1

Introduction

Key learnings after reading this chapter:

- What influence do construction activities exert on the climate?
- What are the requirements of a future-oriented way of building?
- How can structural optimization methods contribute to this?

1.1 Preliminaries

Concrete is one of the oldest building materials in the world. The Romans already used it and achieved strengths of up to about 40 MPa [1]. Concrete exhibits an uneven distribution of strengths. Its compressive strength is high, but its tensile strength equals about one tenth of it. Concrete is therefore predominantly stressed in compression while tension is avoided. Structures whose design is oriented toward the material properties take this aspect into account and primarily bear loads via compressive stresses. Thus, this corresponds to the traditional use of concrete for arches, columns, and domes, where compressive forces prevail.

With the advent of reinforced concrete (RC) in the 19th century, the restriction to structures subjected predominantly to compressive stress was lifted [2], since steel was employed to enhance concrete in tension emerging from bending, shear forces, or axial loads. The same applies to local areas of load application or geometric discontinuities such as corbels, openings, and supports.

Due to three factors, namely the technological feasibility of reinforcement, scarcity of human labor and low material costs for concrete itself, the structures changed. Curved shapes disappeared and were widely substituted by simple, rectangular ones, which prevail to the present day. Typical examples are prismatic plates, walls, or beams. The formwork shapes are simplistic and can be easily produced on a large scale. Thus, the structural designs are often motivated by the simpler construction on site, although larger quantities of concrete and steel are needed.

Building is a question of time, its capabilities and the pursuit of goals [3]. Expensive materials lead to rather slender designs. High labor and formwork costs require automation and simplification of shapes. Furthermore, the demand for short construction times favors prefabricated components.

Optimization Aided Design: Reinforced Concrete, First Edition.
Georgios Gaganelis, Peter Mark, and Patrick Forman.

Compared to other building materials, concrete has the advantage of free formability. The initially liquid material hardens and obtains its permanent, solid shape only through hydration. In this respect, concrete structures are open to virtually unlimited outer shapes. In the same way, its inner shape – namely the layout of reinforcement – is freely adjustable and installable. It does not have to adapt to formwork edges in any way, but can easily follow the tensile trajectories instead.

So what is the right shape? What is the right reinforcement (pattern) and where is it located? How does the right cross-section look like? The answers to these questions depend on the defined objectives and constraints to be met. And these conditions change. They change over time, they change depending on the country and the way of life, and they change according to external influences. Because of this mutability, the approaches to find the right shapes must therefore account for the relevant objectives and constraints. This is the only way to find different answers to similar questions, differing only in the underlying boundary conditions. In this way, the range of answers expands and adapts to the scope.

The book develops a generally applicable method for this purpose, namely the *Optimization Aided Design* (OAD). It is motivated by three fields of investigation. These are:

- the outer shape of structures,
- the inner reinforcement layout, and
- the cross-sectional design.

Briefly, the inner and outer form finding.

1.2 Outer and Inner Shaping

The outer shape of a concrete structure is determined by its intended purpose. This can be, for example, the enclosure of a storeroom, the load-bearing function for a bridge deck, a plane surface of a ceiling, or shielding against soil and groundwater in a tunnel. The shape further characterizes the design.

The outer shape is influenced by the load-bearing and protective function to be met, aspects of economic efficiency, the construction process and the way the structure integrates into the surrounding environment. It is virtually arbitrary due to the ability of free formability, since concrete exhibits the advantage of taking any shape. In this respect, no distinction can be made between “right” and “wrong”, since all designs meet the requirements for load-bearing capacity, serviceability, and durability.

In the case of engineering structures such as bridges or tunnels, their outer shape clearly indicates the static load-bearing system. If the outer form follows the dominant internal force flow (“form follows force”) and further predominantly orients toward compression, lightweight and, in many cases, bionic-like, curved structures result. Typical examples are arches, shells or even pylons of bridges with inclined cables, which experience a distinctly dominant downward load impact due to the deflecting forces of the cables.

Figure 1.1 Concrete shaped to the flow of forces: pylon of the Pont de Terenez (France). Picture: Thomas Putke-Hohmann.

Figure 1.1 shows such a form finding according to the flow of forces by the bridge "Pont de Terenz", located in France [4]. The bridge layout lies within a narrow circular bend. The pylon is shaped similar to an inverted "Y", with the front leg continuing the slightly inclined column shape above the roadway level in a straight line and orienting toward the lateral forces from the cable deviation. In this way, it is mainly subjected to compressive loads. The lower supports act like two legs in step sequence and provide further stability against lateral loads from wind and centrifugal downforces.

Structures designed according to the flow of forces tend to look aesthetically pleasing and require small amounts of material by avoiding redundant flexural load-bearing effects. In contrast, Figure 1.2 shows a solid bridge designed using simple shapes. It is composed of equal single-span beams, each of which is interchangeable. The external cross-sectional geometry of the superstructure remains constant. This results in two bearing rows per column that are accordingly thick and compact.

