KARL-EUGEN KURRER

The History of the Theory of Structures

From Arch Analysis to Computational Mechanics

Ernst & Sohn
A Wiley Company

THE HISTORY OF THE THEORY OF STRUCTURES

KARL-EUGEN KURRER

The History of the Theory of Structures

From Arch Analysis to Computational Mechanics

Ernst & Sohn
A Wiley Company

Author: Dr.-Ing Karl-Eugen Kurrer
Ernst & Sohn Verlag für Architektur und technische
Wissenschaften GmbH & Co. KG
Rotherstraße 21, D -10245 Berlin, Germany

This book contains 667 illustrations.

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie;
detailed bibliographic data is available in the Internet at <http://dnb.ddb.de>.

Cover: Computer-generated drawing of an FEM model for the Göltzsch Viaduct
by Dr. Roger Schlegel (Dynardo GmbH, Wiemar) plus historical illustrations
(sources given in book).

ISBN 978-3-433-01838-5

English translation: Philip Thrift, Hannover
Typodesign: Sophie Bleifuß, Berlin
Typesetting: Uta-Beate Mutz, Leipzig
Drawings: Peter Palm, Berlin
Production: HillerMedien, Berlin
Printing: betz-druck, Darmstadt

Printed in Germany

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

CHAPTER 1

The tasks and aims of a historical study of theory of structures

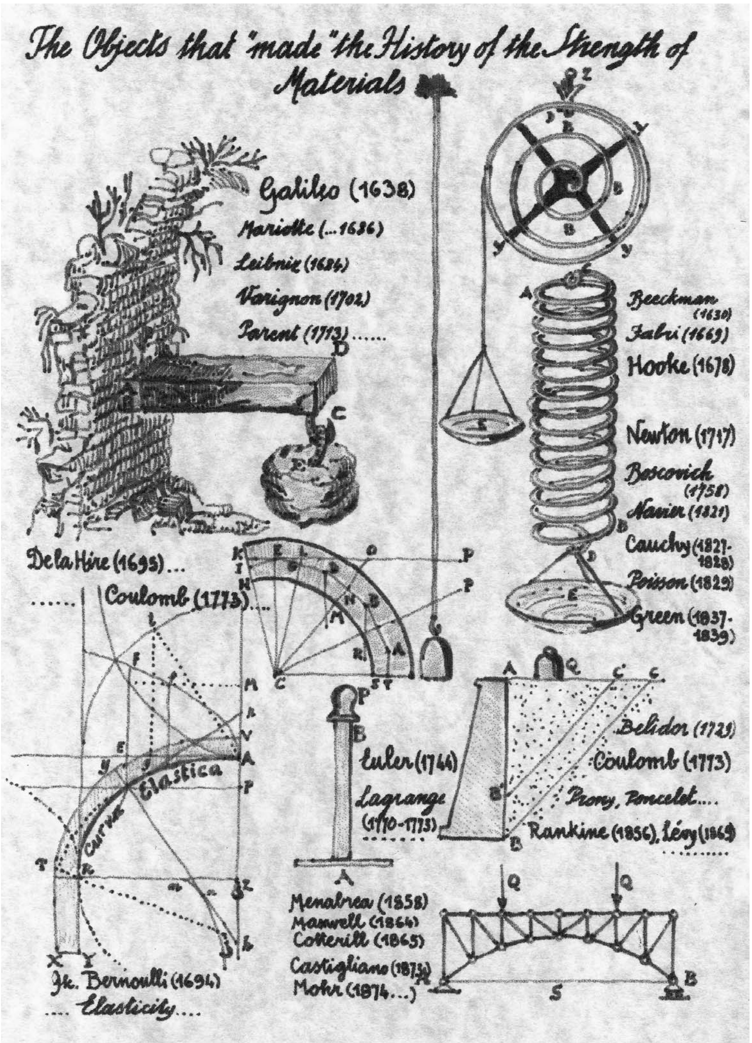


FIGURE 1-1
Drawing by Edoardo Benvenuto

Until the 1990s, the history of theory of structures attracted only marginal interest from historians. At conferences dealing with the history of science and technology, but also in relevant journals and compendiums, the interested reader could find only isolated papers investigating the origins, the chronology, the cultural involvement and the social significance of theory of structures. This gap in our awareness of the history of theory of structures has a passive character: most observers still assume that the stability of structures is guaranteed a priori, that, so to speak, structural analysis wisdom is naturally bonded to the structure, is absorbed by it, indeed disappears, never to be seen again. This is not a suppressive act on the part of the observer, but rather is due to the nature of building itself – theory of structures had appeared at the start of the Industrial Revolution, claiming to be a "mechanics derived from the nature of building itself" [Gerstner, 1789, p. 4].

