THE STRUCTURAL BASIS OF ARCHITECTURE

SECOND EDITION

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ROUTLEDGE

The Structural Basis of Architecture

Second Edition

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The Structural Basis of Architecture

This is a book about structures; it is about beams and columns, arches and cables, frames and trusses, and much more besides. Beyond this, though, it is a book concerned with how to "see" structural forms as an integral part of architecture, and with exploring the link between mechanical forms and conceptual ideas inherent to the art of building.

Analyzing the structural principles behind many of the best known works of architecture from past and present, this book nonetheless firmly situates the subject within a contemporary context. Projects by Alvar Aalto, Le Corbusier, Charles and Ray Eames, and Frank Lloyd Wright are discussed right alongside those by Rem Koolhaas/OMA, Sir Norman Foster, SANAA, Zaha Hadid, Snøhetta, and Santiago Calatrava, to name but a few.

The subject matter is primarily approached in a qualitative and discursive manner, illustrated by many photographs of architectural projects and structural behavior diagrams, but it does not shy away from the relatively accessible mathematical equations and calculations that can be used to reinforce and extend an emerging understanding of the topic.

This new edition is completely updated and rewritten, covers an expanded range of topics, and includes many worked-out examples inspired by built projects. The approach throughout is to present structures as a fundamental basis for architecture.

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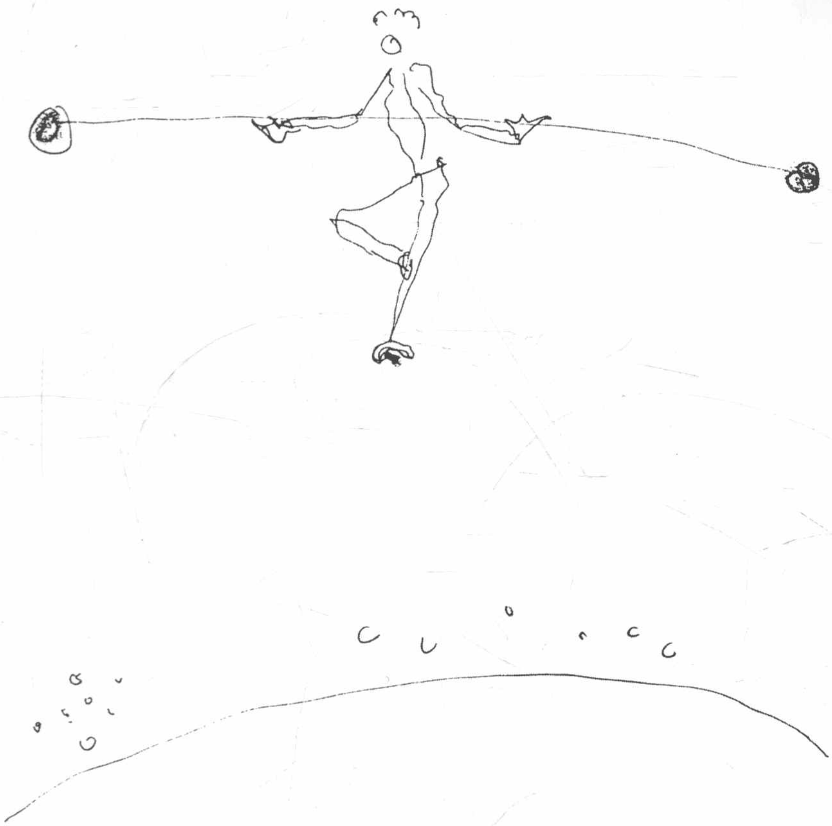

Our traveling globe in galactic endlessness is divided into latitude and longitude.

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. Midst brutality's heat,
beauty is born...

SVERRE FEHN
(1924-2009)

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 the subject, of how to "see" structures as integral to architecture, of how it forms the basis for understanding both the mechanical and conceptual aspects inherent to the art of building. 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 topic – indeed, there are many ways to learn about and from structures. The lessons to be gained span the course of time, and are here drawn both from the architectural canon and the most recent of contemporary projects. Beyond this we also briefly engage the world of art and furniture design, among other related fields, as a means of connecting some of the embedded concepts to a broader cultural context and exploring the relationships between structural behavior and design ideas at vastly different scales.

