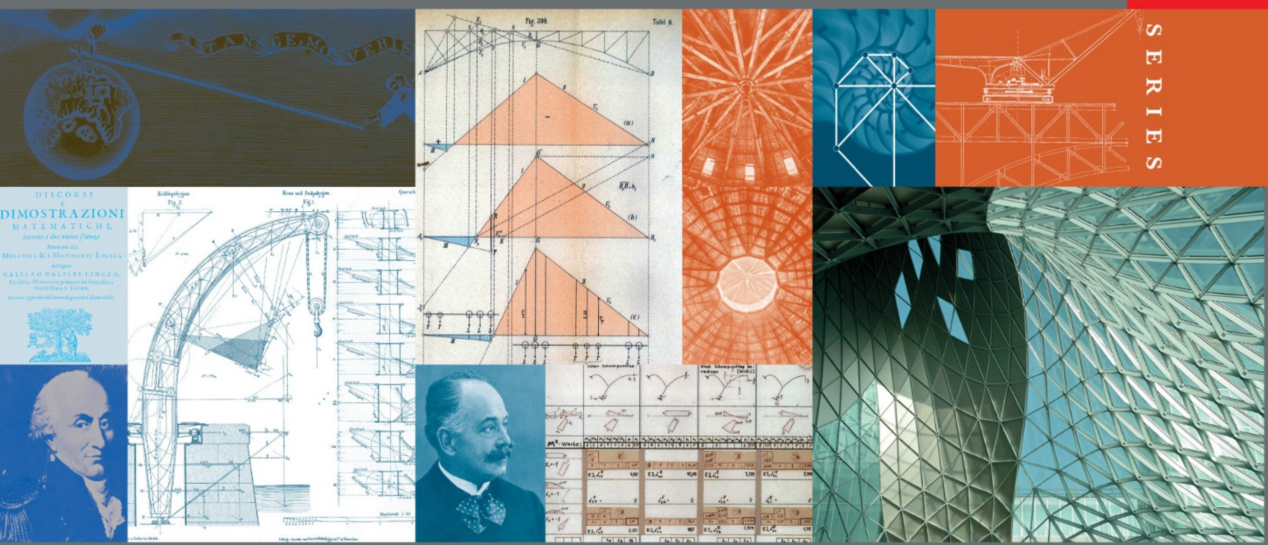
Karl-Eugen Kurrer

The History of the THEORY OF STRUCTURES



Searching for Equilibrium

Second Edition

CONSTRUCTION HISTORY SERIES

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Dr.-Ing. Dr.-Ing. E. h. Karl-Eugen Kurrer
Gleimstr. 20 a
10437 Berlin
Germany

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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 the appearance of the first German edition in 2002, *The History of the Theory of Structures* has become a standard work of reference for this latter field. It continues the series of great works on the history of civil and structural engineering by S. P. Timoshenko and I. Szabó right up to E. Benvenuto and J. Heyman, and enriches them by adding valuable new levels of interpretation and knowledge. We are delighted to be able to publish the second, considerably enlarged, English-language edition as part of the *Construction History Series/ Edition Bautechnikgeschichte*.

Werner Lorenz and *Karl-Eugen Kurrer*
Series editors

Foreword

Ten years after the first English edition of Dr. Kurrer's *The History of the Theory of Structures*, he now presents us with a much enlarged edition, and with a new subtitle: *Searching for Equilibrium* – an addition that reminds us of that most important of all mechanical principles: no equilibrium, no loadbearing system! But the subtitle also expresses the constant search for a balance between theory of structures as a scientific discipline and its prime task in practical applications – totally in keeping with Leibniz' *Theoria cum Praxi*. This interaction has proved beneficial for both sides at all times in history, and runs like a thread through the entire book.

New content in this second edition includes: earth pressure theory, ultimate load method, an analysis of historical textbooks, steel bridges, lightweight construction, plate and shell theory, computational statics, Green's functions, computer-assisted graphical analysis and historical engineering science. Furthermore, the number of brief biographies has been increased from 175 to 260! Compared with the first English edition, the number of printed pages has increased by 50 % to a little over 1,200.

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 journey through time, with highly subjective impressions, more thematic and only roughly chronological, and with a liking for 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.

And what is "theory of structures" anyway? … Gerstner's first book dating from 1789 talks about the "statics of architecture" and Emil Winkler used the term "statics of structures" around 1880. Winkler's term also included earth pressure theory, the evolution of which from 1700 to the present day is now the topic of a new chapter 5 in this second edition.