Only in the event of failure are the formers of public opinion reminded of structural analysis. Therefore, the historical development of theory of structures followed in the historical footsteps of modern building, with the result that the historical contribution of theory of structures to the development of building was given more or less attention in the structural engineering-oriented history of building, and therefore was included in this.

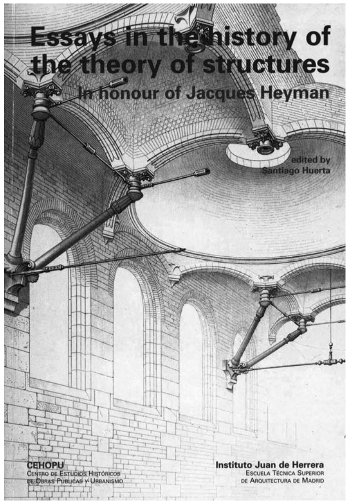


FIGURE 1-2
Cover of the book published to mark the first conference on the history of theory of structures (2005)

The history of science, too, treated the history of theory of structures as a diversion. If indeed theory of structures as a whole strayed into the field of vision, it was only in the sense of one of the many applications of mechanics. Structural engineering, a profession that includes theory of structures as a fundamental engineering science discipline, only rarely finds listeners outside its own disciplinary borders.

Today, theory of structures is, on the one hand, more than ever before committed to formal operations with symbols, and is less apparent to many users of structural design programs. On the other hand, some attempts to introduce formal teaching into theory of structures fail because the knowledge about its historical development is not adequate to define the concrete object of theory of structures. Theory of structures is therefore a necessary but unpopular project.

Notwithstanding, a history of theory of structures has been gradually coming together from various directions since the early 1990s, the first highlight of which was the conference "Historical perspectives on structural analysis" – the world's first conference on the history of theory of structures – organised by Santiago Huerta and held in Madrid in December 2005. The book published on the occasion of the conference (Fig. 1-2) demonstrates that the history of theory of structures already possesses a number of the features important to an engineering science discipline and can be said to be experiencing its constitutional phase.

1.1 Internal scientific tasks

Like every scientific cognition process, the engineering science cognition process in theory of structures also embraces history insofar as the idealised reproduction of the scientific development supplanted by the status of knowledge of an object forms a necessary basis for new types of scientific ideas: science is truly historical. Reflecting on the genesis and development of the object of theory of structures always becomes an element in the engineering science cognition process when rival, or rather coexistent, theories are superseded by a more abstract theory – possibly by a basic theory of a fundamental engineering science discipline. Therefore, the question of the inner consistency of the more abstract theory, which is closely linked with this broadening of the object, is also a question of the historical evolution. This is how Saint-Venant proceeded in 1864 with his extensive historical and critical commentary of Navier's beam theory [Navier, 1864], in the middle of the establishment phase of structural theory (1850 – 75). Theory formation in structural analysis is the classification of the essential properties of technical artefacts or artefact classes reflected in theoretical models. This gives rise to the historically weighted comparison and the criticism of the theoretical approaches, the theoretical models and the theories, especially in those structural analysis theory formation processes that grew very sluggishly, e. g. masonry arch theory. One example of this is Winkler's 1879/80 historico-logical analysis of masonry arch theories in the classical phase of structural theory (1875 –1900) [Winkler, 1879/1880].