Much has happened in the world of architecture since the publication of the first edition of this book in 1989. Stylistic periods such as those of postmodernism, deconstructivism, and high-tech and blob architecture have waxed and waned, and starchitecture and parametric design are currently in vogue; the range of examples that are featured in this second edition partially reflects these changes without, of course, losing sight of the lessons of earlier periods. In terms of the development of understanding 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 20. And while it is certainly true that computer methods for analyzing structures' forces and stresses are more prevalent and efficient today than they were two decades ago, nevertheless these programs have not really changed our fundamental understanding of the subject matter as much as speeded 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 reflect the results of such computational advances, it will become evident throughout this work 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 to developing an intuitive understanding of how structures work and how their forms make sense, but also to enabling more conceptual thinking on the part of architects and structural engineers alike for a deepening of this understanding and extrapolating from it 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 technology adage that keeping things simple and repetitive is necessary in order to make construction economically viable. Today, designs of buildings with seemingly infinite variations of member lengths and connection angles that result in remarkably fluid and curvilinear forms are much more easily accomplished because of rapid advances in integrated digital technologies; examples will be found sprinkled throughout the chapters.

The second edition of *The Structural Basis of Architecture* shares its title and vision with the original, although even a cursory comparison will reveal that the contents have been completely revised, updated, and its scope considerably expanded. The story of how this came to be deserves at least a few lines here. The international success of the first edition, co-authored by two of the three present authors, was obviously the starting point. Later, the interactions of our colleagues Per Olaf Fjeld, Val Warke, and Andrea Simitch helped, whether by design or not, to plant the seed for what eventually became the cross-Atlantic collaboration between the present authors from the Oslo School of Architecture and Design (AHO) and Cornell University's Department of Architecture, and for this serendipitous contribution we are grateful. The three of us eventually came to recognize a common and mutually compatible approach to the consideration and teaching of structures in the context of architecture, and we began to plan for a complete overhaul and updating of the first edition about five years ago. Then-editor Caroline Mallinder at Routledge Publishers encouraged us in this endeavor during those initial stages; since then, with the many competing responsibilities of academic life and architectural practice, years and deadlines have come and gone, but through it all the patience and support of Routledge has been remarkable – in particular, Assistant Editor Georgina Johnson-Cook and Editor Fran Ford have helped carry us along and through to the finish line. We are also obviously greatly indebted to the skill and vision of several text editors and layout designers to help turn what for us began as a vague desire to update an existing book into what in essence became the production of a completely new one.

Of course, there have been many others who have contributed in one way or another to this work. We have certainly benefited from the strong support of the administrative leadership of both our respective institutions, and wish to extend our gratitude for generous funding and the granting of critical sabbatical leaves. In particular, at AHO we wish to thank: Dean Karl Otto Ellefsen, former and present Department Chairs Christian Hermansen and Børre Skodvin, and Head of Library Sidsel Moum. At Cornell: former Provost Don Randel, former Deans Anthony Vidler, Porus Olpadwala, Mohsen Mostafavi, and Stan Taft, and former Department Chair Nasrine Seraji; present Dean Kent Kleinman and Chair Dagmar Richter. And at both institutions: faculty colleagues both past and present, far too numerous to name.

We are also particularly indebted for the excellence, dedication, and patience of several student assistants, whether for the collection of illustrations and rights permissions, the production of line diagrams, or the gathering of factual information. At Cornell: Irina Chernyakova, Courtney Song, Monica Freundt, Patricia Brizzio, Eric Rutgers, Asdren Matoshi, Cayley Lambur, Brian Carli, and Cyrus Dochow. At AHO: Anders Hartmann, Anders Lilleby, and Halvard Amble. Thanks also to architect Nanna Meidell. We wish to also acknowledge the financial support that was provided by the Norwegian Non-fiction Literary Fund.

