Chapter 6

The critical appraisal of structures

6.1 Introduction

It is said, albeit usually by critics, that creative activity is enriched by criticism. The world of structural engineering, in which a very large number of artefacts are created continuously, is, however, curiously devoid of a climate of criticism, and few engineering structures receive anything like the critical attention which is accorded to even the most modest of buildings. There is therefore no tradition of criticism in structural engineering comparable to that which exists in architecture and the other arts[1].

Design has been described as a problem-solving activity, an iterative process in which self-criticism by the designer forms an essential part. It is with this type of criticism, rather than the journalistic type alluded to above, that this chapter is principally concerned. It is not proposed, therefore, to deal comprehensively here with the subject of structural criticism but simply to identify the technical factors by which the merits of structures may be assessed.

Engineering is principally concerned with economy of means – a structure may be considered to have been well engineered if it fulfils its function with a minimum input of materials and other resources. This does not mean that the most efficient[2] structure, which produces the required load-carrying capacity with a minimum weight of material, is necessarily the best; several other technical factors, including the complexity of the construction process and the subsequent durability of the structure, will affect the judgement of whether or not a structure is satisfactory. Frequently, the technical requirements conflict with one another. For example, as was seen in Chapter 4, efficient forms are invariably complex and therefore difficult to design, construct and maintain.

This dichotomy between efficiency and simplicity of form is a fundamental aspect of structural design. The final geometry which is adopted is always a compromise between these two properties, and the elegance with which this compromise is achieved is one of the principal criteria of good structural design. In the context of architecture it affects the relationship between the appearance and the performance of a structure. The factors on which the nature of the best compromise depends are reviewed here.

6.2 Complexity and efficiency in structural design

A fundamental engineering requirement is that economy of means should be achieved. The

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[1] The controversy over whether or not structural engineering is an art will not be entered into here. This is discussed at length in Billington, D. P., *The Tower and the Bridge*, MIT Press, Cambridge, MA, 1983 and Holgate, A., *The Art in Structural Design*, Clarendon Press, Oxford, 1986. See also Addis, W. B., *The Art of the Structural Engineer*, Artemis, London, 1994.

[2] As in Chapter 4, structural efficiency is considered here in terms of the weight of material which has to be provided to carry a given amount of load. The efficiency of a structure is regarded as high if the ratio of its strength to its weight is high.

overall level of resources committed to a project should be as small as possible. A sensible balance should be struck between the complexity required for high structural efficiency (see Chapter 4) and the ease of design, construction and maintenance which the adoption of a simple arrangement allows. It is the nature of this compromise which must be assessed by the critic who wishes to judge the merits of a structure.

The aspects of structure on which efficiency depends, where efficiency is judged primarily in terms of the weight of material which must be provided to give a particular load-carrying capacity, were outlined in Chapter 4. It was shown that the volume and therefore the weight of material required for a structure is dependent principally on its overall form in relation to the pattern of applied load and on the shapes of the structural elements in both cross-section and longitudinal profile. A basic classification system based on the concepts of form-active shape and ‘simple’ and ‘improved’ cross-sections and longitudinal profiles was described; this allows judgements to be made concerning the level of efficiency which is likely to be achieved with a particular structural arrangement. Form-active shapes such as tensile cables and compressive vaults were seen to be potentially the most efficient, and non-form-active beams the least efficient.

A property of structures which was demonstrated by this ordering of elements is that the higher the efficiency the more complex the form[3]. This is generally the case even when relatively minor measures are taken to improve structural efficiency, such as the use of I-shaped or box-shaped cross-sections for beams instead of solid rectangles, or a triangulated internal geometry instead of a solid web for a girder.

The complicated geometry which must be adopted to obtain high efficiency affects the ease with which a structure can be constructed and its constituent components manufactured, and its subsequent durability. For example, a triangulated framework is both more difficult to construct and more difficult to maintain subsequently than is a solid-web beam. The designer of a structure must therefore balance these considerations against the natural desire to minimise the amount of material involved. The level of efficiency which has been achieved should be appropriate for the individual circumstances of the structure.

It is not possible to specify precisely the level of efficiency which should be achieved in a particular structure, such is the complexity of the interrelationships between the various factors involved. It is possible, however, to identify two main influences on this desirable level, namely the size of the span which a structure must achieve and the intensity of the external load which it will carry. The longer the span, the greater is the need for high efficiency; the higher the level of load which is carried, the lower can the efficiency be. These two influences are in fact different aspects of the same phenomenon, namely a requirement to maintain the ratio of self-weight to external load at a more or less constant level. Implicit in this statement is the idea that, in order to achieve the ideal of maximum economy of means, the level of complexity of a structure should be the minimum consistent with achieving a reasonable level of efficiency.

