Some time ago I discovered a teaching film that featured a guide to one of the French cathedrals demonstrating the action of the vaults and flying-buttresses to parties of tourists. This he did by lining up the men in two rows to represent the columns of the nave. They then raised their arms to represent the ribs of the vaults, linking hands with their neighbours and those opposite at the crown. Their wives then stood behind with their hands on their husbands’ shoulders to be the buttresses. The guide then placed his hands over the «bosses» at the meeting of the ribs and lifted his weight off the ground hanging from the outstretched arms of the men. The result was that all could feel the forces thus created. Of course we may object that this is not the loading pattern on the vaults and so is a rather inaccurate model but the demonstration served the purpose for the visitors who surely would never forget this little lesson in structures. Also, when I introduce structures to students I do so by pointing out that the image of structural analysis is that it uses a large number of formulae but for me the most important formula for them to understand is:

\[
\text{Structural calculation} = \text{Guess.}
\]

It is just that some guesses are better than others.

All structural calculations depend upon building some model of the situation that one is trying to understand and the model that one uses has to be appropriate for the task in hand providing a sufficient degree of accuracy in its representation of both the structure and the loads that come onto it. What being «appropriate for the task in hand» means is that it helps to answer the questions that are being asked. Thus being clear about the questions one wants to ask is the first step in the process. But it often seems that this step has been missed out in a rush to calculation? My motto is «Work is no substitute for thought» and this is particularly true when modelling an existing structure as distinct from one that only exists on paper because the two processes are not the same and neither are the purposes for which the analysis is carried out. Many carrying out the analysis of existing buildings seem not to recognise this simple fact and it is also sad to note that there are some who approach the task without looking at all closely at the structures they are purporting to describe.

I would like to address these issues asking how the purpose of calculation affects the methods used and particularly how this affects the historian. In doing so I shall need to consider how some earlier work satisfies my criteria and this will mean directing some brickbats at some distinguished scholars. But I take the view that life would be very boring if we all agreed with each other.

**The reasons for analysis**

The obvious starting point is to consider the different kinds of people who carry out the analysis...
of historic structures and we can identify three kinds: conservators, historians and those academics who do not properly fit in either category. However it is also useful to consider the designers of new structures for the purposes of comparison because most analytical techniques are devised with this task in mind. The designer of a new structure is attempting to produce a design that will be safe and to do so with reasonable economy both in the structure itself and in the design process. This is also the task of the conservation engineer although with the additional requirement to respect the historic fabric.

Of course much of the early work done on the analysis of historic structures was done in the course of restoration work. Well known historic examples of this are the eighteenth-century analysis of the dome of St Peter’s, Rome and Baines’ analysis of the roof of Westminster Hall, London in the last century (Baines 1914). The purpose of such studies was and still is to guide possible strengthening or repair work and the methods need to be appropriate for that. But as historians we have different questions to ask and it is important to be clear about what they are. It is also important to be clear that any calculations carried out both by conservators and historians differ from those used in the design of a structure. Thus there are three different situations and so three different kinds of questions that might be asked and three different approaches needed towards analysis. Although I am not concerned here with calculations carried out for repair purposes it is difficult to ignore these completely in my comparisons.

While both designers of new structures and conservators are concerned with the safety of a structure this is not the concern of the historian. For the historian any analysis is surely carried out to answer one of two kinds of question:

1. How was any particular structure or type of structure designed?
2. How did the behaviour of a given type of structure affect the design of buildings for which they were used.

These will lead to subsidiary questions that we will come to shortly but these seem to me to be the fundamental issues. But we also need to consider the academic who may have neither the safety concerns of design nor the questions of the historian. Nevertheless the results of such work might well be of interest to one or the other.