Finally, we wish to dedicate this book to two groups of people without whom none of this would have been possible or worthwhile. First, to our immediate families: Wenche, Victoria, Nicolay, and Sophie; Sigrid, Sune, Dan and Aron; and Patrick and Lauren. And, second, to our many students over the years as well as those yet to come.

Contents

1 Structuring Space

Illustration 1.1
Galleria Vittorio Emanuele II, Milan, Italy (1865–1877).
The gallery is a covered double arcade formed of two glass-vaulted arcades at right angles intersecting in an octagon, prominently sited on the northern side of the Piazza del Duomo.

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 the 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 hold to be basic structural functions. Toward this end, we may ask: What purpose does the structure serve? What requirements govern the conditions determining 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 surface 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 inflow and quality of daylight, or that reflect today's sustainability concerns, or any number of other assigned functions. Hence, structures can serve many purposes simultaneously to carrying loads, 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 illuminating 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 hand 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 mingle 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.

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 the *spatial function* and the *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

Illustration 1.2
Eames House (Case Study House No. 8), Pacific Palisades, California, USA (1949).
Contrasting rather than adapting to the building site, the Eames House was intended to exploit off-the-shelf, prefabricated industrial building components in steel translated to residential design. Partly exposed, the steel structure is ordering the plan in modular bays of 2.4 by 6.4 m (7.5 by 20 ft). 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." The house is like three houses on top of each other: the lowest one is cave-like – a series of caverns carved out from the hill for the most intimate life of the family. The highest house is divided into a house for the parents and one for the children. The most important house is almost invisible, sandwiched in between: a glass room – half inside, half outside for living.

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

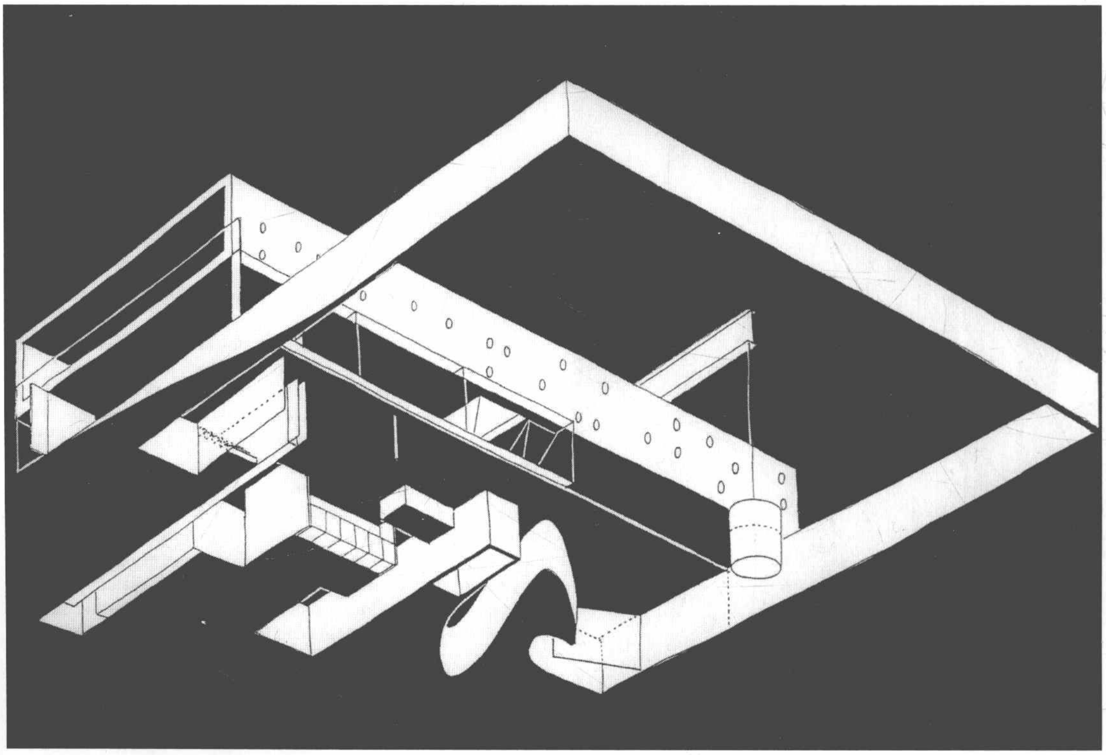

Illustration 1.4
The Bordeaux House.
Diagram showing material elements and structural principles. Moving the supports outside the plan contributed to an opening up of the space.

