THE STRUCTURAL BASIS OF ARCHITECTURE

THIRD EDITION

BJØRN N. SANDAKER, ARNE P. EGGEN
& MARK R. CRUVELLIER

THE
STRUCTURAL BASIS OF ARCHITECTURE

This is a book that shows how to "see" structures as being integral to architecture. It engages a subject that is both about understanding the mechanical aspects of structure as well as being able to relate this to the space, form, and conceptual design ideas that are inherent to the art of building.

Analyzing the structural principles behind many of the best-known works of architecture from past and present alike, this book places the subject within a contemporary context. The subject matter is approached in a qualitative and discursive manner, illustrated by many photographs and structural behavior diagrams. Accessible mathematical equations and worked-out examples are also included so as to deepen a fundamental understanding of the topic.

This new, color edition's format has been thoroughly revised and its content updated and expanded throughout. It is perfect as either an introductory structures course text or as a designer's sourcebook for inspiration, for here two essential questions are addressed in parallel fashion: *"How do structures work?"* and *"What form do structures take in the context of architecture – and why so?"* A rich, varied and engaging rationale for structural form in architecture thus emerges.

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Our traveling globe in galactic endlessness is divided into latitude and longitude.

With help of this grid, every point on the earth's surface has its number.

At the grid's intersections each plant, each creature receives
its individual technology – its structure formed and created
by the clouds' movements, the wind's strength, and the shifting positions of the sun.

On this organic mat, the acrobat (builder) attempts, with the help of instruments,
to deceive gravity and challenge death with every leap.

And when the perplexities of thought within your soul is provided space on earth,
arises a duel with substance. Amidst brutality's heat,
beauty is born…

Sverre Fehn

Sverre Fehn
(1924–2009)

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We wish to dedicate this book to two groups of people without whom
none of this would have been possible or worthwhile:

To our immediate families – Wenche, Victoria, Nicolay, and Sophie;
Sigrid, Sune, Dan, Aron and Maia; and Patrick and Lauren – we are
ever grateful for your longstanding support and sacrifices,
and

To our many students over the years as well as those yet to come.

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Preface

This is a book about structures, more specifically about structures and architecture; it is certainly not the first such book, nor will it be the last. It does represent, however, our view of how to engage a subject that is both about understanding the mechanical aspects of structure as well as being able to relate this to the space, form, and conceptual design ideas that are inherent to the art of building – in other words, how to "see" structures as being fully integral to architecture. It is at once a book that deals with the subject matter in a qualitative and discursive manner, that illustrates this discussion by means of many photographs of architectural projects and structural behavior diagrams, and yet that also doesn't shy away from the relatively accessible mathematical equations and calculations that can be used to reinforce and extend a nascent understanding of the fundamentals of the topic – indeed, there are many ways to learn about and from structures. The lessons about structural forms and behaviors can be derived from building designs that span the course of time, and are here drawn from both the architectural canon as well as recent projects from around the world. Beyond this, we also briefly engage with art and furniture design, among other related fields of interest, as a means of connecting structural principles to a broader cultural context and vastly different physical scale.

Much has happened in the world of architecture since the publication of the first edition of *The Structural Basis of Architecture* in 1989. Stylistic periods such as those of High-Tech, Postmodernism, Deconstructivism, Starchitecture and Blob Architecture have waxed and waned, while Parametric and Computational Design are currently in vogue, as is architecture that is strongly influenced by Sustainability concerns and objectives. The range of examples that are featured in this third edition partially reflects these ongoing changes while at the same time not losing sight of the remarkable designs of earlier periods, most of which still serve as frequent and useful references for building designers today.

In terms of developments in the understanding of structural mechanics, on the other hand, it can be argued that things have been much more stable and that not much is new: statics is still what it was, and beams and domes span space in the manner that we have come to know and understand for hundreds of years, let alone the past 30. And while it is certainly true that computer methods for analyzing structures' forces and stresses are much more prevalent and efficient today than they were three decades ago, nevertheless these programs have not really changed our fundamental understanding of the subject matter as much as sped up its application. Indeed, it has been recognized in both academia and in practice that there can be a certain danger in depending too much on the "black box" of analysis programs without a strong understanding of basic structural behavior. And so, while we recognize and in several places include projects that demonstrate the results of structural analyses derived from such computational advances, it will become evident throughout this book that we still firmly believe in an engagement of the subject matter using simple algebraic formulas and mathematics as well as discussing it in terms that are familiar to us from our everyday living experience. Not only do we see this approach as a means of developing an intuitive basic understanding of how structures work and how their forms make sense, but also that it enables more conceptual thinking on the part of architects and structural engineers alike for extrapolating into uncharted territory. That being said, it can legitimately be argued that where digital technology has had its biggest impact recently is in challenging the age-old building design adage that keeping things simple and repetitive and rectilinear is necessary in order to make construction economically viable. Today, buildings with seemingly infinite variations of member lengths and geometric details can be relatively easily accomplished because of remarkable advances in integrated digital fabrication technologies; some examples of this approach are included in the following chapters, right alongside the more "traditional" – but no less exceptional – forms of building structures.

This third edition of *The Structural Basis of Architecture* shares its title, vision, and basic organization with the original book, although even a cursory comparison will reveal that the contents have been completely revised and the scope substantially expanded since that earliest version. And whereas the second edition involved a comprehensive overhaul of the original, from rewriting the text to expanding and updating the range of illustrated examples, this third edition can perhaps better be characterized as a significant evolutionary step in terms of the development of the book's contents. In that sense, those familiar with the previous edition will recognize and find comfort in numerous similarities. That being said, there are also substantial changes in this new edition that are worth drawing attention to here:

- A new Chapter 2 Introducing Structural Systems serves right from the start to identify fundamental structural actions, consider the basic types of structural elements that can respond to these actions (skeletal vs. surface), and then project how such elements can be combined into three-dimensional building structural systems of various configurations, each having implicit spatial qualities and distinctive forms.

- A completely revamped Chapter 10 The Frame and the Shear Wall greatly expands on the previous treatment of lateral load resisting systems, which we felt in retrospect had been somewhat short-changed in the second edition given their relative importance in the design of buildings – whether from a structural or spatial or conceptual point of view.
- An extended treatment of selected topics in several other chapters, including fleshed-out sections on beam grids, slabs, retaining walls, space frames, etc.
- The addition of many new examples (and the replacement of others) in order to refresh the contents, although without making change just for its own sake; i.e., what we thought served the purpose well in the previous editions has largely been retained.
- And perhaps most obviously at first glance, changes have been made to the layout format: e.g., most illustrations are now in color, more emphasis has been placed on the explanatory structural behavior diagrams, and the running text now has direct call-outs to corresponding illustrations and figures – the better to allow the reader to directly connect images to text commentary. Also, the page layout for this third edition has been changed to a two-column format that more frequently enables text passages to be placed adjacent to related images.

Finally, for those who would like to extend their exposure to the structural basis of architecture, it should also be noted that since the publication of the previous edition of this book two of the present authors – Cruvellier and Sandaker – have co-authored along with colleague Luben Dimcheff the companion book *Model Perspectives: Structure, Architecture, and Culture* (Routledge, 2017). That book's reproductions of many short, insightful essay extracts as well as large-format photos of constructed model studies are intended to be complementary ways of addressing the essential questions at hand in the pages that follow: i.e., *"How do structures work?"* as well as *"What do structures look like in the context of architectural design – and why so?"*

Acknowledgments

Of course, there have been many people who have contributed in one way or another to the contents and production of this book. We are particularly thankful for the excellence, dedication, and patience of several student assistants, whether for the collection of illustrations and rights permissions and the production of line diagrams. At Cornell: Jeremy Bilotti, Ainslie Cullen, Lucy Flieger, Vanille Fricker, Raksarat Vorasucha as well as Patricia Brizzio and Asdren Matoshi. At AHO: Oda Nybø. We have also certainly benefited from the strong support of the administrative leadership of both our respective institutions, and wish to extend our gratitude for this. In particular, at AHO we wish to thank: Dean Ole Gustavsen and Department Chair Thomas McQuillan. At Cornell: former Dean Kent Kleinman and current Dean J. Meejin Yoon and Department Chair Andrea Simitch. And at both institutions, informal discussions and other collaborations with many faculty colleagues both past and present have significantly contributed to this work in various ways, whether by express intention or fortuitous circumstance. In particular, Assistant Professor Solveig Sandness at AHO deserves special mention; her detailed feedback about the second edition's contents has been invaluable.

The patience and support of Routledge Publishers has once again been truly remarkable – in particular, Senior Publisher Fran Ford and Senior Editorial Assistant Trudy Varcianna have helped carry us along and through to the finish line. We are also greatly indebted to the skill and vision of the production team at Routledge, namely Senior Production Editor Alanna Donaldson and layout designer Alex Lazarou for giving this third edition of the book a fresh and compelling new look, but also the copy editors, printers, etc. without whose assistance and commitment this work would not have come to fruition.

Structuring Space

CHAPTER 1

Illustration 1.1
Galleria Vittorio Emanuele II, Milan, Italy (1865–1877).
Prominently sited on the northern side of the Piazza del Duomo, this galleria is a covered double arcade formed by two glass-covered vaults at right angles to each other and intersecting in a domed, octagonal central space.
Architect: Guiseppe Mengoni.

1.1 Structure as Spatial Generator and Mechanical Object

While it is easy to imagine structures without architecture, there can be no architecture without structures. Examples of the first category include construction cranes and transmission towers – structures whose sole purpose it is to keep loads lifted up off the ground. In architecture, the design of buildings commonly includes roofs, floors, and walls whose weight must also be borne and balanced by the help of structures. But beyond that, these elements are typically informed by requirements and conceptual ideas for their interior spaces and exterior forms. Structural issues, therefore, are inherently deeply embedded in architecture. The specific relationship between architecture and structure, however, whereby the one encompasses the other, may vary greatly from one architectural epoch to the next, or even from one building to another within the same time period. Today we are likely both to encounter buildings whose structures are of minor interest for architectural expression as well as others that display a particularly close correlation between structural form and its negative imprint, architectural space.

In order to shed some light on the particular connections that exist between structures and architecture, we first need to establish what we consider to be basic structural functions. Toward this end, we may ask: What purpose does the structure serve? What requirements govern the conditions establishing its overall and detailed form, and in what way do these conditions relate to one another? Addressing such questions allows us not only to develop a broad overview of the technical subject matter but also fosters a deeper understanding of what structures really are and how they can be assessed within the context of architectural design.

A fundamental point to be established from the beginning is that structures in architecture are conceived – and perceived – differently from structures in other contexts, and so they should be evaluated differently. In reflecting on the integral relationship that exists between structures and architectural spaces, forms, and ideas, certain issues arise that differentiate the structures of architecture from structures of other kinds. The most obvious and basic function of a structure is its capacity to keep something above the ground by bearing loads, and the practical use gained from that capacity is to keep floors, walls, and roofs in an elevated position, thereby establishing inhabitable spaces. In many cases in architecture, however, structures are not solely associated with such load-bearing functions. And while engineering is able to solve the necessary safety requirements, the door is luckily left wide open for making the structure even more deeply considered conceptually. Ideally, a close relationship is established between structure, space, and formal expression so that describing and characterizing a structure solely in terms of its load-bearing function is clearly insufficient. To understand structures in a wider sense as being part of an architectural context also means seeing their forms as space-defining elements, or as devices that modulate the amount and quality of daylight, or that reflect today's sustainability concerns, or any number of other assigned functions. Structures can serve many purposes simultaneously to carrying loads, therefore, and we need to keep this in mind not only to enable a more profound understanding of the development of structural forms but also to undertake an appropriate and informed critique of structures within an architectural context.

How can one go about establishing a conceptual model for such a holistic understanding of structures? As a starting point, we can observe that structures play a role both as a provider of necessary stiffness and strength (which are the basic mechanical prerequisites for carrying load safely), and as an instrument for creating architectural spaces that embody certain other qualities. This notion of a dual function, both mechanical *and* spatial, proves rewarding when it comes to understanding and appreciating the multifaceted design of structures in various architectural settings. Structures range from those conceived of as pure force systems that follow a logic of maximum strength for a minimum of materials (i.e., structural efficiency), to those designed to act iconographically as visual images. On the one hand there is a load-bearing function, which helps to explain structural form from the point of view of technology and science, as objects required to supply stiffness, strength, and stability, while on the other the structure may take part in the organization of architectural spaces and the establishment of an architectural expression. Moreover, these dual aspects of structure are not typically wholly separate from one another, but instead tend to mix and their divisions to blur so that certain formal features of a structure may both be explained by mechanics and also be understood in light of their spatial functions. (e.g., Ill. 1.2 and Ill. 1.3, 1.4.)

Illustration 1.2
Eames House (Case Study House No. 8), Pacific Palisades, CA, USA (1949).
Contrasting rather than adapting to the building site, the Eames House was intended to exploit off-the-shelf, prefabricated, industrial building components made of steel and make these applicable to residential design. Partly exposed, the steel structure orders the plan in modular bays of 2.4 by 6.4m (7.5 by 20ft). Quoting the architect: "In the structural system that evolved from these materials and techniques, it was not difficult to house a pleasant space for living and working. The structural approach became an expansive one in that it encouraged use of space, as such, beyond the optimum requirements of living." And: "it is interesting to consider how the rigidity of the system was responsible for the free use of space and to see how the most matter-of-fact structure resulted in pattern and texture."[1]

Architect: Charles and Ray Eames. Structural engineer: MacIntosh and MacIntosh Company. Photographer: Julius Schulman. Title/date: [Eames House (Los Angeles, CA): exterior], [1950] © J. Paul Getty Trust.