**The nature of the problem**

It is in the nature of the problems presented to these different people that determines the suitability of the methods available to them; the nature of the problem being a combination of the questions that are asked and the practical problems presented by the analytical task. The intention of the designer has been clearly stated by Heyman in his discussion of Westminster Hall roof. It is to demonstrate that there is a «distribution of forces (in the structure), in equilibrium with the external loads and not exceeding the... limits for individual members». If this condition is satisfied then the structure will be safe and it does not matter whether or not it behaves exactly as predicted by the model (Heyman 1967, 159). Of course, the designer has the luxury of being able to specify the properties of members to ensure that this condition will be met.

This is not true of someone studying an existing structure. One cannot specify the properties of the members and one may not be able to measure them with any degree of accuracy. Therefore one has to devise methods that take into account the uncertainties that one has both about the nature of the assembly and the properties of individual members. Jacques Heyman’s approach to historic structures, as stated above, has advantages in that he does not need to know the properties of all of the members in the actual structure, simply those of the modelled structure. Thus for Westminster Hall roof could ignore the properties of the arch brace which was assumed not to be acting. But this overall philosophy hardly seems adequate for a conservator.

Suppose, for example, that I have a model of the structure that ensures its overall safety but that there is a member that is in fact carrying load although it is not relied upon in this model. Failure of the member will not cause collapse but simply a redistribution of the load in a way that accords more closely with my idealized model. This result would be a loss of integrity of the failed member and possibly some other damage or unacceptable deflections as loads are redistributed. It might also mean that the structure is no longer working as its designer intended. For these
reasons, as a conservator as well as an historian, I have some sympathy with Roland Mainstone when he asked of Westminster Hall roof how the structure was actually working (Heyman 1967, 788–92). A conservation engineer might need to know how the load is actually being transmitted in the structure because of a concern for states of distress within it and perhaps because of a need to replace some members. The problems being faced may also involve determining loads on temporary supports to be used in the course of restoration work.

For the historian.

While an historian who wishes to carry out an analysis of a structure has the same practical problems as the conservator there can also be the additional complication that the structure in question no longer exists. Having been demolished some time ago it might only be known through historic records that themselves may be of uncertain accuracy. This was Heyman’s position when he carried out an analysis of the Cismone bridge (Heyman 2000) and it is true of a number of structures that I have been interested in; the roof structures of Inigo Jones for example (Yeomans 1986) while others, including Dorn and Mark (Dorn and Mark 1981) have considered the structure of Wren’s roof for the Sheldonian Theatre, Oxford that was replaced in the early nineteenth century and for which the various drawings disagree. The reason for one’s interest in such structures is that they might be significant to the development of structural design or might lead to insights into the structural understanding of the time.

Both the two basic historical questions set out above seem to a number of subsidiary questions but I shall confine myself here to the first, i.e. How was any particular structure or type of structure designed? This applies either to the design of a single structure or to the development of a structural type and requires that we ask such questions as:

i) What was the general level of structural understanding at the time?

ii) How was this applied to a particular structure?

iii) Would feedback from the behaviour of the structure have modified such understanding?

iv) What understanding did the designers have of the materials they were handling?

v) Who actually carried out the design?

I don’t pretend that this is a comprehensive list but it shows the range of questions that might be asked.

Some of these can be answered from documentary sources but our concern here is those for which structural analysis is of some help. If we are trying to put ourselves in the mind of the designers of the time then until the eighteenth century these would have had only very simple ideas of structural behaviour. Moreover much structural design would have been carried out by men of limited scientific or mathematical knowledge. Methods of design depended upon different kinds of rules but might have been modified by observation of the behaviour of structures. My instinct therefore is to assume that one should if possible look at the documentary sources for the way in which structures were designed and to structural analysis for their behaviour and so for ways in which designers might have learnt from that. This means that timber and masonry structures present quite different problems because of the very different nature of the two materials.