The effect on efficiency of increasing span is demonstrated in the very simple example of a beam of rectangular cross-section carrying a uniformly distributed load (Fig. 6.1). In the figure, two beams of different spans are shown, each carrying the same intensity of load. The one with the longer span must have a greater depth so as to have adequate strength. The self-weight of each beam is directly proportional to its depth and so the ratio of load carried to self-weight per unit length of beam (the structural efficiency) is less favourable for the larger span.

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[3] The concept of the optimum structure provides further evidence that complexity is necessary to achieve high levels of efficiency – see Cox, H. L., *The Design of Structures of Least Weight*, Pergamon, London, 1965 and Majid, K. I., *Optimum Design of Structures*, Newnes-Butterworth, London, 1974.

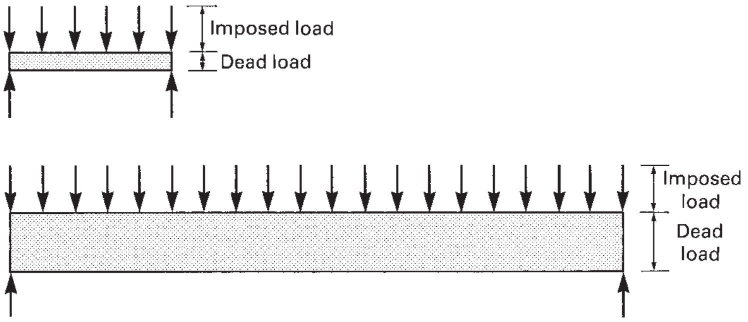

Fig. 6.1 The weight of a beam is proportional to its depth, which must increase as span increases. Thus, the ratio of self-weight to imposed load carried becomes less favourable as span is increased.

Another way of demonstrating the same effect would be to use a beam element with a particular cross-section across a range of spans. The strength of the beam – its moment of resistance (see Appendix 2.3) – would be constant. At small spans the maximum bending moment generated by the self-weight would be low and the beam might have a reasonable capacity to carry additional load. As the span was increased the bending moment generated by the self-weight would increase and an ever greater proportion of the strength available would have to be devoted to carrying the self-weight. Eventually a span would be reached in which all of the strength available was required to support only the self-weight. The structural efficiency of the beam (its capacity to carry external load divided by its weight) would steadily diminish as the span increased.

Thus, in the case of a horizontal span, which is the most common type of structure found in architecture, the efficiency of an element with a particular shape of cross-section decreases as the span increases. To maintain a constant level of efficiency over a range of spans, different shapes of cross-section have to be used. More efficient shapes have to be used as the span is increased if a constant level of load to self-weight (efficiency) is to be maintained.

The general principle involved here is that the larger the span, the greater the number of ‘improvements’ required to maintain a constant level of efficiency. The principle may be extended to the overall form of a structure and indeed to the full range of factors which affect efficiency. Thus, to maintain a constant level of efficiency over a wide range of span, simple non-form-active structures might be appropriate for short spans. As the span is increased, elements with progressively more of the features associated with efficiency are required to maintain a constant level of efficiency. At intermediate spans semi-form-active types are required, again progressing through the range of possibilities for ‘improvement’. For the very largest spans, form-active structures have to be specified.

The relationship between structural efficiency and intensity of applied load, which is the other significant factor affecting ‘economy of means’, can also be fairly easily demonstrated. Taking again the simple example of a beam with a rectangular cross-section, the weight of this increases in direct proportion with its depth while its strength increases with the square of its depth (see Appendix 2.3). Thus, if the external load is increased by a factor of two the doubling in strength which is required to carry this can be achieved by an increase in the depth which is less than twofold (in fact, by a factor of 1.4). The increase in the weight of the beam is therefore also less than twofold and the overall efficiency of the element carrying the double load is greater. Thus, for a given span and shape of cross-section, the efficiency of the element increases as the intensity of load increases and larger cross-sections must be specified. Conversely, if a particular level of efficiency is required, this can be achieved with less efficient shapes of cross-section when heavier loads are carried (the relationship between efficiency and shape of cross-section is discussed in Section 4.3 and in Appendix 2.3).