In their monumental work on the history of strength of materials, Todhunter and Pearson had good reasons for focusing on elastic theory (see [Todhunter & Pearson, 1886 & 1893; Pearson, 1889]), which immediately became the foundation for materials theory in applied mechanics as well as theory of structures in its discipline-formation period (1825 –1900), and was able to sustain its position as a fundamental theory in these two engineering science disciplines during the consolidation period (1900 – 50). The mathematical elastic theory first appeared in 1820 with Navier's *Mémoire sur la flexion des plans élastiques* (Fig. 1-3). It inspired Cauchy and others to contribute significantly to the establishment of the scientific structure of elastic theory and induced a paradigm change in the constitution phase of structural theory (1825 – 50), which was essentially completed by the middle of the establishment phase of structural theory (1850 – 75). One important outcome of the discipline-formation period of structural theory (1825 –1900) was the constitution of the discipline's own conception of its epistemology – and elastic theory contributed substantially to this. Theory of structures thus created for itself the prerequisite to help define consciously the development of construction on the disciplinary scale. And looked at from the construction engineering side, Gustav Lang approached the subject in his evolutionary portrayal of the interaction between loadbearing construction and theory of structures in the 19th century [Lang, 1890] – the first monograph on the history of theory of structures.

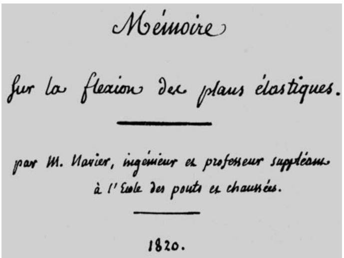

Mémoire
sur la flexion des plans élastiques.
par M. Navier, ingénieur et professeur suppléant à l'Ecole des ponts et chaussées.
1820.

FIGURE 1-3
Lithographic cover page of Navier's
Mémoire sur la flexion des plans élastiques
[Roberts & Trent, 1991, p. 234]

Up until the consolidation period of structural theory (1900 – 50), the structural analysis theory formation processes anchored in the emerging specialist literature on construction theory contained a historical element that was more than mere references to works already in print. It appears, after all, to be a criterion of the discipline-formation period of structural theory that recording the relationship between the logical and historical was a necessary element in the emerging engineering science cognition process. If we understand the logical to be the theoretical knowledge reflecting the laws of the object concerned in abstract and systematic form, and the historical to be the knowledge and reproduction of the genesis and evolution of the object, then it can be shown that the knowledge of an object's chronology had to be a secondary component in the theoretical knowledge of the object. This is especially true when seen in terms of the leaps in development in the discipline-formation period of structural theory. Whereas Pierre Duhem pursued the thinking of natural philosophy from the theory of structures of the Middle Ages to the end of the 17th century in his two-volume work *Les origines de la Statique* [Duhem, 1905/06], the comprehensive contributions of Mehrtens [Mehrtens, 1900 & 1905], Hertwig [Hertwig, 1906 & 1941], Westergaard [Westergaard, 1930/1], Ramme [Ramme, 1939] and Hamilton [Hamilton, 1952] to the origins of the discipline of theory of structures provide reasons for the history of theory of structures in a narrower sense. The famous book by Timoshenko on the history of strength of materials (Fig. 1-4) contains sections on the history of structural theory [Timoshenko, 1953].

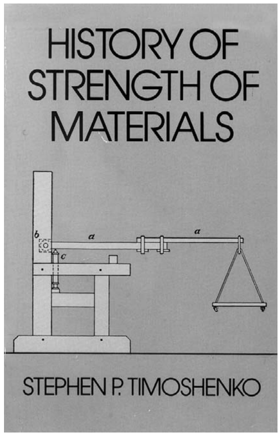


FIGURE 1-4
Cover of Timoshenko's *History of strength of materials* [Timoshenko, 1953]

In the former USSR, Rabinovich [1949, 1960, 1969] and Bernshtein [1957, 1961] contributed to the history of strength of materials and theory of structures in particular and structural mechanics in general. But of all those monographs, only one has appeared in English [Rabinovich, 1960], made available by George Herrmann in the wake of the Sputnik shock. In that book, Rabinovich describes the future task of a type of universal history of structural mechanics as follows: "[Up] to the present time [early 1957 – the author] no history of structural mechanics exists. Isolated excerpts and sketches which are the elements do not fill the place of one. There is [a] need for a history covering all divisions of the science with reasonable thoroughness and containing an analysis of ideas and methods, their mutual influences, economics, and the characteristics of different countries, their connection with the development of other sciences and, finally, their influence upon design and construction" [Rabinovich, 1960, p. 79]. Unfortunately, apart from this one exception, the Soviet contributions to the history of structural mechanics were not taken up in non-Communist countries – a fate also suffered by Rabinovich's monograph on the history of structural mechanics in the USSR from 1917 to 1967 (Fig. 1-5).

