on span and space

exploring structures in architecture

Bjørn Normann Sandaker

On Span and Space

Using materials and structures to form the guiding principles for architectural knowledge, *On Span and Space* offers an understanding of architecture from the consideration of how architectural works are actually put together.

The physical way our houses and buildings are constructed greatly influences their appearance and the way they are experienced. Today, the challenges for architectural engineering come from the new and increasing complexities of architectural concepts of space. With an increasing number of building materials as well as ever more refined manufacturing technologies, architecture can be expected to become more structurally complex, displaying a wider range of forms and geometries.

Formulating and discussing the main requisites for structural form in architecture, *On Span and Space* brings together concepts from both of the disciplines of architecture and engineering. The book is structured in three parts, each presenting a unique approach: it moves from a philosophical consideration of the ways and means of approaching structures in architecture, to discussing mechanical aspects of structural form – structural materials, structural efficiency and structural scale – to a final focus on an aesthetics of the structures of architecture, based on how beams, columns, arches and other structure types act spatially and mechanically in forming features of works of architecture.

An important text for any student, lecturer or researcher in architectural engineering, architectural design, history or theory, architectural or building technology and structural mechanics, this book provides for the first time both architectural and engineering areas of wisdom united in one theory which allows for a thorough understanding and solid knowledge base for one of architecture's most central means of expression.

Bjørn Normann Sandaker is Professor of Architectural Technology at the Oslo School of Architecture and Design in Norway. For over twenty years he has specialised in the crossover discipline of structural design in architecture, teaching undergraduate and postgraduate courses in which structural mechanics are taught alongside studio work for architectural design.

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Front cover The Nordic Pavilion, Venice (1962). Architect Sverre Fehn, structural engineer Arne Neegård.

To Wenche, my dear wife,
and Victoria, Nicolay and Sophie,
the loveliest of children

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Preface and acknowledgements

Today, the challenges for architectural engineering come from the new and increasing complexity of architectural concepts of space. Technology is rapidly changing and traditional design ideals seem to be losing ground. Now that traditional materials like steel and reinforced concrete can be adapted to virtually any structural form, the current problem is not how to implement the paradigms of structural efficiency and honesty but, rather, how to recognise structural qualities. In this book I shall ask on what basis can we establish a new critique that can appraise structures both as mechanical systems and as expressions of architecturo-spatial intentionality, both as *techne* and *telo*s.

My formulation of problems in this book is the outcome of years of experience teaching structural design at schools of architecture, and of being a consultant to practising architects. My primary objective is to help raise the discussion of the design of structures in architecture to the level of a professional discourse. My main strategy is to try to establish a dialogue between theoretical disciplines and the practical knowledge held by the professions involved, namely engineering and architecture.

I would like to thank the Oslo School of Architecture and Design for their continued encouragement, as well as for giving me the opportunity to reflect on matters which interest me greatly. Of the many people who have helped me, I will mention only very few. For giving me precise advice at a crucial moment during the writing process I would like to thank Dr Bill Addis. He is exceptionally well qualified in the subjects this book deals with; his comments have been invaluable. I want to express my sincere thanks, also, to Caroline Mallinder at Taylor & Francis, whose trust in me has made this book possible. Her support, advice and great patience – and that of her assistant Georgina Johnson – have been hugely important to me. How easy it is to miscalculate the time needed to do all the work in presenting a manuscript! Likewise, I want to thank David Williams of The Running Head, who has made my manuscript into a book. My cooperation with him on both text and pages has been both interesting and stimulating. I am exceptionally pleased with the result. My sincere thanks also go to A. Espen Baerheim, student of the Oslo School of Architecture and Design, for making all the drawings and for producing the electronic images. Without him taking charge of those, I would hardly have been able to concentrate on all the rest.

Lastly, many thanks to my family, who have shown great patience and understanding throughout the long gestation from idea to finished book.

Bjørn Normann Sandaker, Oslo, 23 February 2007

PART 1

PHILOSOPHY

Fundamental aspects of structures

To understand the role and rationale of structures in architecture we need to look at their individual details. This requires some theorising in order to establish a solid footing from which we can develop deeper insights. My intention is to present first a brief but foundational philosophy of structures. My initial attempts to understand, then, will not be restricted to the study of specific empirical evidence but will look at load-bearing structures in general. What are structures? What conditions influence their making, shape and appearance, and why?

