SECOND EDITION

STRUCTURE AS ARCHITECTURE

A SOURCE BOOK FOR ARCHITECTS AND STRUCTURAL ENGINEERS

ANDREW CHARLESON

ROUTLEDGE

Structure as Architecture

Structure as Architecture presents a comprehensive analysis of the indispensable role of structure in architecture. An exploration, as well as a celebration, of structure, the book draws on a series of design studies and case study examples to illustrate how structure can be employed to realize a wide range of concepts in contemporary architecture. By examining design principles that relate to both architecture and structural engineering, Andrew Charleson provides new insights into the relationship between both the technical and aesthetic aspects of architecture.

Now in its second edition, the text has been extensively revised and updated throughout. Features include:

- a brand new chapter on hidden structure, adding to the material on exposed structures
- two new chapters on using structure to realize common architectural concepts through a combination of precedents and creative design
- over fifty new case studies from across the globe
- easy-to-understand diagrams and a highly visual design to aid understanding and accessibility

More than two hundred case studies of contemporary buildings from countries such as the UK, the US, France, Germany, Spain, Hong Kong, Australia and Japan illustrate how a thorough integration of structure adds layers of richness and enhances the realization of architectural design concepts.

Andrew Charleson has visited, photographed and analysed almost all of the case-study buildings included in this book. He is an Associate Professor at the School of Architecture, Victoria University of Wellington, New Zealand. Bringing over forty years' structural engineering experience to the topic, he has also written *Seismic Design for Architects: Outwitting the Quake* and published many papers relating both to the subject of this book and to his other main areas of research interest – earthquake engineering and architecture.

'*Structure as Architecture* cuts to the heart of the architectural and engineering relationship. This book explores how form and function blend, where structural and architectural concepts interweave and support each other for a technically and aesthetically enhanced work. Andrew Charleson demonstrates his holistic approach to architecture and engineering through stunning case studies where designers seamlessly and elegantly blend structural engineering with the architect's design intent. As a structural engineer and architect, I truly believe this book is a must-read.'

Holger S. Schulze Ehring, Structural Designer, New York City

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Andrew Charleson

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Preface

The second edition of this book is based largely on the first, with a number of significant enhancements. Three new chapters have been introduced, of which two consider the topic of structure in architecture from a new perspective. The first edition concentrated upon an *analysis* of architectural structure. It analysed and illustrated the many architectural roles structure plays in both physical and conceptual ways. Its starting point was structure as manifest in existing architecture. Now, the additional two chapters focus on the same topic, but from the perspective of *design*. They begin from the basis of architects' design concepts and architectural qualities and show how structure positively reinforces the most common contemporary design concepts and facilitates desired spatial and other qualities.

This new emphasis on design, rather than analysis, brings a welcome balance to the book. The process of developing this material involved an interesting journey to identify and summarize current architectural concepts and qualities, and then illustrate them from existing works of architecture. One of the most rewarding aspects of this design-orientated emphasis was the design study undertaken by one of my postgraduate classes. Students designed spatial structure to convey a wide range of design concepts. The most relevant outcomes are presented in Chapter 11.

As well as the introduction of this design-related content, the third new chapter shifts the focus upon *exposed* structure to structure that is *hidden*. This exploration not only acknowledges pragmatic aspects of structural hiddenness, but also aims to stimulate greater creativity in the concealment of structure.

This new edition has also provided an opportunity to update case-studies, and broaden their geographical catchment. Thirty per cent of the case-studies are new additions, many from countries previously unrepresented, most notably Japan.

In spite of all of these and other improvements, the central theme of the book remains unchanged: where structure contributes architecturally, other than in its primary load-bearing role, it contributes other layers of aesthetic and functional richness to designs. It reinforces architectural design concepts and intended architectural qualities, thereby increasing the interest in and enjoyment of buildings, raising the spirits of their occupants.

Andrew Charleson
February 2014

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I thank the following 2012 fourth-year architectural students, whose ARCI421 design assignment coursework has provided the inspiration and been modified for the design studies presented in Chapter 11: Emily Batchelor, Hamish Beattie, Alexandra Sawicka-Ritchie, Thomas Seear-Budd, Annabel Fraser, Amber Marie Gray, Henry Velvin, Jae Warrander, Bronwyn Phillipps, Qing Liao, Jorle Wiesen and Monique Mackenzie.

