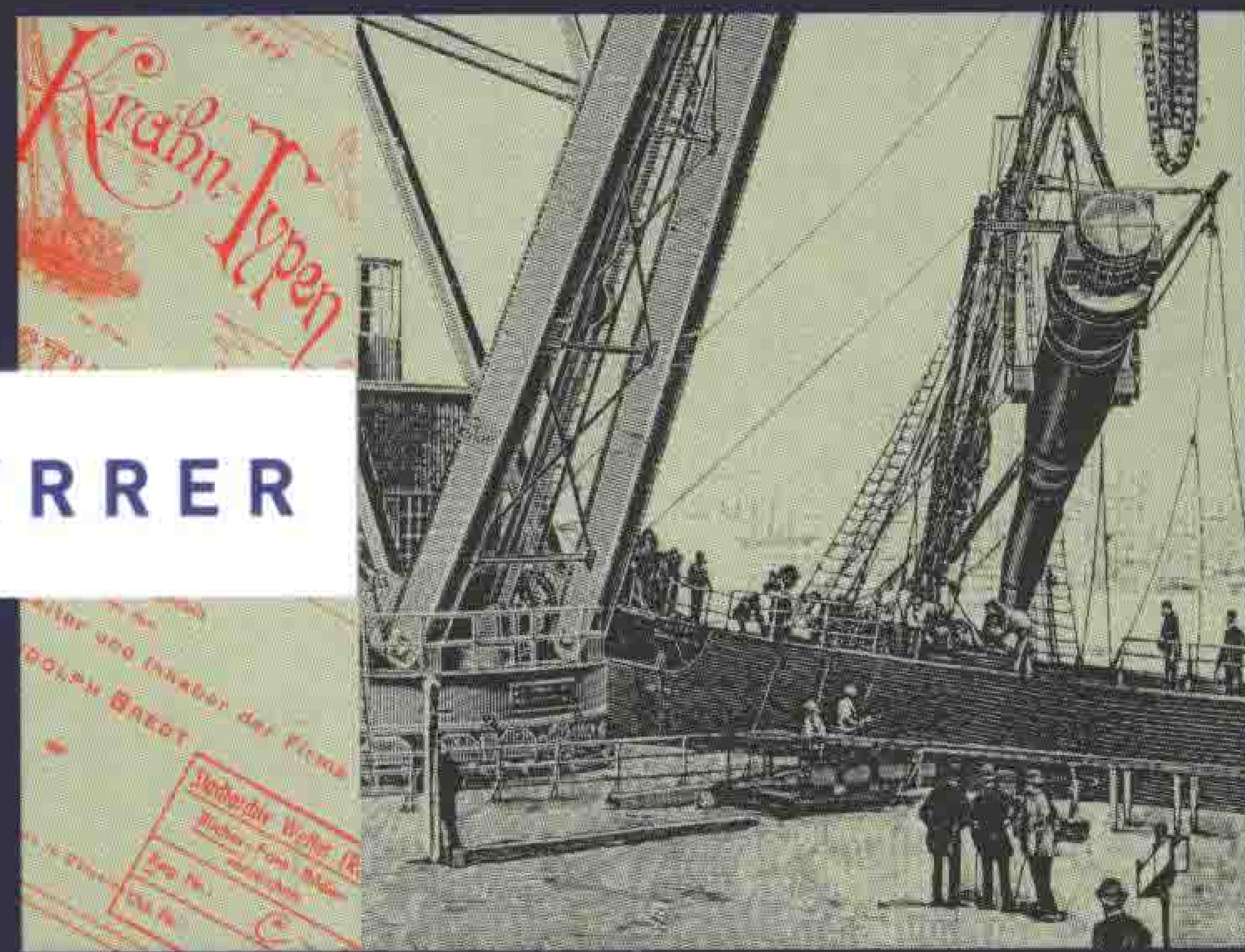
