thorough assessment of a structure, is its durability. Both the durability properties of the individual constituent materials and the durability implications of combinations of materials must be considered. In some cases, where a structure will be subjected to a particularly hostile environment, the question of durability will be given a high priority at the design stage and will affect both the choice of material and the choice of form. More often, choices will be dictated by other criteria – such as span and load – and the question then to be answered is whether the material has been used sensibly. If, for example, the material selected is steel, which, in its unprotected state is one of the least corrosion-resistant materials, the problem of durability should be recognised. This would mitigate against using steel exposed on the exterior of a building, especially in humid climates.

The structure should be capable of fulfilling the function for which it is designed throughout the intended life of the building, without requiring that an unreasonable amount of maintenance be carried out on it. This raises the question of what is reasonable in this context, which brings us back to the question of economy of means and relative costs. So far as durability is concerned, a balance must be struck between initial cost and subsequent maintenance and repair costs. No definite best solution to this can be specified, but an assessment of the implications for durability must form part of any serious assessment of the merits of a structure.

6.3 Reading a building as a structural object

The idea that structural criticism should be an aspect of the standard critical appraisal of a work of architecture requires an ability, on the part of the critic, to read a building as a structural object. The classification system proposed in Chapter 4 provides a basis for this. The system is based on a categorisation of elements according to structural efficiency. As has been discussed in Section 6.2, the measure of a good structure is not that the *highest* level of structural efficiency has been achieved, but that an *appropriate* level has been achieved. The judgement of the latter can only be made from a position of knowledge concerning the factors which affect efficiency. A few examples are now considered to demonstrate the use of the system for the appraisal of structures.

The Forth Railway Bridge[4] (Fig. 6.6) is a spectacular example of a work of more or less 'pure' engineering which makes an appropriate beginning. Although the general arrangement of the bridge may seem very complex, it may be seen to be fairly straightforward if visualised in accordance with the concepts of 'form-action' and 'improvement'. The principal elements of this structure are paired, balanced cantilevers. This configuration was adopted so that the bridge could be constructed without the use of temporary supports. The structure was self-supporting throughout the entire construction process. The cantilevers are linked by short suspended spans, a clever arrangement which allows the advantages of structural continuity to be achieved in a discontinuous structure[5].

The arrangement was therefore non-form-active and potentially inefficient. Given the spans involved, extensive measures were justified to achieve an acceptable level of efficiency. These took several forms: the profile of the main structure was made to conform to the bending-moment diagram resulting from the principal load condition (a uniformly distributed gravitational load across the whole structure) and the internal geometry of this profile was fully triangulated. The rail tracks were carried on an internal viaduct – itself a

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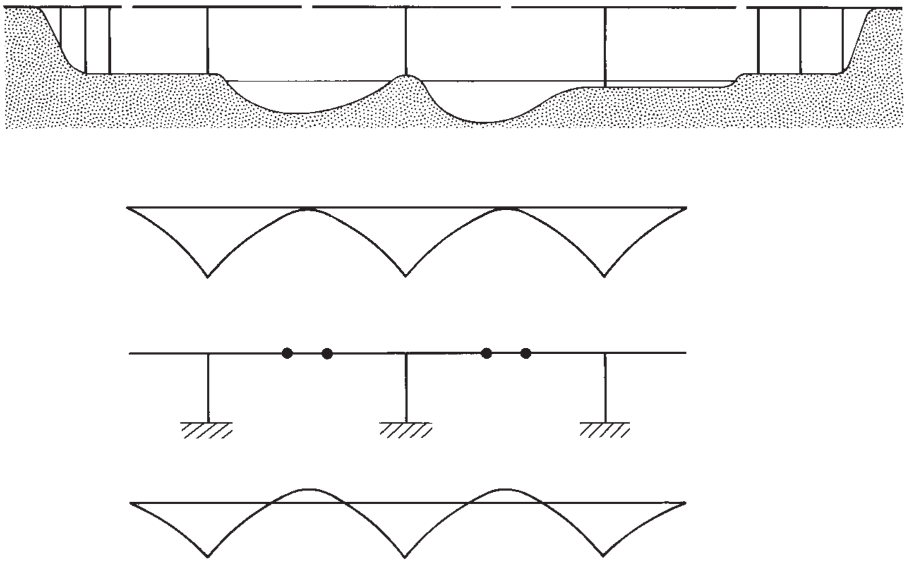
[4] See Macdonald, Angus J. and Boyd Whyte, I., *The Forth Bridge*, Axel Menges, Stuttgart, 1997 for a more complete description of the structure and discussion of its cultural significance.