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. Dr. Kurrer calls this period from 1575 to 1825 the "preparatory period" – times in which structural design was still very much dominated 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 repairs to the dome of St. Peter's in Rome (1742/1743) 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 13.2.5). 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 humankind's ideas and actions. Mapping the loadbearing properties of building structures in a theoretical model is a typical case. Classic examples are the development of masonry and elastic arch theories (see chapter 4) and the continuum mechanics models of earth pressure of Rankine and Boussinesq (see sections 5.4 and 5.5). 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 7). Theory of structures is not just the solving of an equilibrium problem, 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 *Mechanik der Baukunst* of 1826, he describes the work of engineers thus: "... after the works have been designed and drawn, [they] 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 2.1.2.1). Navier was the first to establish theory of structures as an independent scientific discipline. Important structural theories and methods of calculation would be devised in the following years, linked with names such as 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 theory of structures.

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 13 by way of 13 examples.

In the following decades, 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 8, 9 and 10). Independent materials-specific systems and methods were devised. Expressed in simple terms, structural steelwork, owing to its modularity and the fabrication methods, initially concentrated on assemblies of linear members, not embracing plate and shell structures until the 1950s. On the other hand, reinforced concrete preferred its own two-dimensional design language, which manifested itself in slabs, plates and shells. Therefore, chapters 8 and 10 in this second English edition have been considerably enlarged by the addition of plate and shell structures. The space frames dealt with in chapter 9 represent a link to some extent. This materials-based split was also reflected in the teaching of theory of structures 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.

Dr. 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 in the form of the force method – 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 plate and shell structures and the consideration of non-linear effects. Only after this does the 'modern' age of theory of structures 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 draft design – analysis – detailed design – construction in this period. 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 tendencies of recent years indicate the opposite.

The story of yesterday and today is also the story 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 focus of our attention. The remit includes dynamics alongside statics; in terms of the role they play, plate and shell structures are almost equal to trusses, 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 when launching relevant computer programs. Theory of structures continues to play an important mediating role between mechanics on the one side and the draft 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 chapters 11 and 12. 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 (see section 11.4). 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 12.1).

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, formula-based business so that we can concentrate on the essentials? The role of modern theory of structures is discussed in section 14.1, also in the context of the relationship between the structural engineer and the architect. 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 structures and to loadbearing structure synthesis, to a new way of teaching structural engineering (see section 14.1.4). 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, aerospace, 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 universal. And we are witnessing similar developments in teaching, too. No wonder Dr. Kurrer also refers to leading figures from these disciplines. That fact becomes particularly clear in chapter 15, which contains 260 brief biographies of persons who have featured prominently in the theory of structures.

In terms of quality and quantity, this second English edition of *The History of the Theory of Structures* goes way beyond the first edition. This book 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 so intensely is a rare thing. But this is one such lucky instance. We should be very grateful to Dr.-Ing. Dr.-Ing. E.h. Karl-Eugen Kurrer, and also 'his' publisher, Ernst & Sohn (John Wiley & Sons), for his *magnum opus*.

Stuttgart, February 2018
Ekkehard Ramm, University of Stuttgart

Preface to the second English edition

Encouraged by the positive feedback from the engineering world regarding the first German edition of my *Geschichte der Baustatik* (2002) and the first English edition *The History of the Theory of Structures* (2008), two years ago I set myself the task of revising my manuscripts, adding new material once again and bringing everything up to date. Increasing the number of pages by a little over 50% was unavoidable, because my goal now was to present a total picture of the evolution of the theory of structures.