FIGURE 1-5
Dust cover of the monograph entitled *Structural Mechanics in the USSR 1917–67* [Rabinovich, 1969]

In his dissertation *The art of building and the science of mechanics*, Harold I. Dorn deals with the relationship between theory and practice in Great Britain during the preparatory period of structural theory (1575–1825) [Dorn, 1971]. T. M. Charlton concentrates on the discipline-formation period of structural theory in his book [Charlton, 1982]. He concludes the internal scientific view of the development of theory of structures as the history of structural theory enters its initial phase. And as early as 1972, Jacques Heyman's monograph *Coulomb's memoir on* *statics: An essay in the history of civil engineering* [Heyman, 1972/1] was not only lending a new emphasis to the treatment and interpretation of historical sources, but was also showing how practical engineering can profit from historical knowledge. This was followed nine years later by Edoardo Benvenuto's universal work *La scienza delle costruzioni e il suo sviluppo storico* [Benvenuto, 1981], the English edition of which – in a much abridged form – did not appear until 10 years later [Benvenuto, 1991]. Heyman's later monographs [Heyman, 1982, 1995/1, 1998/1] in particular demonstrate that the history of theory of structures is able to advance the scientific development of structural analysis. Many of Heyman's books have been published in Spanish in the *Textos sobre teoría e historia de las construcciones* series founded and edited by Santiago Huerta (see, for example, Fig. 1-6).

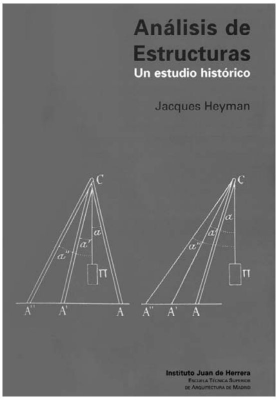
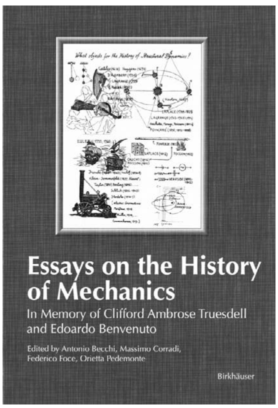


FIGURE 1-6
Dust cover of the Spanish edition of Heyman's *Structural analysis. A historical approach* [Heyman, 2004]

In 1993 Benvenuto initiated the series of international conferences under the title of *Between Mechanics and Architecture* together with the Belgian science historian Patricia Radelet-de Grave. The conferences gradually became the programme for a school and after Benvenuto's early death were continued by the Edoardo Benvenuto Association headed by its honorary president Jacques Heyman. Only six results of this programme will be mentioned here:

- The first volume in this series edited by Benvenuto and Radelet-de Grave and entitled *Entre Mécanique et Architecture. Between Mechanics and Architecture* [Benvenuto & Radelet-de Grave, 1995].
- The compendium *Towards a History of Construction* edited by Becchi, Corradi, Foce and Pedemonte [Becchi et al., 2002].
- *Degli archi e delle volte* [Becchi & Foce, 2002], a bibliography of structural and geometrical analysis of masonry arches past and present with an expert commentary by Becchi and Foce.
- The volume of essays on the history of mechanics edited by Becchi, Corradi, Foce and Pedemonte (Fig. 1-7) [Becchi et al., 2003].
- The compendium on the status of the history of construction engineering edited by Becchi, Corradi, Foce and Pedemonte *Construction History. Research Perspectives in Europe* [Becchi et al., 2004/2].
- The reprint of Edoardo Benvenuto's principal work *La scienza delle costruzioni e il suo sviluppo storico* made available by Becchi, Corradi and Foce [Benvenuto, 2006].

