# On Span and Space

## Exploring structures in architecture

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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

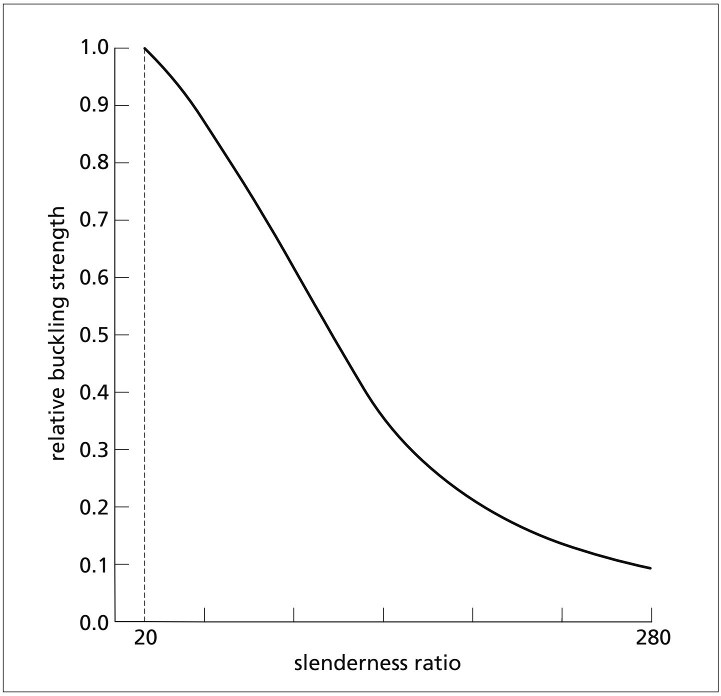
**1.1** Anthony Caro, *End Game* (1971–4), exhibited at Trajan's Markets, Rome, 1992. The sculpture is readily understood as structural, and can act as a metaphor for architecture.

**2.15** Sawmill at Tunhovd, Norway.

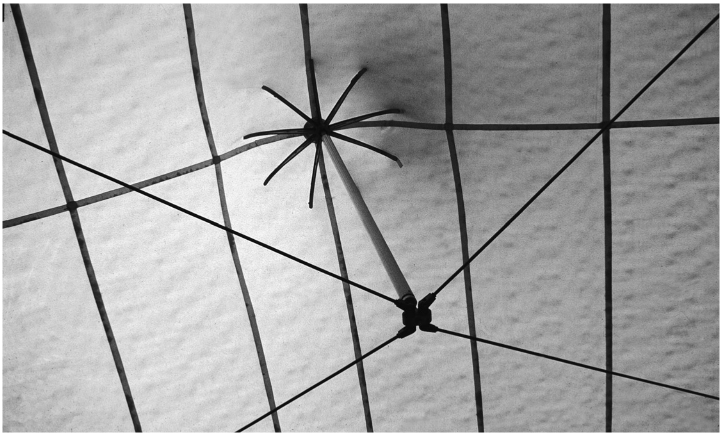
**2.16** Structures. Architects Foster Associates, engineers Ove Arup and Partners: the Century Tower (1991), Tokyo.

**2.17** Detail. Sawmill at Tunhovd, Norway.

**2.18** Detail. The Century Tower, Tokyo.




**2.43** A diagram of theoretical buckling strength versus slenderness ratios for steel.



**2.44** Short, efficient compression struts with a modest slenderness ratio supporting an efficient and form-active membrane structure. Architect Ron Herron: Imagination Headquarters (1990), London.

For slender compression members there is another effect related to buckling that affects efficiency: a subdivision of a compression force by using more members means increased structural weight. This is because each compression member can only support a portion of the total load restricted by the buckling load of each individual member, and a subdivision increases the slenderness of each member. We can therefore state as a fourth requisite for efficiency that:

*Structures are most efficient when a subdivision of compression forces is avoided.*

