1 Introduction

Why Read This Book?

Concrete is by far the most used building material in the world. Concrete can be given arbitrary forms, its basic constituents are available everywhere, its processing is basically simple, and it is inexpensive. Furthermore, concrete can be customised to fulfil special requirements – e.g. high strength, resistance in rough environments, impermeability, ductility – through adjustment of binder, aggregates, fibres, and additives. Its major characteristic from a mechanical point of view is given by a relatively high compressive strength but a low tensile strength. Thus, it is reinforced with bars, wire mats, fabrics of steel, carbon, glass, and more, which leads to an immense variety of composite building materials.

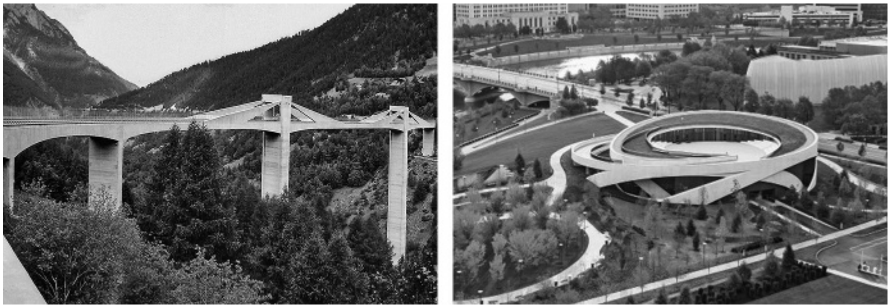
With this we see architectural landmark buildings like the television tower in Stuttgart, Germany, the first of this type designed and engineered by Fritz Leonhardt and built in 1956, Figure 1.1a, the Palazzetto dello Sport in Rome, Italy, a coliseum for the Olympic games 1960 built in 1956 and engineered by Pier Lucri Nervi, Figure 1.1b, the Ganter bridge within the access road to the Simplon pass in the Swiss Alps built in 1980 and designed and engineered by Christian Menn, Figure 1.2a, and


(a)


(b)

Figure 1.1 (a) Stuttgart television tower, from Kleinmanns and Weber (2009), photography: Landesmedienzentrum Baden-Württemberg: Albrecht Brugger. (b) Palazetto dello Sport, from Ehmann and Pfeffer (1999).

Computational Structural Concrete – Theory and Applications, Second Edition. Ulrich Häussler-Combe.



(a) (b)

Figure 1.2 (a) Ganter bridge, from Billington (2014), photography: Nicolas Janberg. (b) National Veterans Memorial and Museum, from Helbig et al. (2020), photography: Knippers Helbig Stuttgart – New York – Berlin.

(a) (b)

Figure 1.3 (a) Office building: Züblin-Haus, from Bachmann et al. (2021). (b) High-speed railway viaduct over the valley Unstruttal, Germany, photomontage, from Schenkel et al. (2009).

the National Veterans Memorial and Museum, Columbus, Ohio, USA, built in 2018 and engineered by Knippers Helbig, Figure 1.2b, to mention only a few.

A countless number of concrete buildings contribute to everyday life; for example, office buildings, Figure 1.3a (Züblin headquarters, Stuttgart, Germany; precast concrete with steel–glass atrium), railway bridges, Figure 1.3b (Unstruttal viaduct, Thuringia, Germany), power plants, Figure 1.4a (RWE, Niederaußem, Germany), station concourses, Figure 1.4b (Stuttgart 21, Germany; final state visualisation, still under construction). This demonstrates some visible contributions of the application of concrete. Indispensable infrastructures providing freshwater, drainage, and wastewater processing, waste disposal processing in general, generation and provision of electricity, support of transport via vehicles, trains, ships, and airplanes are generally hidden from immediate visibility. To sum it up, today's civilisation would be unthinkable without concrete as a building material.

It can be stated that reinforced concrete is the building material of the twentieth century. But will it also be the building material of the twenty-first century?

Presumably yes, due to its advantages listed above. But sustainability has to become a predominant topic also for reinforced concrete besides bearing capacity, usabili-

(a) **(b)**

Figure 1.4 (a) Power plant, RWE, Niederaußem, Germany, from Krätzig et al. (2007), photography: RWE. (b) Underground station concourse, Stuttgart 21, from Bechmann et al. (2019), visualisation: Ingenhoven Architekten, Düsseldorf.

ty, and durability. Production of cement – the predominant binder for concrete – causes a high output of CO_2 due to its energy consumption on the one hand and chemical conversion processes on the other hand. The same also applies to reinforcing steel whereupon its contribution to reinforced concrete is relatively small measured by weight ratio. Construction waste makes up the largest proportion of the total amount of waste. What is the conclusion?