Many individuals have provided images and given permission for their use. They are acknowledged in the figure captions. Unless otherwise noted, photographs are by the author.

Finally, thanks again to my wife Annette for her support and encouragement throughout this project.

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one

Introduction

> Structure is columnar, planar, or a combination of these which a designer can intentionally use to reinforce or realize ideas. In this context, columns, walls and beams can be thought of in terms of concepts of frequency, pattern, simplicity, regularity, randomness and complexity. As such, structure can be used to define space, create units, articulate circulation, suggest movement, or develop composition and modulations. In this way, it becomes inextricably linked to the very elements which create architecture, its quality and excitement.[1]

The potential for structure to enrich architecture

Clark and Pause's statement above begins by describing the architectural qualities of structure and then suggests how structure might enrich architecture. But is such a positive attitude to structure realistic? What was the last building *you* experienced where structure either created the architecture or contributed a sense of excitement to it? Where do we find examples of structure playing such active architectural roles as defining space and modulating surfaces? And, how else might structure contribute architecturally? These questions set the agenda of this book, informing its focus and scope, and initiating an exploration of architecturally enriching structure.

Some readers may consider Clark and Pause's attitude towards structure as a fully integrated architectural element rather unrealistic. So often our day-to-day experience of structure can be described as unmemorable. In much of our built environment structure is either concealed or nondescript. Opaque façade panels or mirror-glass panes hide structure located on a building's perimeter. Inside a building, suspended ceilings conceal beams, and vertical structural elements like columns, cross-bracing and structural walls are either enveloped within partition walls or else visually indistinguishable from them. Even if structure *is* exposed, often its repetitive and predictable configuration in plan and elevation, as well as its unrefined member and connection detailing, can rarely be described as 'creating architecture, its quality and excitement'.

Fortunately, in addition to these ubiquitous and bland structural encounters, sufficient precedents of positive structural contributions to architecture exist. They point towards bolder and more exciting possibilities and have convinced critical observers, like Clark and Pause and others, of the potential for structure to engage with architecture more actively and creatively. Peter Collins, the architectural theorist, shares similarly constructive convictions regarding structure's architectural roles. In concluding a discussion on eighteenth- and nineteenth-century Rationalism, he suggests:

> However much the emphasis on structural expression may have been exaggerated in the past by a craving for ostentation, or reduced by the competing emphases on spatial effects, sculptural effects and new planning requirements, it is still potentially one of the most vigorous ideals of the modern age, and it would not be an exaggeration to say that it is the notion which offers the most fruitful prospects for the future development of modern architectural thought.[2]

Like the authors quoted above, I will also be looking beyond the physical necessity of structure towards its functional and aesthetic possibilities. Just because structure is essential

for built architecture, providing it with necessary stability, strength and stiffness, it does not have to be architecturally mute – unless of course its designers make that choice. This book provides many examples of structures 'speaking' and even 'shouting' in their architectural contexts. In these cases their designers, usually both architects and structural engineers, have made structural decisions that do not detract from but rather strengthen their architectural ideas and requirements. Structure no longer remains silent; it is a voice to be heard.

Where structure is given a voice, as illustrated in the following chapters, it contributes architectural meaning and richness, sometimes becoming the most significant of all architectural elements in a building. Endless opportunities exist for structure to enhance architecture and thereby enrich our architectural experiences. As designers we can allow structure to speak and to be heard; or, to change the metaphor, we can design structure so that its viewers not only see and experience it, but, due to its well-considered architectural qualities, are enticed into 'reading' it.

Experiencing structure: reading and listening

Architects analyse structure by experiencing and reading it. In their succinct summary, Clarke and Pause suggest the ways structure might be read or analysed architecturally. In some architectural reviews of buildings, particularly where structure is exposed, structural readings are made. Although reviewers usually make little more than a passing comment, analysing structure in this way remains valid. The following two examples illustrate architecturally focused structural readings.