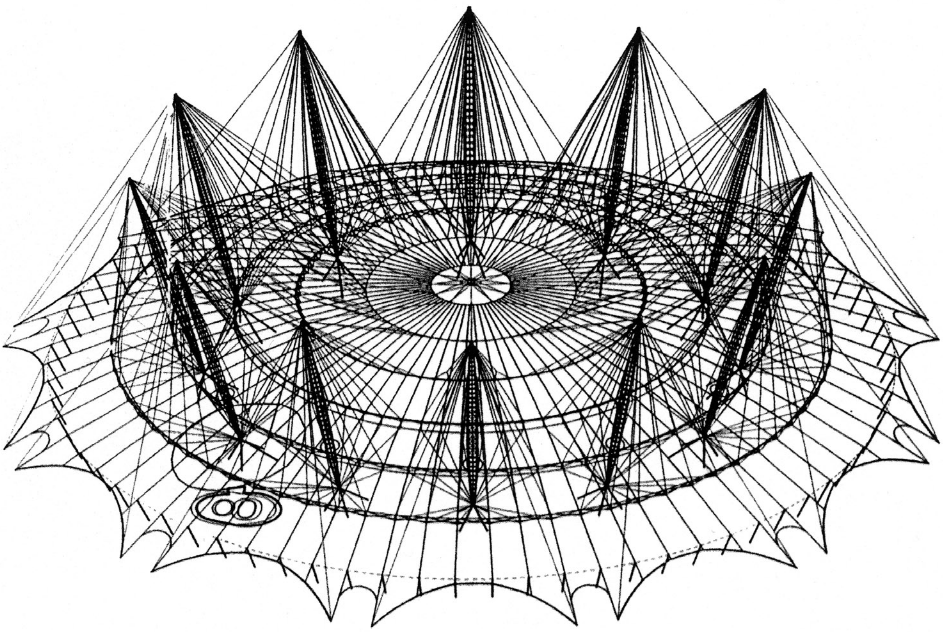
2.45 A group of slender columns with no local bracing. Architect Zaha Hadid, engineers Ove Arup and Partners: the Vitra Fire Station (1993), Weil-am-Rhein, Germany.

The effect of subdivision can easily be calculated. We will find that the use of n slender compression members to resist a certain load leads to a weight increase by $\sqrt{n}$ relative to that of a single member. It should be made clear, however, that this is only correct if the members dividing a force between them are not connected to each other along the length in a way that the buckling stability of the group of members is increased. Likewise it should be pointed out that the relationship noted above only considers the weight of the actual compression members, and does not say anything about the consequences for the structure being supported by one or more compression members.

Up to now, we have looked at form-active structures and structural members subjected to axial forces and comparing them as means of global structural efficiency. Most structures in architecture, however, are not form-active, but semi- or non-form-active. Those are structures that usually work by a combination of axial forces and bending or by bending alone. The extent to which semi-form-active structures are globally efficient will depend on the level of bending stresses in relation to the level of axial stresses in the system. The closer they are to form-active principles, the more efficient they are. However, for all types of semi-form-active or non-form-active structures, and also compressive form-active structures where buckling is of relevance, there is obviously a reservoir of efficiency inherent in the principle of changing the form of the element along the length. We may formulate a fifth requisite for structural efficiency which contributes to local structural efficiency:

ing the global form of the present structure. This 'dome' needs twelve masts 100 m high to stand up, masts which clearly perforate its surface. If we look at the structure, then, from the point of view of its global form and with a mind to the relationship between form and materials, the experience is certainly not one of appropriateness. The global shape of a spherical dome does not go well with the tensile materials we in fact observe, and the huge, protruding masts seem alien to the overall, dome-like shape. What looks like point-loading on the domed surface from those masts is particularly disturbing. A basic problem resulting from the choice of global, structural shape is also that the radial cables necessarily become straight between their points of support from hangers. Between each cable, the fabric surface is thus also straight. Hence both cables and glass-fibre fabric carry loads transversal to their natural line of forces, resulting in considerable deflection. Both cables and fabric need to deflect to be able to carry those loads. To restrict the deflection, the radial cables are pre-stressed by 400 kN, using up as much as 70% of their ultimate strength before external loads even act on the system.[109] This gives us a numerical expression of the difficulty of letting straight tension members form into what is fundamentally a compressive, global form.

Is there really a problem here? That depends on what we are looking for. In terms of engineering success, measured by parameters like structural weight-to-span ratios, construction time and cost, the design decisions made for the Millennium Dome are probably both rational and appropriate. The Dome's chief claim to innovation, however, lies primarily in a structural strategy that seems to offer a rational construction of a huge space. The Dome's structural aesthetics in fact do not



**3.21** The Millennium Dome. Isometric drawing of the cable net.

**3.22** The Millennium Dome. Structural details.

**3.23** The Millennium Dome. Cable net before the textile covering was put on.