[5] See Section 5.1 and Appendix 3 for an explanation of the terms continuous and discontinuous structures.

Fig. 6.6 Basic structural arrangement of the Forth Railway Bridge, Firth of Forth, UK. This structure is a post-and-beam framework but, as with the Renault Headquarters (Figs 3.19 & 6.8), it has been ‘improved’ at various levels. There is more justification for the complexity in this case due to the large span involved. (Photo: A. & P. Macdonald)



non-form-active structure 'improved' by triangulation – which was connected to the main structure only at the nodes of the triangles. Thus, the principal sub-elements of the structure carried either direct tension or direct compression. The individual sub-elements were given 'improved' cross-sections. The main compression sub-elements, for example, are hollow tubes, most of them with a cross-section which is circular, which is the most efficient shape for resisting axial compression. Thus, the structure of the Forth Railway Bridge has a basic form which is potentially rather inefficient but which was 'improved' in a number of ways.

The most common structural arrangement in the world of architecture is the post-and-beam form in which horizontal elements are supported on vertical columns or walls. In the most basic version of this, the horizontal elements are non-form-active, under the action of gravitational load, and the vertical elements are axially loaded and may therefore be regarded as form-active. Countless versions of this arrangement have been used through the centuries, and it is significant that the greatest variations are to be seen in the non-form-active horizontal elements where the advantages to be gained from the 'improvement' of cross-sections and longitudinal profiles are greatest.

The temples of Greek antiquity, of which the Parthenon in Athens (see Fig. 7.1) is the supreme example, are a very basic version of the post-and-beam arrangement. The level of efficiency achieved here is low, and this is due partly to the presence of non-form-active elements and partly to the methods used to determine the sizes and proportions of the elements. The priorities of the designers were not those of the present-day engineer, and the idea of achieving efficiency in a materialistic sense was probably the last consideration in the minds of Ictinus and his collaborators when the dimensions of the Parthenon were determined. The building is perhaps the best illustration of the fact that the achievement of structural efficiency is not a necessary requirement for great architecture.

In the twentieth century, by contrast, efficiency in the use of material was given a high priority partly in a genuine attempt to economise on material in order to save cost, but also as a consequence of the prevalence of the belief in the modernist ideal of 'rational' design. The overall geometry of the inefficient non-form-active post-and-beam form is so convenient, however, that it has nevertheless continued to be the most widely used type of architectural structure. It was normal in the modern period, however, for at least the horizontal elements to have some form of 'improvement' built into them. This was especially true of steel frameworks in which the beams and columns invariably had 'improved' I-shaped cross-sections and much use was made of the technique of internal triangulation.

In the Centre Pompidou, in Paris (Figs 6.7 and 1.10), the basic arrangement of the

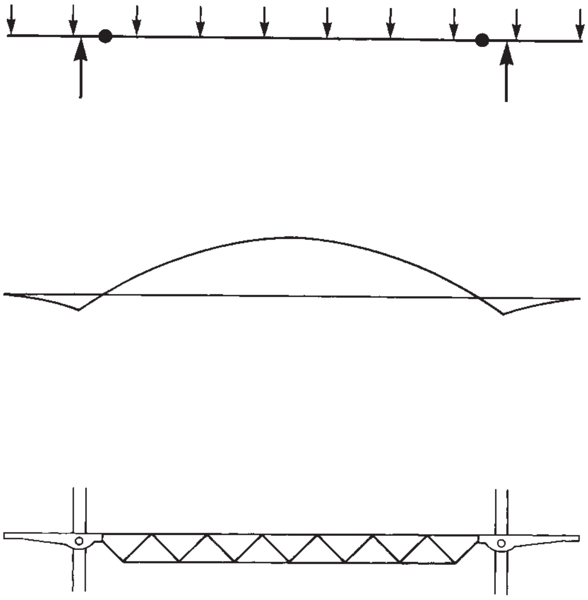


Fig. 6.7 Load, bending moment and structural diagrams for one of the principal elements in the floor structure of the Centre Pompidou, Paris, France. This is a non-form-active beam but the relatively long span involved justified the incorporation of 'improvements'. Height restrictions prevented the matching of the longitudinal profile to the bending moment diagram, except in the cantilevered 'gerberette brackets' at the extremities of the structure. Triangulation was the only form of 'improvement' which was feasible here for the main element (see also Figs 1.10, 3.17, 7.7 and 7.8).