Defining structures

In this context, 'structure' means a physical object or a system of material elements necessary for enabling people to cross a river, to lift goods, to enclose a certain space and numerous other functions. These functions always involve the keeping of materials up in the air, resulting in a continuous struggle against gravity. The primary reason, of course, for the existence of structures is the practical purpose they serve. By serving those purposes the logical outcome is that structures have to 'transport' loads from the point of their origin and down to the ground. Structures become load-bearing. This is the natural order of the relationship between the 'why' and the 'how', or reason and consequence: practical purpose comes first, and physical necessity follows.[1]

Offering a definition, however, of the notion of structure solely by stating its purpose does not really answer the question: what is this object that serves a practical function by transporting loads to the ground? Many writers on the subject are content with an operational description, but a notable exception is Daniel Schodek, who suggests a more elaborate but slightly abstract definition. A structure is, he says, 'a physical entity having a unitary character that can be conceived of as an organization of positioned constituent elements in space in which the character of the whole dominates the interrelationship of the parts'.[2]

With the help of this fairly complex definition, Schodek is able to make clear some important points. First, structure in our context is a real physical object, not a kind of abstract organisation. Also, the structure is subjected to gravitational forces as well as to other loads, and will respond to those according to its geometrical configuration and material properties. Furthermore, Schodek's suggestive definition emphasises that a structure functions as a whole: beams, struts, ties, columns or whatever are parts of its constituent elements; they work together and influence each other's physical behaviour. That they should do so is a

1.1 Anthony Caro, *End Game* (1971–4), exhibited at Trajan's Markets, Rome, 1992. The sculpture is readily understood as structural, and can act as a metaphor for architecture.

necessary condition for speaking of a structure at all. A clarification that should be made, however, is that we should think of the word 'character' in terms of physicality and concreteness rather than appearance or aesthetics. The structure does not necessarily have to be designed in a way that its form is *perceived* as having a unitary character, or that the character of the whole dominates the way the parts relate visually to each other. Moreover, in order to keep in mind the operational purpose of the structure, we need to supplement our definition with a reference to the load-bearing function. With these qualifications, however, there should be no problem adopting the definition as offered by Schodek.

What is, then, the purpose or function of a load-bearing structure? 'The function of a structure', Macdonald says, 'is to supply the strength and rigidity which are required to prevent a building from collapsing.'[3] None will disagree with this. Yet if we are considering structures in an architectural context, this statement suggests only the minimum solution to the question of function. That the structure is designed to prevent the collapse of a building is the very least we should expect from it. Engineering is able to solve the most basic requirements, but luckily it leaves the door wide open for making the structure even more momentous. In many cases in architecture, structures are not solely associated with their load-bearing function. In architecture, there is traditionally a very close relationship between structure, architectural space and expression, so that a characterisation in terms of the load-bearing function alone is not enough. Understanding structures will frequently also mean that we see structures as space-defining elements or as devices that control the inflow of daylight; or we may assign them numerous other functions that are required of architectural spaces. Structures serve many purposes; it is important that we keep this in mind, not only for our understanding of structural form in architecture but also for a judicious and illuminating critique of a particular structure.

Generally speaking, we will look at structures that form parts of a work of architecture, as opposed to structures for machines, cranes or aircraft. Since there are obvious difficulties in trying to delimit the field of architecture, we shall keep this part of the definition as open as possible. The main point is that structures in architecture are conceived – and perceived – differently from structures in other contexts. In the integral relationship that exists between structures and architectural spaces certain issues surface which help to characterise those structures, and which differentiate the structures of architecture from structures of other kinds. I will elaborate on those issues in the following chapters.

The relationship between architecture and one of its prime constituent elements, structure, was not always as multifarious or diverse as it is today. In contemporary architecture, structural elements or systems can play a major role as an organiser of the space or as a means for expression – or no role at all, depending on the architect's preferences. It was not always like that: Greek classical architecture depended upon its beams and columns for expression. Proportion, dimension and a refined articulation of form were all related to the structural elements, as was the rich vocabulary of ornamental treatment of primarily structural details and structural connections. This was originally a constructive art where structural elements had both a technological as well as a more abstract and expressive purpose. During the Renaissance this classical inheritance was taken up and looked upon anew. While structural elements were still a prominent part of the architectural vocabulary, they became subordinate to aesthetic and symbolic systems developed from contemporary ideals and theories on universal proportions. Still, expression was linked to construction.