But that goal did not just consist of including the research findings of the past few years. Instead, I would now be devoting more space to a detailed treatment of the development of modern numerical methods of structural analysis and structural mechanics as well as the connection between the formation of structural analysis theories and constructional-technical progress. It is for this reason that, for example, plate, shell and stability theories have been paid particular attention, as these theories played an important part in the development of the design languages of steel, reinforced concrete, aircraft, vehicles and ships. As a result, the chapters on steel (chapter 8) and reinforced concrete (chapter 10) have been greatly enlarged. Without doubt, the finite element method (FEM), spawned by structural mechanics and numerical mathematics, was the most important intellectual technology of the second half of the 20th century. Therefore, the historico-logical sources of computational statics plus their development and establishment are now presented in detail separately in chapter 12. Also new is the substantial chapter on the 300-year-old history of earth pressure theory (chapter 5). Earth pressure theory was the first genuine engineering science theory that shaped the scientific self-conception of modern civil engineering, a profession that was beginning to emerge in 18th-century France. It is the reference theory for this profession, and not beam theory, as is often assumed. Not until the 20th century did earth pressure theory gradually become divorced from theory of structures. As in earth pressure theory, it is the search for equilibrium that grabs our historico-logical attention in masonry arch theory. Chapter 4, "From masonry arch to elastic arch", has therefore been expanded. The same is true for chapter 3, which covers the development of theory of structures and applied mechanics as the first fundamental engineering science disciplines. That chapter not only contains the first analysis of textbooks on these two sciences published in the 19th and 20th centuries, but also attempts to extract the scientific and epistemological characteristics of theory of structures and applied mechanics. That therefore also forms the starting point for chapter 14, "Perspectives for a historical theory of structures", the integral constituent of my concept for a historical engineering science, which is explained in detail in this book. Current research into graphical statics is one example mentioned in this chapter, which I summarise under the term "computer-aided graphic statics" (CAGS). The number of brief biographies of the protagonists of theory of structures and structural mechanics has increased by 85 to 260, and the bibliography also contains many new additions.

Probably the greatest pleasure during the preparation of this book was experiencing the support that my many friends and colleagues afforded me. I would therefore like to thank: Katherine Alben (Niskayuna, N. Y.), William Baker (Chicago), Ivan Baláž (Bratislava), Jennifer Beal (Chichester), Norbert Becker (Stuttgart), Antonio Becchi (Berlin), Alexandra R. Brown (Hoboken), José Calavera (Madrid), Christopher R. Calladine (Cambridge, UK), Kostas Chatzis (Paris), Mike Chrimes (London), Ilhan Citak (Lehigh), Zbigniew Cywiński (Gdańsk), René de Borst (Delft), Giovanni Di Pasquale (Florence), Cengiz Dicleli (Constance), Werner Dirschmid (Ingolstadt), Albert Duda (Berlin), Holger Eggemann (Brühl), Bernard Espion (Brussels), Jorun Fahle (Gothenburg), Amy Flessert (Minneapolis), Hubert Flomenhoft (Palm Beach Gardens), Peter Groth (Pfullingen), Carl-Eric Hagentoft (Gothenburg), Friedel Hartmann (Kassel), Hans-Joachim Haubold (Darmstadt), Eva Haubold-Marguerre (Darmstadt), Torsten Hoffmeister (Berlin), Santiago Huerta (Madrid), Peter Jahn (Kassel), Andreas Kahlow (Potsdam), Christiane Kaiser (Potsdam), Sándor Kaliszky (Budapest), Andreas Kirchner (Würzburg), Klaus Knothe (Berlin), Winfried B. Krätzig (Bochum), Arnold Krawietz (Berlin), Eike Lehmann (Lübeck), Werner Lorenz (Cottbus/Berlin), Andreas Luetjen (Braunschweig), Stephan Luther (Chemnitz), René Maquoi (Liège), William J. Maher (Urbana), Gleb Mikhailov (Moscow), Juliane Mikoletzky (Vienna), Klaus Nippert (Karlsruhe), John Ochsendorf (Cambridge, Mass.), Eberhard Pelke (Mainz), Christian Petersen (Ottobrunn), Ines Prokop (Berlin), Frank Purtak (Dresden), Ekkehard Ramm (Stuttgart), Patricia Radelet-de Grave (Louvain-la-Neuve), Anette Rühlmann (London), Jan Peter Schäfermeyer (Berlin), Lutz Schöne (Rosenheim), Sabine Schroyen (Düsseldorf), Luigi Sorrentino (Rome), Valery T. Troshchenko (Kiev), Stephanie Van de Voorde (Brussels), Volker Wetzk (Cottbus), Jutta Wiese (Dresden), Erwin Wodarczak (Vancouver) and Ine Wouters (Brussels).

I am indebted to the technical and design skills of Sophie Bleifuß (typodesign), Siegmar Hiller (production), Uta-Beate Mutz (typesetting) and Peter Palm (drawings), who together helped to guarantee a high-quality production. And without the great support of my family, this book would have been impossible. My dear wife and editor, Claudia Ozimek, initiated the project at the Ernst & Sohn publishing house, and it was my colleague Ute-Marlen Günther who steered the project 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 the knowledge laid out in this book and not only benefit from it, but also simply enjoy the learning experience.