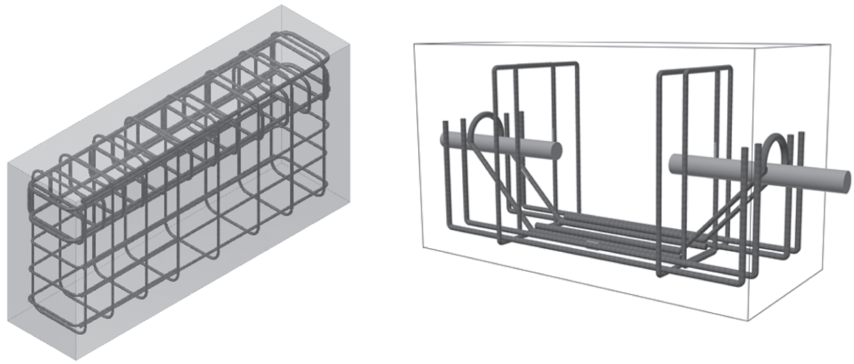
The bridge can be built with constant scaffolding and formwork layout. The dominant design aspect here is an effective fabrication with a repetitive sequence,

Figure 1.2 Railway concrete bridge with uniform single span girders and compact columns.

meaning that every single beam is made with the same formwork and scaffolding, the same reinforcement and the same casting concept. The result is a repetitive pattern justified from cost-efficiency in manufacturing. Due to the homogeneous shape across the entire bridge, its beam-like load-bearing behavior and the necessary limitation of distinct rotation angles at the ends of each girder for the train passage, massive, heavy cross-sections result and the spacings between the columns become compact and monotonous. Compared to a structure following the flow of forces, great additional material amount is needed. For the specific case, this is mass concrete, as well as prestressing and reinforcing steel. At the same time, aesthetics suffer due to the obstructed view and consistent pattern of equal spans, equal columns, and the tall and heavy-looking superstructure.

Similar to the external shape, the internal load transfer can also be designed intentionally. The reinforcement is typically adapted to the formwork shape and not primarily to the tensile trajectories of the load transfer. For common rectangular cross-sections, reinforcement cages are produced from longitudinal bars and vertical stirrups, thus forming a rectangular grid that follows the formwork's edges (Figure 1.3a). This type of reinforcement suits the convenience of production. Due to the constant orientation, tensile trajectories and reinforcement directions differ, which automatically leads to an increased amount of required reinforcement. In other words, fabrication outweighs material efficiency.

Figure 1.3b shows an alternative layout. Like the outer shape of the concrete cross-section, the reinforcement can also be laid in a virtually arbitrary spatial manner and does not necessarily has to follow a rectangular pattern. The depicted



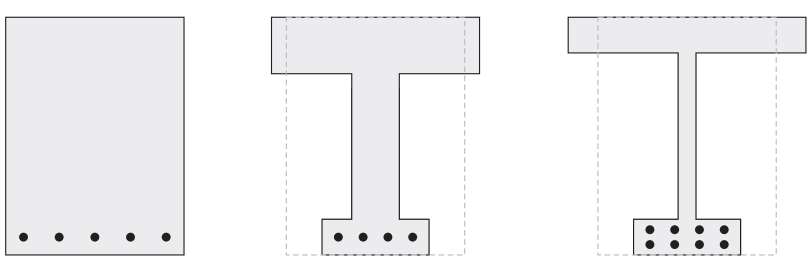
(a) (b)

Figure 1.3 Reinforcement cages: (a) typical rectangular pattern of longitudinal bars and side aligned stirrups, (b) freely bend reinforcement derived from strut-and-tie modeling [5].

shear force transfer reinforcement layout with shear dowels was developed from a strut-and-tie model adapted to the force flow [6].

Generally, it can be stated that the outer and the inner shape of RC structures are not limited. If they follow the flow of forces, low material consumption and mostly aesthetic designs result.

The following example of a cross-section choice will illustrate how much the underlying objectives influence the design. A RC cross-section for a beam in axial bending is sought. The cross-section needs to be both sustainable and cost-effectively designed for various monetary boundary conditions, however, the bending moment remains equal in each case. Figure 1.4a shows a cross-section with expensive formwork and subordinate material prices for both concrete and steel reinforcement. The result is a simple rectangular shape. In Figure 1.4b, the high price for steel is the governing criterion. A more elaborate I-shape exhibiting a large lever arm of internal forces now minimizes the reinforcement amount. The third cross-section design (Figure 1.4c) arises from the scenario, where the price for concrete is dominant. Here, the web width decreases, the top flange is thinned,



(a) (b) (c)

Figure 1.4 RC cross section designed under cost boundaries: (a) expensive formwork, (b) expensive reinforcing steel, (c) expensive concrete.

and further reinforcing steel is added in order to shift the neutral axis of elongation down into the web.

This simple example demonstrates the need to formulate distinct and measurable objectives in order to find adequate structural designs for different boundary conditions. Although, a fixed preliminary specification of the cross-section satisfies load-bearing capacity, serviceability and durability, it is not capable to respect other, often multifunctional requirements, concerning, for instance, material, fabrication, and time. For this purpose, load-bearing capacity, serviceability, and durability must be downgraded to become auxiliary conditions to the design problem. They must be met in any case but not as primary design objectives. Instead, the aim must be to find the right shape, freely according to descriptive objectives such as, e.g. cost minimization or short construction times.