Fontein offers a reading of the interior structure of her School of Architecture building. She concentrates upon a single column, differentiated from others by virtue of its circular cross-section and increased height. She asserts that this column 'plays a pivotal role in the building' by marking and sheltering the intersection of two internal streets. It also connects that street junction to the school's main collective space whose activities it both supports and obstructs. Ultimately it 'establishes structure as a primary ordering device in the architecture of the School . . . and has the palpable effect of anchoring the life of the School'.[3]

LaVine tends towards less personified readings as he discerns significant architectural roles played by structure in his four house case-studies.[4] He notes how a ridge beam can symbolize the social centre of a house, and how a superstructure orders space by virtue of its regularity and hierarchy. In other examples, columns 'signify human activities of special significance' or 'portray a mechanical idealism'. He reads walls as separating occupants from the outside world, and frames as ordering interior space. As he reads structure, each structural element is laden with meaning and makes an important architectural contribution.

For many, the reading of architecture is as natural as breathing. For example, Stan Allen comments on the Tama Art Library, designed by Toyo Ito, that

> it is impossible not to read the arches as a sign, a reference to a recognizable form in the repertory of classical architecture. They *are* that, but they are many other things, too . . . Ito produces work that is richer and more nuanced precisely for its capacity to hold these multiple readings in a delicate equilibrium.[5]

All architectural readings incorporate a degree of subjectivity. To a certain extent, each reading is personal. It reflects the reader's background and architectural knowledge. The quality of their experience of a building is another factor which depends on the duration of the visit and the depth of reflection during and after it.

The views of two or more readers are unlikely to be identical. Each person brings their own perspective. For example, an architect and structural engineer will read a structure quite differently. Each approaches it with his or her professional interest and concerns to the forefront. Whereas an architect might focus on how structure impacts the surrounding space, an engineer will most likely perceive structure as facilitating a load-path.

The discussion above considers structure as a passive architectural element – like a book waiting to be read. However, could it be that structure plays a more active role and actually speaks to us? So as well as reading structure must we also listen to it? According to Alain de Botton, we should.[6] To ease us into this possibly surprising idea, in his chapter 'Talking buildings' he reminds us how sculpture generates in us a thoughtful and responsive attitude towards objects. 'The great abstract sculptures', he says, 'have

succeeded in speaking to us, in their particular dissociated language, of the important themes of our lives.'[7] The argument continues that if objects in a gallery can speak, and even pencil squiggles on paper can convey emotions, such as peacefulness and confusion, how much more can buildings communicate? Buildings are therefore pregnant with expressive potential, as are their elements, including structure, and de Botton acknowledges this by suggesting that 'we can be moved by a column that meets a roof with grace'.[8]

So, my architectural analyses of structure inevitably reflect who I am, how I read and listen to structure, and this is affected by my structural engineering background, my experience of teaching in a school of architecture, and my intense interest in how structure can enrich architecture.

Before commencing to read building structures and explore their architectural contributions, the next section clarifies the meaning of the book's central focus – exposed structure.

Structure and its degree of exposure

At this stage it is necessary to come to a common understanding of what constitutes structure, and to comment on aspects of its exposure. For the purpose of sensibly limiting the scope of the book, structure is taken to mean any structural element that bears load other than that arising from its self-weight or self-induced loads, like those from wind or snow.

This definition therefore excludes consideration of purely decorative elements without wanting to deny any significant architectural roles they might play. Imitative structure and authentic structural members that are not load-bearing, even though they might clearly express their materiality and display standard structural dimensions, lie outside the scope of this book. Examples of the latter category include exposed frameworks whose sole purpose is to contribute to a building's composition, perhaps visually linking together disparate forms.

Although this discussion omits structure whose rationale is *solely* aesthetic, structural elements and details with minimal structural effectiveness *are* included. Structural details like the attached shafts on Gothic piers fall into this category. Even though their architectural contribution may be seen as more aesthetic than structural, by increasing the cross-sectional area and depth of a pier, the details slightly increase its compression strength and overall stability.

Having established a working definition of structure, an explanation for the focus upon *exposed* structure is warranted and quite simple. Where structure is not exposed but concealed, perhaps hidden within wall cavities, screened by suspended ceilings or undifferentiated from partition walling, it possesses very limited opportunities to enrich architecture. In these situations, where the architecture must rely on other devices and elements for its qualities, any skeletal, wall-like or expressive structural qualities remain latent – structure cannot be read.