An examination of extant structures demonstrates that the majority are in fact designed in accordance with an awareness of the relationship between span, load and efficiency described above. Although it is always possible to find exceptions, it is nevertheless generally true that structures of short span are mainly produced in configurations which are inefficient, i.e. post-and-beam non-form-active arrangements with 'simple' shapes in cross-section and longitudinal profile. As spans increase the incidence of features which produce increased efficiency is greater and structures with very long spans are always constructed in efficient formats. This is very obvious in bridge engineering, as is illustrated in Fig. 6.2, and can be demonstrated to be broadly true of building structures.

The most obvious demonstration of the influence of load intensity on the type of element which is employed is found in multi-storey frameworks. The principal loads on the horizontal structural elements of these are gravitational loads and, of these, floor loads are of much higher intensity than roof loads (from two to ten times as much). In multi-storey frameworks it is very common for different structural configurations to be used for floor and roof structures, with roof structures being given more of the features which are associated with greater structural efficiency, even though the spans are the same (see Fig. 5.13).

From all of the foregoing it is possible to picture a fairly tidy taxonomy of structures in which the type of structure which would be most suitable for a particular application would range from the simplest post-and-beam non-form-active types for very short spans, through a series of 'improved' non-form-active or semi-form-active types in the medium span range, to form-active structures for the longest spans. Because the underlying requirement of structural design is to produce a ratio of load to self-weight which is approximately constant, the precise levels of span at which transitions from less to more efficient types of element would be appropriate would be affected by the load intensity: the higher the load carried, the longer would be the span at which the change to a more efficient type would be justified. The technical factor which determines the precise level of span for which a particular structural configuration is most appropriate is the fundamental engineering requirement that economy of means should be achieved.

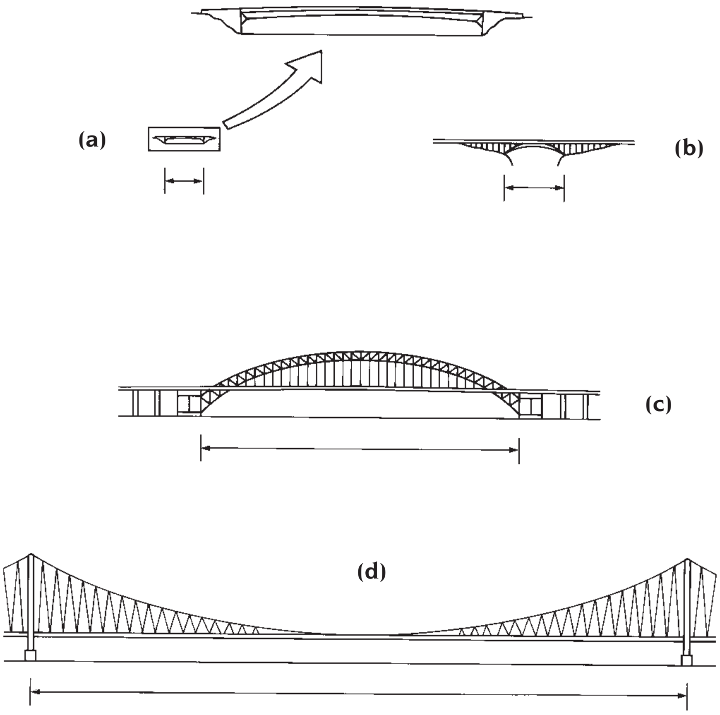

Fig. 6.2 The four bridges illustrated here demonstrate the tendency for structural complexity to increase with span due to the need for greater efficiency. (a) Luzancy Bridge; span 55 m, post-and-beam. (b) Salginatobel Bridge; span 90 m, compressive-form-active arch with solid cross-section. (c) Bayonne Bridge, span 504 m, compressive form-active arch with 'improved' triangulated longitudinal profile. (d) Severn Bridge, span 990 m, tensile form-active.

One indicator of the extent to which the correct balance between complexity (and therefore efficiency) and simplicity has been achieved is cost. Although monetary cost is not strictly a technical aspect of the performance of a structure it does give an indication of the level of resources of all kinds which will have been involved in its realisation. Cost is therefore a measure of the level of economy of means which has been achieved and is frequently crucial in determining the balance of efficiency and complexity which is appropriate in a particular case.

Cost is, of course, an artificial yardstick which is affected by the ways in which a society chooses to order its priorities. These are likely, increasingly, to be related to the realities of shortages of materials and energy, and to the need to reduce levels of industrial pollution. Cost, which, in the economic context of the modern world of the twentieth century, was largely unrelated to these aspects of reality and which was eschewed by critics of architecture as a measure of the worth of a building, may, in the twenty-first century become an important consideration in the assessment of the appropriateness of a structure.