1.3 Environmental Demands

Concrete is by far the most widely used building material in the world [7, 8]. Its major advantages are first, the easy availability of the raw materials, namely cement, aggregates, and water, second, the free formability, third, the simple handling and, fourth, most importantly, its low price. Even bottled water is more expensive per unit volume than concrete.

The amount of concrete used worldwide each year is gigantic, estimated at more than 10 billion tons in 2019 [9]. This equals a per capita consumption of about 1.3 t/a (tons per year) – 1 for each of the almost 8 billion people on earth. If the total annual amount were to be distributed over a land area such as that of Germany (~ 360 000 km^2), it would be covered with about 1.4 cm of concrete. Taking the more reliable data of the total amount of globally produced cement for the calculation (4.1 billion tons in 2017 [10]) and assuming a proportion of 300 kg of cement per cubic meter of concrete, this even leads to 3.8 cm of concrete cover. An unimaginable amount of material per year.

However, when it comes to its impact on the climate, concrete is not a particularly unfavorable material. In fact, rather the opposite is the case [11]. With usually short transport distances and almost worldwide availability of the raw materials, concrete proves to be very efficient compared to other building materials in terms of the

Table 1.1 Specific strengths of construction materials: normal strength concrete (NC), structural steel, high performance concrete (HPC), ultra-high performance concrete (UHPC), fiberglass, carbon.

	NC	Structural steel	HPC	UHPC	Fiberglass	Carbon
Strength [MPa]	16–50	235–355	55–100	150–250	1200–1300	2000–6000
Density [t/m^3]	2.1–2.6	7.85	2.1–2.6	2.4–2.6	1.9	1.8
Specific strength [MNm/t]	6–24	30–45	21–48	58–104	632–684	1111–3333

load-bearing capacity provided per unit volume ("specific strength"), see Table 1.1. Concrete becomes a highly climate-relevant construction material only due to its vast quantity. The production of cement alone, its most important raw component, is responsible for 5–10% of the global CO_2 emissions each year [12–15]. The combustion process in cement production is thus the largest single emitter worldwide.

The increase in global use of concrete is closely linked to the beginning of industrialization in the 19th and 20th centuries and the associated population growth. Figure 1.5 shows the development of the main raw materials of concrete over the years. These are water, cement and crushed or round aggregates. Concrete consumption has increased significantly. Its application has been particularly intensified in the last three decades throughout the world. Closely related to concrete is the demand for aggregates, which account for around 70% of its volume. Over 40 billion tons are used each year, which equals about half of the total sand

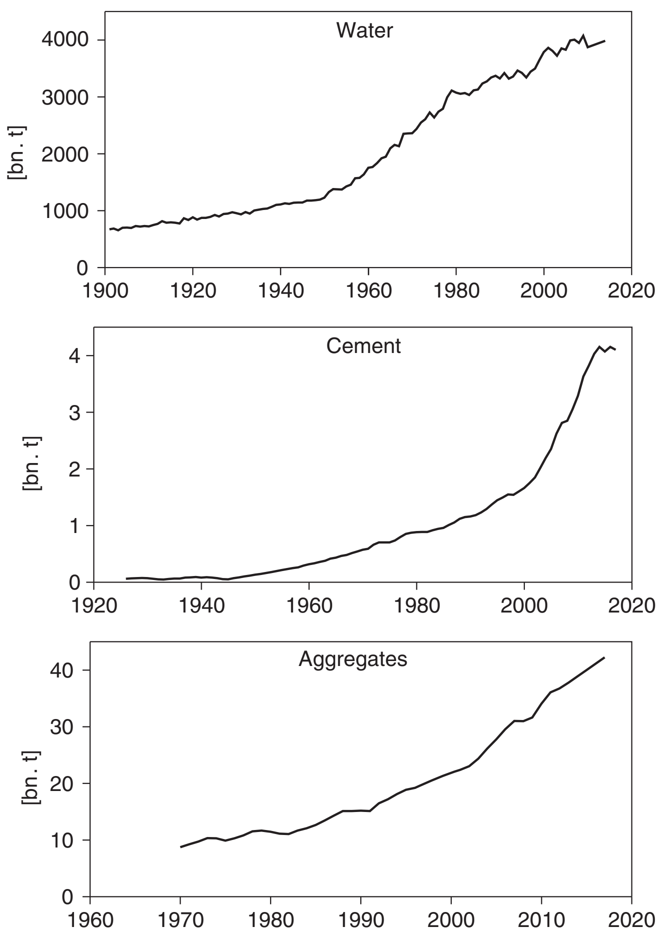


Figure 1.5 Annual world consumption of water, cement, and aggregates, according to [10, 16, 17].

and grain mining [17]. The consumption of cement and water has increased sharply within the last decades, which is closely related to concrete consumption. It should be noted, however, that Figure 1.5 depicts the total water use worldwide, meaning that it also includes the use for drinking water, irrigation, livestock, and other industries.

