Reflections on the related histories of construction and design

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Construction is always a means to an end: to provide passage over an obstacle, to enclose space and provide shelter, to serve as a containment or barrier. Its history is therefore intimately linked with the broader histories of architecture, bridges and the like, and the histories of individual works.

But if this history is to be recognised as a separate discipline we must take a narrower view. I shall accordingly concentrate here on two aspects to which, for many years, I have continually returned while pursuing an interest in the broader histories alongside a primary concern with design today. They are the two things that distinguish all human construction from the natural growth of living forms. One is the construction process. During this process the built form is only an incomplete and sometimes hardly recognisable approximation to what is finally intended and may not even be able to stand unaided. The living form is always complete and self sufficient as when, for instance, seedling develops into sapling and sapling into tall tree. The other is human choice. At most this can marginally influence natural growth. But, as exercised in the process of design, it is central to all construction. It determines the final form and the processes whereby it is realised. It may be exercised once for all. More often it is seen as a sequence of choices made as the design is developed and as construction proceeds. Then especially, it is closely related to the construction process and this interrelation will be a secondary theme of what follows.

Tracing the histories of both construction and design processes presents the greatest challenge when we look back beyond the 18th century.

As we approach the present day the picture, although more complex, becomes clearer. Far more of what has been built survives and there is an increasingly copious, readily accessible, and easily intelligible contemporary documentation beginning with new types of treatise such as those of Belidor (1729) and Rondelet (1814) and detailed accounts of particular works such as Perronet's bridges (Perronet 1782-83) and the Eddystone lighthouse (Smeaton 1793). There is also plentiful evidence for related developments in materials, in construction plant, in the understanding of structural behaviour and requirements, in the ability to analyse and predict these, and in the powerful aid now offered by computers in such analysis.

Since there is already an almost equally large corpus of relevant studies of its history, it seems unnecessary to do more here than outline some salient features of this more recent period before turning to what happened earlier.

Construction possibilities and the construction process since the 18th century

Construction possibilities are determined in the first place by the available choice of materials. Over a
little more than two centuries that choice has widened greatly and that widening has been increasingly a global phenomenon as a result of easier transport and world-wide trade.

It began with the large-scale production first of iron and then of steel. Both materials called for new kinds of industrialised off-site fabrication of the beams and columns and other components that replaced earlier timber counterparts and for new ways of jointing them on site.

Next came Portland cement followed by the highly versatile composite material, reinforced concrete. Improvements in the quality and strength of the concrete coupled with the development of higher-strength steels then presented the possibility of prestressing the steel and concrete.

More recently there have been numerous further developments including the introduction of steels of much higher strength, aluminium alloys, and various plastics.

New methods of fabrication and erection have also been introduced. They have included the use of sliding formwork for casting concrete, cantilevered launching or extrusion of long spans from a support at one end, the jacking up of elements and even complete floor systems after casting and of timber grids after initial assembly on the ground, and the use of internal air pressure to inflate large membranes. Complementing them have been new techniques for accurate setting out and for controlling the erection process.

Most important among these developments has probably been prestressing, not only of individual components of a structure such as precast beams but of assemblies of components and major parts of complete structures. Since it can alter significantly the way in which the loads will be supported, it confers new freedoms on the choices of both erection procedure and final form.

DESIGN SINCE THE 18TH CENTURY

To exploit all these new possibilities in design, an adequate understanding of them and an ability to quantify requirements and assess whether they will be met have been essential. Reductions in weight that have become possible in spite of large increases in other loads have made it essential to consider these other loads explicitly, and the exploitation of tensile and flexural continuity has called for new understandings of strengths and stiffnesses and the parts they play in ensuring overall strength and stability. Successive developments from earlier largely intuitive understandings of structural behaviour to the more precise quantitative understandings made explicit in modern theory have therefore been highly important parallel changes.

These latter developments were initially an outcome of purely disinterested enquiry into the characteristic strengths of different materials and the balance of forces acting in any direction and not merely vertically.