Illustration 1.3
The Bordeaux House, Bordeaux, France (1998).
"Contrary to what you would expect," the disabled client told the architect, "I do not want a simple house. I want a complex house, because the house will define my world."[2]
The house consists of three distinct levels: the lowest is cave-like – a series of spaces carved out from the hill for the most intimate life of the family. The highest level is divided into an area for the parents and another for the children. The most important level is almost invisible, sandwiched in between the other two: a glass room – half inside, half outside – that is used for living.
Architect: OMA/Rem Koolhaas. Structural engineer: Arup/Cecil Balmond.

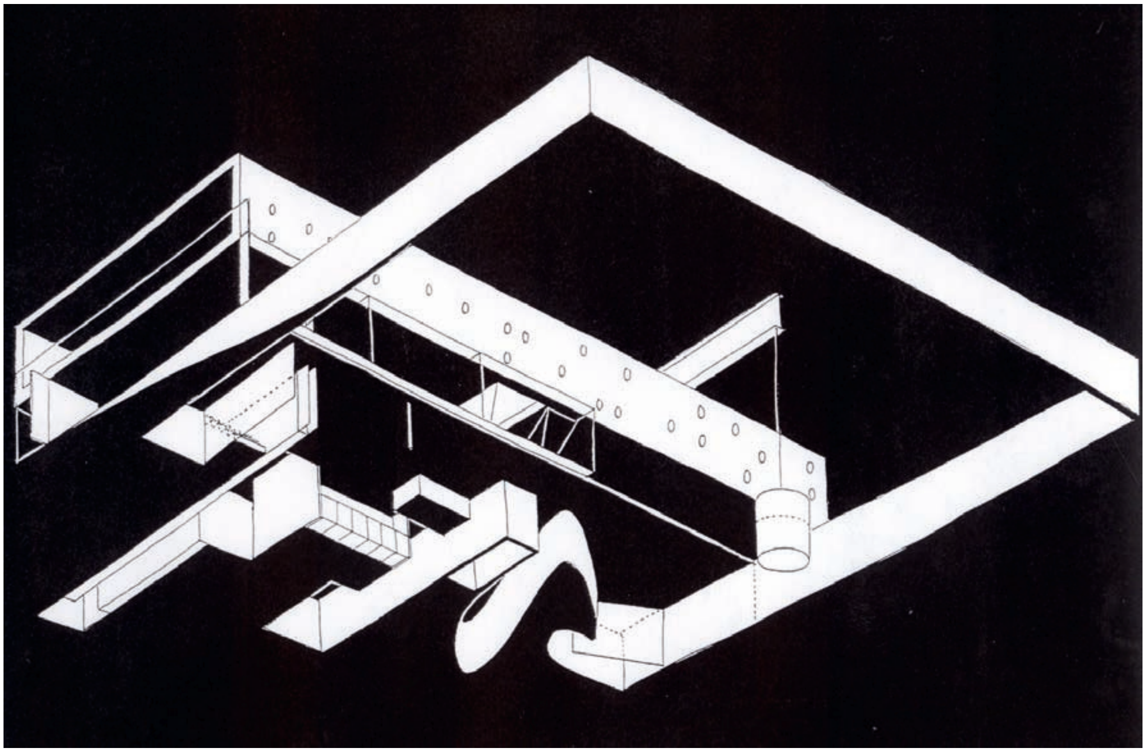

Illustration 1.4
The Bordeaux House.
A worm's-eye view diagram showing material elements and structural principles. Moving the supports outside the plan contributed to an opening up of the space.

Illustration 1.5
The Grande Arche de la Défense, Paris, France (1989).
The large Vierendeel beams enable utility functions, accommodating people and their through-passage within the overall structural depth.
Architect: Otto von Spreckelsen. Structural engineer: Erik Reitzel.

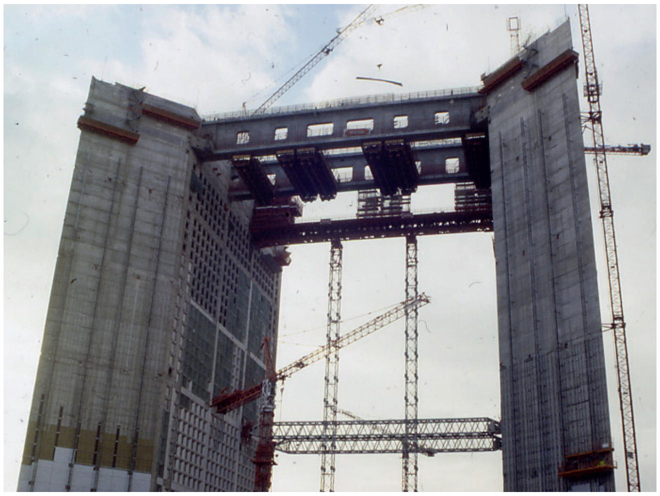

Illustration 1.6
The Grande Arche de la Défense.
Vierendeel beams can be seen at the top during construction.

This object/space duality can serve as a starting point but, as is the case with most conceptual models, it may simplify too much the world of real structures. Nevertheless, as long as we keep in mind that theoretical models of this kind can act as catalysts for increased insight while not necessarily being able to embrace absolutely every possibility, it will be found to be rewarding to identify both *spatial function* and *mechanical function* as the two prime concepts that establish the basis for a holistic understanding of structures in the context of architecture.

1.2 Spatial Aspects

The primary reason for the existence of structures is, of course, the practical purpose that they serve. Structures support loads from their location of application down to the ground, although typically not by means of the shortest possible “route” between those points since open and structure-free spaces of various sizes and shapes are needed in order to inhabit a building. This is the natural order of the relationship between the “why” and the “how,” of reason and consequence: practical purpose comes first, and physical necessity follows. The practical purpose that the structure is assigned, its *utility* aspect, is fairly straightforward to accept and appreciate: in the case of bridges, for example, this is made clear by acknowledging the fact that the principal utility function, its “raison d’être” so to speak, is typically that of transporting people and goods across a valley, a river, or even an expanse of sea; i.e., it is all about establishing a transport line from one bank to the other. The straight line of communication that this link commonly results in will most likely suggest a certain structural configuration, either as a construct that becomes an integral part of the structural system, or else as setting up the conditions for how this line should be supported. The utility function provides in either case highly important input for how a structure is actually designed as well as an understanding of the form of bridge that is possible.

The same thing is generally true with the structuring of architectural spaces: the choice of a structural system and its particular articulation is highly dependent on the practical function that is associated with it. For example, in the case of the large beams at the top level of the Grande Arche de la Défense in Paris by architect Johan Otto von Spreckelsen (1929–1987) and engineer Erik Reitzel (1941–2012), there is no way to fully understand the choice of that particular beam type without also recognizing that the structure is actually accommodating human activity within its structural depth, and enabling people to walk freely in the large space within and between these beams, all the while looking at art exhibitions. (Ill. 1.5, 1.6.) This relationship is made possible because the beams are of a type that have large, rectangular openings in them, termed Vierendeels. Hence, what we experience in the interior spaces of this upper level is actually the horizontal and vertical parts of these huge beams that span an impressive 70m (219ft) over the open public plaza located far below.

Illustration 1.7
Museum for the Menil Collection, Houston, Texas (1983). In addition to providing a load-bearing function, the lower part of the spanning elements for the roof are shaped to act as light reflectors; these are precisely spaced apart so as to prevent direct sunlight from entering the museum galleries, however. The lower part of each of these composite structural elements is a curved ferrocement form, while their upper part (unseen in this image) is trussed. Mechanical requirements for the combined strength and stiffness of these elements meet the demands of a particular type of spatial utility function.

Architect: Renzo Piano Building Workshop. Structural engineer: Arup by Peter Rice.

With the Grande Arche it is relatively simple to point out the use-of-space utility function as a factor that offers design constraints and therefore has the ability to influence the chosen structural form. A second, perhaps somewhat more subtle, example of such a utility function may be in a situation where there is a central concern with the diffusion of natural light, which in the case of the Museum for the Menil Collection in Houston, Texas, resulted in a unique design for its roof trusses/reflectors that were made from a combination of different materials. (Ill. 1.7.) Generally, then, it can be said that for people to be able to do whatever they are meant to do in a particular architectural space, or so as to enable a certain non-load-bearing performance on the part of the structure, structural form

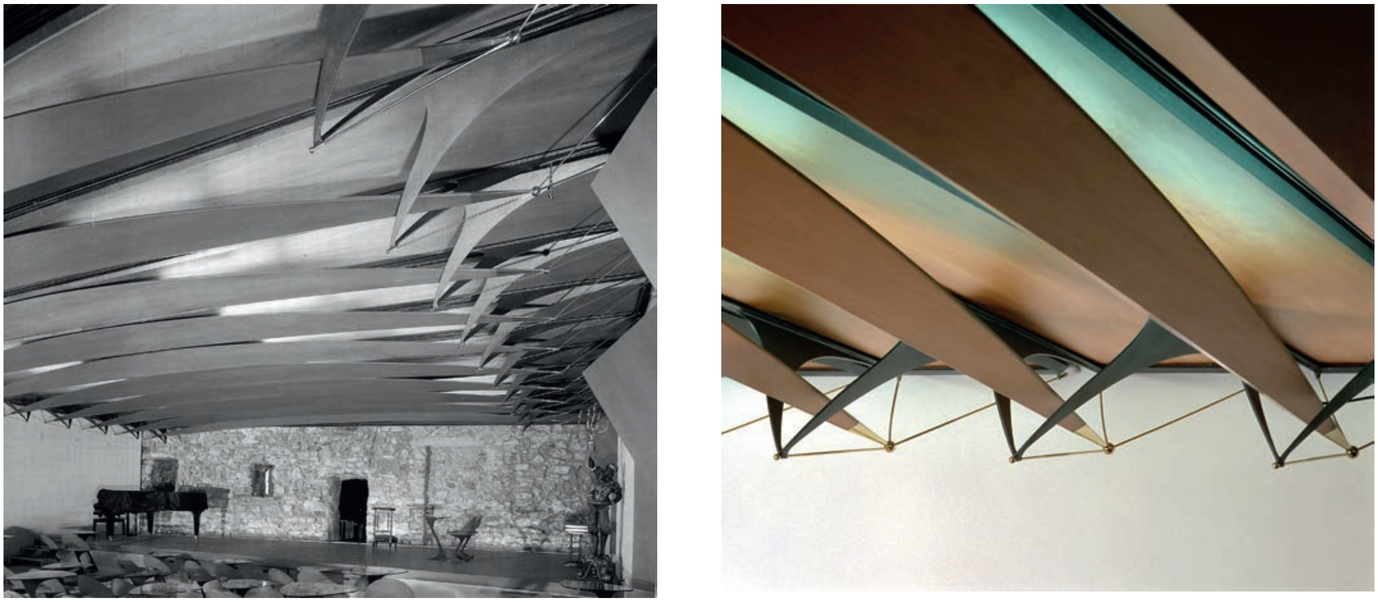

Illustration 1.8
The Cabaret Tabourettli, Bern, Switzerland (1987).
(a) Ceiling beams having iconographic function, designed to hint at the musical activities that take place in the room. (b) End-of-beam connection detail.
Architect and structural engineer: Santiago Calatrava.

may sometimes be shaped and configured in very particular ways. Without knowledge of the broader scope of such architectural utility functions in a building, therefore, a complete understanding of a particular structural configuration is not possible.

Beyond such variations of practical "utility," there are other performance functions that are also frequently associated with structures in architecture. In some cases we may find that structures are designed to make observers see something else in them, representing an object outside of itself, or something that is not really there. And in certain of these instances, architects have chosen to design structures in a manner that gives their form a certain similarity to other objects. One reason for this design approach is to bring the imagination of the observer into the visual experience, and to strengthen the perception of a particular presence that is thought to enhance a structure's architectural qualities. We may thus think of these structures as having *iconographical* functions. Among the numerous examples of this type are architect and engineer Santiago Calatrava's "musical" beams for the Cabaret Tabourettli concert hall in Bern, Switzerland, and the lively structures of architect Zaha Hadid's (1950–2016) Vitra Fire Station in Weil-am-Rhein, Germany. Neither of the structures used for these buildings can be fully understood without invoking the concept of mimicry. In the case of the concert hall, beams are given a shape and a materiality that closely resembles that of instruments like violins and cellos, making the observer acutely aware of the type of room one is experiencing; indeed, the thin steel ties that are secured to each beam have an unmistakable likeness to the strings of musical instruments. (Ill. 1.8.) And at the Vitra Fire Station, sharp angles activate the whole composition of structural elements of columns, walls, and slabs alike, creating an unmistakably hyper-active, kinetic image that makes one think of flickering and dancing flames. (Ill. 1.9.)

Illustration 1.9
Vitra Fire Station, Weil-am-Rhein, Germany (1993).
Structural composition of elements in a design that takes the lively flickering of flames as a point of departure. Eventually, there was no longer need for a separate fire station at the Vitra industrial complex, and the building was repurposed to house lectures, concerts, exhibitions, and social events.
Architect: Zaha Hadid. Structural engineer: Sigma Karlsruhe Gmbh and Arup by John Thornton.

Illustration 1.10
Experience Music Project, Seattle, Washington State, USA (2000).
Structural form adapts to the overall, formal concept, letting the architectural context and conceptual ideas act as a form generator.

Architect: Frank O. Gehry. Structural engineer: Hoffman Construction Company.