At the same time, global population is growing. Growth increased sharply after the two World Wars and has followed an almost linear progression since the 1960s. Figure 1.6 shows the development until 2020 with a mean prediction until 2100 according to estimations of the United Nations [18]. Following an average prognosis, about 1 billion people are added every 10–15 years. In 2100, approximately 3.2 billion more people are expected to live on earth than do today. Simultaneously, the living standard of people is increasing and along with that the need for housing, infrastructure, and energy supply. By comparison, the population increase from 2020 to 2050 will be around the total number of people in the world in 1930. At that time, about 2.0 billion people lived on earth. About the same volume of housing and associated infrastructure at that time is to be provided over the next 30 years in addition to the current state [19, 20]. However, this additional amount represents rather a lower estimate of demand, since rising living standards are not included in the calculation.

New construction is increasingly being accompanied by the necessary preservation of existing structures as an ongoing task. On the one hand, bearing structures – like all technical equipment – must be regularly maintained and repaired. On the other hand, they have a limited service life. The service life varies from about 50 years for buildings to 200 years for extraordinary infrastructure or utility constructions. After their use, structures need to be replaced by new ones.

The substitution of existing structures by new ones is called replacement construction. It is typical for structural tasks in, for example, Western Europe or North America. Replacement constructions are built at the same place as the structures to be replaced. Consequently, construction activities take place in a dense urban

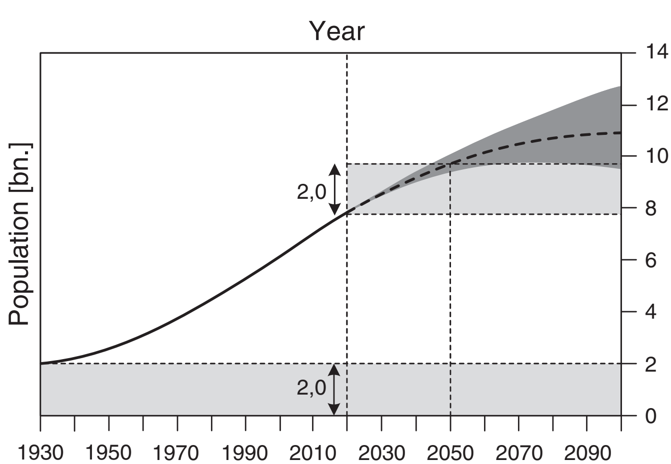


Figure 1.6 Development of the world population from 1930 till 2100, according to [18].

Figure 1.7 Traffic jam caused by a lane constriction to pass a construction site of a road bridge replacement.

environment and in existing road or utility networks. Inevitably, this leads to restrictions and disruptions in the flow of goods and traffic.

This is particularly evident at bridge construction sites. The ongoing traffic is to be diverted around the construction site and the lanes must be restricted. Figure 1.7 shows a typical example of a lane constriction at a construction site of a road bridge. Truck and passenger traffic is narrowed from initially three lanes to only one. This causes vehicles to back up a long way. The result is a waste of time, human labor, and fossil fuel – without generating any economic gain.

Replacement construction rarely takes place consistently. Consistency in this context refers to a distribution over time, across locations and in terms of monetary and personnel efforts. Usually, construction activities tend to take place in waves and are therefore clustered in places of particular economic growth and are focused on few years. This hardly makes sense for builders, contractors, and planners. Figure 1.8 shows an example of bridge building activities in a western German city. Gray columns represent amounts of installed bridge deck areas. Bridge construction is concentrated around the 1960s to 1980s and the distribution resembles a bell-shaped curve. If the bridges are replaced after a service life of 80 years, which is assumed to be the same for all structures in a simplified manner, the distribution of replacement construction shown on the right in light gray is obtained. It repeats the dark gray bars and merely shifts them 80 years into the future. The unfavorably clustered construction activities repeat. Now, however, they take place within the existing traffic network. They thus entail considerable restrictions from the

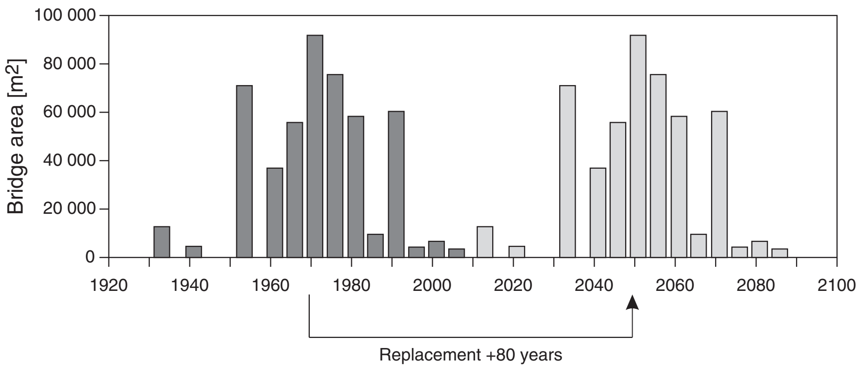


Figure 1.8 Age distribution of built bridges of a German city according to [21] and proportional prognosis of its rebuild after 80 years of service life.

significantly increased traffic over the recent years and the ever more densely linked flows of goods of industrial supply delivered "just in time". Extending the service life of structures to far beyond 100 years seems to offer a reasonable solution in order to distribute construction activities more evenly over time [22]. Generally, the key issue lies in a more uniform distribution. This results in almost constant demands on building, costs, and human engagement.