The resulting simple statical theory made possible, in 1742, the first recorded analyses to assess the

![Figure 1](image1.png)

Simplified models of possible collapse modes of the dome of St Peter's based on observed cracking to permit analysis of its stability. (Le Seur, Jacquier and Boscovich)
stability of a standing structure, Figure 1. (Le Seur, Jacquier and Boscovich 1743).

Less than two decades later, similar analysis was pressed into service for the first time to justify a highly innovative design of what became the Paris Panthéon while it was still in the earliest stages of construction (Gauthey 1771).

The first extension of this understanding came when other loads became as important as self weight or more important, and when more costly iron replaced timber or masonry and created a new incentive to make the best use of the material. It became common practice to apply proof-loads to columns, beams, and the links of suspension chains and the like, before they left the foundry. Then, to reduce this dependence on tests, it became desirable to be able to predict both strengths and stiffnesses.

Prediction involved taking into account the relationship between load and deformation or, as we should now say, between stress and strain — initially on the basis of what is now known as Hooke's Law. Doing this was not as easy as had been the application of simple statical theory to arches and domes. It was necessary to look afresh at each new form and test the validity of the predictions, the testing also serving to carry understanding further.

The power of the new approach was well demonstrated in the design of the Conway and Britannia railway bridges (Fairbairn 1849; Clark and Stephenson 1850).

Once the idea of making the spans tubular had arisen, exploratory tests were made on small tubes of various cross-sections followed by tests to failure on a much larger model tube which was modified after each test to eliminate the principal weakness that had been disclosed. By the time that the last of these tests had been made, enough had been learnt to proceed to the detailed design of the single-span Conway tubes. Measurements on these after erection provided confirmation of the calculated deflection and assisted in determining the amounts by which the outer ends of the outer Britannia tubes had to be raised above their final bearings before connection to the central spans to make all three spans continuous.

Subsequent developments in theory have greatly extended the possibilities of drawing on past experience
to foresee and analyse the performance of a projected new structure both during construction and afterwards, and the advent of ever more powerful computers has immeasurably speeded the analysis. This has made it far easier to compare alternative designs and even sometimes to generate them automatically within prescribed limits. Where tests have still been called for to validate new theories or analyses of particular designs, they can now be performed more expeditiously and much more can be learnt from them thanks to developments in instrumentation and the recording and processing of data.
Complementary studies of likely loadings and other requirements have provided the necessary more widely applicable bases for assessment that are now commonly set down in Codes of Practice and similar advisory or regulatory documents. Cautious specification of limits allows for most inevitable uncertainties although they cannot in the same way allow for human error and unanticipated consequences of venturing into new territory. But when failures do occur, more searching enquiries than were previously possible allow revisions to be made to reduce the likelihood of repetitions.

Through all these developments, a designer’s potential personal understanding of the range and limits of structural feasibility has been greatly enlarged, allowing the creative imagination to range more freely and inspiration to be sought more widely in the initial conceptual phases of design. But to attain that understanding calls for considerable effort and experience. Together with the increasing range of other requirements to be satisfied, this has led to the growth of a number of different design professions and to multi-professional working on projects of any size.

An outstandingly successful recent example was the collaboration between Utzon and Arup in the difficult realisation of most of Utzon’s dream for the Sydney Opera House—a realisation in which devising the construction procedure for the «shells» was a more than usually integral part of the design. (Arup and Zunz 1969; Mikami 2001)

Some of the best modern work, including many of Maillart’s, Freyssinet’s and Leonhardt’s bridges and Arup’s Durham footbridge, has nevertheless probably resulted when, as for the Conway and Britannia Bridges, the requirements have been largely or purely structural and the designer has been responsible for the construction procedure as well as the structural details and final form.

**Earlier built fabric and forms**

When we turn to the earlier period, we can only speculate about the beginnings. It is nevertheless reasonable to assume that the earliest wholly built shelters most closely resembled the simplest ones that we still see in many places around the world: round beehive-shaped huts constructed from readily available local materials. The archaeological evidence is at least consistent with this possibility and, as with the typical bird’s nest, only the simplest operations would have been called for to build them. There would be no corners to turn and no difficult joints to make.