> We have to use less concrete and fewer reinforcement materials and at the same time achieve a higher quality of building components.

Structural design plays a key role to reach this goal. We should gain a better understanding of load carrying mechanisms of building components in order to fully utilise load bearing potentials and to optimise structural forms and materials. There is still a lot of room for improvement in this regard.

Computational methods are an extremely important tool for this. Numerical simulation in combination with experimental investigations allows for a comprehensive understanding of the deformation behaviour, force flow, and failure mechanisms of building components. This permits weak points to be identified and eliminated in a targeted manner. New concepts may be initiated, and a simulation-based rapid prototyping may be performed for initial assessments of new innovative structural forms and materials. On the basis of the knowledge gained from this, the design and elaboration of components in building practice can be carried out more efficiently and with higher quality using computational methods.

Topics of the Book

Such methods are generally demanding with respect to methodology, implementation, and application. This is especially true for nonlinear problems as are typical for structural concrete. Computational methods for nonlinear structural analysis offer a wide range of capabilities. But they are made available to users as black boxes.

This hides the fact that numerical methods usually have application limits. If these are not observed, the results become questionable. Often, this is not obvious to users providing input for black boxes and accepting output without hesitation. This motivates the goals and contents of this textbook about computational methods – in particular, the finite element method (FEM) – for reinforced concrete (RC):

- Survey of the key aspects of the FEM.
- Understanding of basic mechanisms of RC regarding interaction of concrete and reinforcement through bond.
- Specifics of FEM regarding structural elements like RC-beams, plates, slabs, and shells.
- Essential characteristics of the multi-axial mechanical behaviour of concrete.
- Pitfalls related to FEM treating structural concrete and in particular the failure behaviour.

Knowing these issues, the black boxes should become more transparent, and their results should be better comprehensible. The finite element method is the preferred method also for the computation of reinforced concrete structures due to its versatility and adaptability.

Chapter 2 gives an overview of modelling in general and summarises items of FEM as far as is required for its application to reinforced concrete structures. *Chapter* 3 describes basic mechanisms of structural concrete, which relies on the interaction of concrete and reinforcement by continuous transfer of forces through bond. This is restricted to uniaxial behaviour in a first approach to point out essential properties and describes the mechanisms of the reinforced uniaxial tension bar as prototype of structural concrete. In *Chapter* 4, this is extended to reinforced concrete beams and frames, which are characterised by bending that may be superimposed with normal forces whereby still basing on uniaxial behaviour of materials. This also includes first aspects of creep, temperature, and shrinkage. Furthermore, prestressing of beams is treated, which is an important technology to extend the application range of reinforced concrete. The chapter closes with the analysis of large displacements and dynamics, exemplarily in each case with their application to beams. A first extension of bending of beams to high beams and plates is given in *Chapter* 5 with strut-and-tie models, which utilise the uniaxial behaviour of concrete and reinforcement for a design of plane structures with in-plane loading. Furthermore, limit theorems of plasticity – which are an important basis for design in structural concrete – are exemplarily developed within this context. *Chapter* 6 treats multi-axial concrete behaviour as extension of the uniaxial approach applied in the foregoing chapters. Multi-axial material concrete models are the basis for the structural models for plates, slabs, and shells treated in the following chapters. Basic topics of continuum mechanics are described in as far as they are necessary to understand multi-axial nonlinear stress–strain and failure behaviour of concrete. Material models like elasto-plasticity, damage, and microplane are applied with respect to concrete modelling. A major item regarding material modelling occurs with strain softening – increasing strains with decreasing stresses – which requires a regularisation to reach reliable numerical solution. A further major item concerns the cracking of concrete, which separates parts of a continuum into a discontinuum. This couples discretisation issues with material modelling and is described in *Chapter* 7. *Chapter* 8 treats design and simulation of reinforced concrete plates with high beams as a special but common case. In this respect, the design is considered separately, as it may be based on linear solutions for plate stresses utilizing a limit theorem of plasticity. On the other hand, simulation considers nonlinear stress–strain relations additionally leading to solutions for the deformation behaviour. Reinforced concrete slabs, which are treated in *Chapter* 9, extend uniaxial 1D-bending of beams into biaxial 2D-bending. As before with plates, aspects of design and simulation may be separated in an analogous manner. The most general approach for structural analysis is given with shells, which combine in-plane actions of plates and transverse actions of slabs whereby extending flat geometries to folded or curved geometries. Shells require complex mechanical models, which is exemplarily treated in *Chapter* 10 together with the application to reinforced concrete. *Chapter* 11 treats first aspects of randomness, which is a major topic regarding structural concrete behaviour. Deterministic models – however sophisticated they may be – always give a more or less restricted view of the real world. First notions of an extended view are given in this chapter. Finally, a number of topics are treated in the appendices insofar they are reasonable for better understanding of the main text but might disturb the line of concise arguing therein.