Building is further associated with a high personnel expenditure. Many activities are still conducted by hand and structures hardly involve serial repetition. As an example, Figure 1.9 shows several workers distributing and planning a concrete subbase for a tunnel trough. Human labor is becoming a rare commodity, particularly in industrialized countries, and must be conserved in the same way as

Figure 1.9 Workers manually distributing and planning a concrete subbase.

materials, time, money, and climate sensitivity. This endeavor will become even more important in the future than it has been in the past.

The examples of current construction serve to illustrate that objectives of reasonable structural designs may depend on various boundary conditions. This may be saving of materials, but also minimizing construction times, human labor costs, and greenhouse gas emissions or ensuring more uniformly distributed construction activities. Building reflects the time, its respective boundary conditions, as well as primary and secondary objectives. However, both objectives and constraints may change over time, but this does not apply to their fundamental components, namely objectives and constraints. For this reason, it seems reasonable to define the design and dimensioning of structures following a corresponding approach, namely by using objectives consisting of one or multiple (weighted) aims and boundary conditions to be met (constraints).

OAD provides such a uniform approach. One or more goals are formulated as the objective function. Typical examples include minimizing the total costs, weight, structural compliance, or manufacturing labor. In doing so, various boundary conditions must be complied with. Typical examples for the latter are stress limits, ensuring equilibrium, restricting the material amount, or geometric limits. This reveals a generally applicable method toward finding structural designs capable of meeting the complex requirements of the modern world more effectively.

1.4 Optimization Aided Design (OAD)

OAD refers to the design and dimensioning of structures and structural components using optimization methods. For RC, this involves finding the most suitable outer shapes, identifying efficient reinforcement layouts, and employing reasonable cross-sections. OAD therefore refers to a general methodology that can be applied to a great extent. It is suitable for the use with any concrete (normal strength to ultra-high performance) and arbitrary types of reinforcement (steel, carbon, fibers), and is further transferable to numerous fields of structural engineering such as steel, timber or foundation engineering.

OAD uses the concept of mathematical optimization [23–28]. In doing so, generally, the aim is to minimize the formulated objective function. This can be, for example, the structural weight, a reinforcement quantity, or even combinations of conflicting functions, for instance, minimizing material usage, while also minimizing shuttering edges. Additionally, several restrictions must be met. These restrictions take the form of equality and inequality constraints. Typical equality constraints are the equilibrium between external actions and internal forces. Inequality constraints may include geometric limits, stress constraints, or an upper limit of the material amount. Within mathematical optimization, OAD relies on structural optimization approaches, and focuses in particular on the topology optimization method.

As an introduction, Figure 1.10 shows the gradual adaptation of the outer shape of a single span girder under uniform loading. The designs are depicted along with

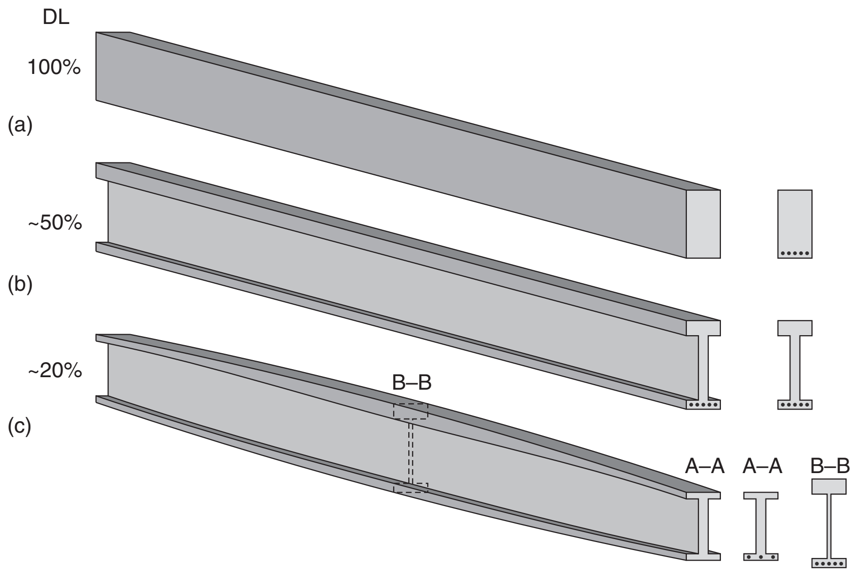


Figure 1.10 Stepwise shaping of a single span girder with reduction in dead loads: (a) constant rectangular cross section, (b) shaping of the web, (c) force affine shaping of heights, flanges and the web thickness.