Architects take an unlimited number of approaches towards structural exposure. In its fully exposed state, the raw materiality of structure is visible, be it masonry, concrete, steel or natural timber. Even if coatings or claddings partially or fully veil structural members and their materiality, structural form can still play significant and expressive architectural roles. Steel structural members may be wrapped with corrosion and fire protection coatings and even cladding panels, but their structural forms can still enliven façades and interior spaces. Hence, in this book, *exposed* structure includes any visible structural forms, irrespective of whether their materiality is concealed.

This apparent preoccupation with exposed structure does not mean it is a requirement of exemplary architecture. Exposed structure has rightly been deemed inappropriate on many past occasions given the design ideals current at those times. Cowan gives examples of periods in architectural history, such as the Renaissance and the Baroque, when exposed structure would have detracted from the forms and embellished surfaces that designers were attempting to achieve.[9] Absence of exposed structure in contemporary buildings may also be completely defensible. For example, exterior exposed structure might compromise architectural forms exhibiting sculptural qualities and curved surfaces, and interior exposed structure would impact negatively upon an architectural goal of achieving spaces defined by pure planar surfaces.

Decisions regarding the extent to which structure should be exposed in an architectural design, if at all, are best made after revisiting the design concept and asking

whether exposed structure will enhance its realization. Then, irrespective of the answer, design ideas will be communicated with greater clarity. Structural exposure should therefore be limited to buildings where structure integrates with and clearly strengthens the expression of architectural ideas.

Book outline

The following chapter analyses the structures of two contrasting buildings to set the scene for more focused and detailed explorations of many other buildings in the remainder of the book. Both buildings exemplify structure contributing architecturally in the context of specific architectural programmes. Exposed structure plays significant architectural roles on the exterior of the first building, while in the second, structure creates special interior spaces. Due to the inevitably limited range of architectural contributions illustrated by the two case-studies, the following chapters explore and illustrate exposed structure enriching specific areas of architecture in more detail.

Beginning with Chapter 3, chapter sequencing up to and including Chapter 9 reflects a typical progression of experiences when visiting a building. First, imagine approaching a building from a distance. When only architectural massing may be discerned, the diversity of relationship between architectural and structural form is explored. Then, in Chapter 4, drawing closer to the building, one observes structural elements enlivening façades in various ways, including forming surface patterns and textures, providing visual clues of entry, connecting exterior and interior architecture, and playing diverse expressive roles.

Having entered the building, the next three chapters consider relationships between the structure and interior architecture. Chapter 5 examines how structure enhances and, in some cases, defines building function. Structure maximizes planning flexibility, subdivides space to facilitate separate functions, and articulates circulation paths. Chapter 6 focuses on interior structure as an architectural element in its own right. It addresses the question of how structure enlivens and articulates interior spaces and surfaces. Examples illustrate structure providing a wide range of surface and spatial qualities. Some interior structures read as responding to aspects such as a building's geometry or function, or, alternatively, expressing external factors like soil pressures or other site-specific characteristics.

Exploration of interior structure narrows in scope in Chapter 7 with an examination of structural detailing. After noting the importance of detailing being driven by a design concept, examples of expressive and responsive details are provided. They comprise two categories of details, one of which gains its inspiration from within the building, and the other from without. Some structural members are so elegantly detailed as to be considered objects of aesthetic delight, considerably increasing one's enjoyment and interest in architecture. A plethora of structural detailing languages with diverse architectural qualities strengthens designers' abilities to realize overarching architectural design concepts.

Chapter 8 investigates the relationship between structure and light, both natural and artificial. It illustrates structure's dual roles, as both a source and modifier of light, and introduces a number of different strategies designers use to maximize the ingress of light into buildings. Chapter 9 reflects on the symbolic and representational roles structure plays. Structure references naturally occurring objects like trees and processes such as erosion, as well as human artefacts, notions and experiences as diverse as oppression and humour.