structure is such that all of the horizontal elements are straight, non-form-active beams and this configuration is therefore potentially very inefficient. The triangulation of the main girders and the use of 'improved' shapes in cross-section and longitudinal profile of the cantilevered gerberettes (see Fig. 3.17) compensates for the potential inefficiency of the form, however, and the overall level of efficiency which was achieved may be judged to be moderate.

The framework of the Renault Building at Swindon, UK (see Fig. 3.19), may also be regarded as a post-and-beam frame as the basic form of the structure is rectilinear (Fig. 6.8). The beam-to-column junctions are rigid, however, and provide a degree of structural continuity, so that both horizontal and vertical elements are subjected to a combination of axial and bending-type internal force under the action of gravitational loads. The latter are therefore semi-form-active. Because the basic shape of the structure is markedly different from the form-active shape[6], the magnitudes of the bending moments are high and the structure is therefore potentially rather inefficient. The longitudinal profiles of the horizontal elements have, however, been 'improved' in a number of ways. The overall depth is varied in accordance with the bending-moment diagram and the profile itself is subdivided into a combination of a bar element and an I-section element, the relative positions of which are adjusted so that the bar element forms the tensile component in the combined cross-section and the I-section the compressive element[7]. The circular cross-section of the bar is a sensible shape to carry the tensile load, while the I-section of the compressive part is a suitable choice in view of the need to resist compressive instability, which is a bending phenomenon. The cutting of circular holes from its web (see Fig. 3.19) is another form of 'improvement'. A similar breakdown of the cross-section occurs in the vertical elements, but in these the compressive components are circular hollow sections instead of I-sections. This is again sensible because these components are subjected to a greater amount of compression than their counterparts in the horizontal elements, and the circle is an ideal shape of cross-section with which to resist compression. The choice of basic form, that of a semi-form-active rectilinear framework, is potentially only moderately efficient but, as in the case of the Centre Pompidou, a number of measures have been adopted to compensate

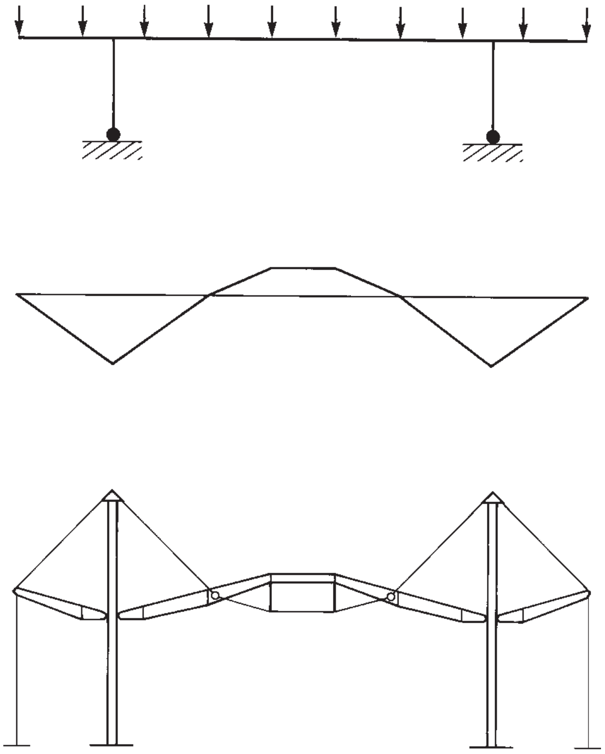


Fig. 6.8 Load, bending moment and structural diagrams of the Renault Headquarters building, Swindon, UK. The basic form of this structure is a post-and-beam non-form-active frame. 'Improvements' have been introduced at several levels: the overall profile of the structure has been made to conform to the bending moment diagram for gravitational load, the structure has been triangulated internally and some of the sub-elements have been further 'improved' by having I-shaped cross-sections and circular holes cut in their webs (see also Figs 3.19).

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[6] The load pattern on the primary structure is a series of closely-spaced concentrated loads. The form-active shape for this is similar to a catenary.