FIGURE 1-7
Cover of the volume of essays on the history of mechanics [Becchi et al., 2003]



Erhard Scholz has investigated the development of graphical statics in his habilitation thesis [Scholz, 1989] from the viewpoint of the mathematics historian. Dieter Herbert's dissertation [Herbert, 1991] analyses the origins of tensor calculus from the beginnings of elastic theory with Cauchy (1827) to its use in shell theory by Green and Zerna at the end of the consolidation period of structural theory (1900 – 50).

In the past two decades, we have seen a slowly accelerating upswing in working through the backlog in the history of modern structural mechanics by specialists. The development of modern numerical engineering methods was the subject of a conference held in Princeton by the Association for Computing Machinery (ACM) in May 1987 [Crane, 1987]. Ekkehard Ramm provides a fine insight into the second half of the consolidation period (1900 – 50) and the subsequent integration period of structural theory (1950 to date) [Ramm, 2000]. As a professor at the Institute of Theory of Structures at the University of Stuttgart, Ramm supervised Bertram Maurer's dissertation *Karl Culmann und die graphische Statik* (Karl Culmann and graphical statics) [Maurer, 1998]. And Malinin's book *Kto jest' kto v soprotivlenii materialov* (who's who in strength of materials) [Malinin, 2000] continued the biographical tradition popular in the Soviet history of mechanics.

Publications by Samuelsson and Zienkiewicz [Samuelsson & Zienkiewicz, 2006] plus Kurrer [Kurrer, 2003] have appeared on the history of the displacement method. Carlos A. Felippa deals with the development of matrix methods in structural mechanics [Felippa, 2001] and the theory of the shear-flexible beam [Felippa, 2005]. On the other hand, the pioneers of the finite element method (FEM) Zienkiewicz [Zienkiewicz, 1995 & 2004] and Clough [Clough, 2004] concentrate on describing the history of FEM. It seems that a comprehensive presentation of the evolution of modern structural mechanics is necessary. Only then could the history of theory of structures make a contribution to a historical engineering science in general and a historical theory of structures in particular, both of which are still awaiting development.

1.2 Practical engineering tasks

Every structure moves in space and time. The question regarding the causes of this movement is the question regarding the history of the structure, its genesis, utilisation and nature. Whereas the first dimension of the historicity of structures consists of the planning and building process, the second dimension extends over the life of the structure and its interaction with the environment. The historicity of the knowledge about structures and their theories plus its influence on the history of the structure form the third dimension of the historicity of structures. In truth, the history of the genesis, usage and nature of the structure form a whole. Nevertheless, the historicity of structures is always broken down into its three dimensions. Whereas historicity in the first dimension is typically reduced to the timetable parameters of the participants in the case of new structures, understanding the second dimension is an object of history of building, preservation of monuments and construction research plus the evolving history of construction engineering and structural design. One vital task of the history of theory of structures would be to help develop the third dimension, e. g. through preparing, adapting and re-interpreting historical masonry arch theories. Its task in practical engineering is not limited to the province of the expanding volume of work among the historical building stock. The knowledge gleaned from the history of theory of structures could become a functional element in the modern construction process because the unity of the three-dimensionality in the historicity of structures is an intrinsic anticipation in this; for the engineering science theory formation and the research trials, the conception, the calculation and the design as well as the fabrication, erection and usage can no longer be separated from the conversion, preservation and upkeep of the building stock. The task of the history of theory of structures lies not only in feeding the planning process with ideas from its historical knowledge database, but also in introducing its experiences from work on historical structures into the modern construction process. In this sense, the history of theory of structures could be further developed into a productive energy in engineering.

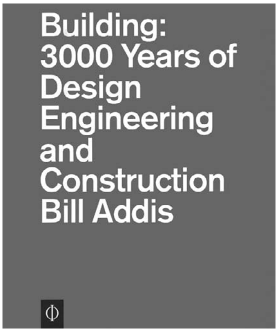


FIGURE 1-8
Cover of the new book by Bill Addis *Building: 3000 Years of Design Engineering and Construction* [Addis, 2007]

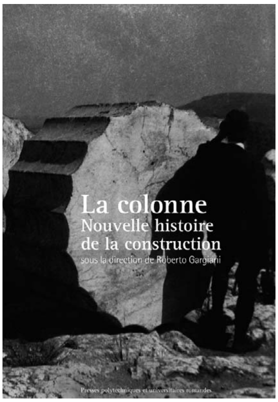
When engineers conceive a building, they have to be sure, even before the design process begins, that it will function exactly as envisaged and planned. That applies today and it also applied just the same to engineers in Roman times, in the Middle Ages, in the Renaissance and in the 19th century. All that has changed is the methods with which engineers achieve this peace of mind. Bill Addis has written a history of design engineering and construction which focuses on the development of design methods for buildings (Fig. 1-8).