"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 a stretch 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, 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. This relationship is made possible because the beams are of a type that have large, rectangular

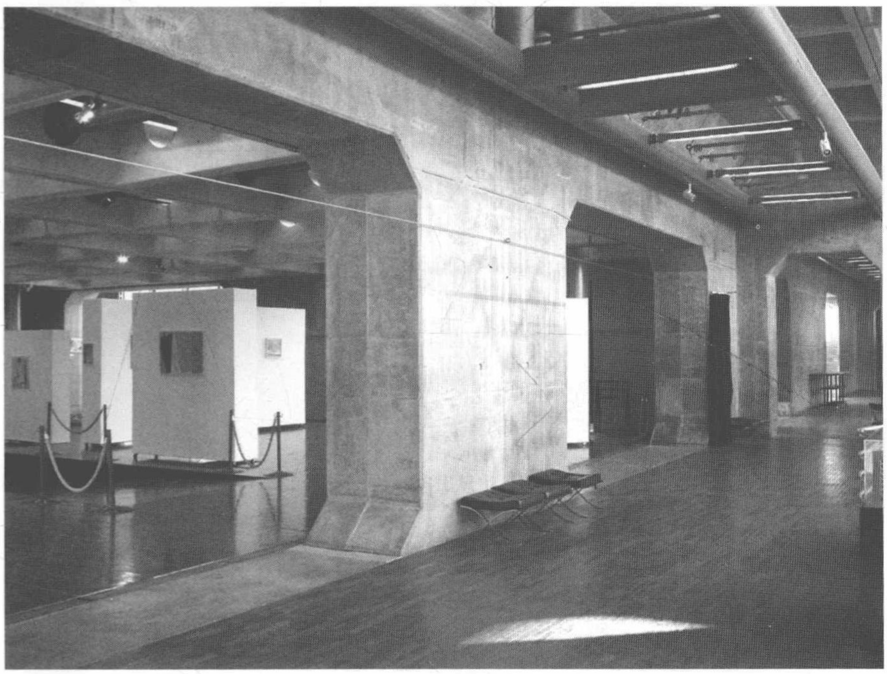

Illustration 1.5
The Grande Arche de la Défense, Paris, France (1989).
The large Vierendeel beams enable utility functions, accommodating people within its structural depth.
Architect: Otto von Spreckelsen. Structural engineer: Erik Reitzel.

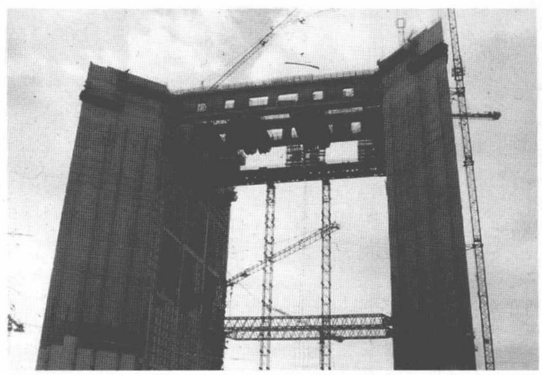

Illustration 1.6
The Grande Arche de la Défense.
Under construction.

openings in them (see Chapter 9 for more on this particular type of structure, so-called Vierendeels). Hence, what we experience in the interior spaces is actually the horizontal and vertical parts of these huge beams that span an impressive 70 m (219 ft) over the open public plaza located far below.

With the Grande Arche it is relatively simple to point out the space–use 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 a central concern with the diffusion of natural light, which resulted in the composite material roof trusses/reflectors of the Museum for the Menil Collection in Houston, Texas. 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 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.