In yet other cases, structures are so closely tied to a particular idea that the *architectural context* is seen to strongly suggest their shape and organization. Structures of this "type" are designed with a primary concern for their ability to enhance an overriding theoretical concept – or at least their design is guided by a certain logic that makes their structural form dependent on formal or conceptual imperatives. Although not necessarily so, the result of such a contextual design approach may well be a structural form in which the "traditional" load-bearing logic that dictates an efficient use of materials and manufacturing methods is significantly disturbed. Some of the work of the architect Frank O. Gehry might be seen to promote structures of this type: the EMP project in Seattle, for example, displays steel beams of varying and not-particularly-efficient shape in order to accommodate the highly intricate external forms of the building, and can be said to be designed "from the skin-in." (Ill. 1.10, 1.11.) Such a close link between this type of architectural

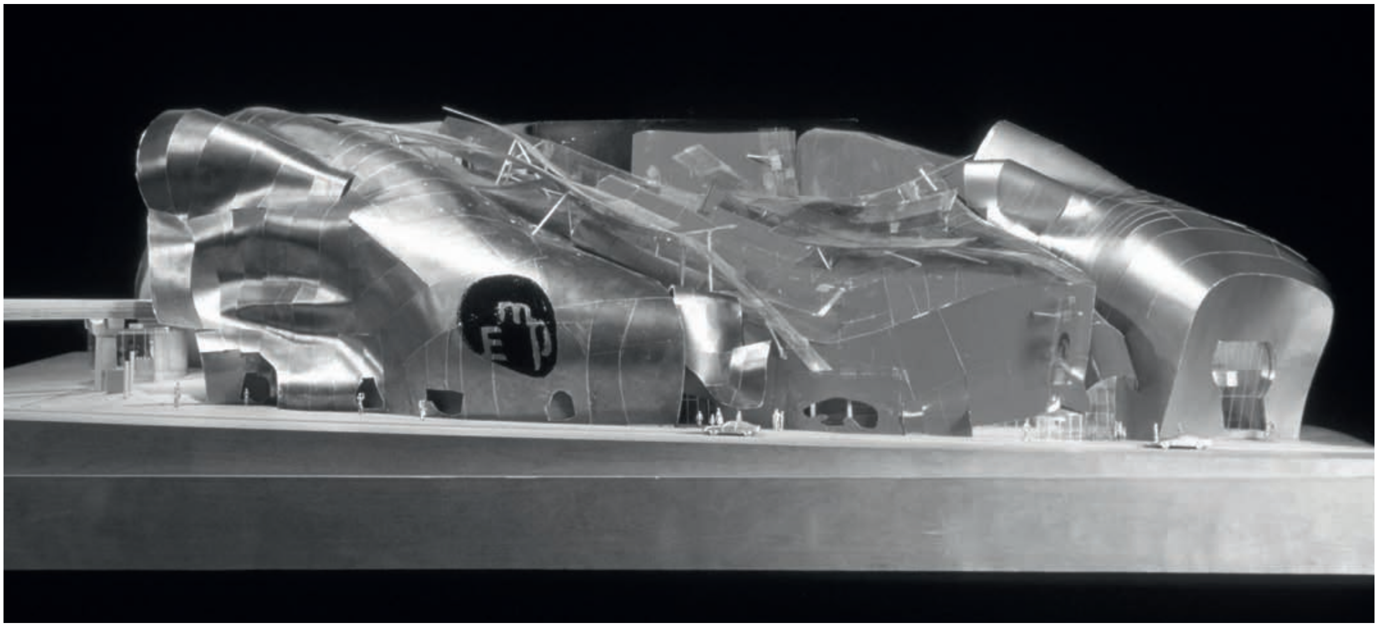

Illustration 1.11
Experience Music Project.
Model. Design concepts and exterior form establish rationale for structural frames' curving profile seen in Ill. 1.10.

Illustration 1.12
The Blur Building, Yverdon-les-Bains, Switzerland (2002).
Blurring the presence of a building with the help of 11 000 fog nozzles spraying water from the lake.
Architect: Diller Scofidio + Renfro.
Structural engineer: Passera and Pedretti.

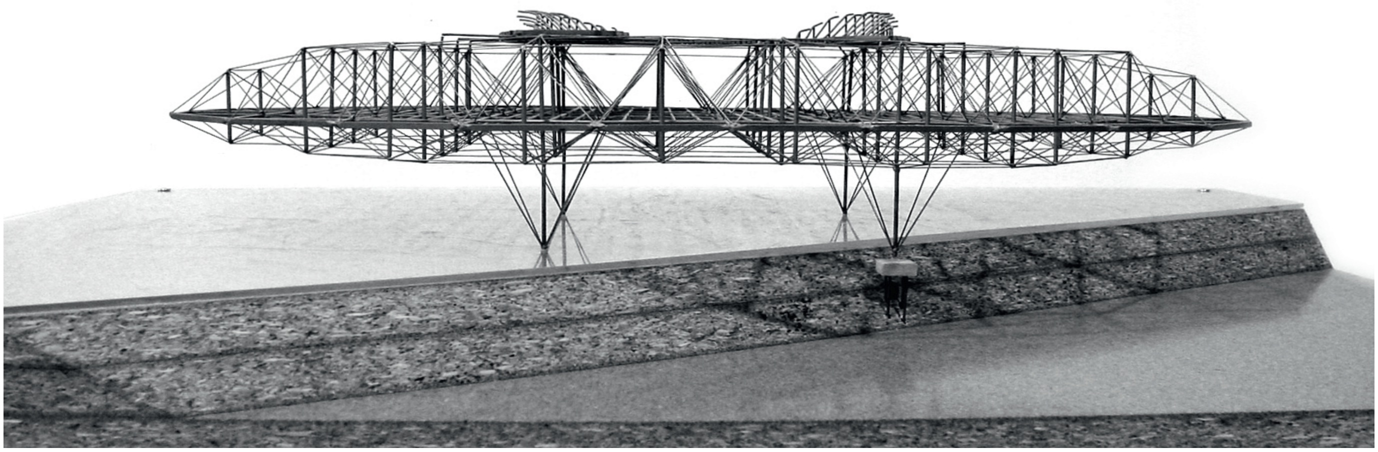

Illustration 1.13
The Blur Building.
A filigree trussed structure made possible the desired light appearance of the building.
Cornell model by Adam LeGrand.

expression and the structural form calls for a different attitude toward evaluating structure than that which is appropriate when confronted by structures that have a more obvious technological basis. In these cases, structural forms cannot properly be understood in isolation as force systems that "purely" meet specific functional demands, but should instead be assessed within the framework of the governing design concepts and ideas. In other words, a "conventional" evaluation of such structures strictly in terms of concepts like strength and stiffness and the most efficient production methods, while not to be ignored, will be completely inadequate to fully explain and appreciate their design.

Of course, the various spatial aspect categories that we have so far identified need not exist in isolation from one another. The Blur Building, erected as a temporary media pavilion for the Swiss Expo 2002 and designed by architects Diller Scofidio + Renfro is an example of a work of architecture in which the structure is part of a design that features both iconographic and contextual qualities, while also maintaining an efficient load-bearing strategy. This is a "both/and" rather than an "either/or" condition. The pavilion was characterized as "an inhabitable cloud whirling above a lake": set on pillars in Lake Neuchatel in Switzerland, it was enveloped in a fine mist created by a huge number of fog nozzles spraying water from the lake and creating an artificial cloud. (Ill. 1.12.) To further strengthen this image, the architects and engineers took care to design a structure that could be considered to have a similarly blurred image. The lightweight structural system was composed of a multitude of the thinnest possible structural members, all arranged according to a strategy of efficient resistance to loads; these structural members were clearly meant to visually disappear into the cloud. (Ill. 1.13.)

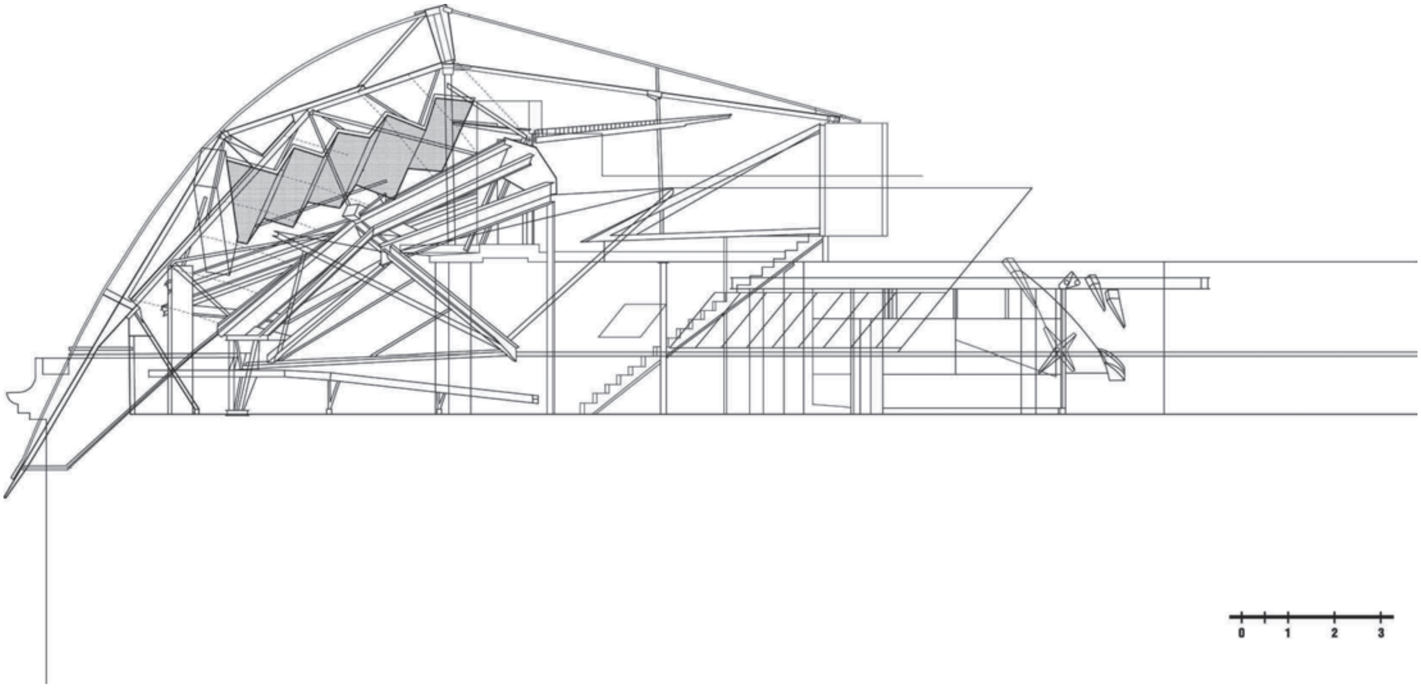

Illustration 1.14
Roof-top Remodeling, Falkestrasse, Vienna (1988).
The structural spine with a distorted and complex look enhances the high-energy character of the architecture.
Architect: Coop-Himmelb(l)au. Structural engineer: Oskar Graf.

As a general observation from examining many other buildings besides the Blur pavilion, it can be stated that design requirements which primarily address the spatial aspects of structures are frequently found to also be in strong agreement with the requirements of a more mechanical nature. In other cases, however, structures that are meant to bring about particular spatial qualities may seem to cause their purely load-bearing and material-efficiency logic to "suffer." At the extreme, a seeming incompatibility between spatial and mechanical requirements may even be seen to exist, lending the structure a certain ambiguous character, but this is still not necessarily to be considered a negative feature of structural form. On the contrary, such a condition can contribute to visual interest and to a clarification of a certain conceptual approach to the architecture/structure relationship. And we should not forget that even structures of this type are inevitably designed to be both safe and sound.

As an example, we can consider architect Coop-Himmelb(l)au's Roof-top Remodeling intervention in Vienna which precisely represents this delicate balance between spatial ambition for structural form on the one hand, and a somewhat-less-than-common mechanical logic on the other. (Ill. 1.14.) Far from being randomly designed, the former qualities can be seen to have led the design and the latter to have become of less importance. One can quickly spot what might be termed a spine in the form of a complex assemblage of steel sections aligned in a skewed plane that cuts right through the project, forming a line of symmetry or, rather, something that resembles symmetry. This is obviously an important structural element. The most spectacular feature of this spine is the thin curving line formed by a steel rod that binds the different members together. In fact, because of their standard structural profiles, all of the steel members seem to have a certain load-bearing function except for that thin, curving rod which is used to establish a visual demarcation line around the whole structural composition. The rod also projects out from the edge of the roof, hovering over the street below where it connects with other steel profiles in order to terminate the whole visual/structural composition. We might ask: Is this apparent complexity of structural pathways and the absence of a clear structural system a negative feature in this design? To which we would answer: No, based on the rationale that both the great intensity of the lines and the ambiguous character of the structure add to the experience of a "high energy" work of architecture. Wolf Prix once said that "structures, although metaphors for forces, follow another force, not of weight, but of energy."[3] We experience the structure of this Viennese rooftop addition, as distorted as it is, as being highly appropriate for such an equally distorted spatial configuration;

Illustration 1.15
The Copenhagen Opera House, Copenhagen, Denmark (2004).
The variation of the thickness of the projecting roof form follows the changing magnitude of forces within its (hidden) beam structure.
Architect: Henning Larsen. Structural engineers: Rambøll, Buro Happold.

indeed, a regular and geometrically simpler structure would have significantly weakened the desired spatial quality.