As with other aspects of design the issues which affect cost are related in complicated ways. For example, in considering cost in relation to structural design, the designer must take into account not only the cost of the structure itself but also the effect of the selection of a particular structure type on other building costs. If, for example, it proved possible to reduce the cost of a multi-storey structure by slightly increasing the structural depth of each floor, this saving might be counteracted by an increase in the cost of the cladding and other building components. If a structure type were selected which, although more expensive than an alternative, allowed the building to be erected more quickly (e.g. a steel rather than a reinforced concrete frame), the increase in the cost of the structure might be more than offset by the savings involved in having the building completed more quickly. The issue of cost, in relation to structural design, must therefore involve a consideration of other issues besides those which are solely concerned with the structure. Such factors are especially important when the cost of the structure itself may form a relatively small proportion of the total cost of the building. In spite of these reservations, it is nevertheless possible to make certain general observations concerning the issue of purely structural costs.

Cost, and in particular the relationship between labour costs and material costs in the economy within which the structure is constructed, strongly influences the ratio of load carried to self-weight which is appropriate within a particular economic regime. This is a major factor in determining the spans at which the transition from less to more structurally efficient forms are made.

This can be illustrated by considering the relationship between material and labour costs for a particular structure. Consider, for example, the problem of a single-storey building of moderate span – an example might be the Renault Centre (Fig. 3.19). It may be assumed that a steel framework is a sensible form of structure to support such an enclosure but the range of structural possibilities available to the designer is very large. Simple post-and-beam forms with parallel-sided beams would be the least structurally efficient option. Semi-form-active portal frameworks with triangulated elements would be more efficient. A cable supported structure or tent would give the greatest efficiency in the use of material. The higher the efficiency, the greater the complexity and therefore the higher would be the design and construction costs.

The relationship between material and labour costs of all kinds is represented diagramatically in Fig. 6.3. The optimum level of efficiency corresponds with the minimum point in the curve indicating the total costs; this will correspond to a particular type of structure. Figure 6.3 also illustrates the effect of a variation in labour cost. The effect of an increase in labour costs, relative to material costs, is to reduce the level of efficiency at which the optimum level of economy of means occurs. This effect accounts for variations in patterns of building in different parts of the world. The higher the cost of materials in relation to labour, the greater is the incentive to achieve high efficiency and the smaller is the span at which the transition from less to more efficient and therefore more complex configurations is justified.

Extreme examples of this are found in tribal societies in which the economic conditions are such that very complex structural forms are used for structures of relatively short span. The

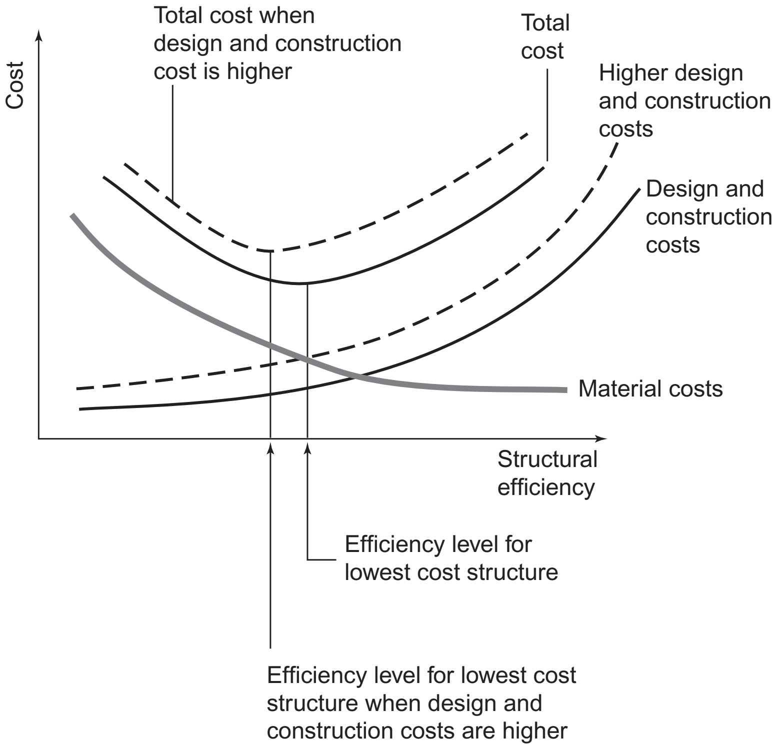

Fig. 6.3 The relationship between structural efficiency and structural costs for a structure with a particular span and load condition are shown here diagramatically. The quantity and therefore cost of material decreases as more efficient types of structure are used. The latter have more complex forms, however, so the cost of construction and design increases with increased structural efficiency. The curve showing total cost has a minimum point which gives the level of efficiency which is most cost-effective for that particular structure. If labour costs increase in relation to material costs, the location of the minimum in the total cost curve is displaced to the left indicating that a structural form of lower efficiency will now be the most cost-effective.