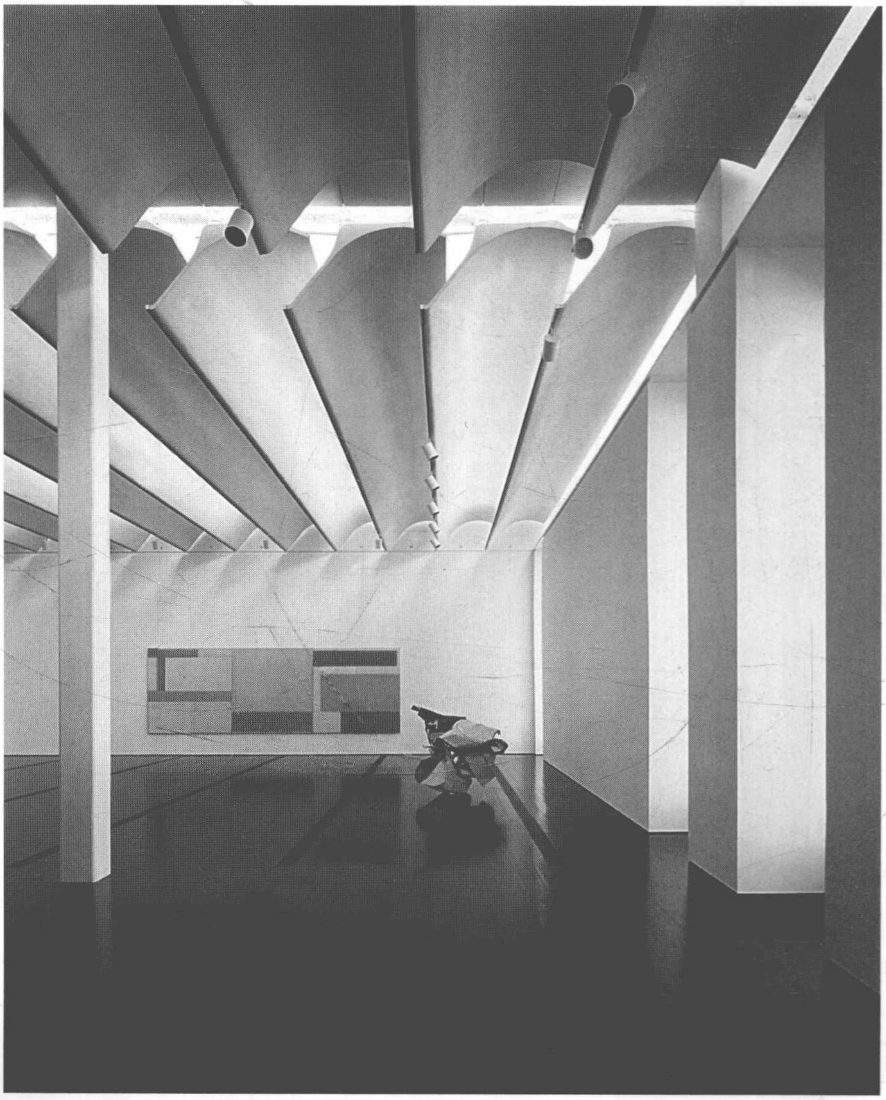

Illustration 1.7
Museum for the Menil Collection, Houston, Texas (1983).
In addition to providing for their load-bearing function, beams are shaped to act as reflectors while also preventing direct light from entering the museum space. Mechanical requirements for beam strength and stiffness meet requirements of a spatial utility nature.

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

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 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 kind 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. And at the (former) Fire Station, sharp angles activate the whole composition of structural elements of columns,

Illustration 1.8
The Cabaret Tabourettli, Bern, Switzerland (1987).
Structures having iconographic function, designed to hint at musical activities that take place in the room.

Architect and structural engineer: Santiago Calatrava.

Illustration 1.9
Vitra Fire Station, Weil-am-Rhein, Germany (1993).
Structural composition of elements in a design that take the lively flickering of flames as a point of departure.

Architect: Zaha Hadid. Structural engineer: Sigma Karlsruhe Gmbh and Arup by John Thornton.