their respective cross-sections and the relative change in dead loads (DL). In order to illustrate the concept, the example is intentionally kept simple and can in principle be solved intuitively without applying any optimization technique. Starting point is a simple beam with rectangular cross-section (a). Decisive for the bending design is the bending moment at midspan. The shear reinforcement is determined close to the supports from the maximum shear force. The outer shape of the structure is dictated by the respective required cross-section. In doing so, excess material is used almost throughout the entire beam since only two particular cross-sections are decisive. The web is generally too thick, the maximum flexural reinforcement is only required in the center of the field, as is the resultant in the compression zone, which decreases considerably toward the bearings. In the second step (b), the web is reduced to the actual necessary width from the load-bearing capacity of the inclined compression strut. Although, the beam remains prismatic in its outer shape, the DL is already decreasing considerably. A slight increase in height also maintains the stiffness. In the third step (c), each cross-section of the beam is formed in such a way that compression zone, tension zone, web width and stirrup quantity are always fully utilized. The shape in the longitudinal direction is adapted to the parabolic shape of the bending moment, the web width to the respective inclined compression force and the flanges to the necessary widths for compression force and tensile reinforcement. Single cross-sections are no longer decisive. Instead, each cross-section along the entire length of the beam is now relevant, which also means that reserves are no longer available. A reduction of the DL up to about 20% is achieved compared to the simple beam with rectangular cross-section.

Conceptually, OAD follows the same approach: searching for design solutions that ensure efficient stress utilization and accumulate material only where it is most effective for the load-bearing mechanism. This applies equally to the outer and inner form finding.

For typical structures, several load cases with varying actions have to be taken into account, thus full utilization in superposition of different scenarios, for instance, maximum vertical loads versus maximum horizontal loads, obviously may not be achieved everywhere.

Taking into account the relevant boundary conditions is particularly important in OAD. Such boundary conditions are especially geometric limits such as clearances and smooth edges for connection, but also maximum and minimum dimensions. In the case of a ceiling slab, for example, the flat, smooth surface is mandatory and curved shapes or recesses must be prevented, even if they would favor the load-bearing mechanism.

Figure 1.11 shows an example for the influence of the geometric boundary conditions of a roof girder. The static system with permissible design space (gray) and the imposed action consisting of several point loads F are depicted in (a). From the topological optimization, minimizing the mean structural compliance (=maximizing stiffness) and limiting the allowed material amount, leads to the density distribution shown in (b), which essentially represents a load-bearing structure consisting of axially loaded struts. Bending is thus decomposed into a truss-like system including tension and compression members. The density distribution serves as an inspiration for the design. This is interpreted into two different variants shown in Figure 1.11c. On the left, a mostly clear truss structure is shown, which follows the optimization result. Alternatively, a RC solution is developed on the right, which transfers the single compression and tension struts

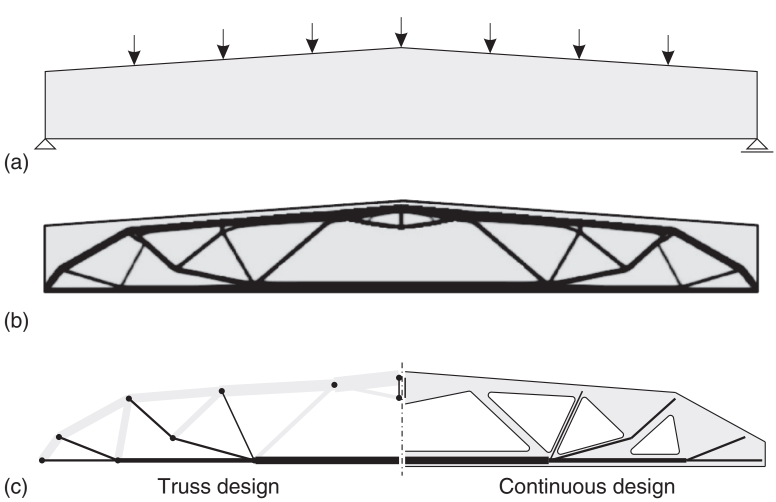


Figure 1.11 OAD of a roof girder: (a) static system and design space, (b) optimization result, (c) resulting truss structure and RC structure with free reinforcement layout.