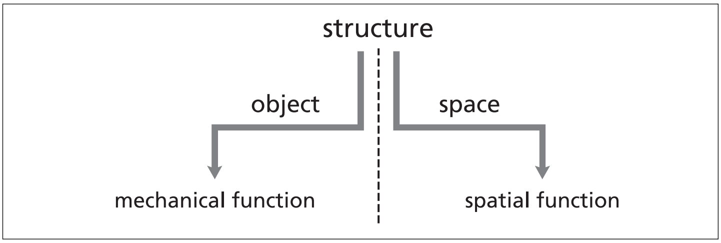
With the advent of modernism, things changed. Auguste Perret and particularly his assistant Le Corbusier made a rhetorical point of separating constructive elements from functional/expressive elements. Even though this was a well-known principle at the time, not least among the architects and engineers of the Chicago School, Le Corbusier advocated it in his role as architectural ideologist. In his Dom-Ino concept the structure has virtually been emptied of any meaning except the purely technical. Architecture could now be seen as two autonomous systems, the purely structural and the purely aesthetic. While the structural system had been reduced to a question of technicalities, the aesthetic system was raised to a kind of abstract, formal composition that included the free plan, the free façade, and a play of surface texture and colour.[4] This ideal inherited from the early modernists is very much present in contemporary architecture too, but is (fortunately) not always the guiding principle. Here we will not pay particular attention to the purely technical aspects of structures. Those are not the kinds of structures I have in mind when we explore the structures of architecture. At least, they are a special case. The skeleton structures of that type have a fairly simple logic: they are products of technical and economic optimisation. *The characteristic feature of the structures I want to look at is that they are somehow part of architectural expression, and influence – or are influenced by – the architectural space.* I would like to see building structures as architecture, or at least as parts of an architectural composition. To be able to understand such structures fully requires the mobilisation not only of scientific and technological knowledge but also architectural competence and sensibility. The concept of technology itself takes on a slightly different meaning in this situation, because existential aspects like 'memory and time are legitimate aspects of an architectural technology that pure engineering technologies do not encompass'.[5] Thus historical references as well as visual representation may both form parts of a structural vocabulary.

Closely linked to the problems of definition is the problem of sorting out the objects of interest (the structures) from the architectural work as a whole. Where does the structure begin and end? The example of a dome is a case where delimitation could prove difficult. Even though a dome is easily identified as a form or *gestalt*, the structure of the dome does not necessarily correspond entirely to this form, but also involves abutment walls and foundations. Such walls are almost certainly also parts of other architectonic configurations. Similarly, a skeletal structure is relatively easy to identify and define as a separable, structural entity, while a solid wall structure defies such a clear-cut and purely structural identification. In the case of a three- or four-storey brick building, the load-bearing structures are also the same objects, or walls, that enclose the interior architectural space. In this case, then, both the physical delimitation of space as well as the support function are aspects of the same objects. From one point of view the walls are enclosures and have spatial properties, while from another the same walls need to be considered as load-bearing devices. Typically, structures in architecture are assigned different functions and take part in complex physical and spatial relationships. We will need to identify those in order to bring the discussion further.

Aspects of structural form

If the purposes of structures are indeed multifarious, their identification and definition really depend on where we direct our attention. If the load-bearing element is the same physical object as the space-enclosing element, we can certainly follow more than one line of reasoning to explain its form properly. Structures in architecture, where they are integral parts of architectural spaces, can only be understood by applying different kinds of knowledge. When we look at a wall we should be able to say whether or not this particular wall is load-bearing – that is, if it is really a part of the structure. If it is, we can comment on the form of the wall – its thickness, the number and size of its openings, its

1.2 Solid timber walls both bear loads and delimit the architectural space. Architects Brendeland and Kristoffersen, engineers Reinertsen AS: low-cost housing (2004), Svartlamoen, Trondheim, Norway.



1.3 The main functions of structures in architecture concern mechanics and space.

connections to other building components – on the basis of its function as a supporting element. To do this with any precision we will have to know about the properties of the actual material, its strength and its general behaviour when loaded. We also need to know, at least in general terms, how loads can be transferred through matter. The concepts and laws of the mechanical sciences can help us understand these kinds of problems. The form and proportions of the wall may hence be partly explained by how this wall behaves when subjected to external, physical influences, to loads. We would also expect to find that the particular shape and texture of the wall in some way reflects the making process: the treatment of the raw material, the manufacturing as well as the construction of the wall itself. The latter is the technological aspect. Consequently, the wall may be helpfully – but not fully –interpreted from a technologico-scientific point of view. Such characteristics defined by the natural sciences and technology will be referred to as the mechanical aspects of structures. I will refer to them when addressing the structures' *mechanical functions*.

On the other hand, the same wall may also be intended to close off or visually delimit the architectural space, and thus have a practical purpose other than the role of support. This purpose, referred to here as its *spatial functions*, may easily influence some of the properties of the wall such as thickness, shape and openings. Even if architectural elements have a load-bearing function, their form must also be interpreted with reference to their spatial use. Some might choose not to speak of *structural* elements in such cases, but how is one to distinguish one from the other? As long as an element has several architectural functions, including the support function, then all we can do is to distinguish between aspects of that form according to the different points of view from which they can be studied. If an understanding of structural elements is the aim, we need to look at them in their full, including spatial, context.