Bill Addis looks into the development of graphical and numerical methods plus the use of models for analysing physical phenomena, but also shows which methods engineers employ to convey their designs. To illustrate this, he uses examples from structural engineering, building services, acoustics and lighting engineering drawn from 3000 years of construction engineering history. Consequently, the knowledge gleaned from the history of theory of structures serves as one of the cornerstones in his evolution of the design methods used by structural engineers.

Roberto Gargiani pursues an artefact-based approach in his collection of essays on columns [Gargiani, 2008] (Fig. 1-9), which are presented from the history of building, history of art, history of construction engineering, history of science and history of structural theory perspectives. The discipline-oriented straightforwardness of the history of theory of structures is especially evident here.

1.3 Didactic tasks

FIGURE 1-9
Cover to the collection of essays on columns *La colonne. Nouvelle histoire de la construction* [Gargiani, 2008]



The work of the American Society for Engineering Education (ASEE), founded in 1893, brought professionalism to issues of engineers' education in the USA and led to the formation of engineering pedagogy as a subdiscipline of the pedagogic sciences. In the quarterly *Journal of Engineering Education*, the publication of the ASEE, scientists and practitioners have always reported on progress and discussions in the field of engineering teaching. For example, the journal reprinted the famous *Grinter Report* [Grinter, 1955; Harris et al., 1994, pp. 74 – 94], which can be classed as a classic of engineering pedagogy and which calls for the next generation of engineers to devote 20 % of their study time on social sciences and the humanities, e. g. history [Harris et al., 1994, p. 82]. Prior to L. E. Grinter, another prominent civil engineering professor who contributed to the debate about the education of engineers was G. F. Swain. In his book *The Young Man and Civil Engineering* (Fig. 1-10), Swain links the training of engineers with the history of civil engineering in the USA [Swain, 1922].

Nevertheless, students of the engineering sciences still experience the division of their courses of study into foundation studies, basic specialist studies and further studies as a separation between the basic subjects and the specific engineering science disciplines, and the latter are often presented only in the form of the applications of subjects such as mathematics and mechanics. Even the applied mechanics obligatory for many engineering science disciplines at the fundamental stage are understood by many students as general collections of unshakeable principles – illustrated by working through idealised technical artefacts. Closely related to this is the partition of the engineering sciences in in-depth studies; they are not studied as a scientific system comprised of specific internal relationships, for example, but rather as an amorphous assemblage of unconnected explicit disciplines whose object is only a narrow range of technical artefacts. The integrative character of the engineering sciences thus appears in the form of the additive assembly of the most diverse individual scientific facts, with the result that the fundamental engineering science disciplines are learned by the students essentially in the nature of formulas. The task of a history of theory of structures is to help eliminate the students' formula-like acquisition of theory of structures. In doing so, the separation of the teaching of theory of structures into structural analysis for civil and structural engineers and structural engineering studies for architects presents a challenge. Proposals for a historicised didactic approach to structural engineering studies have been made by Rolf Gerhardt [Gerhardt, 1989]. Introducing the historical context into the teaching material of theory of structures in the project studies in the form of a historic-genetic teaching of structural theory could help the methods of structural engineering to be understood, experienced and illustrated as a historico-logical development product, and hence made more popular. The history of theory of structures would thus expand significantly the knowledge database for a future historic-genetic method of teaching for all those involved in the building industry.