Unless there are problems of foundations settlement, which of course was not unknown, masonry structures tend to fail catastrophically so that there is little sign of distress until the building is close to failure. There is certainly no indication of the level of stress within the structure that could act as a guide to improvements in design. Thus, I must take issue with Robert Mark’s apparent assumption that because analysis of a sequence of the structures of French cathedral shows improving structural efficiency the designers were somehow aware of this and were consciously developing their designs for that reason (Mark 1982). However, his demonstration that Chartres would suffer distress at a high level without the upper flying buttresses and his subsequent observation of cracking in this area shows that while his model technique is not strictly correct, it can provide useful insights. It had the effect of directing attention to that part of the structure that would have exhibited movement that could be observed by the builders of this time and responded to (Boug & Mark 1973).

Naturally I agree with Huerta (2001) that the «equilibrium approach» is best for the analysis and design of masonry structures and also that Mark’s
application of photoelastic methods is strictly incorrect, in that we are neither dealing with an elastic material nor with one that can take tension. Nevertheless, the above example shows that his photoelastic approach does have some advantages the study of Chartres being an example where the method was sensibly applied to a particular problem. But this particular analytical technique can say nothing about the general level of structural understanding at the time these buildings were constructed nor about how the designs were developed.

The other limitation of this method, and others that simply consider the final structure, is that they fail to consider the whole process that the designers of masonry structures would have been only too aware of. The problem was not simply to ensure that the completed structure would stand but to be able to get it there in the first place so that questions of setting out and of temporary supports during construction would also have taxed the minds of the designers. If we are trying to understand how designers behaved in the past then surely we must be trying to create in our minds the conditions that they observed when they built and loaded their structures so that we can «observe» what they observed. How did this structure behave when built? How were the components of the structure placed in position? What was the sequence used? All of these are questions that involve understanding the behaviour of the structure during construction. These were the questions behind Mainstone’s study of St Maria del Fiore (Mainstone 1969/70) but unfortunately we have precious little evidence for construction processes. Even the most celebrated buildings have left little in the way of documentary evidence for this so that we are left with a certain amount of speculation. Mainstone’s study showed how the Brunelleschi dome could have worked while a Heyman demonstrated the form that flying buttresses must take in order to cope with two extreme states: their own self weight acting alone and the thrust of the vaults. What neither studies tell us is how the designers of the time might have come to these necessary forms.

TIMBER STRUCTURES

It is in timber structures that we are likely to see the kind of behaviour from which later designers might learn because of the extent of movement in the material. Timber structures also offer the advantage that collapse would seldom be catastrophic but be preceded by a period when distress could be observed and during which remedial action might be taken. Of course movement of the timbers is as much associated with drying shrinkage and creep deflections as it is with elastic deformation. Moreover the behaviour of various kinds of framework might also be affected by the accuracy of the carpentry. It is these uncertainties in the behaviour of timber structures that makes one question the validity and usefulness of many of the sophisticated methods of analysis that have been used and it only takes a simple example to demonstrate this.

The effect of shrinkage of the timbers is most clearly seen in the so-called clasped purlin roof, typical of English medieval construction. The sequence of assembly of this structure suggests the load carrying mechanism. Posts were stood on the tie beam to support a collar that in turn supported the purlins. Finally the principal rafters were added clasping the purlin between them and the collar (Fig 1). Clearly the initial structural action on completion of the roof was that the purlin loads were be transmitted via the posts to the tie beam. (Fig 2a) However subsequent shrinkage of the tie beam commonly results in a gap between the bottom of the posts and the top of the beam. Obviously load is no longer being transmitted by this route and one must conclude that the purlins are now supported by arch action of the principal rafters and collar. (Fig. 2b) Analysis of such a structure must begin with observation of its present condition.