As we have seen throughout this section, the particularities of structural form can be closely related to spatial functions and to conceptions of space. We can thus interpret structure as being part of an integrated design approach in which we cannot completely explain, understand, or appreciate structural form without recognizing its strong co-dependence on the particular character and use of the architectural space. It is of importance to note, however, that any gross deviation from what can be considered to be a reasonable concern for mechanical requirements should not be the result of random, uninformed, or thoughtless design, but rather of carefully considered ideas related to other design imperatives.

1.3 Mechanical Aspects

We now turn to what can be considered to be the basic mechanical function of structures: that of being load-bearing objects that possess and display specific physical properties. As has been previously mentioned, among such properties is their ability to withstand loads and forces imposed by nature and derived from human activities, qualities that are typically embodied in the physical concepts of strength, stiffness, and stability. All of these latter concepts will be thoroughly explained in the chapters that follow; at this stage, however, it is sufficient to say that they all relate to how structures perform when loads act on them, and that these concepts address the way nature works and lend themselves readily to *scientific analysis* which may involve mathematics and physics. This means that there is a direct relationship that can be demonstrated between structural form, the direction and magnitude of loads, the properties of the materials, and the response of structures. We can illustrate the point in question by referring to one example among many where structural form is revealed or explained by referring to this relationship: i.e., the steel beams that are hidden within the roof of the Copenhagen Opera House clearly have varying structural depth. (Ill. 1.15.) There are no supports at the outer end of the roof cantilever, and so the beams must therefore carry the loads inward toward their line of support, collecting more and more loads along the way and needing to get progressively deeper in order to accommodate this.

Furthermore, there are architectural examples where the connection between form and nature's laws is no longer just intuitively grasped but clearly depends on scientific analysis for their design, not merely for a confirmation of structural dimensions (while also that),

Illustration 1.16
CCTV Tower, Beijing, China (2008).
The diagonal pattern of structural members exposed in this building's façades is irregular, closely following the stress pattern that results from the building's particular shape and loading conditions. Where the intensity of these stresses increases, more structural members are inserted, thus tightening the "web" of structural lines needed to accommodate this.

Architect: OMA/Rem Koolhaas. Structural engineer: Arup by Cecil Balmond.

but more explicitly that their shape cannot be properly explained without addressing theoretical knowledge of the strength/stiffness/stability relationship. Among the many possibilities to illustrate this particular observation is the CCTV Tower in Beijing by architects OMA/Rem Koolhaas and structural engineer Arup/Cecil Balmond, where structures that are exposed in the façade are configured so as to follow a logic of structural sub-optimization that puts its distinctive mark on the character of the building;[4] i.e., the pattern of diagonal lines is noticeably denser where the structure is more highly stressed. (Ill. 1.16.)

Historically, of course, the planning and construction of large objects and structures had nothing to do with science. Such constructs most certainly obeyed scientific laws, regardless of what their builders were aware of, but science played an insignificant role in explaining at the time just how they worked and why they were designed the way they were. Architecture, for its part, had for much of its existence been perfectly happy employing certain building technologies without benefiting from the input of science. For example, even the most advanced Gothic cathedrals were built without theoretical knowledge of mass, gravity, forces, and stability. Their builders employed available construction technologies, but did not command science as a tool for analysis. Today, we may explain the shapes of Gothic cathedrals by invoking scientific concepts, but at that time forms were arrived at following craft-based traditions and by trial and error; consequently, failures happened and these have been duly recorded.

For the past 150 years, however, architecture has become ever more dependent upon and intertwined with the development of scientific knowledge. Part of the reason for this has to do with the sheer size of many architectural projects and that the consequences of construction failures are so grave that mistakes cannot afford to be made, whether for reasons of moral, financial, or legal responsibility. Of course, scientific knowledge also helps to bring about an efficient use of materials, enabling the fewest natural resources to be used. And, finally, we should also remember that architecture is typically concerned with developing "one-off" designs for buildings that explore and account for site specificity and individual programming and conceptual designs that make each building unique. In order to be able to cope with the inherent uncertainties of such new and untried designs, we take advantage of one of the natural sciences' most wonderful abilities: the possibility of predicting the outcome by means of theories developed for material and structural form behavior. Architectural projects can thus be analyzed scientifically as the physical objects that they are, or are about to become, and the behavior of their masses of stones or skeletons of steel can be foretold in advance of construction. Physics, obviously, is the prime instigator in that respect, aided by mathematics.

Looking at structures from a mechanical point of view is not restricted to a study of behavior based on scientific principles, however. It also involves a consideration of what we may think of as being structures' *technological* aspects; i.e., how their parts are manufactured and how they are actually built. Decisions about how structures and structural components are produced and erected also make their imprint on structural form, especially at the detailing level. Consequently, technological matters should also be brought up for consideration when seeking to understand and critique structural form. It is particularly important when we study structures that they are considered not only as finished products, but also as manifestations of certain manufacturing and construction processes. Therefore, we need to look upon the mechanical aspects of a structure from both a scientific *and* a technological point of view, recognizing that there is a difference between the two that enables us to observe and understand the different qualities that these may bring to a design.

Building technology deals with the "making" processes. As such, it simultaneously addresses several production and manufacturing issues, from the production of building materials and structural elements, to their adaptation to suit a particular situation, and, finally, to the actual construction phase of a building. Technology thus involves operations like casting and rolling of metals to form components, sawing of timber boards and gluing them into laminated elements, as well as casting concrete into formwork made of various materials to produce different shapes and surface textures. To understand building *technology*, therefore, means to know how buildings are made. And to understand architecture and structures from *a technological point of view* means to look upon form, shape, and texture as the response of materials and components to their being processed, trimmed, outfitted, and assembled for a particular purpose, namely that of constituting an occupiable building volume. We may thus think of structural form and its articulation as testifying to the manufacturing and construction processes.

As an example we can consider the church Chiesa Mater Misericordiae designed by architects Angelo Mangiarotti (1921–2012) and Bruno Morassutti (1920–2008) with engineer Aldo Favini

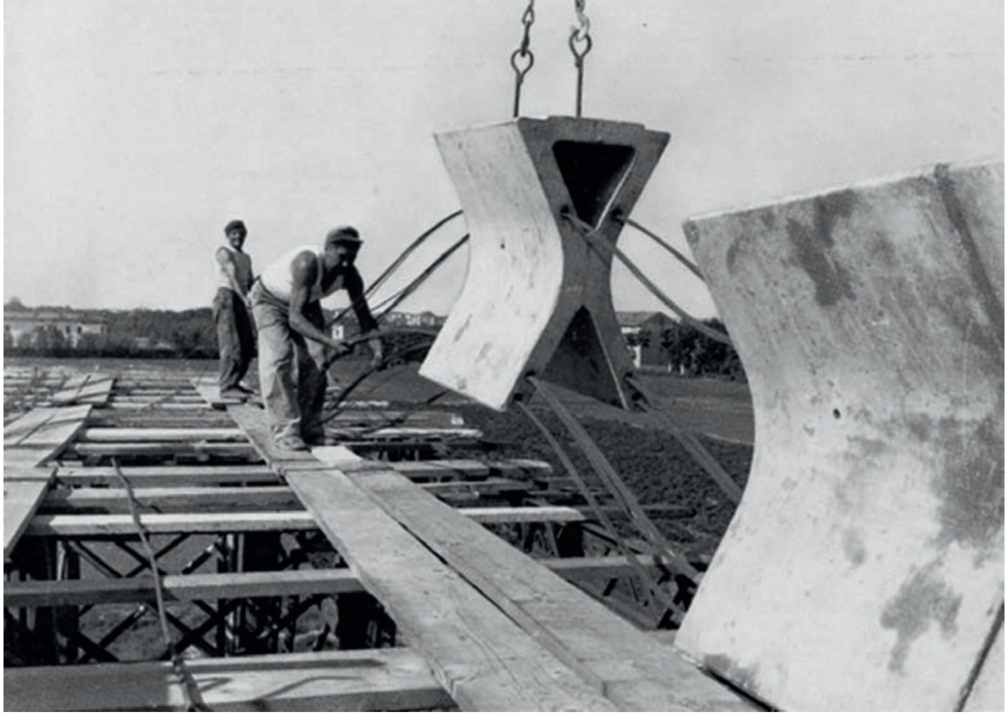

Illustration 1.17
Chiesa Mater Misericordiae, Baranzate, Milan, Italy (1957). Construction technology, or the way the beams are actually built, becomes an important design factor. Here, post-tensioning cables are run through X-shaped precast concrete segments in order to be able to create long-span roof beams.

Architect: Angelo Mangiarotti and Bruno Morassutti. Structural engineer: Aldo Favini.

Illustration 1.18
Chiesa Mater Misericordiae.
Long-span beams seen in ceiling open up the interior space; these beams also project beyond the line of column support. The alternating open and closed-off bottom of these X-shaped beams reflects the variation of their internal compression and tension stresses according to the behavior of continuous beams.

Illustration 1.19
IAA "Dynaform" Pavilion, Frankfurt, Germany (2001). Undulating structural frames reflect the overall architectural context as well as attest to the technological methods used to manufacture them.

Architect: ABB Architects with Bernhard Franken. Structural engineers: Bollinger + Grohmann.

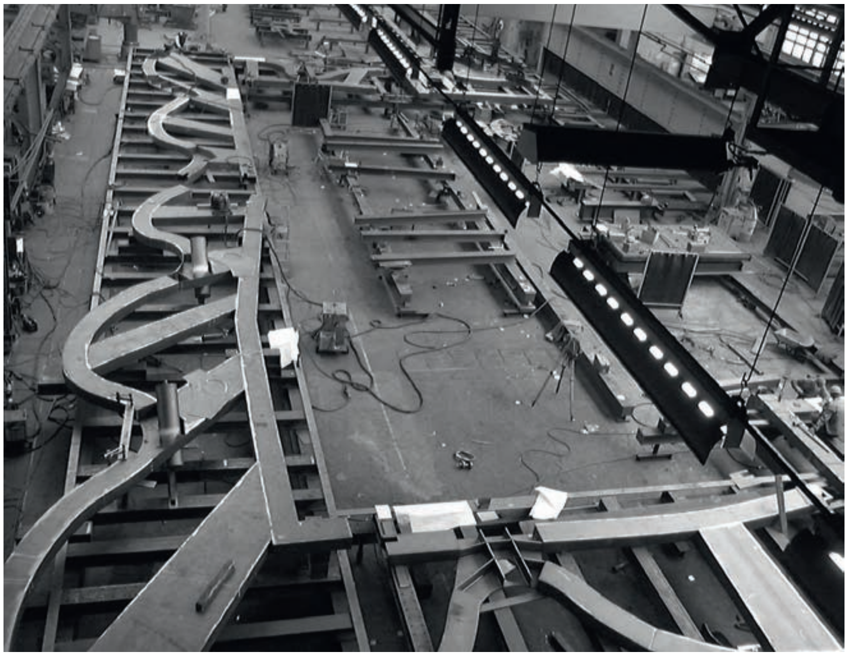

Illustration 1.20
IAA "Dynaform" Pavilion.
CNC laser-cutting of steel plates that are then welded together to create the structural frames.[5]

(1916–2013), in which the roof beams consist of a large number of precast reinforced concrete sections or elements that are poured in a factory, transported to the building site, and then connected together by means of (post-tensioned) cables that run along the length of the beams. (Ill. 1.17.) The discrete component character of these beams stands as "proof" of how the structure is actually built, displaying simultaneously the technology of manufacture and construction that was employed. Beyond this, the church structure is also a good example of the value of invoking the scientific analysis perspective that relates form and strength: each element of the beams basically forms the letter X in cross-section, but with one side (upper or lower, depending on location in the span) closed off with a concrete slab that acts like the lid of a box. This extra material provides a greater resistance to compressive force on the side of the beam that it is on, and such extra capacity alternates from the top to the bottom of the beam along its length according to the behavior of continuous beams. Thus, by keeping in mind both technological and scientific matters, in this case we can better explain and understand the reasons for the particular structural form in the context of the working of the overall system, and of the desired spatial intentions. (Ill. 1.18.)

A second example requiring a technological approach to understanding structure can be found in the IAA pavilion built for BMW exhibitions that was designed by Bernhard Franken of ABB Architects and engineers Bollinger + Grohmann. The roof and walls of this building have an undulating form, with irregular ridges running along its length, while the structure is composed of a series of steel frames that cut transversely across it. Reflecting the overriding architectural design concept and geometry, these frames take on the curving, wave-like shape of the exterior of the building. (Ill. 1.19.) The complex curves of the frames had to be created by using technologically advanced manufacturing methods: they are built up from discrete pieces that are machined out of steel plates using computer-controlled cutters, and then these components are welded together. (Ill. 1.20.) The relatively thick and multiply curved profiles of the structural members making up these frames

Illustration 1.21
ICD-ITKE Pavilion, University of Stuttgart, Germany (2014).
Biomimetic form of this domed, double-layered fiber structure was inspired by the protective shells of beetles' wings, and it is composed of 36 modules, each having unique 3D geometry.

Architects and engineers: ICD-ITKE University of Stuttgart. Prof. Achim Menges and Prof. Jan Knippers.