We are on surer ground when we look at survivals built of masonry and other more permanent materials. Many survive only in part. But their partial collapse or loss of facings has often laid bare details of their structural fabric that would have been hidden in the finished structure. Much attention has already been given to these details and there is a copious record of them beginning with the pioneering studies of Viollet-le-Duc (1860), Choisy (1873 and 1883), Clarke and Engelbach (1930) and Orlandos (1955, 1958).

With some exceptions, the materials used were of fairly local origin and the manner of use indicates strong local traditions. The most durable materials were initially natural stones followed by fired brick and Roman concrete. Although strong in compression, these materials had limited tensile capacity and hence were also relatively weak in bending. Where greater tensile or bending capacity was called for, timber was the usual choice, with iron employed to a limited extent and rope and woven fabrics for some types of temporary shelter like the Roman velarium. Problems in effectively jointing these latter materials greatly reduced their effective tensile strengths in many situations however.

*Figure 5*
(author)
Consequently most major structures were largely masonry and had to stand by virtue of a balanced opposition of internal compressions, aided at a few points by cramps or ties.

Walls show the greatest variety, ranging from rubble masonry to fine masonry of cut stone, brickwork of either mud or fired brick, and different forms of Roman concrete. Rubble masonry was sometimes held together by bonding timbers as, less frequently, was brickwork. And, although some walls and piers were of uniform construction throughout their thickness, many had only skins of brick or cut stone with comparatively weak rubble cores. Gaps were spanned and spaces were covered by beamed systems usually of timber but sometimes of stone, by arches and vaults, or by timber trusses.

ASSOCIATED EARLIER CONSTRUCTION PROCESSES

The construction processes employed are no longer open to inspection and there are few records of them. Vitruvius largely ignores them, and so do most surviving later texts and other records prior to Alberti’s De re Aedificatoria (first printed 1485). Pictorial representations rarely disclose much that could not be deduced without them. It is therefore necessary, for the most part, to draw such conclusions as are possible from surviving structures themselves.

How much can be learnt in this way about setting-out and other dimensional control is doubtful since, solely by measuring the structures, it is too easy to find whatever one chooses to look for. It seems likely at least that considerable reliance was placed on working with one or two basic modules and simple geometry. But more can be learnt about the subsequent processes.

Jointing details are most revealing for timber structures. Since joints would normally be cut before the members were erected, interpretation of erection procedures calls chiefly for a consideration of assembly possibilities with the resources likely to have been available.

For masonry structures, there are more possible clues. In addition to bonding patterns and unbonded joints, these clues include likely supports for centring and relative deformations indicative of construction sequences.

When foundations, walls and piers were built dry, there would have been a need merely for careful placing of the masonry and the provision of scaffolds to give suitable access to the working level. When they were built of wet concrete there would have been an additional requirement for temporary formwork whose imprint can still sometimes be seen.

Figure 6
A lintel arch in the Baths of Trajan, Rome, in which loss of most of the facing bricks has exposed the construction behind.

(author)
Circular domes could have been built without centring if they were constructed throughout in complete rings of dry masonry. At each level the upper rings would act in compression to bear the thrusts of the incomplete meridional arches leaning against them. For the same reason, any formwork called for in wet construction need only have been circumferential and limited to the working level rather than spanning the whole void, provided that time was allowed for successive rings to harden before they were called upon to bear these thrusts. But most arches, arched ribs, and most shapes of vault other than circular domes, would normally have required full centring above a level at which they inclined appreciably inwards.

There is evidence, however, of the adoption of numerous expedients to reduce or eliminate the need for formwork or centring, especially in regions where timber was relatively scarce. The practice of facing later Roman concrete walls with brickwork might be counted as one of them. So might the very early practice of corbelled construction of pseudo arches and vaults with steep V-shaped profiles—a practice akin to that seen later in the Gothic *tus-de-charg*.

In constructing true arches, vaults, and domes of brick, the most widely adopted expedient was to set the bricks with their faces following the curve and leaning somewhat backwards against the similarly inclined face of the last completed arch or ring. This allowed successive rings to be virtually glued to the previous ones, either by first scoring the face to provide a better key for the mortar or by using a fast-setting mortar. A variant of this procedure was the use of interlocking tubular units.