Having completed explorations of exposed structure, Chapter 10 enters the world of hidden structure and contemplates its contribution to architecture, even though it is concealed. Then, in the following two chapters, the focus shifts from analysis of structure to design. Rather than analysing the roles of structure beyond load-bearing, the intent of Chapters 11 and 12 is to show how structure can reinforce architectural concepts, and realize specific architectural qualities.

The final chapter offers a brief distillation of the main themes that have emerged throughout the book – namely the transformative power of structure, the diversity with which it enriches architecture, and implications for the architectural and structural engineering professions.

Notes

1. R. H. Clark and M. Pause, *Precedents in architecture*, Hoboken, NJ: Van Nostrand Reinhold, 1985, p. 3.
2. P. Collins, *Changing ideals in modern architecture 1750–1950*, 2nd edn, Montreal: McGill-Queen's University Press, 1998, p. 217.
3. L. Fontein, 'Reading structure through the frame', *Perspecta* 31, 2000, 50–9.
4. L. LaVine, *Mechanics and meaning in architecture*, Minneapolis: University of Minnesota Press, 2001.
5. S. Allen, 'Toyo Ito's patient search', in J. Turnbull (ed.), *Toyo Ito – forces of nature*, New York: Princeton Architectural Press, 2012, p. 24.
6. A. de Botton, *The architecture of happiness*, London: Hamish Hamilton/Penguin, 2006.
7. Ibid., p. 81.
8. Ibid., p. 98.
9. H. Cowan, 'A note on structural honesty', *Architecture Australia* 1,1980, 28–32.

two

Two building studies

This chapter presents structural analyses of two very different buildings. Between them, they exemplify structure enriching most aspects and areas of architecture. These analyses introduce the many ways structure contributes to architecture and prepares the way for a more detailed investigation and categorization of the architectural potential of structure in subsequent chapters.

The following two case-studies illustrate the considered use of exposed structure in very different architectural contexts. First, the National Stadium, Beijing, displays an exuberant and chaotic exterior structure, but it is more muted when experienced from the interior. Exterior and interior expression reverses in the second building, the Baumschulenweg Crematorium. Within its formal minimalist exterior envelope, impressive exposed interior structure in the form of 'randomly placed' columns transforms the main space, leading to alternative architectural readings.

National Stadium, Beijing

Built for the Beijing XXIXth Olympiad, which was held during August 2008, the National Stadium is the largest and most dominant building at the Olympic site. Accommodating 91,000 spectators during the Olympics, the oval-shaped stadium has a roof structure 313 m long by 266 m wide, including a large elliptical opening above the stadium pitch. A retractable roof was originally designed, but omitted at a late stage during the design process. The height of the saddle-shaped top surface varies from 40 m at its lowest point to the approximate height of a 20-storey building – 70 m – at its highest (Figure 2.1).

The rounded vessel-like form comprises two independent free-standing structures: an interior reinforced concrete bowl with its three tiers of sloping seating, and the perimeter and roof steel structure. The bowl structure is itself divided

Figure 2.1
National Stadium, Beijing, China, Herzog & De Meuron, 2008. An elevation of the stadium.