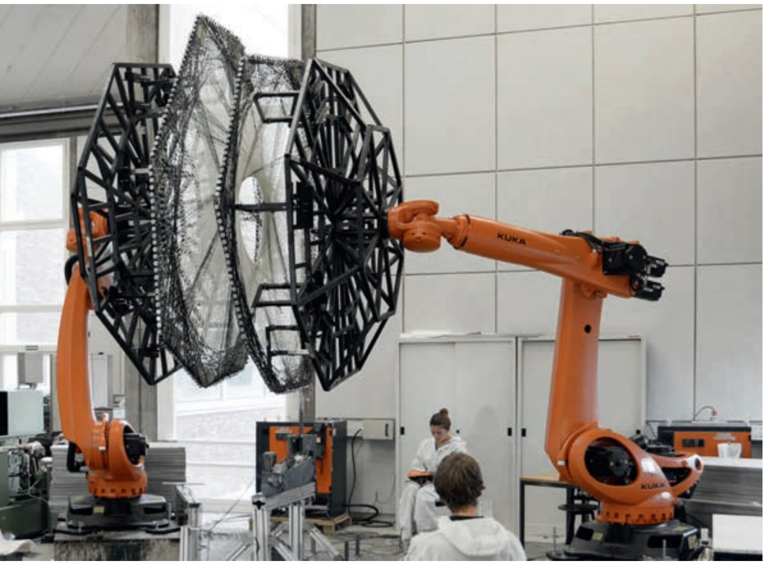

Illustration 1.22
ICD-ITKE Research Pavilion 2013–14.
Seemingly "dueling" 6-axis robots in fact work together in tandem in a highly precise digital choreography, with resin-impregnated fibers spun together according to the results of advanced structural analyses.

would have been impossible to produce by any other method, and acknowledging these structures' particular technological basis and resolution becomes a precondition for gaining an understanding of and appreciation for their overall design.

Advanced technological fabrication methods are taken several steps further with the 2013–14 ICD-ITKE Research Pavilion, designed by teams from the University of Stuttgart's Institute for Computational Design and Institute of Building Structures and Structural Design led by Profs. Achim Menges and Jan Knippers, respectively. (Ill. 1.21.) Inspired by a close study of the structure of beetles' wings and shell abdomens and built as an exquisite adaptation of biomimicry, the distinctively domed structure for this pavilion covered $50m^2$ ($540ft^2$), enclosed a volume of $122m^3$ ($4300ft^3$) and yet weighed only 593kg (1300lbs), with the whole of it dependent on resin-impregnated glass and carbon fibers that were woven together by a pair of carefully synchronized 6-axis industrial robots. (Ill. 1.22.) A highly irregular overall geometry results in the end, taking its cues from specific site conditions, but that was able to be composed and easily erected from 36 prefabricated, double-layered, doubly curved modular units, each one unique in form and size, and each one completely dependent for form and strength on its dense web of woven fibers connecting the inside and outside layers. Moreover, the highly specific layout of these fibers was established by the forces anticipated for the overall structure by means of advanced finite element analyses. In the end, quite a pleasant place to sit and gather with others was created, one which highlighted an essential and creative interaction between innovative material selections, design objectives, structural system configuration and logic as well as the application of state-of-the-art fabrication technology.

These last three examples have shown that building technology is a body of knowledge that helps to bring about the transformation of raw materials into works of architecture, but we also know that scientific principles and mathematical analysis are necessary to make sure that the buildings we design perform according to our expectations and our basic need for safety and efficiency. Thus, both technological decisions *and* scientific reasoning become critical design factors, and while each, on its own terms, puts its imprint on the finished design, only when considered together do they allow for a complete understanding of structures as mechanical objects.

We will stress throughout this book the importance of taking a truly holistic approach to structures by considering *all* the different aspects that we have discussed in this chapter and that may influence structural form in one way or another, from those that relate to mechanical requirements to those that are derived from overall spatial ambitions. (Ill. 1.23.) This broadly based approach allows for the engagement of conceptual ideas that inform the design of structures, and provides an instrument for an informed evaluation of structures as the basis of architecture. Admitting structural issues into the more general architectural assessment of a building project is unfortunately as rare today as it is important; our explicit ambition in communicating structural knowledge is to discuss mechanical issues as an integral part of an overall consideration of architectural spaces, ideas, and forms.[6]

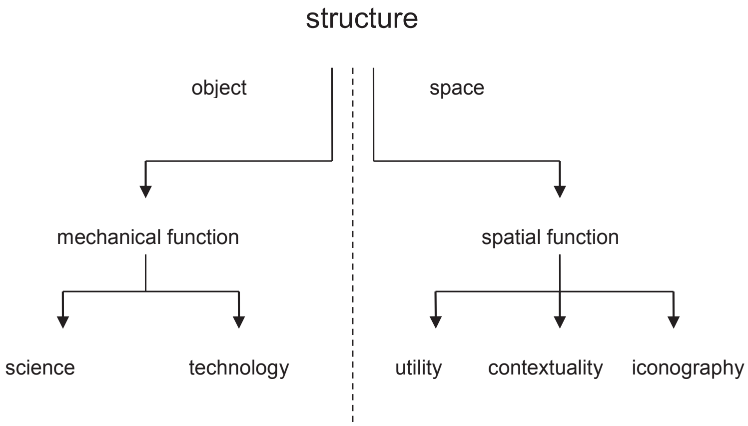

Illustration 1.23
A chart of various aspects of structural form based on a space/object duality.

Introducing Structural Systems

CHAPTER 2

Illustration 2.1
Streetscape in Arles, France. Prominent in the city's historic urban core: the two-tiered, exposed stone arcade of the Arènes d'Arles, a Roman amphitheatre built in about AD 90 based on the Coliseum in Rome, and the pointed Gothic-style Cordeliers steeple erected in 1469 and restored in 1993.

2.1 Revealing Structures

Our first impression of a building, whether looking at it from a city street or a country road, is usually of its volume; i.e., its height and width and overall shape. Next, we will probably notice its surface, identified by the texture, color, and material nature of the building façade. As we gradually take in the situation, this particular building's relationship to its immediate surroundings will begin to register; for example, whether it is larger or smaller than its neighbors, has similar or different window openings, whether its precise orientation aligns with that of other buildings in the area or perhaps with certain landscape elements instead – or else none of these, as the case may be. We are likely to quickly notice whether this building we are concerned with "blends in" with other buildings, or represents a "contrast" to those, or maybe it stands alone in relative isolation. To learn more about it, we will at this point need to enter the building and investigate its interior spaces – their size and shape and daylight conditions, for example. The main purpose that the building fulfills will probably become clear at this point, if it was not already made evident from the outside. It is also at this stage that we often begin to notice the way in which the building is constructed; i.e., we may see columns and beams or other traces of the building's load-bearing structure, and perhaps also observe a certain pattern or hierarchy that these structural elements follow in order to create the form and size of the different rooms and spaces within the building, and that enable these to be kept up in the air and in specific relation to each other in spite of the forces of gravity that are trying to bring them down to the ground in a heap.

It is also the case, however, that a building structure's form and the material of which it is made may not be evident at all, whether the building is seen from the outside or from within; i.e., in some cases the structural elements are completely hidden from view. This could be for aesthetic reasons according to which an architect does not wish to have structure impart a certain type of character and atmosphere to the building façade nor to its internal spaces, whether as part of her/his general design approach or perhaps it is only in a particular instance for very specific conceptual reasons. Or, perhaps, the covering of structural elements may be for more pragmatic reasons such as shielding them from exterior temperature variations, or due to fire-protection regulations, or perhaps because of a desire to hide what may be considered to be, in certain situations, rather unsightly ventilation ducts, plumbing pipes, electrical conduits, etc., that are often attached to and running alongside the structural components. The question of whether to expose or hide structural elements and systems can be debated, and there is no right or wrong answer. Indeed, there are enough compelling examples at both ends of this spectrum to demonstrate that a building design can be considered to be successful according to one approach or the other, or to one that lies somewhere in the middle. What is irrefutable and what all buildings have in common, however, is that an overall structural system and its component elements must be present somewhere, and for our purposes here in this book it is simply a matter that this structure needs to be revealed in order for us to be able to study it. We shall begin this chapter by doing just that for the Pavilion Suisse, designed by the architect Le Corbusier and completed in 1932, and then for the Kunsthaus Bregenz by Peter Zumthor, which opened in 1997.

The Pavilion Suisse was designed as a facility that would house students from Switzerland at the Cité Internationale Universitaire in Paris. The building has three distinct volumes that essentially each accommodate a different function: there is a low, one-story portion containing the common meeting room for all residents, there is a tower-like middle part incorporating stairs and bathrooms, and finally there is a four-story vertical dormitory block where the students live. (Ill. 2.2.) Each volume has its own separate and different structural system, but it is the one for the dormitory which we will focus on here. We see from the outside that this building block is raised on thick, exposed concrete pillars, called "pilotis" in the vocabulary of Le Corbusier. These are placed in rows along both sides of the long, central axis of the building and support a pair of longitudinal beams, which in turn carry on top of them a slab of substantial thickness – all of which are made of reinforced concrete. As we will see, there is quite a different structural system arrangement for the dormitory levels above, one which is supported on this thick concrete transition slab.

Looking at the south façade of the building we see that glass is the dominant material, and that this exterior wall is visually organized by a grid of horizontal and vertical lines; these lines demarcate the positions of floor levels and interior room-partition walls, respectively. We do not actually see the structural components, but nevertheless we do get a strong indication of where these are located. The north façade, however, shows no such trace of the

Illustration 2.2
Pavilion Suisse, Paris (1932).
Exterior view of south façade of dormitory block.
Architect: Le Corbusier.

structural system. Here we see a uniform wall surface made of prefabricated concrete cladding panels, the only relief to which are square openings for windows. It may come as a surprise, then, when it is revealed that behind these façade walls and throughout the whole of the volume of the dormitory block there is actually a three-dimensional structural grid of steel columns and beams. (Ill. 2.3.) It can be said by analogy, therefore, that there is within this building volume a hidden skeleton that enables it to stand up just as is the case in nature with human beings and animals. Moreover, and also in common with these biological bodies, this structural skeleton can be seen to have a close functional and formal relationship to the internal spaces/organs of what it is supporting as well as to the overall external shape of its enveloping enclosure/skin. For example, in the Pavilion Suisse we find that the distance between the steel columns along the south façade is the same as the width of each student's room and that the height of the rooms is defined by the vertical distance between the steel beams of the frame. But at the same time as the dimensions of the structural grid can be seen to have a clear spatial relationship and visual impact, it is also true that its columns and beams themselves are in fact mostly hidden from direct view by the exterior cladding and by being wholly absorbed within room partition walls and covered over by floor slabs.

In contrast to the situation at the Pavilion Suisse, the exterior of the art gallery building in Bregenz, Austria, is even less revealing: here there are no external indications of a structural assembly

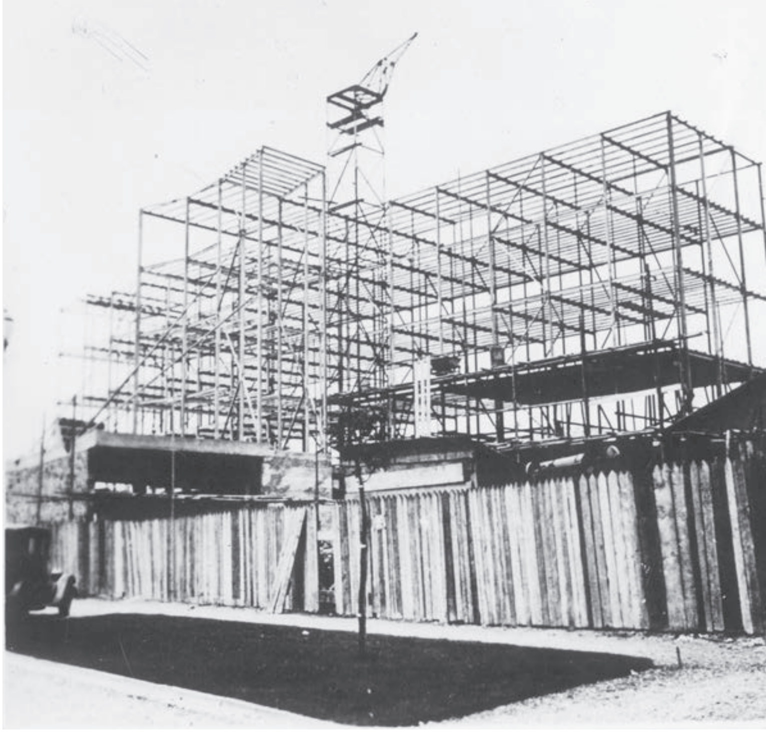

Illustration 2.3
Pavilion Suisse.
Steel skeletal structure is used to support the dormitory floor levels, as seen during construction.

