doctoral students. I have not attempted to present the first instance of each model-testing technique, nor to cover every field of civil and building engineering that has made use of models, nor to look at the use of models in experimental science with purely scientific aims, nor to present the model-testing efforts of every country. The focus of the book has been on the use of models to inform engineering design, and it uses examples wherever it has been possible to find them. While aiming to provide an overview of the whole subject, I am aware of the unintentional biases that have pervaded my own researches due to the libraries I have been able to use, the relatively few languages that I speak, and the cultural filtering of information via the non-egalitarian Internet. I have done my best to overcome these challenges.

I would like to acknowledge the assistance I have been given in compiling the book – first, and most of all, from the authors, many of whom have squeezed the work required for their chapter into very tight work schedules. I would also like to thank the authors of Chapters 3, 4, 11, 13, 16 and 19 for the help they gave me in translating their contributions from their original languages. I would like to thank colleagues and library staff in several universities and the Institution of Structural Engineers in London for the help they gave me. I give special thanks to Annette Ruehlmann in the Institution of Civil Engineers in London, who found many sources and scanned many images for me. And finally, I give my heartfelt thanks to my partner, Martine Gowie, who has been very patient while I have written and compiled the book, and who has been such a great supporter of my project, in so many ways.

Before delving further into the book, it is worth shedding any idea that the model testing discussed in the book, especially since the mid-nineteenth century, is mainly a lot of (usually) men playing with toys. Even though two articles in a 1920s popular-science journal about model tests for the Boulder Dam were informative and 'serious', their titles portrayed a rather different image – 'Toys that save millions' and 'Toy dams to save lives'! The care and accuracy with which model tests were carried out was extraordinary – often measuring strains or deflections to a hundredth of a millimetre or better. They were no more 'playing' than when brain surgeon is at work. Nevertheless, even in the 1930s, there were engineers who scorned model testing – 'a vet would hardly be entrusted to operate on an elephant if he had gained his knowledge of anatomy from a mouse'. On the other hand, another engineer noted that you can learn a lot about the behaviour of dogs by observing puppies. It is to be hoped that this book will clarify matters.

Bill Addis
May 2020

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