[7] The bar element is sometimes above the I-section and sometimes below, depending upon the sense of the bending moment and therefore upon whether the top or the bottom of the combined section is in tension.

for this. The question of whether an appropriate overall level of efficiency has been achieved in this case is discussed in Section 7.2.2.

'Improvements' to element cross-sections are seen less often in buildings with reinforced concrete structures because concrete is both lighter and cheaper than steel, so there is not the same incentive to achieve even the moderate levels of structural efficiency of steel frameworks. Coffered slabs are used in the Willis, Faber and Dumas building (see Figs 1.6 and 5.19), however, and are examples of 'improved' non-form-active elements in a post-and-beam, reinforced concrete arrangement. Versions of this type of 'improvement' are incorporated into most reinforced concrete structures if the span is greater than 6 m.

These few examples of structural classification serve to illustrate the usefulness of the system described in Section 4.4 as a means of assessing the level of efficiency achieved in a structure. It should never be assumed, however, when judging the appropriateness of a structural design for a particular application, that the most efficient structure is necessarily the best. Even in the case of a 'purely' engineering structure, such as a bridge, other factors such as the level of complexity of the construction process or the implications of the form for long-term durability have to be considered and there are many situations in which a simple beam with a rectangular cross-section – perhaps the least efficient of structural forms – constitutes the best technical solution to a structural support problem. The question to be decided when a technical judgement is made about a structure is not so much one of whether the maximum possible level of efficiency has been achieved as of whether an *appropriate* level has been achieved.

6.4 Conclusion

Any formulation of the criteria by which the merits of a structure could be judged is inevitably controversial. Most people would, however, feel able to agree with the statement that the principal objective of engineering design is to provide an object which will function satisfactorily with maximum economy of means. This is summed up in the old engineering adage that 'an engineer is someone who can do for £1 what any fool can do for £3'.

The assessment of whether or not a reasonable level of economy of means has been achieved involves the examination of a number of different aspects of the design of an artefact. It is principally a matter of being satisfied that a reasonable balance has been achieved between the quantity of material used, the complexity of the design and construction processes, and the subsequent durability and dependability of the artefact. In the context of structural engineering, the achievement of economy of means is not simply a matter of minimising the amount of material which is required for a structure, but rather of making the best possible use of all the material, effort and energy which are involved in its production. Because these factors are interrelated in complicated ways, the overall judgement required is not straightforward.

One measure of the extent to which economy of means has been achieved is cost, since the cost of the structure in monetary terms is related to the total input of resources to the structure. Cost is, of course, almost entirely an artificial yardstick dependent on the current market prices of labour, energy and materials. It is always related to a particular economic culture, but also to the resources, both human and environmental, which a society has at its disposal. All of these considerations are subject to change over time.

It is possible to argue that from a purely engineering point of view the structure which is cheapest constitutes the best solution to the problem of supporting an enclosure. In most cultures the majority of 'ordinary' buildings are in fact constructed in such a way as to minimise cost. The judgement of whether or not a particular structure constitutes good engineering could therefore be made by comparing it to the mainstream of contemporary practice. If it is broadly similar to the majority of comparable structures it is probably well engineered.

By this criterion the standard and ubiquitous portal-frame shed, which is used to house supermarkets and warehouses throughout the industrialised world, would qualify as good engineering and the so-called 'high-tech' supersheds which appeared in the architectural journals in the 1980s would not, and would at best be regarded as expensive toys. It is necessary to bear in mind that what is being discussed here is engineering and not architecture although, in the context of the need to evolve forms of building which meet the requirements of sustainability, these disciplines may have to become more closely related in the future. If there were more contact between these two extremes of building strategy, this might benefit both the visual and the engineering environments.

It must always be borne in mind that engineering is not about image making. It is about the provision of artefacts which are useful. If the problem to be solved is very difficult technically – e.g. a very long span building, a vehicle which must move with great speed or fly through the air, or a structure which supports life in an inhospitable environment – then the object which is created is likely to be spectacular in some way and, if a building structure, may be visually exciting. If the problem is not technically difficult – e.g. a building of modest span – then the best engineering solution will also be modest although it may nevertheless be subtle; if it is well designed and elegant from an engineering point of view it will be exciting to those who appreciate engineering design. Twentieth-century modernists who believed that the 'celebration' of the 'excitement' of technology was a necessary part of all architectural expression applied different criteria to the assessment of structure.