Over larger spans the centring requirement was sometimes reduced by building up the required total depth in superimposed rings laid vousoir-fashion. Or spans were reduced by progressively narrowing a void by means of bridging arches, squinches, or free-standing ribs around its perimeter.

In Roman arches constructed of *opus caementicium*, another technique was adopted. Full bricks were
The development of hoop stress as construction proceeds in a circular dome of pointed profile such as that contained within the Florence dome. Tension is shown as negative and compression positive. (author)

inserted at intervals between groups of broken facing bricks to divide the otherwise undifferentiated concrete mass into voussoir-shaped blocks, Figure 6. These would have reduced the risk, particularly in flat or segmental arches, of its partial collapse and thereby allowed earlier removal of the supporting formwork.

In a similar manner, effective groin and meridional ribs were created within the concrete of vaults and domes as shown in Figure 7 and (somewhat idealised) in many of Choisy's plates, though their value in reducing centring needs as distinct from channelling thrusts to supporting piers is less easy to assess.

The outstanding achievement was the construction of the vast double-shelled non-circular dome of Florence cathedral without using centring. Since I have discussed this in detail elsewhere (Mainstone 1969/70; Mainstone 1977a), I now merely outline and illustrate its most significant features. The basic idea was to make the inner shell thick enough to contain within its thickness at all levels an adequate complete circular ring (shown stippled in the larger detail). Above the level at which the inward inclination became appreciable, this whole shell was then constructed of brickwork with inverted-conical setting beds as if it were part of a thicker true circular dome. Construction of successive courses without temporary local support was made possible by means of the ingenious bond illustrated in the details. This also keyed to the circular ring the masonry inside and somewhat below it, and was probably suggested by the Roman construction shown in Figure 6 (Mainstone 1980). Construction was further simplified by the pointed profile and an open eye at the top, later covered by a lantern.

This achievement was also uniquely well documented, notably in a series of agreed specifications of the design (Doren 1898). Interpretation of these specifications has nevertheless presented difficulties in the past, partly because existing terms had to be pressed into service to describe new procedures and forms. To understand them fully it was necessary to read them
with a full appreciation of the structural possibilities and needs and the consequences of proceeding in different ways.

To confirm this understanding, a rough idea of the development of hoop stress as construction proceeded was obtained by analysing a simple model of the circular dome contained within the thickness, Figure 9.

**EARLIER DESIGN**

Modern structural analysis is, however, of no direct value in establishing earlier design processes. Indeed much finite element analysis of early masonry structures now undertaken is grossly misleading even as a basis for assessing present stability because it ignores the influences on behaviour of the heterogeneity, extensive cracking, construction breaks, and sequence of construction. On the other hand, analysis that takes proper account of these can assist by clarifying the successive structural requirements of different construction procedures as in the Florentine study. It can also throw some light on problems that might arise and on the ways in which they would have become apparent to the builders, and can contribute to a better understanding of the significance of the visible evidence presented by a standing structure (Mainstone 1997). In attempting to envisage how our predecessors might have proceeded, we must merely divest ourselves of most other insights such analysis offers and try to think as they could have thought.

Contemporary documentation is also of limited value. What was learnt directly on the worksite seems largely to have gone unrecorded. This poses a risk of placing undue evidence on what was recorded and has come down to us. Since, also, the records were not intended for our enlightenment, they are today even less self-explanatory than the Florentine specifications.

Building regulations did little more than place restrictions on what was permitted and were mostly

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**Figure 10**

Plan of a tower of Laon Cathedral from Villard de Honnecourt’s «notebook» (author, based on f. 9v of *Bibliotheque Nationale MS francais 19093* with the addition of original scribed construction lines visible in glancing light)

**Figure 11**

concerned with a limited range of building types and with aspects like fire safety. Other surviving records from Vitruvius onwards are largely restricted to simple proportional rules and simple geometric procedures that could have served equally for design, setting out on site, or stone cutting (Mainstone 1968).

Even where they do relate specifically to such things as room proportions on the one hand or wall thicknesses and column girths on the other, it is mostly unclear whether they were intended to contribute to firmness or convenience and delight.