Bedouin tent, the igloo (Fig. 1.2) and the yurt (Fig. 6.4), all of which are form-active structures, may represent the very many examples which might be cited. The availability of ample reserves of labour to build and maintain complex structures and the fact that they are the most effective ways of using locally available materials are responsible for this use of a wide range of different forms for short spans, all of them very efficient.

The situation in the industrialised societies of the developed world is that labour is expensive in relation to material. This favours the use of forms which are structurally inefficient but which are straightforward to build. The majority of the structures found in the developed world are inefficient post-and-beam types, an excellent example of the profligacy with material of the industrialised culture.

It is possible to suggest that for a particular span and load requirement and within a particular set of economic circumstances there will be a limited number of appropriate structure

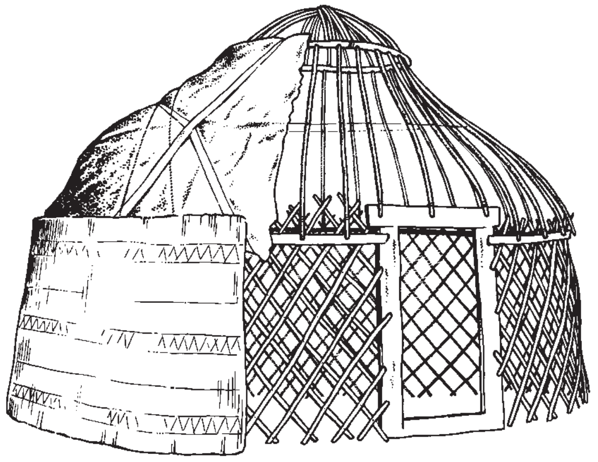

Fig. 6.4 The yurt is the traditional house of the nomadic peoples of Asia. It consists of a highly sophisticated arrangement of self-bracing semi-form-active timber structural elements which support a non-structural felt skin. It is light and its domed shape, which combines maximum internal volume with minimum surface area, is ideal for heat conservation and also minimises wind resistance. When judged by purely technical criteria this building-type will stand comparison with many of those produced by the so-called technological societies of the late twentieth century.

types. These will range from the simplest post-and-beam non-form-active types for the shortest spans, to form-active shells and cable structures for the largest spans. The majority of buildings conform to this pattern but there are exceptions. Some of these could be regarded as simply ill-considered designs. Others can be justified by special circumstances.

For example, if there is a significant requirement for a lightweight structure, this would justify the use of a more efficient structural form than might otherwise be considered appropriate for the span. Perhaps the most extreme example of this is the backpacker's tent, an extremely short-span building for which a tensile form-active structure (the most sophisticated and most efficient type of structure) is used. The requirement for minimum weight is, of course, the justification in this case. Other examples are buildings which are temporary or which must be transported, such as those which are designed to house travelling exhibitions (see Fig. 7.24) or travelling theatres.

Another reason for adopting a structure type which might otherwise be considered inappropriate for the span or load involved might be that the building had to be built quickly. Where speed of erection is given the highest priority, a lightweight steel framework might be a sensible choice even though other considerations such as the shortness of the span might not justify this. The use of lightweight steel framing for short-span buildings such as houses, of which the Hopkins House (Fig. 6.5) is a special case, is an example of this.

Sometimes, where the structure is part of the aesthetic programme of the building, a structure type is selected for its visual features rather than from a consideration of purely technical issues. Many of the structures which are found in so-called 'high-tech' architecture fall into this category. It is always possible to find examples of buildings in which a client was prepared to pay excessively and therefore commit excessive resources in terms of either materials or labour, in order to have a spectacular structure which would be unjustified on purely technical grounds.

A technical issue which has not so far been considered, but which should form part of any

Fig. 6.5 Hopkins House, London, UK, 1977; Michael Hopkins, architect; Anthony Hunt Associates, structural engineers. The very short spans involved here would not normally justify the use of complex triangulated elements for the horizontal structure. Ease and speed of erection were the main technical reasons for their selection. The visual excitement which they produce was, nevertheless, the principal reason for their adoption. (Photo: Anthony Hunt Associates)

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.