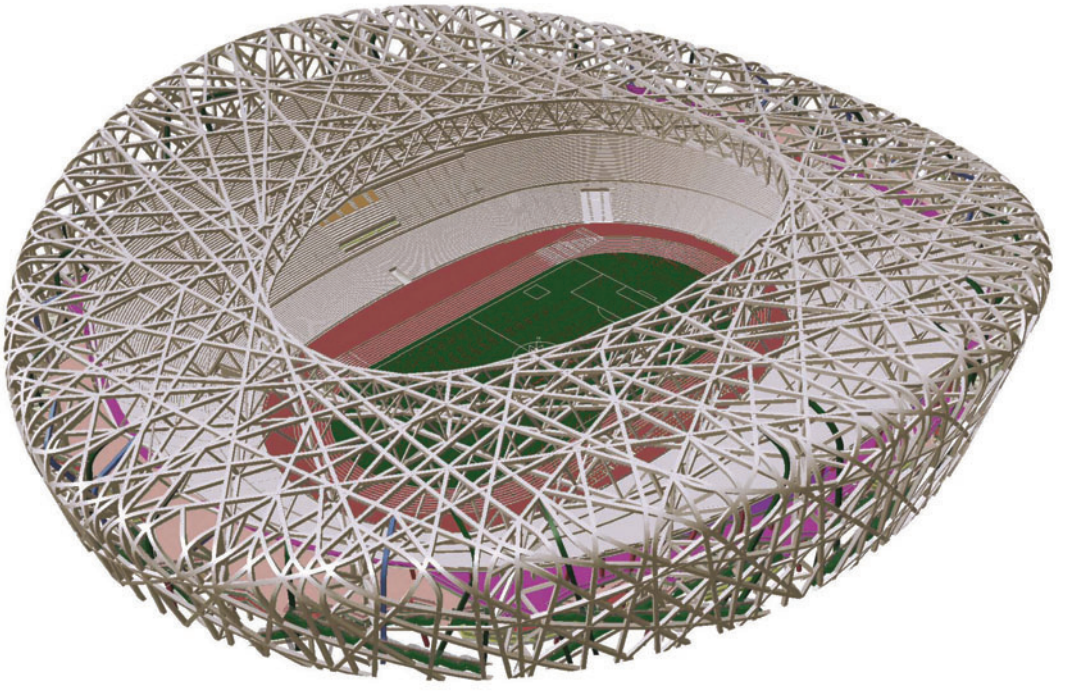

Figure 2.2
The perimeter steel structure wraps around the inner concrete bowl (Arup).

into six structurally independent segments separated by 200 mm-wide gaps for seismic and thermal movements. These structures are frame structures, consisting of beams and columns interconnected by rigid joints. Lateral or horizontal loads arising from wind and earthquake are mainly resisted by structural walls forming the two lift cores of each segment. The roof is clad by two tension membranes supported by the perimeter and roof steel structure. An outer transparent ETFE single-layer provides weather protection to the stands, while a lower PTFE membrane offers shade and improved acoustics.

The perimeter steel structure defines the extent and shape of the building as it wraps around it (Figure 2.2). However, unlike most stadiums with exposed structure, from most vantage points both outside and within the structural rationale, if any, is not at all apparent. How does this chaotic assemblage of inclined members that become curved tangles at roof level possibly constitute a roof structure? How can such an apparently irrational configuration of structural members provide a roof that cantilevers over 40 m from its perimeter to the edge of the internal opening? Is this a case where so much structure is thrown into a building in the absence of structural rationality that highly sophisticated structural engineering analyses indicate the structure will somehow stand up? The answers to these questions can hardly be answered without recourse to engineering drawings. They reveal a most unexpected yet conceptually simple structural solution (Figures 2.3 and 2.4).

Perimeter structural chaos effectively conceals a series of twenty-four symmetrically positioned portal frames. Portal frames, just one level of complexity beyond the most basic of structural systems, the post-and-beam, are responsible for supporting the whole roof. Their presence is even more

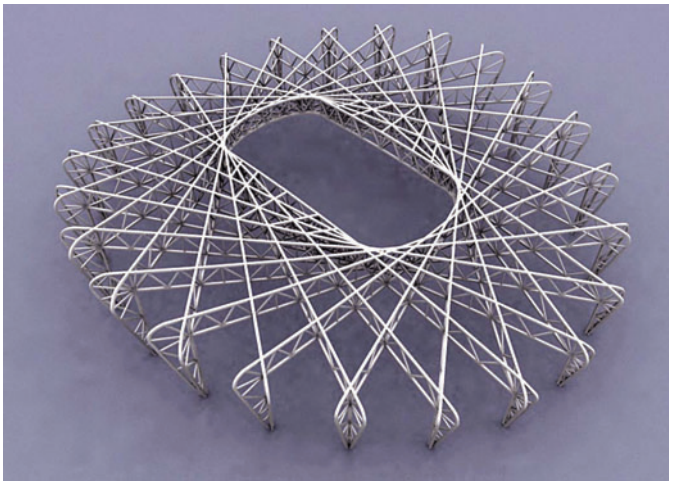

Figure 2.3
A physical model of the perimeter steel and roof gravity-resisting portal frame structure (Arup).