Considering the effects of shrinkage, creep and uncertain standards of craftsmanship together with an
imperfect knowledge of the properties of the timber sections makes any detailed analysis of the structure of very doubtful validity. I must echo Huertas comments about masonry structures when he opines that the very nature of the ashlar and rubble wall means that the use of sophisticated elastic models is contrary to common sense. Faced with this uncertain behaviour my approach to timber structures as a conservator is sometimes to consider quite different modes of behaviour for different members in the frame asking what range of forces I might have to deal with in making a repair. One can ask the same questions when considering the historical behaviour of the structure. A purlin might have carried loads from the rafters back to the supporting frame and this would determine the loads that frame had to carry when the structure was built. With time purlins frequently deflect and shed load back to the rafters that in turn delivered a larger load to the wall plate. How might this have affected the carpenters’ approach to the design of such structures?

As with masonry structures, stresses in timber structures were generally low; what would have concerned their builders were deflections, particularly shrinkage deflections, as is clear from early carpenters’ manuals (for example Nicholson 1792). Of course stresses would be high at joints and a concern for this is sometimes seen in their detailed design. For the 60ft spanning trusses over the portico of St Martin’s in the Fields, London, James Gibbs had wedges driven into the head of the king post to tighten it against the ends of the principal rafters. This might not have done much to counter shrinkage effects but would certainly have taken up any initial lack of fit in the carpentry. The ends of posts or braces on long-span trusses might be notched into tie beams or principal rafters to take the thrusts from the inclined struts (Fig. 3). Without such details these thrusts would have been taken on a comparatively narrow tenon so that it is clear that their designers recognized the nature of the forces involved. But could the stresses on the tenons have been sufficient to produce noticeable stress, i.e. to have resulted in some crushing of the timber in long-span trusses? Here is a question that asks for some analysis in order to
answer it—but how detailed need this analysis be? Assuming that the tie beam is in two lengths, which was common at the time, a simple king post truss is indeterminate because of the continuity of the principal rafter. But if the principal rafter is strutted so that there is no deflection in it then we can reduce the structure first to the principal rafter as a continuous beam over rigid supports to find the support force and then the roof truss to a pin jointed frame. This will then give the maximum forces that could be generated in the strutting members and would be sufficient to give an indication of the joint stresses. By this simple means one can have an answer to the question. And note how the question was phrased: it was could the stresses have been high enough to produce crushing of the timber not would they have been high enough. Thus an upper bound for the value of the stress is appropriate.

FAILURES AS A MEANS OF FEEDBACK

One obvious method of learning from timber structures is the observation of distress in structures and some of the early roof trusses built in England did indeed give trouble, presumably because of either poor design or poor execution. Inigo Jones’s roof of the Banqueting House in London gave problems from a very early date, so much so that for a while the interior of the building was scaffolded to give some support to the roof. Drawings made at the time of its construction, or shortly after, show a poor design of timber truss with iron bars that may have been added in an attempt to strengthen it, but these are not clear enough to be certain of the construction details. The roof was eventually replaced by Soane in the nineteenth century. The same architect’s roof for St Paul’s, Covent Garden also had timbers added in an attempt to improve it as shown in contemporary drawings but this structure was eventually destroyed by fire. One of the puzzles about the roof of the Sheldonian Theatre, Oxford, an early design by Christopher Wren, is the reason for its early nineteenth century replacement—but here we do have some reasonable drawings. This was an ingenious piece of carpentry that was much admired in its day for the design of the tie beam that comprised seven timbers joined together to transmit the tension force (Plot 1677). However there was some early concern for its deflection that might have been as a result of shrinkage of the posts. As the overall geometry of the roof is known, the likely extent of any deflection resulting from shrinkage can be determined from some fairly basic calculations.

In all of these cases the structures no longer exist but their place in the development of structural carpentry in England makes their behaviour a matter of some interest (Yeomans 1992). The kind of questions that one might ask of these is how they were designed, how they performed in service and what lessons might have been taken from their behaviour that could have affected the design of later structures. Any analysis used in an attempt to answer these questions needs to model the structure as realistically as possible and to be clearly directed towards the phenomena in question. Consider these requirements in relation to the photoelastic analysis of the Sheldonian roof structure by Dorn and Mark (1981) and it is seen to say nothing useful, nor does it consider the actual construction of the structure.