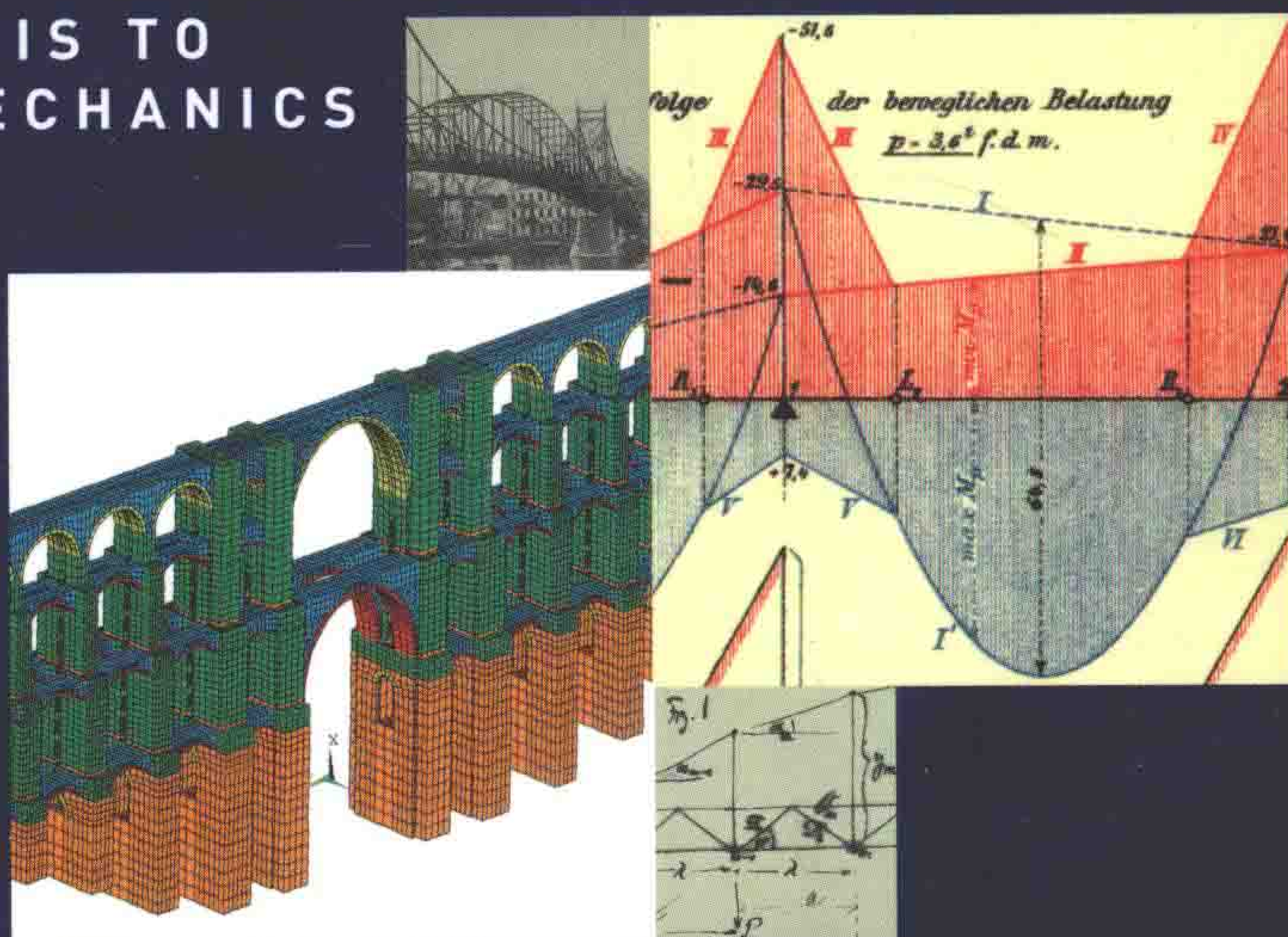
KARL-EUGEN KURRER