Berlin, March 2018
Karl-Eugen Kurrer

Contents

About this series

The *Construction History Series/Edition Bautechnikgeschichte* gives the new discipline of construction history a home for the publication of important works reflecting the full diversity of this subject. The scope of the series ranges from overviews to monographs on individual aspects or structures to biographies of prominent engineers. The two main orientations in construction history – either focusing more on the history of design or more on the history of theory – both receive due consideration.

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About the series editors

Karl-Eugen Kurrer was born in 1952 in Heilbronn, Germany. Following his degree in civil engineering at Stuttgart University of Applied Sciences, he worked as a structural timber engineer in Heilbronn. He then returned to university to study civil engineering, history of technology and physical engineering sciences at TU Berlin. His dissertation on the development of vault theory from the 18th century to 1980 was completed in 1981, and that was followed by the award of a doctorate by TU Berlin in 1986. Between 1989 and 1995, Dr. Kurrer worked for Telefunken Sendertechnik GmbH in Berlin as a designer of antenna systems.

Since 1996, Dr. Kurrer has chaired the Working Group on the History of Technology at the VDI (Association of German Engineers) in Berlin. Between 1996 and February 2018, he was chief editor of *Stahlbau* and (from 2008) *Steel Construction – Design and Research*, journals published by Ernst & Sohn. For more than 35 years, Dr. Kurrer has carried out research on the subject of construction history with special emphasis on theory of structures and structural mechanics. He has published more than 180 papers and several monographs.

Werner Lorenz, born in 1953, graduated from TU Berlin in 1980 with a degree in structural engineering. After his first practical experience in an engineering practice in Berlin (1980–1984), he returned to TU Berlin to give his first seminars on construction history (1984–1989). He spent a period as visiting professor at the École Nationale des Ponts et Chaussées in Paris (1988) and gained his doctorate with a thesis about the early history of building with iron and steel in Berlin and Potsdam (1992). The next year he was appointed to the newly created Chair of Construction History at BTU Cottbus, where he was able to establish a system of consecutive courses in construction history and structural preservation for undergraduates in civil engineering and architecture. In 1996 he founded a consultancy for structural engineering which specialises in the structural rehabilitation of historic buildings and bridges. The main fields of his research concentrate on construction shaped by industry history of the 18th, 19th and 20th centuries. He has been a member of various advisory boards and international scientific committees and was co-founder and first chairman (2013–2017) of the "Gesellschaft für Bautechnikgeschichte".

About the author

Karl-Eugen Kurrer was born in Heilbronn, Germany, in 1952. After graduating from Stuttgart University of Applied Sciences with a general civil engineering degree in 1973, he worked as a structural timber engineer for Losberger GmbH in Heilbronn.

He then returned to university to study civil engineering and physical engineering sciences at TU Berlin, the city's science and technology university. As a tutor in the Theory of Structures Department at TU Berlin between 1977 and 1981, one of Karl-Eugen Kurrer's most important teaching and learning experiences was grasping the basic principles of structural analysis from the historical point of view. The intention of his handwritten introductory lecture notes on the history of each method of structural analysis was to help students understand that theory of structures, too, is the outcome of a socio-historical everyday process in which they themselves play a part and, in the end, help to shape. Another goal was to create a deeper sense of the motivation for and enjoyment of the learning of structural analysis. It was crucial to overcome the formula-type acquisition of the subject matter by introducing a didactic approach to the fundamentals of theory of structures through their historical appreciation. By 1998 this had evolved into a plea for a historico-genetic approach to the teaching of theory of structures.

His dissertation "Entwicklung der Gewölbetheorie vom 19. Jahrhundert bis zum heutigen Stand der Wissenschaft am Beispiel der Berechnung einer Bogenbrücke" (the development of vault theory from the 19th century to today using the example of structural calculations for an arch bridge) was completed in 1981. Since 1980, his many articles on the history of science and technology in general and construction history in particular have appeared in journals, newspapers, books and exhibition publications.

Karl-Eugen Kurrer completed his PhD – on the internal kinematic and kinetic of tube vibratory mills (advisers: Eberhard Gock, Wolfgang Simonis, Gerd Brunk) – with the highest level of distinction, *summa cum laude*, at TU Berlin in 1986 and went on to carry out externally funded research on energy efficiency in industry. He contributed to the development of a new eccentric vibratory mill that uses 50% less energy than comparable models. After 1995 the design successfully established itself on the international machine market (US and EU patents). The head of the "Eccentric vibratory mill" team at Clausthal University of Technology, Prof. Dr. Eberhard Gock (1937–2016), received an innovation award ("Technologietransferpreis der Industrie- und Handelskammer Braunschweig") for this work in 1998.