Figure 2.4
The bottom chords of the portal girders can be seen from the seating bowl.

surprising given their general relegation by architects to structure less elegant constructions, like light-industrial buildings. Admittedly, these portal frames are not the normal run-of-the-mill type. Detailed as trusses, and 12 m deep, they interconnect to support each other and form a three-dimensional truss network. Each column, V-shaped in plan, deepens from a pin joint at its base to reach the 12 m depth before bending over to become a portal frame girder (Figures 2.5 and 2.6). This is the roof structure, designed for gravity loads, vertical loads from wind, and earthquake loads.

The horizontal load resistance of the free-standing perimeter and roof structure is also another puzzle inviting resolution. Damage to the portal frames must be prevented during a large earthquake. The stability of the whole roof structure cannot be jeopardized. And yet there are no visible shear walls, bays of conventional cross-bracing or obvious moment frames – the three most conventional seismic force-resisting systems. However, we can discern within the irregularity of the layout of façade members patterns of triangulation, albeit not from any textbook. This irregular triangulated structure, which seems to be a consequence of structural randomization, provides sufficient strength and stiffness to satisfy the demanding engineering design criteria.

Structural elements visually dominate the exterior of this building by their random and dynamic arrangement. Rather than relying upon monumentality conferred by massive structural walls or columns, the modestly sized members exude expressive qualities due to their geometrical configuration. At least on the outer structural layer no vertical nor horizontal members are found. Orthogonality has been

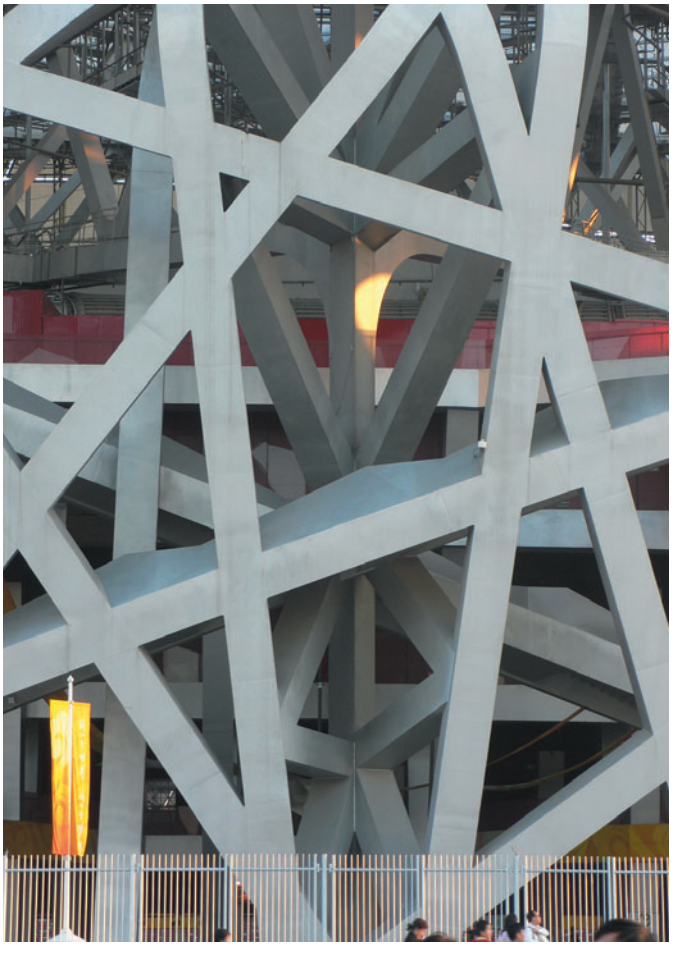

Figure 2.5
A view of a V-shaped truss-column near its base.

Figure 2.6
Horizontal and diagonal members of portal girders are visible beyond the upper curved structure.

Figure 2.7
Columns supporting the concrete bowl are also inclined.

banished entirely from the perimeter structure, but it is still able to fulfil its load-bearing roles (and others). For example, its bewildering number and orientation of members act to screen the seating bowl, whose visual presence is enhanced by red-painted exterior surfaces. The 'screen', up to 12 m deep, is also very porous, if not welcoming. A lack of perimeter structural barriers means there can be many possible entrances.