THE HISTORY OF THE THEORY OF STRUCTURES

FROM ARCH ANALYSIS TO COMPUTATIONAL MECHANICS



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The History of the Theory of Structures

From Arch Analysis to Computational Mechanics

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THE HISTORY OF THE THEORY OF STRUCTURES

FOREWORD

The title of the book alone makes us curious: What is "theory of structures" anyway? Used cursorily, the term describes one of the most successful and most fascinating applied science disciplines. But actually, you can't use this term cursorily; for this is not just about theory, not just about methods of calculation, but rather those fields plus their application to real loadbearing structures, and in the first place to the constructions in civil engineering. Languages sometimes find it difficult to define such a wide field rigorously and, above all, briefly; in the author's country, the term *Baustatik* (literally "building statics") has acquired a widely accepted meaning, even though that meaning is also too narrow. And even the English expression "structural analysis" does not tell the whole story precisely because this is not just about analysis, but about synthesis, too, the overall picture in the creation of a loadbearing structure.

Right at the start we learn that the first conference on the history of theory of structures took place in Madrid in 2005. This theme, its parts dealt with many times, is simply crying out for a comprehensive treatment. However, this book is not a history book in which the contributions of our predecessors to this theme are listed chronologically and described systematically. No, this is "Kurrer's History of Theory of Structures" with his interpretations and classifications; luckily – because that makes it an exciting treatise, with highly subjective impressions, more thematic than chronological, and with a liking for definitions and scientific theory; indeed, a description of the evolution of an important fundamental engineering science discipline with its many facets in teaching, research and, first and foremost, practice.

The history of theory of structures is in the first place the history of mechanics and mathematics, which in earlier centuries were most definitely understood to be applied sciences. K.-E. Kurrer calls this period up to 1825 the preparatory period – times in which structural design was still dominated very clearly by empirical methods. Nevertheless, it is worth noting that the foundations of many structural theories were laid in this period. It is generally accepted that the structural report for the retrofitting works to St. Peter's Dome in Rome (1742/43) by the *tre mattematici* represents the first structural calculations as we understand them today. In other words, dealing with a constructional task by the application of scientific methods – accompanied, characteristically, by the eternal dispute between theory and practice (see section 11.2.5). These days, the centuries-old process of the theoretical abstraction of natural and technical processes in almost all scientific disciplines is called "modelling and simulation" – as though it had first been introduced with the invention of the computer and the world of IT, whereas in truth it has long since been the driving force behind mankind's ideas and actions. Mapping the loadbearing properties of building constructions in a theoretical model is a typical case. One classic example is the development of masonry and elastic arch theories (see chapter 4). It has become customary to add the term "computational" to these computer-oriented fields in the individual sciences, in this case "computational mechanics".

The year 1825 has been fittingly chosen as the starting point of the discipline-formation period in theory of structures (see chapter 6). Theory of structures is not just the solving of an equilibrium task, not just a computational process. Navier, whose importance as a mechanics theorist we still acknowledge today in the names of numerous theories (Navier stress distribution, Navier-Lamé and Navier-Stokes equations, etc.), was very definitely a practitioner. In his position as professor for applied mechanics at the École des Ponts et Chaussées, it was he who combined the subjects of applied mechanics and strength of materials in order to apply them to the practical tasks of building. For example, in his *Résumé des Leçons* of 1826 he describes the work of engineers thus: "... after the works have been designed and drawn, [the engineers] investigate them to see if all conditions have been satisfied and improve their design until this is the case. Economy is one of the most important conditions here; stability and durability are no less important ..." (see section 2.1.2). Theory of structures as an independent scientific discipline had finally become established. Important structural theories and methods of calculation would be devised in the following years, linked with names like Clapeyron, Lamé, Saint-Venant, Rankine, Maxwell, Cremona, Castigliano, Mohr and Winkler, to name but a few. The graphical statics of Culmann and its gradual development into graphical analysis are milestones in the history of structural theory.