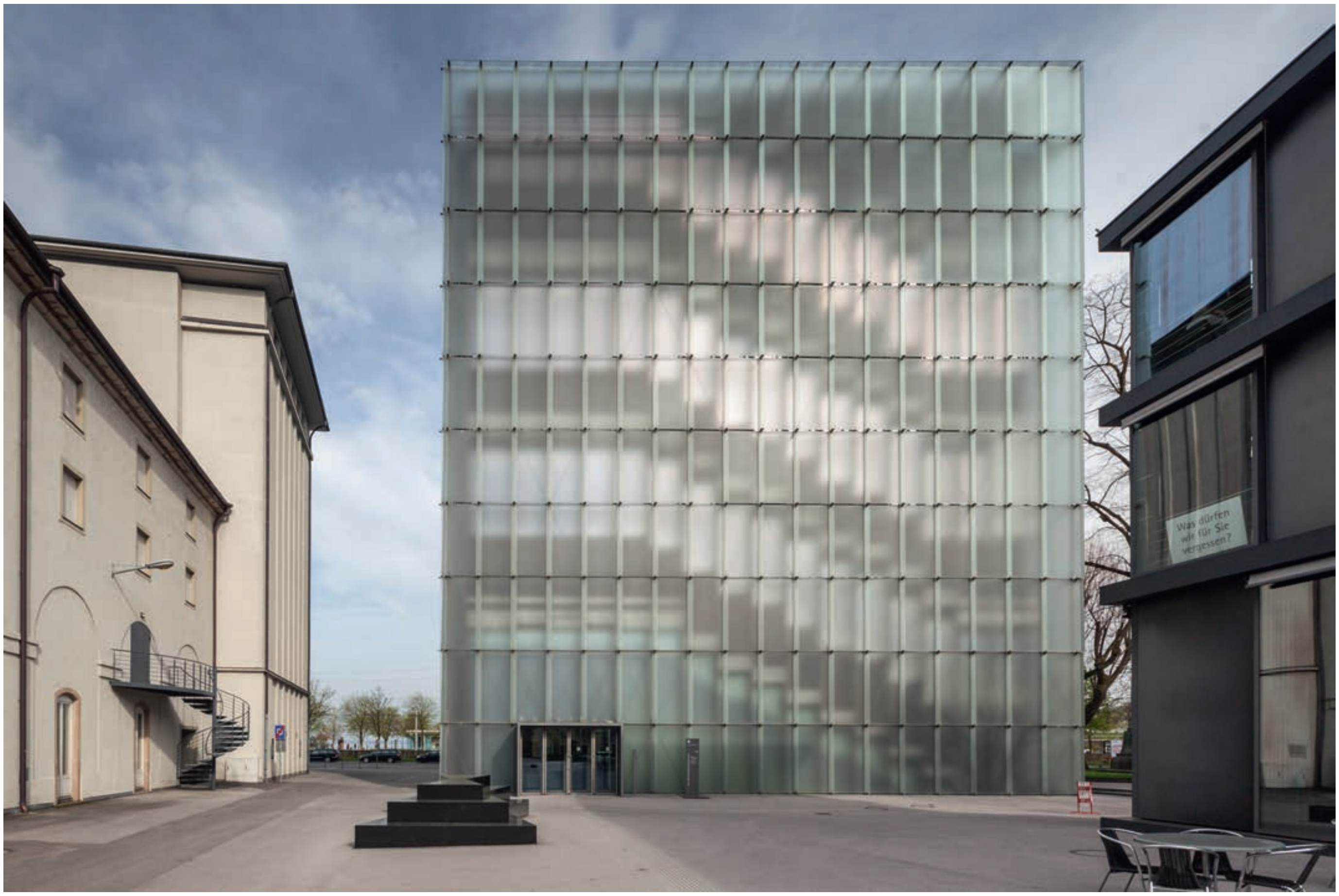

Illustration 2.4
Kunsthaus Bregenz, Bregenz, Austria (1997).
Exterior view; overlapping, etched glass panels cover the entirety of the outside of the building.
Architect: Atelier Peter Zumthor & Partner. Structural engineer: Robert Manahl.

that could begin to suggest, let alone explain, how this particular building is constructed. (Ill. 2.4.) The Kunsthaus is completely clad on all four sides with slightly angled, overlapping, semi-transparent etched glass panels through which we can get a glimpse of the outline of this façade's steel support structure. The glass diffuses the light that enters the building during the daytime, and at night the building is artificially lit from within, turning the whole of the cubical volume into a large urban lantern. We can also see through the façade the blurred outlines of several mysteriously hovering thick horizontal and inclined bands, but there is no hint of what may be holding these up nor of what they may be, or even any recognizable features that would give them scale.

Immediately upon entering the building, however, the load-bearing structure is completely revealed to us: three huge reinforced concrete walls support the accumulating gravity loads at each floor level while also forming the stabilizing system against wind and earthquake lateral loads. (Ill. 2.5, 2.6.) Moreover, these three walls help to organize the building functions and arrange the space according to the daylighting strategy devised by the architect. Contrary to the open skeletal system of the Pavilion Suisse, the structure of the Kunsthaus does not merely indicate where room partition walls might be located, but instead the extensive surfaces of these three load-bearing walls themselves establish the large-scale barriers that isolate the main gallery spaces at each floor level from the circulation stairs and elevators and from the secondary service areas that are located along the outside edges between these walls and the glass façade. The concrete walls are left exposed and, indeed, they delimit space itself.

On the inside of this building, then, the structural system has a clear spatial and visual presence that is not the case for the system of the Pavilion Suisse, at least not to the same extent. On the outside, however, perhaps the opposite could be said, although in neither case is the structural system clearly legible. These two examples show fundamentally different ways of organizing the relationships between structure and architectural form and space, and we will repeatedly return to this way of looking at and considering these various relationships throughout the rest of this book.

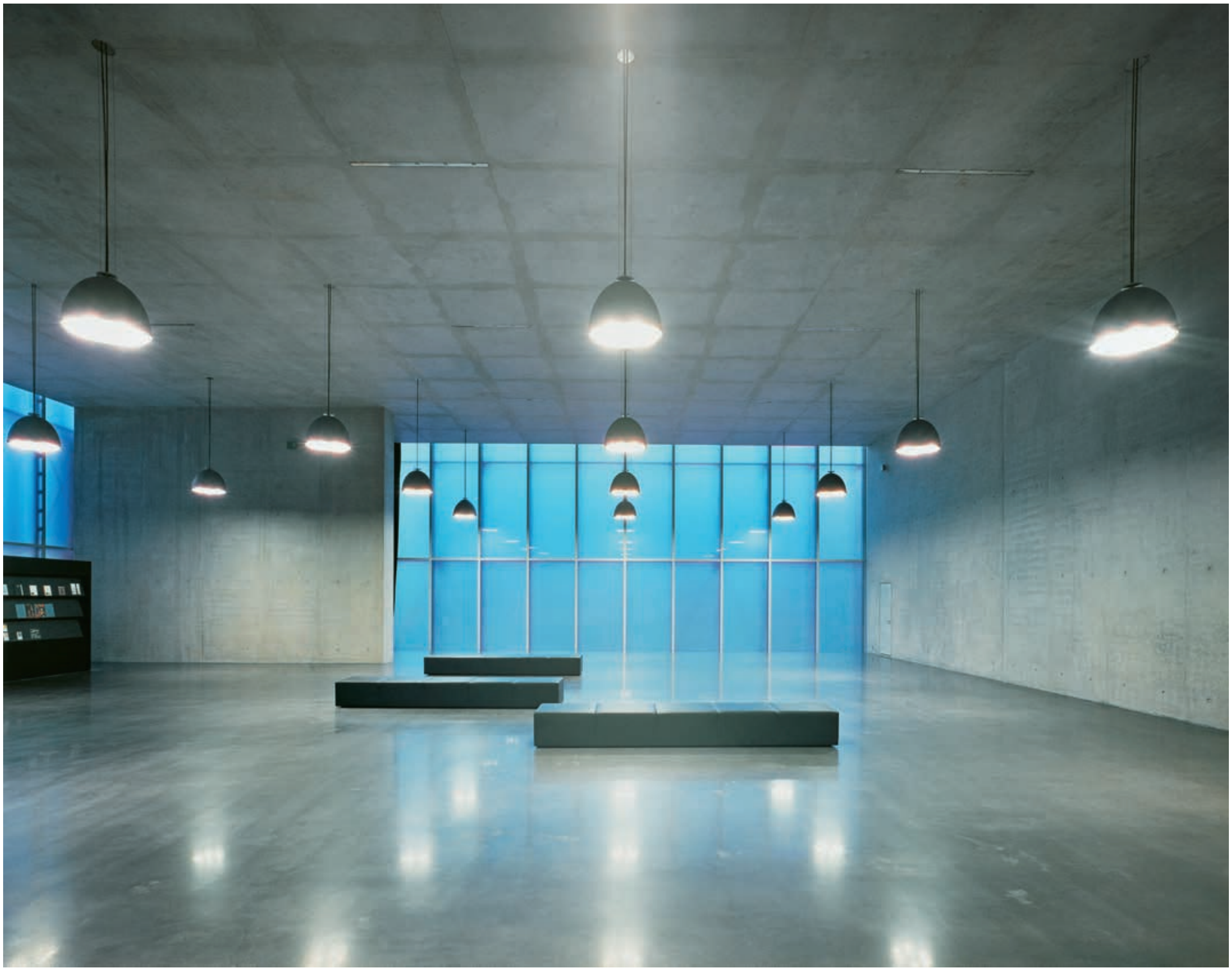

Illustration 2.5
Kunsthaus Bregenz.
Building's vertical structure consists of concrete load-bearing walls; these are in full view in the interior spaces.

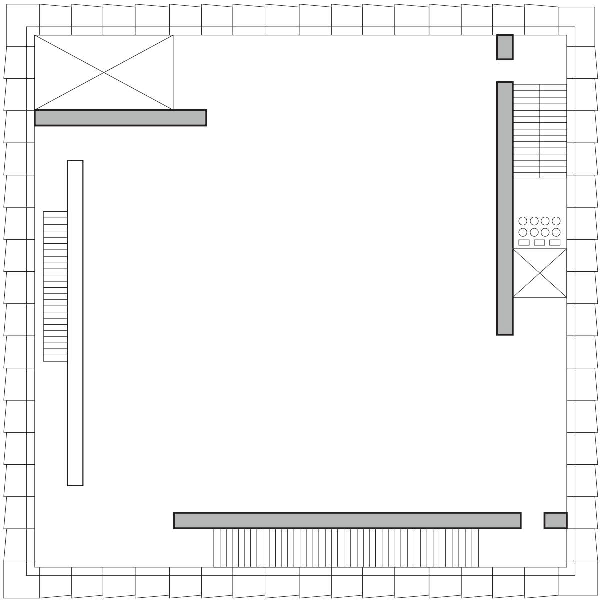

Illustration 2.6
Kunsthaus Bregenz.
Floor plan showing location of the building's three reinforced concrete walls, which are the only vertical structural elements in the building.

2.2 Basic Structural Elements and Systems

Basic Functions and Terms

As has been discussed in the introductory Chapter 1 as well as in the previous section, buildings need a physical structure to keep them standing up. The materials that we use to construct our buildings, whether for the structure itself but also for all the other building components including partition walls and façade claddings and insulation materials, etc., generally constitute considerable weights that are lifted up from the ground and that need to stay there. This also applies to the weight of all the additional things that we put into buildings, including our own weight as building occupants as well as that of furniture and equipment. Moreover, buildings are obviously exposed to the weather and so they need to be able to resist loads caused by such things as wind and snow (perhaps) and in the parts of the world that are prone to earthquakes building structures need to be designed to withstand seismic forces. All this will be covered in much more detail in Chapter 3 Loads. In order to be able to withstand all of these various forces and their effects over long periods of time we have to provide physical *structural elements* in the form of beams and columns and/or walls or, perhaps, and as we will see later, arches or cables or frames or other basic structural components that have as one of their primary functions that of providing our buildings with the physical robustness needed to make them stand up. All of these individual elements considered together as one is known as the building's *structural system*.

We established in Chapter 1 that in addition to providing adequate resistance to weight and other loads, a building structure is frequently called upon to perform other functions such as organizing internal spaces, defining external forms, controlling daylight, establishing circulation paths, etc. A structural system thus frequently also plays a part, to a greater or lesser degree as the case may be, in what might be characterized as the aesthetic and/or functional and/or conceptual agenda influencing the design of a building and, therefore, it may affect the visual expression of the architectural work as a whole. Yet even while acknowledging and even highlighting such a holistic approach to the design of buildings, it remains that the present book is one that is centrally concerned with the physical mechanics of structural behavior as well as how various aspects of construction and material technologies need to be observed in order to ensure that a structural system is able to provide its essential resistance to collapse. In order to do this, we need to first go back to the fundamentals of structural response and discuss what actually happens within structural components when loads are acting on them. Indeed, even before we are able to do that, it is useful here to take one further step back by trying to describe more precisely just what a structure actually is.

A *structure* is commonly thought to be a material element or a number of such elements working together, providing strength, stiffness, and stability in order for loads to be held aloft. The reason, of course, that we need to organize physical matter in particular ways is to satisfy our basic need for shelter. To protect us from the natural elements while at the same time providing inhabitable spaces of various sizes within that shelter calls for an instrument of a sort, otherwise known as a structure, whose function it is to make sure that all loads remain right where they are applied and that these do not cause the shelter to collapse upon us. The loads will nonetheless cause various parts of the structure to respond with smaller-scale deformations, explainable as the result of internal member forces that are established within the structural system in response to the loads that are applied to it. Moreover, these internal forces and the structure's deformations will be of a magnitude and type that is largely established by the structure's overall configuration. Summarizing all this, we can say that for a structure to be functional it needs to be made of sufficiently strong and stiff materials, and that the way it works is heavily influenced by its geometry – which, admittedly, may still seem to be a somewhat vague statement at this point, but it nevertheless establishes the defining principles that will be returned to and refined throughout the rest of this book.