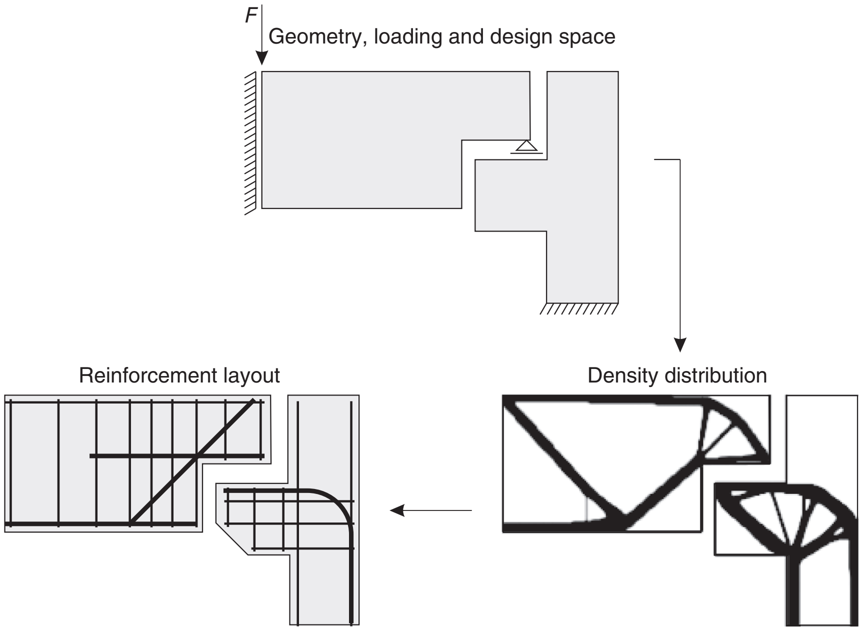


Figure 1.12 Optimization aided reinforcement design for a stepped beam placed on a corbel.

into concrete and reinforcement areas, respectively. This results in a structure with variable cross-sections, block-outs and a free reinforcement layout.

For the inner reinforcement design, OAD leads to concepts similar to those known and proven from strut-and-tie models.

Figure 1.12 shows the example of a stepped beam that is supported by the corbel of a column and is loaded in bending. The applied topology optimization yields a density distribution that exhibits partly truss-like and bionically curved shapes. Stress evaluation using the Finite Element Method (FEM) reveals tension and compression struts, representing concrete or reinforcement areas. From this, a reinforcement design can be derived for both cases. Alternatively, for implicit quantitative evaluation, more advanced truss topology optimization approaches are ideal. They offer the benefit of assigning a specific force to each member, which can then be directly converted into required reinforcement and concrete areas.

1.5 Structure of the Book

Apart from this introduction, the book is divided into five more chapters.

Chapters 2 and 3 briefly summarize the main principles of RC design and structural optimization. For Chapter 2 this involves the material behavior of concrete and reinforcement and basic RC design concepts. Chapter 3 deals with the basic optimization procedure, fundamental formulation of the optimization problem as well as important concepts like the Lagrange function, sensitivity analysis, and general solution methods.

The focus of Chapter 4 lies on the identification of the outer shape of structures. Various approaches are introduced for one and bi-material structures. Moreover, concepts for steering one-material structures toward a compression or tension dominant load-bearing behavior as well as bi-material designs including tension-only and compression-only materials like reinforcement and concrete, respectively, are introduced. The resulting material distributions yield, on the one hand, structural designs containing axially loaded members, like truss-like structures and arcs, and, on the other hand, apply the materials with respect to their particular stress-affinities. Multiple numerical examples illustrate the approaches. In addition, several applications demonstrate the applicability and great resource saving potential for structures in practice.

Chapter 5 introduces approaches seeking the inner shape. This essentially includes identifying the internal force flow and deriving suitable strut-and-tie models. In doing so, some of the methods already described in the previous chapter are adapted to the different scope. However, also an alternative approach based on truss topology optimization is presented, which holds several advantages over the continuum-based methods. In addition, especially for particular challenging problems, a more sophisticated topology optimization approach, employing both continuum and truss finite elements within optimization, is derived. Again, numerous examples and applications emphasize the applicability.

Chapter 6 deals with optimized design of cross-sections. The aim is to find the optimal shape and design while complying with stress and strain limits. The starting point is an arbitrary composite cross-section under axial or biaxial bending with and without normal force. In a second step, the concept is limited to RC cross-sections. It is shown how optimization methods can be applied to identify the right cross-sectional shape, determine reinforcement amounts and solve the equilibrium iterations in order to compute the strain distribution. The method is applied to several examples. They contain primarily RC cross-sections, but also foundations, in order to demonstrate the general applicability. The aim is to improve the shape in order to save material and implement particularly effective designs. The actual verification of the load-bearing capacity is provided automatically, since strain and stress limitations are met via boundary conditions.

References

1. Lamprecht, H.-O. (2001). *Opus caementitium: Bautechnik der Römer*. Düsseldorf: Bau + Technik. ISBN: 3764003502.
2. Mörsch, E. (1909). *Der Eisenbetonbau: Seine Theorie und Anwendung*. The Engineering News Publishing Company.
3. Gaganelis, G., Forman, P., and Mark, P. (2021). Stahlbeton optimiert - für ein Mehr an Weniger. In: *Nachhaltigkeit, Ressourceneffizienz und Klimaschutz*

(ed. B. Hauke, Institut Bauen und Umwelt e.V., and DGNB e.V.). Ernst & Sohn, 159–167. ISBN: 9783433033357.

4 Virlogeux, M., Motard, M., Bouchon, E. et al. (2004). Design of the Terenez cable-stayed bridge. In: Fédération internationale du béton (fib) *Concrete Structures*, Avignon, France: FIB/CEB-FIP, 228–229.