Already at this juncture it is worth pointing out that the development did not always proceed smoothly: controversies concerning the content of theories, or competition between disciplines, or priority disputes raised their heads along the way. This exciting theme is explored in detail in Chapter 11 by way of 12 examples.

In the following years, the evolution of methods in theory of structures became strongly associated with specific structural systems and hence, quite naturally, with the building materials employed, such as iron (steel) and later reinforced concrete (see chapters 7, 8 and 9). Independent materials-specific systems and methods were devised. Expressed in simple terms, structural steelwork, owing to its modularity and the fabrication methods, concentrated on assemblies of linear members, whereas reinforced concrete preferred two-dimensional structures such as slabs, plates and shells. The space frames dealt with in chapter 8 represent a fulcrum to some extent.

This materials-based split was also reflected in the teaching of structural theory in the form of separate studies. It was not until many years later that the parts were brought together in a homogeneous theory of structures, albeit frequently "neutralised", i.e. no longer related to the specific properties of the particular building material – an approach that must be criticised in retrospect. Of course, the methods of structural analysis can encompass any material in principle, but in a specific case they must take account of the particular characteristics of the material.

Kurrer places the transition from the discipline-formation period – with its great successes in the shape of graphical statics and the systematic approach to methods of calculation in member analysis – to the consolidation period around 1900. This latter period, which lasted until 1950, is characterised by refinements and extensions, e.g. a growing interest in shell structures, and the consideration of non-linear effects. Only after this does the "modern" age begin – designated the integration period in this instance and typified by the use of modern computers and powerful numerical methods. Theory of structures is integrated into the structural planning process of conceptual design – analysis – detailing – construction – manufacturing. Have we reached the end of the evolutionary road? Does this development mean that theory of structures, as an independent engineering science, is losing its profile and its justification? The developments of recent years indicate the opposite.

The history of yesterday and today is also the history of tomorrow. In the world of data processing and information technology, theory of structures has undergone rapid progress in conjunction with numerous paradigm changes. It is no longer the calculation process and method issues, but rather principles, modelling, realism, quality assurance and many other aspects that form the focal point. The remit includes dynamics alongside statics; in terms of the role they play, thin-walled structures like plates and shells are almost equal to trusses and frames, and taking account of true material behaviour is obligatory these days. During its history so far, theory of structures was always the trademark of structural engineering; it was never the discipline of "number crunchers", even if this was and still is occasionally proclaimed as such upon launching relevant computing programs. Theory of structures continues to play an important mediating role between mechanics on the one side and the conceptual and detailed design subjects on the other side in teaching, research and practice. Statics and dynamics have in the meantime advanced to what is known internationally as "computational structural mechanics", a modern application-related structural mechanics.

The author takes stock of this important development in chapter 10. He mentions the considerable rationalisation and formalisation, the foundations for the subsequent automation. It was no surprise when, as early as the 1930s, the structural engineer Konrad Zuse began to develop the first computer. However, the rapid development of numerical methods for structural calculations in later years could not be envisaged at that time. J. H. Argyris, one of the founding fathers of the modern finite element method, recognised this at an early stage in his visionary remark "the computer shapes the theory" (1965): besides theory and experimentation, there is a new pillar – numerical simulation (see section 10.4).

By their very nature, computers and programs have revolutionised the work of the structural engineer. Have we not finally reached the stage where we are liberated from the craftsman-like, recipe-based business so that we can concentrate on the essentials? The role of "modern theory of structures" is also discussed here, also in the context of the relationship between the structural engineer and the architect (see chapter 12). A new "graphical statics" has appeared, not in the sense of the automation and visual presentation of Culmann's graphical statics, but rather in the form of graphic displays and animated simulations of mechanical relationships and processes. This is a decisive step towards the evolution of constructions and to loadbearing structure synthesis, to a new type of structural doctrine. This potential as a living interpretation and design tool has not yet been fully exploited.