Line vs. Surface Structural Elements

What kinds of structures exist? This is a big question that may be answered in very different ways. We could speak of spanning structures having as their primary function the "transport" of loads over horizontal distances, and of vertical support structures doing the same for loads acting over a building's height.[1] These two groups of structures are identified according to their spatial orientation. We could also identify structures by their physical response characteristics, applying terms like rigid or flexible structures. Furthermore, we might speak of *skeletal structures versus massive structures*, identifying structures by how much space

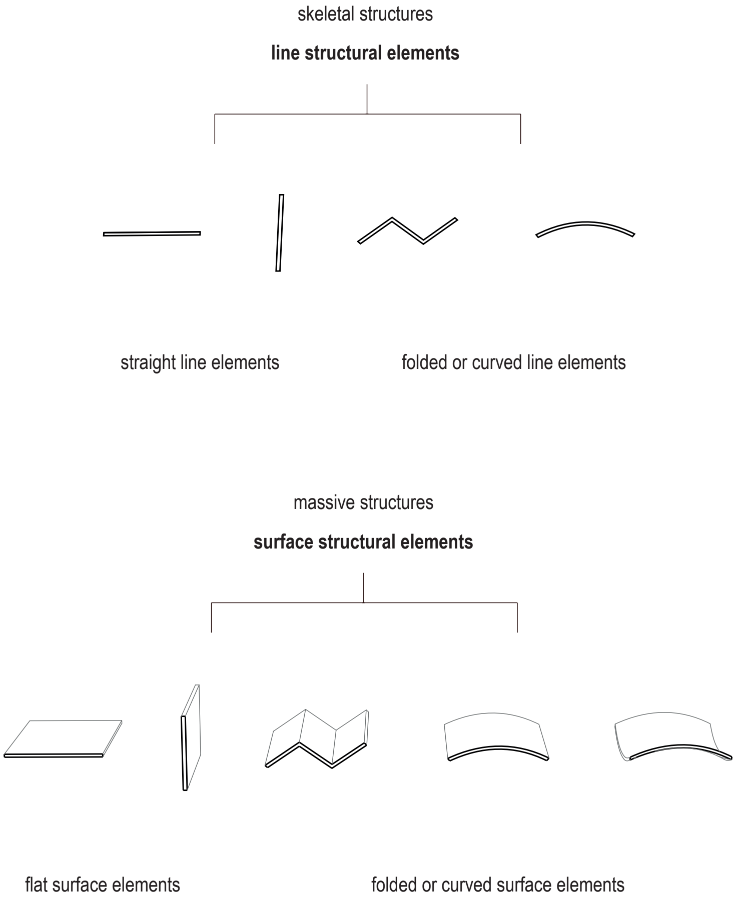

Figure 2.1
Skeletal structures' line structural elements versus
massive structures' surface structural elements.

Illustration 2.7
"Construction Work" (1989).
A composition of skeletal structural elements.
Painting by Tom Slaughter.

they occupy and which correspond to *line structural elements versus surface elements,* respectively.[2] (Fig. 2.1; e.g., Ill. 2.7, 2.8.) There are many more ways to make such distinctions between structures, of course, but for now we will elaborate a bit more on this last classification and then go on to discuss the ways in which these two main groups of structural forms relate differently to the architectural spaces that they help create.

The line elements that make up skeletal structures may be classified according to their geometry as straight line elements and folded/curved line elements. *Straight line elements* typically form ties, columns, and beams, and on a more detailed level they also make up trusses that, geometrically speaking, are aggregations of many straight line elements. *Folded or curved line elements* typically form frames, arches, and cable structures. We shall discuss all of these basic structural types in much more detail later in the book.

If we take a closer look at skeletal structural systems that are built up of linear elements we will usually find that the different parts are arranged according to a *system hierarchy.* (Fig. 2.2.) To be able to actually construct the building envelope needed to seal off interior space from the exterior environment, for example, we frequently need a secondary system of linear structural elements attached to

Illustration 2.8
"Torqued Ellipses," *The Matter of Time* Exhibition (2005), Guggenheim Museum, Bilbao, Spain.
Surface elements can be considered structural just as much as they are sculptural.
Sculptures by Richard Serra.

Figure 2.2
System hierarchy; primary and secondary structural elements.

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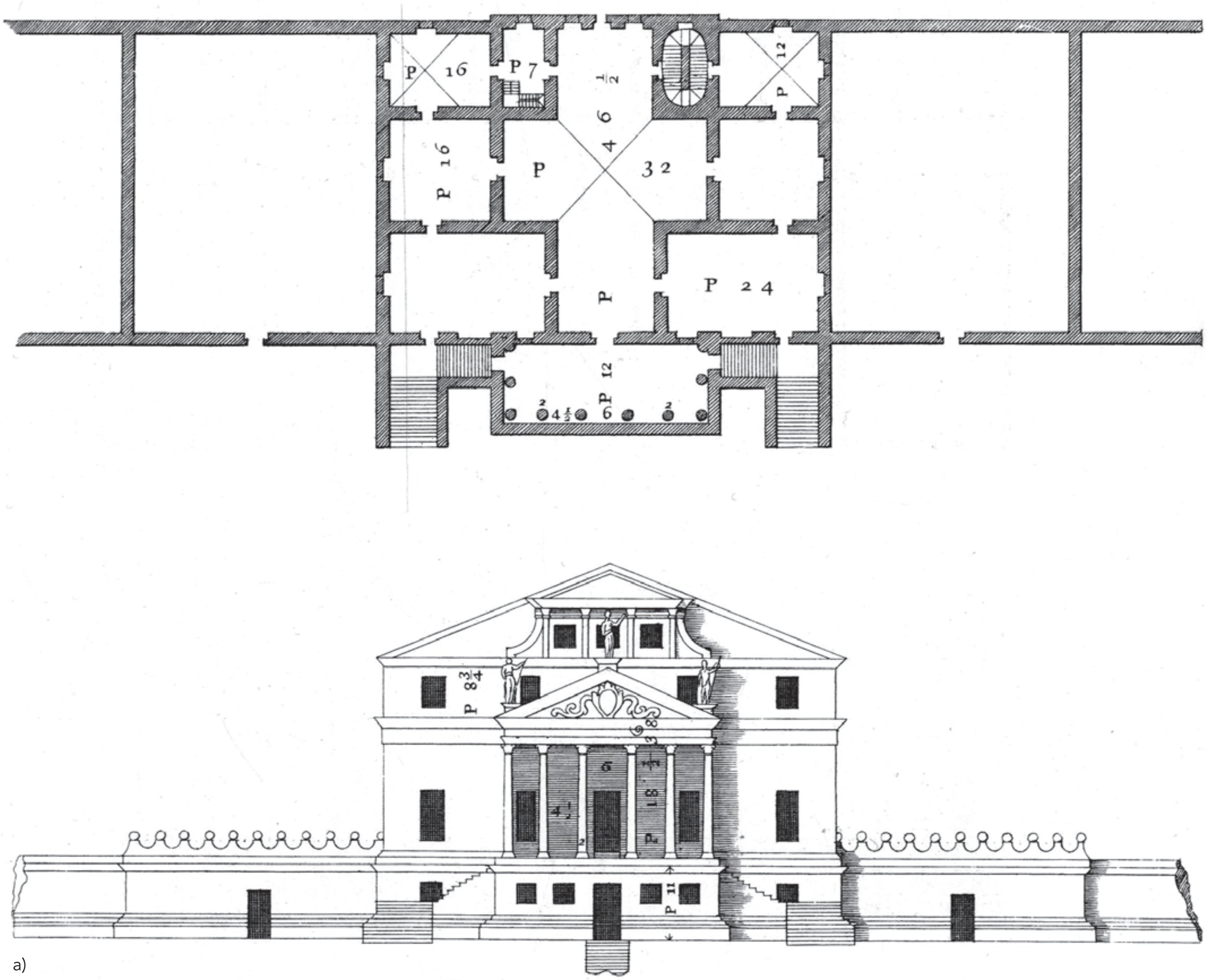
Illustration 2.9
Ground floor plans of three houses that represent both the massive structural system with load-bearing walls, and the skeletal structural system with columns that carry vertical loads.
(a) In the Villa Foscari, Malcontenta, Italy (1560) by the architect Andrea Palladio the load-bearing walls throughout also clearly establish the interior spaces. This is true for traditional building systems in which masonry of one sort or another was the most likely choice for structural materials.
(b) In the Tugendhat House, Brno, Czech Republic (1930) by the architect Ludwig Mies van der Rohe, the skeletal structure enables the limits of the space to be independent of the support structure.
(c) In the brick country house (1923) also designed by Mies in which load-bearing walls do not form closed rooms as they do in the Villa Foscari, but rather create open spaces where movement is relatively free and uninhibited, and yet where they still suggest room zones and to a certain extent also control view sightlines.

the primary structure. As a particular example of this condition, we might find that spanning between large inclined roof beams (also known as rafters) there are a number of smaller transverse beams (called purlins) running parallel to each other which, in turn, directly support a wood sheeting material that is used to make the roof surface. Structural elements such as these purlins are likely to span orthogonally with respect to their supporting elements, and to have a shorter spanning distance and therefore also be smaller; these are then typically termed *secondary structural elements* as opposed to the main beams that are the *primary structural elements*. In some cases there can even be a third layer of structural elements called *tertiary structural elements*.

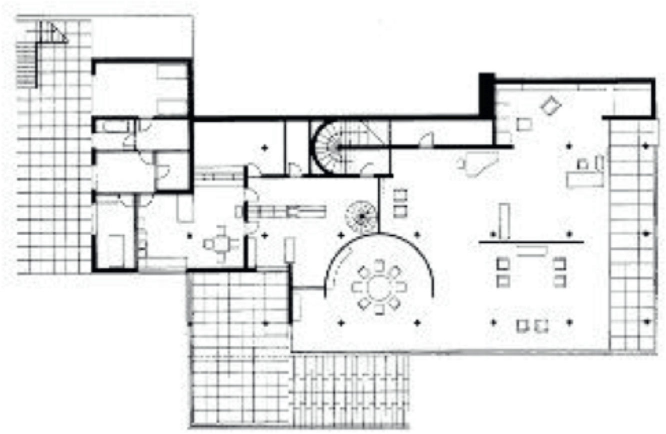
Looking now at the other broad group of structures that we have called *surface elements*, we will find that these can generally be characterized as being essentially two-dimensional, with significant dimensions of both length and width, while having a thickness that is typically much smaller than the other two dimensions. As we did with line elements, we can also classify surface elements geometrically into two groups as flat surface elements and folded/curved surface elements. *Flat* or *planar surface elements* form walls, slabs, and plate structures, while *folded or curved surface elements* in buildings may refer to the components of folded plate structures or else to singly curved arched vaults and cylindrical shells or to doubly curved tension membranes and domes and rigid shells. We will also find undulating surface elements within this last grouping, in the form of roof or floor slabs having varying curvatures, for example. For the time being, however, there is no need to worry about all of these new terms and structural forms; the later chapters of this book will eventually discuss just how all these different surface elements are shaped and how they behave when loads are applied to them.

As was previously discussed, structural systems have broader implications in the context of architecture than "simply" that of carrying and resisting loads. For example, one can observe the differences in terms of the *spatial qualities* produced by the two distinct vertical load-carrying systems of skeletal/line structures (columns) and massive/surface structures (walls) that were introduced above. Let us first consider, for example, the spaces within two well-known residences: the Villa Foscari at Malcontenta in Italy dating from 1560, and the Tugendhat Haus in Brno in the Czech Republic completed in 1930. The house from the Renaissance period designed by Andrea Palladio (1508–1580) represents a traditional building type in which masonry walls carry all the roof and floor loads and self-weight of the walls themselves down to the ground. (Ill. 2.9a.) These surface-type wall elements also very clearly establish the dimensions and sense of enclosure of the interior spaces of the house. It can be said that there is, therefore, an intimate relationship here between the functional aspect and quality of the architectural space on the one hand and the dimensions and geometrical arrangement of the load-bearing structure on the other. This has been the most common condition throughout building history when brick and/or stone structures were dominant and it continued to be the most important structural system until the twentieth century.

In contrast to this, within the 1930 Modernist period Tugendhat House by Ludwig Mies van der Rohe (1886–1969) line structural elements in the form of steel columns carry the vertical loads, and in doing so these hardly interfere with the open space all around them. (Ill. 2.9b.) Indeed, in this house the limits of the different functions within its large room occur in ways that are totally independent of the grid that the columns set out, and these are infinitely changeable. This is an example, then, of the so-called "free plan" advocated by the architect Le Corbusier early in his career, and which is made possible here by the steel column grid; the relationship between the vertical support structure and the space of the house is one that is very free and open.



a)



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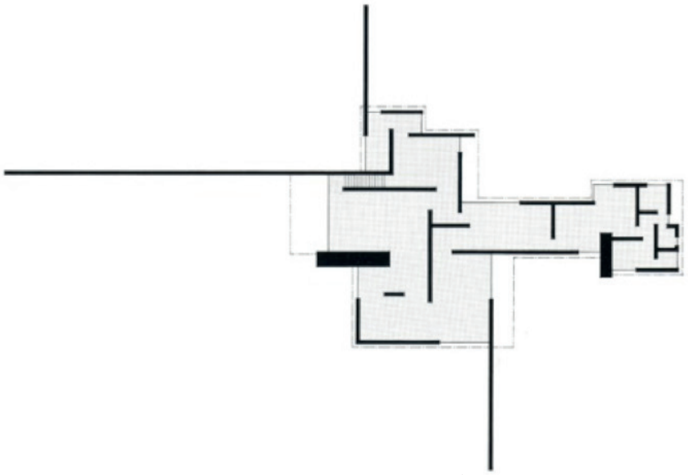

c)

Looking just at these two examples might lead to the conclusion that load-bearing wall structures belong in the past. But that is not the case. In fact, in just the preceding section we saw that within the Bregenz Kunsthaus from 1997 there are three massive reinforced concrete walls that are the only means of support for the loads of the multilevel art gallery and that these walls also organize the plans and help to define the spaces of the museum, control their lighting, etc., and by doing so clearly demonstrating that the wall has not lost its place in contemporary architecture. In fact, in a similar vein it is interesting to note that early in his career Mies also worked with load-bearing walls as a way of establishing room zones within a basically open living space, as exemplified by his project for a brick country house from 1923. (Fig. 2.9c.) Both of these examples exploit the spatial potential of load-bearing walls in a different way than does the traditional building type in which walls completely enclosed and defined interior spaces. Instead, in the more contemporary examples, overall spaces are much more open and movement is relatively unconstrained in spite of the presence of structural walls.