A potential danger of expressing such dynamic perimeter structure is that more conventional interior structure, by comparison, could be considered an anticlimax. This has been avoided by the inclination of columns around both the perimeter and inner edges of the concrete bowl (Figure 2.7). Steel and concrete members speak the same dynamic language so there is no aesthetic disjuncture between these two structures.

As well as the perimeter structure functioning as a fully load-bearing assemblage and an expressive façade with screening qualities, it hosts most of the stadium's vertical circulation in the form of stairs. The stairs are integral with the least-inclined sloping members which conceal them from view (Figure 2.8). As they rise, the stairs snake around and through the structure. This strategy of embedding circulation within the structural width or depth is observed in other buildings too, such as the Sainsbury Centre, whose perimeter structure along its sides provides space for stairs and other functions (see Figure 5.12).

One of the architectural characteristics of the exposed steel structure that requires comment is its detailing: that is, the form and finishing of the structural members and their

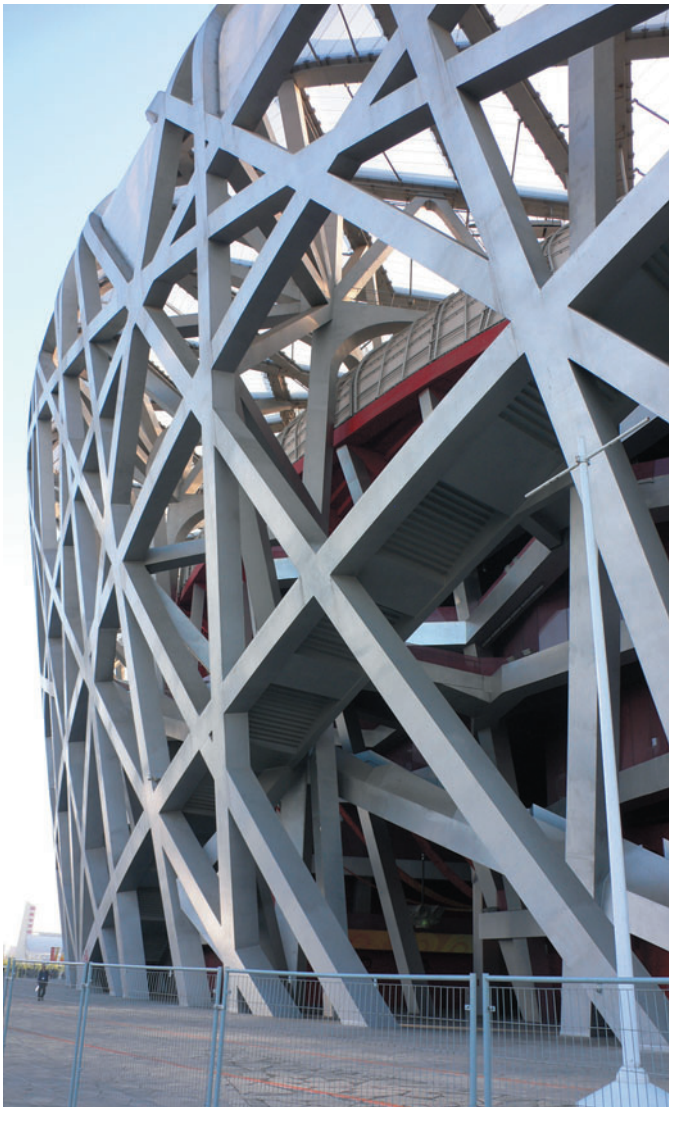

Figure 2.8
A flight of stairs with a visible soffit fully integrated with an inclined perimeter member.

connections. The most significant aspect of detailing is that all exposed members, square steel box sections, have the same external dimension of 1.2 m × 1.2 m. The tremendous variation in forces within members is economically accommodated by adjusting the wall thicknesses of the sections. Plate thickness varies from 10 mm to 100 mm, but the resulting variation in strength is not apparent.

So, not only is there no visual hierarchy of strength or structural importance in the structural members, but since every member, whether primary, secondary or tertiary, has the same dimensions, there is no structural hierarchy *at all*.