It is also worth mentioning that the boundaries to the other construction engineering disciplines (mechanical engineering, automotive engineering, shipbuilding, the aerospace industry, biomechanics) are becoming more and more blurred in the field of computational mechanics; the relevant conferences no longer make any distinctions. The concepts, methods and tools are likewise universal. And we are witnessing similar developments in teaching, too.

This "history of theory of structures" could only have been written by an expert, an engineer who knows the discipline inside out. Engineering scientists getting to grips with their own history is a rare thing. But this is one such lucky instance. This fully revised English edition, which explores international developments in greater depth, follows on from the highly successful German edition. We should be very grateful to Dr. Kurrer, and also "his" publisher, Ernst & Sohn, for this treatise.

Stuttgart, September 2007
Ekkehard Ramm
Professor of Structural Mechanics, University of Stuttgart

Preface

Encouraged by the engineering profession's positive response to the first edition of this book, which appeared in German only under the title of *Geschichte der Baustatik* in 2002, and the repeated requests for an English edition, two years ago I set myself the task of revising, expanding and updating the book. Although this new version still contains much of the original edition unaltered, the content now goes much further, in terms of quantity and quality. My aim was not only to take account of the research findings of the intervening years, but also to include the historical development of modern numerical methods of structural analysis and structural mechanics; further, I wanted to clarify more rigorously the relationship between the formation of structural analysis theories and progress in construction engineering. The history of the theory of spatial frameworks, plus plate, shell and stability theory, to name just a few examples, have therefore been given special attention because these theories played an important role in the evolution of the design language of lightweight steel, reinforced concrete, aircraft and ship structures. Without doubt, the finite element method (FEM) – a child of structural mechanics – is one of the most important intellectual technologies of the second half of the 20th century. I have therefore presented the historico-logical sources of FEM, their development and establishment in this new edition. Another addition is the chapter on scientific controversies in mechanics and theory of structures, which represents a "pocket guide" to the entire historical development from Galileo to the early 1960s and therefore allows an easy overview. There are now 175 brief biographies of prominent figures in theory of structures and structural mechanics, over 60 more than in the first edition, and the bibliography has been considerably enlarged.

Certainly the greatest pleasure during the preparation of this book was experiencing the support of friends and colleagues. I should like to thank Jennifer Beal (Chichester), Antonio Becchi (Berlin), Norbert Becker (Stuttgart), Alexandra R. Brown (Hoboken), José Calavera (Madrid), Christopher R. Calladine (Cambridge, UK), Kostas Chatzis (Paris), Mike Chrimes (London), Ilhan Citak (Lehigh), René de Borst (Delft), Giovanni Di Pasquale (Florence), Werner Dirschmid (Ingolstadt), Holger Eggemann (Aachen), Jorun Fahle (Gothenburg), Amy Flessert (Minneapolis), Hubert Flomenhoft (Palm Beach Gardens), Peter Groth (Pfullingen), Carl-Eric Hagentoft (Gothenburg), Torsten Hoffmeister (Berlin), Santiago Huerta (Madrid), Andreas Kahlow (Potsdam), Sándor Kaliszky (Budapest), Klaus Knothe (Berlin), Eike Lehmann (Lübeck), Werner Lorenz (Cottbus/Berlin), Andreas Luetjen (Braunschweig), Stephan Luther (Chemnitz), William J. Maher (Urbana), René Maquoi (Liège), Gleb Mikhailov (Moscow), Juliane Mikoletzky (Vienna), Klaus Nippert (Karlsruhe), John Ochsendorf (Cambridge, USA), Ines Prokop (Berlin), Patricia Radelet-de Grave (Louvain-la-Neuve), Ekkehard Ramm (Stuttgart), Anette Ruehlmann (London), Sabine Schroyen (Düsseldorf), Luigi Sorrentino (Rome), Valery T. Troshchenko (Kiev), Stephanie Van de Voorde (Ghent), Volker Wetzk (Cottbus), Jutta Wiese (Dresden), Erwin Wodarczak (Vancouver) and Ine Wouters (Brussels).