But at the same time it should also be noted that while the Modernist architectural style mostly developed from the early 1920s onward based on an exploration of new open spatial concepts and of structural systems involving skeletal frameworks, both of these innovations can not-so-coincidentally also be connected with the significant material advances that have occurred over the past 100 years or so; i.e., the industrial production of structural steel and of high-strength concrete – but this is yet another topic that we will come back to repeatedly throughout this book, and especially in Chapter 5 Materials. Of course, Modernism has had a lasting legacy well into our time, with much of what we build today being based at least on some level on its fundamental principles, even as enclosed spaces still find their place and raison d'être today and as surface elements continue to be with us in the form of contemporary load-bearing walls, slabs, folded structures, vaults, and shells. In fact, these structural forms can be said to be experiencing a renaissance of sorts in our age of computer-aided design and computer-assisted manufacturing, and we shall encounter some interesting examples of them in the chapters to come.

Structural System Categories: Long span vs. Low-to-mid-rise vs. Tall Building

It should be pointed out that so far in this section we have primarily been discussing the differences between *vertical* structural elements and the impact of these on certain architectural design objectives. The reason for this is that the majority of buildings around us are relatively *low-to-mid-rise multistory buildings* intended for common purposes; i.e., most are probably residential while a significant percentage will be commercial office buildings. An essential aspect of knowing about structural systems, therefore, must necessarily involve knowing how stories can be stacked up one on top of another and what the structural implications are when this takes place, both spatially and physically.

In this very common building type, horizontal spans for the floors and the roof are typically relatively modest. This means that the structural logic and behavior of these spanning subsystems does not need to vary very much from one case to the next, and that these are thus of lesser importance at this very early stage of the discussion about structural element choices and their overall spatial consequences. The horizontally spanning structure in such buildings could be a flat concrete slab or a slab strengthened by underlying steel beams or else a timber beam system with a walking surface layer of wooden boards, etc. – and the typical spanning range for all of these falls within 3–10m (10–30ft), i.e., certainly enough to cover a typical room's plan dimensions. Because floors generally need to be flat and uniformly solid in order for people to be able to occupy a space and circulate within it, aside from any resultant surface textures and visual patterns (e.g., beam spacing, material choices, etc.) there will be relatively little difference among these horizontal subsystem alternatives that would strongly affect an overall sense of space within this building category. Horizontal spans start to be more structurally challenging and of significant spatial and visual interest, however, when the spans go beyond this, and so we will return to this topic a bit later in the book to discuss the various options that are available for this purpose.

So if we think of the low-to-mid-rise multistory building as a "core" building category, we may start to be able to see that the long-span building and the tall building are both "extensions" of this, one in the horizontal direction and the other in the vertical. (Fig. 2.3.) At one extreme of this range, one-story buildings may be asked to provide large, open spaces that are uninterrupted by structural

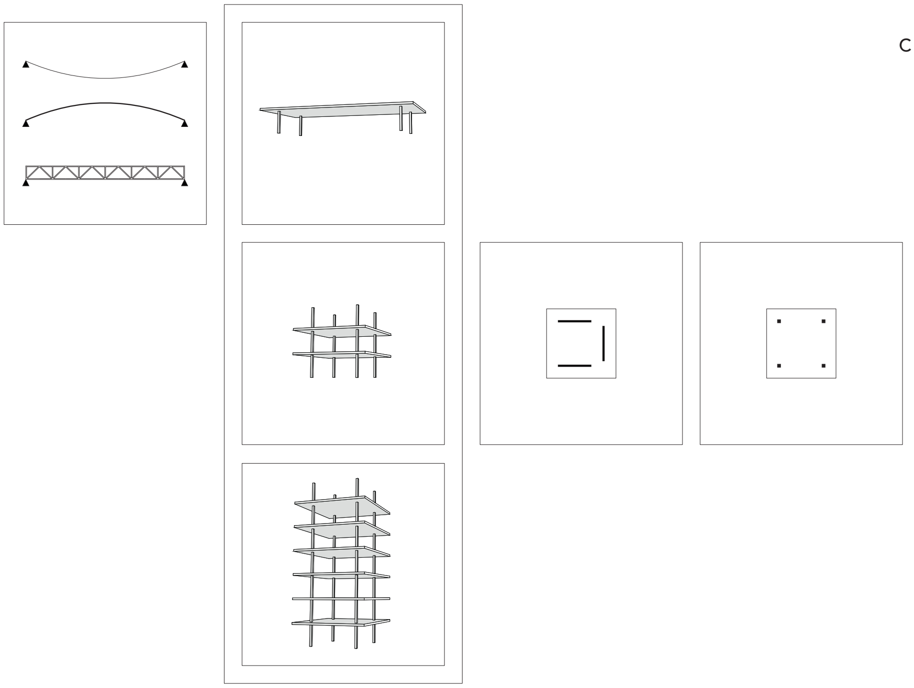

Figure 2.3
With the *low-to-mid-rise building* having a limited number of stories established as the "core" building category, by extending the vertical load-bearing system we may also identify a different building category, namely that of the *tall building.* Whether low or tall, a vertical structural system in a building is typically based on variations of the two fundamental structural element types: the column-based skeletal/line structure or the wall-based massive/surface structure. Likewise, at the other end of the spectrum, by extending the horizontal structural system of a building a large, horizontal span emerges. This third category of the *long-span building* typically leads to a discussion of alternative structural forms for coping with these large spans such as beams, arches, or cable structures.

elements. This calls for structures having *long horizontal spans*, which can be considered to be its own particular building category with its own set of structural and spatial considerations, such as strategically shaped beams, trusses, cable-supported structures, as well as vaults, domes, folded plates, and shells. At the other end of the spectrum, however, we have *tall buildings* in which both vertical gravity loads and lateral forces due to wind pressures and seismic conditions can become very substantial, and these impose new challenges on the structural system, including overall stability and dynamic movement. In our discussion of structural forms throughout this book, we will encounter examples associated with all three of these categories of (highly simplified) building types; i.e., the long-span building, the low-to-mid-rise building, and the tall building.

Locating and Arranging Vertical Structural Elements

Quite often the vertical supporting elements in a building are *located* according to the intersection points of a regular grid, with the horizontal distances between these structural elements found to be similar over most of the building plan. This regularity has the advantage of allowing for a standardized construction process and the eventual flexibility of occupancy arrangements.

Different overall building plan configurations may lead to other ways of positioning the various vertical support elements, however. In a rectangular building, for example, columns and walls may, in a similar way to that which we have just described, be more or less uniformly distributed in each orthogonal direction according to a square grid overlaid over the building plan, resulting in roughly equal floor-beam or floor-slab spans in each direction. Or, perhaps, the grid is not symmetrical and these vertical supporting elements may be more closely spaced in rows that run parallel to the long sides of the building, leading to different span lengths for the beams or slab in the two directions. Or else yet again, columns and walls may be concentrated at certain points in the plan while still maintaining a certain overall geometrical regularity; there are, indeed, numerous ways of doing this within a floor-plan layout's "spacing rules" that can be established by such a grid.

Whether vertical structural elements are located according to positions established by a grid or not, however, we also need to consider their many possible combinations or *arrangements* over a building plan – keeping in mind, of course, that these elements are intended to support the many types of loads, both vertical and horizontal, that act on an overall building structure. To begin this discussion, we will once again start for simplicity's sake and ease of classification with the basic premise that we will distinguish between arrangements that are made up of skeletal/line and massive/surface structural elements, the two basic element form categories that we have described above.

Four basic variations of the many possible plan arrangements for these structural elements are shown in Figure 2.4. We can easily recognize the case of a "pure" skeletal system composed of line-element columns and beams, with a variant of this being a system in which such columns support horizontal surface structural elements in the form of floor slabs. For our limited purposes here, however, in which we are only concerned with the form and arrangement of vertical structural elements, we will label both of these systems as belonging to the "skeletal structure" type. Instead of columns for the vertical structure, however, we may have massive/surface elements in the form of load-bearing walls that are located in the plan either as isolated planar elements, or else several of these may be arranged together in such a way that they form more-or-less-closed "boxes." This latter grouping arrangement of intersecting walls effectively form vertical structural members having a hollow prismatic space in the middle, and these are known to have significant load-bearing capacity while at the same time possessing distinct spatial qualities. All of these four basic vertical structure arrangements can obviously be reconfigured in many different ways according to programmatic needs, design intentions, loading demands, etc. – some examples of which are shown in Figure 2.4.

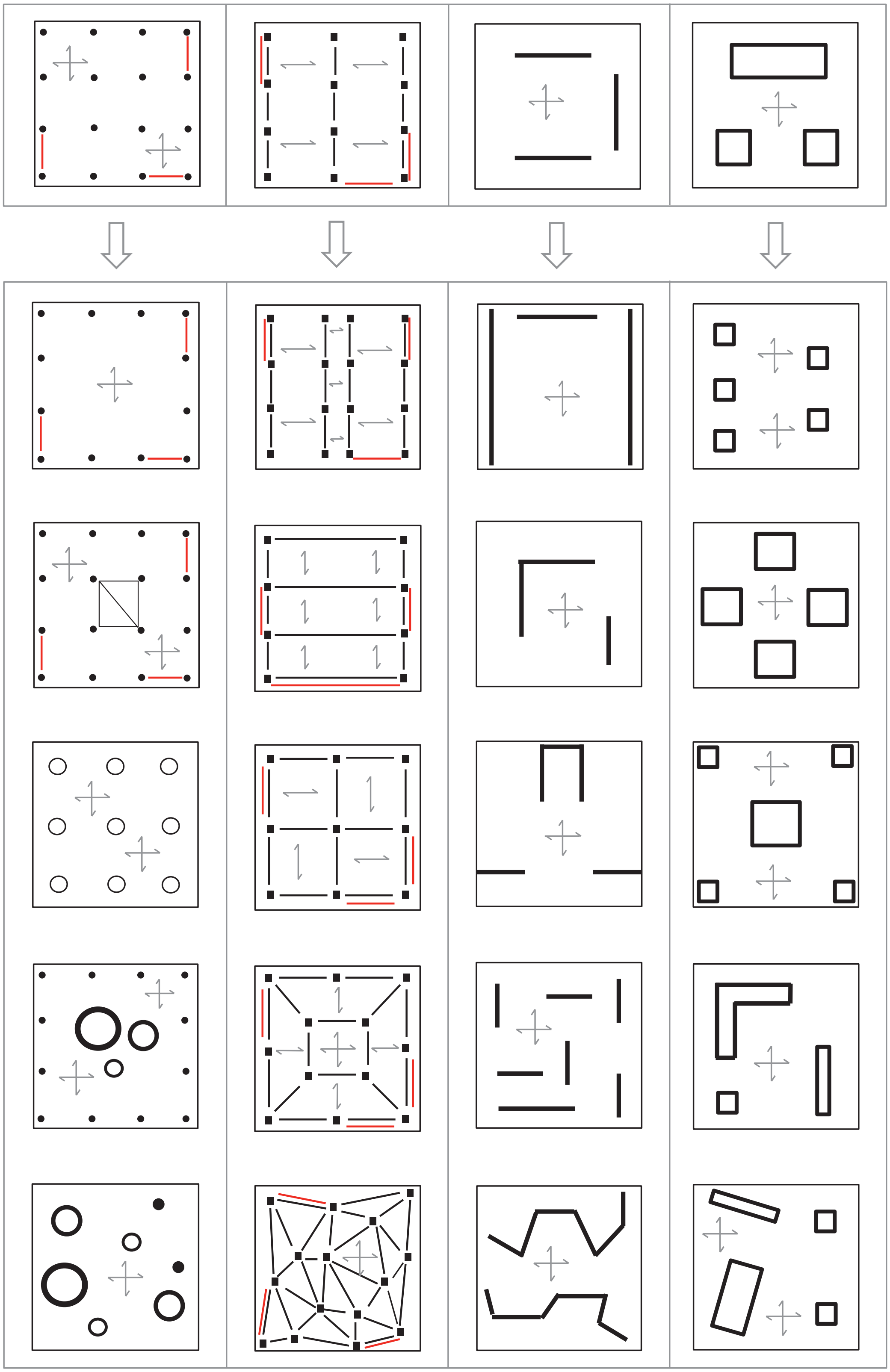

Figure 2.4
Four basic plan variations of vertical structural element arrangements are shown, while a large number of other related arrangements are possible, only some of which are represented. It should be noted that these are merely schematic suggestions and that they do not reflect all there is to a real-life building plan.

Dots indicate column positions and thick black lines indicate the locations of load-bearing walls. Thin black lines between the dots (columns) represent beams, and arrows point out the spanning direction of the floor structure. Where no beams are indicated by straight lines between columns, the horizontal (floor) structure is being thought of as a flat slab of reinforced concrete. Where arrows cross, two-way action of the floor slab is being suggested. Red lines represent the need for some sort of lateral bracing in the vertical structural system.