The proportional rules for wall thicknesses and column girths and the like and later geometric constructions to determine buttressing requirements, Figure 10, would simply have been codifications of past experience that certain proportions had proved adequate. Close conformity to them, or more directly to the experience itself, must usually have served as the best available assurance of safety when something new was attempted. Indeed a failure to conform more closely to the proportions previously adopted for the piers at St Peter’s, St Paul’s, the Val de Grace, the Invalides and elsewhere was still the main basis of Patte’s criticism of Soufflot’s original design for rebuilding the church of Sainte Geneviève (Patte 1770).

The purposes served by generalised procedures based on manipulating a few geometric figures as in Figure 11 are more enigmatic. How far were they thought to be valid guides to more innovative structural design? The minutes of the late 14th century discussions of the proposed design for the nave of Milan Cathedral suggest that, at least in part, they were (Ackerman 1949). But they contained in themselves no clues as to how they should be interpreted and choices made between alternative possibilities. It must be assumed that they were supplemented in practice by unwritten further rules as the discussions at Milan also suggest. Even so, they must have been flexible enough to permit the large variations to be seen from building to building where it is to be expected that the same procedures would have been followed.

Clearly, successful innovative design must have had some further basis (Mainstone 1973), though it could have been much simpler than today because of the simpler modes of behaviour brought into play. For the earliest huts it was probably no more than an appreciation of the natural tendency of everything to fall and a realisation that the fall might be prevented by a suitable obstacle or obstacles. Given this appreciation, the primary focus of attention would have been on the operations involved in creating a potentially stable assemblage. For more ambitious works some fuller prior concept of the form aimed at would have been needed. But I suspect that once the desired form had been chosen, the emphasis would usually have been more on the successful completion of each stage of construction than on final stability.

Avoidance of the difficulty of a horizontal closure of a hemispherical dome might well, for instance, have been a more important reason for adopting a pointed profile than the reduction of horizontal thrusts.

As experience grew, the simple intuitive understanding of the hut builder would have been developed by the experience gained in tackling any problems, coupled with observation of the evidence of their behaviour presented by standing structures. Some further guidance may occasionally have been sought by constructing reduced scale models as happened in the early stages of design of the dome in Florence. But there is little evidence of this happening elsewhere. Even in Florence, the last clause of the initial design specification for the dome still left open the procedure to be adopted in the later stages of the work because «in building, practice teaches what should be done», clearly indicating the importance placed on critical observation of the actual progress of construction as the best guide to what should be done next.

The importance of observing behaviour as construction proceeded was also well demonstrated by the construction history of another major achievement, Justinian’s Hagia Sophia in present-day Istanbul (Mainstone 1988). Study of the building today has shown that, when construction of the main transverse arches generated significant thrusts, the original interconnections of the piers lettered A,A began to give way. This allowed the piers to tilt alarmingly, especially at gallery level, and it was only then that the projections lettered B.B, constructed entirely of closely fitting stone blocks, were added in hasty response, Figure 12.

Because design as innovative as seen at Hagia Sophia and in Florence was rare, there would have usually been less need for a similarly empirical approach. The development of the Gothic structural system, for instance, went ahead by numerous much
movements were then similarly countered by strengthening weak elements or adding restraints such as buttresses or ties. Since the behaviour observed would have been effectively statically determinate, no more was needed.

**CONTINUITY AND CHANGE**

Looking back over the whole history (Mainstone [1975] 1998), I see both continuity and change. Changes between earlier and more recent times have been emphasised. But it should not be assumed that there was a complete change at some time in the 18th century. Major changes began then. They continue at an increasing pace. But they have not affected all construction equally and perhaps never will. Nor have they affected every aspect of design. The behaviour of the incomplete structure at all stages of construction must still be borne in mind even when focusing primarily on final behaviour. So there is always a link with the construction process. Except when no more is done than play variations on what has been done before, keeping well below the ceiling of proven practice, creative input is required. This still calls for personal understanding of all that is relevant and for skilled professional judgement, and runs risks that perhaps can never be wholly eliminated.

**REFERENCE LIST**

Space limitations and the breadth of the field covered preclude the extensive list of references that would otherwise have been desirable. Many further references will be found in those of my works that are listed below.