Philip Thrift (Hannover) is responsible for the English translation. This present edition has benefited from his particular dedication, his wealth of ideas based on his good knowledge of this subject, his sound pragmatism and his precision. I am therefore particularly indebted to him, not least owing to his friendly patience with this writer! At this point I should also like to pay tribute to the technical and design skills of Peter Palm (drawings), Sophie Bleifuß (typodesign), Uta-Beate Mutz (typesetting) and Siegmar Hiller (production), all of whom helped ensure a high-quality production. My dear wife and editor Claudia Ozimek initiated the project at the Ernst & Sohn publishing house and steered it safely to a successful conclusion. Finally, I would like to thank all my colleagues at Ernst & Sohn who have supported this project and who are involved in the distribution of my book.

I hope that you, dear reader, will be able to absorb some of the knowledge laid out in this book, and not only benefit from it, but also simply enjoy the learning experience.

Berlin, January 2008
Karl-Eugen Kurrer

Preface to the first, German edition

For more than 25 years, my interest in the history of structural analysis has been growing steadily – and this book is the result of that interest. Whereas my initial goal was to add substance to the unmasking and discovery of the logical nature of structural analysis, later I ventured to find the historical sources of that science. Gradually, my collection of data on the history of structural analysis – covering the didactics, theory of science, history of engineering science and construction engineering, cultural and historical aspects, aesthetics, biographical and bibliographical information – painted a picture of that history. The reader is invited to participate actively by considering, interpreting and forming his or her own picture of the theory of structures.

I encountered numerous personalities as that picture took shape and I would like to thank them for their attention, receptiveness and suggestions – they are too numerous to mention them all by name here. In writing this book I received generous assistance – also in the form of texts and illustrations – from the following:

- Dr. Bill Addis, London (biographies of British structural engineers),
- Dr. Antonio Becchi, Genoa (general assistance with the biographies and the bibliography),
- Emer. Prof. Dr. Zbigniew Cywiński, Gdańsk (biographies of Polish structural engineers),
- Prof. Dr. Ladislav Frýba, Prague (biographies of Czechoslovakian structural engineers),
- Prof. Dr. Santiago Huerta, Madrid (biography of Eduardo Saavedra),
- Prof. Dr. René Maquoi, Liège (biographies of Belgian structural engineers),
- Dr. Gleb Mikhailov, Moscow (biographies of Russian structural engineers),
- Prof. Dr. Ekkehard Ramm, Stuttgart (foreword),
- Prof. Dr. Enrico Straub, Berlin (biography of his father, Hans Straub),
- Emer. Prof. Dr. Minoru Yamada, Kyoto (biographies of Japanese structural engineers).

I would also like to thank Mike Chrimes, London, Prof. Dr. Massimo Corradi, Genoa, Dr. Federico Foce, Genoa, Prof. Dr. Mario Fontana, Zurich, Prof. Dr. Wolfgang Graße, Dresden, Prof. Dr. Werner Guggenberger, Graz, and Prof. Dr. Patricia Radelet-de Grave, Louvain-la-Neuve, who helped me with literature sources.

This book would not have been possible without the valued assistance of my very dearest friend Claudia Ozimek, who was responsible for the prudent supervision by the editorial staff. And I should also like to thank all my other colleagues at Ernst & Sohn for their help in the realisation of this book.

I very much hope that all the work that has gone into this book will prove worthwhile reading for you, the reader.

Berlin, September 2002
Dr.-Ing. Karl-Eugen Kurrer

CONTENTS