How to Read This Book

The treatment of the above combines methods of mechanics, structural analysis, and applied mathematics. This recourse should be self-explanatory and conclusive to a large degree, so that a study of accompanying literature is generally not required. In doing so, essential lines of development are worked out on the one hand, but on the other hand, the available concepts and methods cannot be described with all details. Furthermore, not every problem addressed is provided with a comprehensive solution. The book is intended to encourage the reader to deepen and explore such topics independently.

Nevertheless, the book involves a large volume. Proposals for shorter tracks are given in the following thereby also enlightening the structure of the book content and the relations between sections. Major groups are characterised as

- FEM and reinforced concrete bases, see Figure 1.5a.
- Uniaxial structures, see Figure 1.5b.
- Multi-axial concrete and its implications for numerical methods, see Figure 1.6a.
- Multi-axial structures such as plates, slabs, and shells, see Figure 1.6b.

This includes a short track (left column) and branches (right column) for each of these. Chapter 11.1 *Randomness and Reliability* falls out of this scheme. Nevertheless, basic knowledge of stochastics related to reinforced concrete is considered necessary.

Many topics are illustrated with examples. Most of them are computational and are processed with the PYTHON 3.6 program package CONFEM. A few are performed

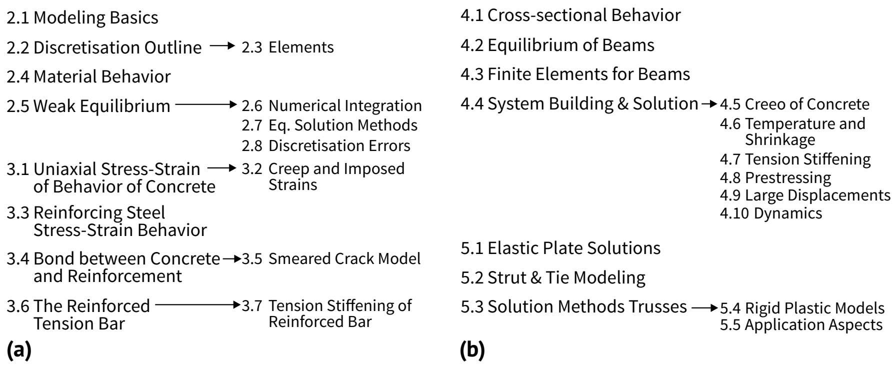


Figure 1.5 (a) FEM and reinforced concrete bases. (b) Uniaxial structures.

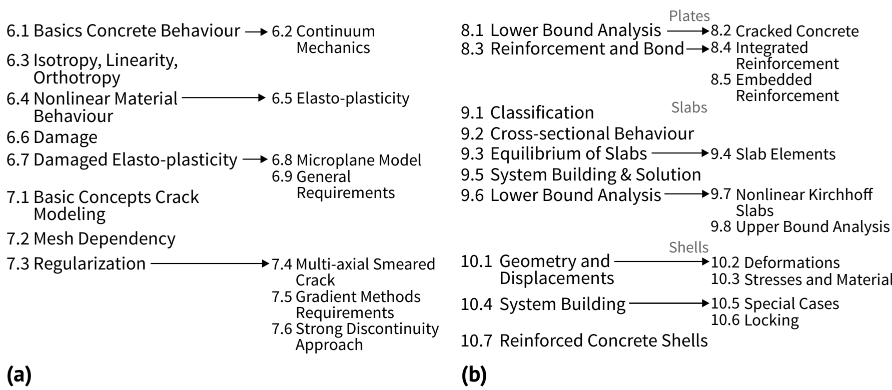


Figure 1.6 (a) Multi-axial concrete and its implications. (b) Multi-axial structures.

with stand-alone PYTHON scripts or are short, illustrating theoretical derivations. Environments to perform PYTHON are freely available on the internet for all common platforms.

All PYTHON sources for CONFEM, a basic documentation, example input data, and reference result data are available at https://www.concrete-fem.com under open-source conditions.

Thus, all book examples should be reproducible by the reader. But the CONFEM project is not finished and may be subject to continuous development. The user should see it as an inspiring challenge to master this tool. The interplay of theory, implementation, and application – possibly with overcoming resistance – ultimately leads to a deeper understanding of numerical methods, structural concrete, and their dependencies.