We can see how the load-bearing function makes it necessary to consider the structure as an object in its own right, whereas issues concerning utility functions relate structures to questions of the architectural space. We will hence look upon structures as mechanical objects as well as spatial objects that constitute vital elements of architectural spaces. This *object versus space* duality of structures in architecture makes them particularly interesting to design and to study. Any architectural analysis of structural form should therefore take into consideration the two main

1.4 Two extreme structural opposites: one is expressive and relates to the space – a work of art. The other represents pure utility – a crane. Both have to comply with a set of mechanical requirements, enabling them to remain standing. Sculpture in Rotterdam by Coop-Himmelb(l)au and Rotterdam harbour.

aspects of structures: that structures have both a mechanical as well as a spatial function. By considering structures from both viewpoints we can begin to understand fully the complexity and richness of form and expression that characterises structures in architecture.[6]

To illustrate how an aspect-based approach can be applied to an architectural analysis focusing on structures, we shall take a look at the National Gallery in Parma, Italy. The so-called La Pilotta museum (1986) was designed by the architect Guido Canali.[7] Among many other items, a number of heavy stone sculptures are exhibited, some on a white-painted steel frame. An important *spatial function* of this structure is of course the very simple one of keeping the sculptures in an elevated position so that the public can see them properly; at the same time, the space and the floor area underneath the sculptures are left open. The choice of structural form reflects both functional intentions. However, the deci-

1.5 Heavy stone sculptures raised on a light structural frame. Architect Guido Canali: The National Gallery ('La Pilotta') (1986), Parma, Italy.

sion to support all four stone sculptures by only one structural frame – rather than to bring each one directly and separately down to floor level – must be interpreted in light of the architect's wish to keep the floor space free of obstruction. Both refer to the spatial *utility* aspect of the structure. An interesting feature of the structural detailing, moreover, is that it actually consists of two separate frames. The size of the sculptures' bases are so large that the supporting structure needs to be wide enough for the sculptures to be balanced. The architect secures their stability by splitting the frame into two parallel halves put relatively close together, and makes sure the sculptures are resting on both.

This particular design decision reflects both the structure's practical use and the importance of its relation to architectural space. The introduction of two parallel frames instead of one makes the cross-sections of the frames significantly smaller. Visually, the result is that the structure appears lighter and thus presents an effective contrast to the heavy stone sculptures. In fact, we can recognise an architectural intention if we consider the structure part of the architectural space, heightening our experience of the space itself. This is achieved by the use of contrasting materials and by different forms of visual expressiveness that counterpose lightness and weight. The sculptures and the existing building fabric both visually outweigh the new steel structure and thus appear more perceptually distinct. All three establish a unity of relationship between structure and constructed room with its contents, between span and space. There is a striving here for some sort of spatial coherence where the structure and the space are both meant to form parts of the same context. What we may term *contextuality* (structural form in its architectural and spatial context) is an important aspect of structural design, and one we need to take into consideration if we are to understand the structures of architecture in clarity and depth.

To assert there is a relation between structural form and spatial intentions does not necessarily infer the relationship is harmonious. Indeed, some structures in architecture are best understood by admitting that there are other kinds of relationships than mere 'harmony between the structural system and the architectural form'.[8] Yet 'an important aspect of the art of architecture is to choose a structural strategy that will be in some sort of accord with the intended spatial organisation'.[9] Some sort of coherence between the structure and the space should be identifiable, but it may take many forms.

We may observe that the ability of structures to carry loads is based on the mechanical and geometrical properties of the structural frame, as well as the strength and elasticity of its materials. The frame is able to carry the loads acting on the beam and, through its vertical members, to transport those loads to other more rigid parts of the building. Horizontal stability is secured by the rigidity of the frame (with help from the adjoining walls). The size and shape of the structural members, as well as their strength and elasticity, need (obviously) to be adequate to avoid collapse or undue deformation. The mechanical *sciences* (notably statics and the science of materials) offer some of the available explanations for this particular structural form. By applying theory from these fields, aspects of the structural form become explicable as mechanical features. Those explanations do not point to *a* specific design solution but help to identify one possible candidate among many others. Facts derived from thinking based on mechanics will rule out, in principle, a range of other design proposals, and will help clarify why a particular solution was chosen.[10]

Next, if we direct our attention to Canali's white-painted, scaffolding-like structure spanning the width of the old palace almost at roof level, we will be able to identify more detailed aspects of structural form. This particular structure's main utility functions are obviously to establish

1.6 The National Gallery, Parma. Interior view with the structures of the additional exposition area hovering above.

1.7 The National Gallery, Parma. Structural details.

elevated floors as additional exposition areas in the generous space of the converted palace, as well as to provide an adaptable structural framework which supports (or from which is suspended) a modular panelling system for the display of paintings. We can interpret the structure even better, however, if we look at aspects of its representation: by employing a structural system normally found on construction sites, recognisable by its clumsy but effective mechanical detailing, the structure in some respects looks like tube and clamp scaffolding. This associative likeness is clearly intentional; by noticing it we are helped towards a better understanding of this particular structure. In addition to the many practical functions of structures we may also thus assign a representational or an *iconographic* function.[11] This makes possible an