5 Putke, T. (2016). Optimierungsgestützter Entwurf von Stahlbetonbauteilen am Beispiel von Tunnelschalen. PhD thesis. Bochum: Ruhr University Bochum.

6 Putke, T., Bohun, R., and Mark, P. (2015). Experimental analyses of an optimized shear load transfer in the circumferential joints of concrete segmental linings. *Structural Concrete* 16 (4): 572–582. https://doi.org/10.1002/suco.201500013.

7 Curbach, M. (2013). Bauen für die Zukunft. *Beton- und Stahlbetonbau* 108 (11): 751. https://doi.org/10.1002/best.201390098.

8 World Business Council for Sustainable Development (2016). Cement Industry Energy and CO_2 Performance: Getting the Numbers Right. https://www.wbcsd.org/Sector-Projects/Cement-Sustainability-Initiative/Resources/Cement-Industry-Energy-and-CO2-Performance (accessed 25 August 2021).

9 Byatt, G. (2019) Improving the world through better use of concrete. https://irp-cdn.multiscreensite.com/8bbcaf75/files/uploaded/190805_MRS-1_concrete.pdf (accessed 25 August 2021).

10 Kelly, T.D. and Matos, G.R. (2016). Historical statistics for mineral and material commodities in the United States. https://www.usgs.gov/centers/nmic/historical-statistics-mineral-and-material-commodities-united-states (accessed 5 November 2021).

11 Hammond, G.P. and Jones, C.I. (2008). Embodied energy and carbon in construction materials. *Proceedings of the Institution of Civil Engineers - Energy* 161 (2): 87–98. https://doi.org/10.1680/ener.2008.161.2.87.

12 Mehta, P.K. (2001). Reducing the environmental impact of concrete. *Concrete International* 23 (10): 61–66.

13 Rodrigues, F.A. and Joékes, I. (2011). Cement industry: sustainability, challenges and perspectives. *Environmental Chemistry Letters* 9 (2): 151–166. https://doi.org/10.1007/s10311-010-0302-2.

14 Suhendro, B. (2014). Toward green concrete for better sustainable environment. *Procedia Engineering* 95: 305–320. https://doi.org/10.1016/j.proeng.2014.12.190.

15 Worrell, E., Price, L., Martin, N. et al. (2001). Carbon dioxide emissions from the global cement industry. *Annual Review of Energy and the Environment* 26 (1): 303–329. https://doi.org/10.1146/annurev.energy.26.1.303.

16 Ritchie, H. and Roser, M. (2017). Water Use and Stress. https://ourworldindata.org/water-use-stress (accessed 25 August 2021).

17 United Nations Environment Programme (2021). International Resource Panel: Global Material Flows Database. https://www.resourcepanel.org/global-material-flows-database (accessed 25 August 2021).

18 United Nations, Department of Economic and Social Affairs, Population Division (2019). *World Population Prospects 2019*. New York: United Nations. ISBN: 978-92-1-148316-1.

19 Sobek, W. (2015). Die Zukunft des Leichtbaus: Herausforderungen und mögliche Entwicklungen. *Bautechnik* 92 (12): 879–882.

20 Sobek, W. (2021). Bauen für die Welt von morgen. In: *Nachhaltigkeit, Ressourceneffizienz und Klimaschutz* (ed. B. Hauke, Institut Bauen und Umwelt e.V., and DGNB e.V.). Ernst & Sohn, 31–38. ISBN: 9783433033357.

21 Stratmann, R., Birtel, V., Mark, P. et al. (2008). A digital system to record and analyse cracks. *Beton- und Stahlbetonbau* 103 (4): 252–261.

22 Curbach, M., Bergmeister, K., and Mark, P. (2021). Baukulturingenieure. In: *Nachhaltigkeit, Ressourceneffizienz und Klimaschutz* (ed. B. Hauke, Gaganelis, Forman, Mark - Stahlbeton optimiert, Institut Bauen und Umwelt e.V., and DGNB e.V.). Ernst & Sohn, 39–44. ISBN: 9783433033357.

23 Papageorgiou, M., Leibold, M., and Buss, M. (2015). *Optimierung: Statische, dynamische, stochastische Verfahren für die Anwendung*. Berlin and Heidelberg: Springer Vieweg. ISBN: 9783662469361.

24 Belegundu, A.D. and Chandrupatla, T.R. (2014). *Optimization Concepts and Applications in Engineering*. New York: Cambridge University Press. ISBN: 0521878462.

25 Haftka, R.T. and Gürdal, Z. (1993). *Elements of Structural Optimization*. Dordrecht: Kluwer.

26 Arora, J.S. (2011). *Introduction to Optimum Design*. Amsterdam: Elsevier Academic Press.

27 Schumacher, A. (2013). *Optimierung mechanischer Strukturen: Grundlagen und industrielle Anwendungen*. Berlin and Heidelberg: Springer-Verlag. ISBN: 978-3-642-34699-6.

28 Harzheim, L. (2008). *Strukturoptimierung: Grundlagen und Anwendungen*. Frankfurt am Main.