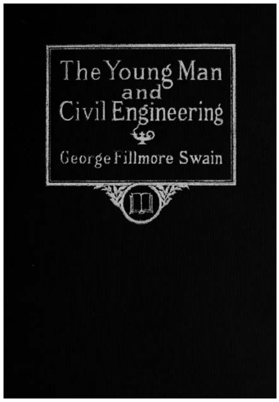
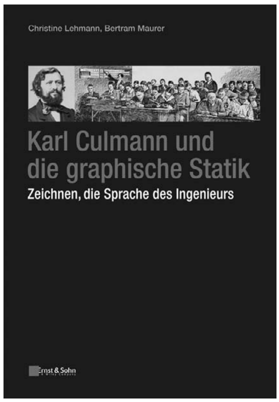


FIGURE 1-10
Cover of Swain's *The Young Man and Civil Engineering* [Swain, 1922]

1.4 Cultural tasks

There is an elementary form of the scientist's social responsibility: the democratising of scientific knowledge through popularising; that is the scientist's account of his work – and without it society as a whole would be impossible. Popular science presentations are not just there to provide readers outside the disciplinary boundaries with the results of scientific knowledge reflected in the social context of scientific work, but rather to stimulate the social discussion about the means and the aims of the sciences. Consequently, the history of theory of structures, too, possesses an inherent cultural value. The author Christine Lehmann, together with her partner the mathematics teacher Bertram Maurer, has written a biography of Karl Culmann (Fig. 1-11) based on Maurer's dissertation [Maurer, 1998] in which the results of research into the history of theory of structures are presented to the layman in an understandable, narrative fashion within an appealing literary framework.

FIGURE 1-11
Cover of the biography of Karl Culmann [Lehmann & Maurer, 2006]



The individual sciences physics, biology and even chemistry transcend again and again the boundaries of their scientific communities. This may be due to their role as constituents of worldly conceptions and the close bond with philosophy and history. But the same does not apply to the engineering sciences; even fundamental engineering science disciplines find it difficult to explain their disciplinary intent in the social context. The fragmentation of the engineering sciences complicates the recognition of their objective coherence, their position and function within the ensemble of the scientific system and hence their relationship as a whole to the society that gave birth to them and which surrounds them. This is certainly the reason why the presentations, papers and newspaper articles of the emeritus professor of structural analysis Heinz Duddeck plead for a paradigm change in the engineering sciences, which in essence would result in a fusion between the engineering sciences and the humanities [Duddeck, 1996]. As the history of theory of structures forms a disciplinary union between structural analysis and applied mechanics with input from the humanities (philosophy, general history, sociology, histories of science, technology, industry and engineering), it is an element of that fusion. It can therefore also assist in overcoming the "speechlessness of the engineer" [Duddeck, 1999].

1.5 Aims

The aim of a history of theory of structures therefore consists of solving the aforementioned scientific, practical engineering, didactic and cultural tasks. This book, written from the didactic, scientific theory, construction history, aesthetic, biographical and bibliographical perspectives (Fig. 1-12), aims to provide assistance.

1.6 An invitation to a journey through the history of theory of structures

In Franz Kafka's parable of the gatekeeper from the chapter entitled "In the Cathedral" in his novel *The Trial* published in 1925, Josef K. searches in vain for a way to enter the law via a gate guarded by a gatekeeper. Kafka's protagonist Josef K. could be studying civil engineering or architecture, history of science or history of technology – for him the motives for acquiring the fundamentals of theory of structures were duly spoiled: he would sit in front of the gate or exit the stage like an actor in a theatre.

Dear Mr. Josef K.! There are various gates through which the laws of structural analysis can be learned with joy (Fig. 1-12). You can consider, dear Mr. Josef K., which phantasmagorical gatekeeper you can evade most easily – but let me tell you this: the gatekeepers don't exist! Please get up, open any gate and pass through it, and you will see the form in which theory of structures appears to you. If you are inquisitive and wish to open all seven gates, then you will be in possession of a picture of the history of structural analysis – your picture. But never guard your picture jealously as if it were your property because then at the final curtain the same will happen to you as happened to your Kafkaesque namesake: you'll be put on trial without knowing who is prosecuting and why – perhaps you'll even prosecute yourself! You would be sentenced to life imprisonment, sitting and waiting, hoping to be allowed in. The shadow cast by your property would seem like the cool draught of your approaching death. So choose