I am also concerned that the questions raised are pertinent to historical issues because it sometimes seems that they are asked simply as an excuse for the analysis. Morris and his co-authors (1995) recently contributed a paper to those that have already discussed the roof structure of Westminster Hall, London. They set out to discover the extent to which the decorative tracery might be contributing to the behaviour of the structure. This was an interesting exercise using finite element analysis but leads me to ask the «so what?» question. It is difficult to imagine that the builders of this roof, or even of a host of smaller related roofs, could have imagined the tracery to be part of the structure. Nor if it were part of the structure in this case that it would also be so a sufficient number of other cases to deceive the carpenters about the structural action of the roof and so affect the development of the type. Therefore the result, whichever way it went, could add nothing to our understanding of the history of this particular roof’s design or that of any other even though it might say something about their long-term behaviour. But most of all I doubt the usefulness of finite element analysis for the understanding of any timber structure on the common-sense grounds that I have already adumbrated.

It should be clear by now that my concern is for clear historical questions if possible addressed...
through the simplest methods of analysis possible. There are several advantage of using simple techniques. The first is that they are quick and easy to carry out. The second is that one has a clearer idea of the meaning of the results and particularly of the effect of any simplifications that are made. The third is that simple methods might possibly be understood by a reasonably numerate architectural historian which means that the historical ideas are more easily communicated. Of course this third reason could seen as a disadvantage. Perhaps it gives people a good feeling to be privy to a mystery that others do not understand, to be able to play the priest among the laity. I am reminded of Bernard Shaw who said «All professions are conspiracies against the laity». Thus when the conservator engineer uses finite element analysis with its wonderfully colourful print out of the results is must surely impress the client. If I don’t understand it, and especially if I have no hope of doing so, then it must be good. And if I use the same techniques in an historical context and the historians cannot understand it then it makes me master of the field. This is not something that I subscribe to because in both areas I would be concerned to facilitate communication and mutual understanding. This means that one of the factors for selecting a particular method of analysis is because of its ability to facilitate communication with others. This brings us back to the tour guide’s demonstration; structurally inaccurate but effective for its purpose. In a similar way Mark’s photoelastic models are popular with students because of their very graphic nature. Better still are Huerta’s reduction of Heyman’s approach to a demonstration using cardboard models because they are not only as graphic as Mark’s models but are a more accurate representation of reality and have the added advantage that it is something that students could do for themselves.

**THE ACADEMIC ANALYSIS**

There are those whose purpose in analysing historic structures seems to go little further than the analysis itself and thus some explanation of observed phenomena within the structure. Of course this is a perfectly respectable academic exercise and there are those who have built distinguished careers on just this. Moreover such studies can also provide valuable information for the conservator. For example, Heyman’s analysis of masonry vaults shows patterns of cracking within them are perfectly normal and need not be of concern. But in doing so they avoid asking any real historical questions. It would be fair to say that while Heyman is interested in the history of structural analysis, as seen his recent publications (Heyman 1998), he would not consider himself an architectural historian and so does not always ask the historical questions suggested by the structures that he analyses. An example here is his recent paper on the behaviour of the Cismone bridge as illustrated by Palladio (Heyman 2000) He does not, for example, consider that the tension forces might have been carried by a metal strap, as suggested by the drawing, nor does he consider the relevance of Inigo Jones’s sketches of connection details on this page of his own copy of Palladio’s book (Allsop 1970)

I am reminded of the study by Eda Kranakis who showed how the different approaches of Finley and Navier to the design of suspension bridges were affected by their social circumstances (Kranakis 1997). She shows that Finley who was concerned to patent a system of design that could be used by others for the construction of relatively cheap bridges developed a system that relied upon a simple model analysis. In contrast, Navier, who worked within the career structure of the Corps de Ponts et Chauses was anxious to demonstrate his ability to carry out a thorough mathematical analyses that dealt with a range of questions irrespective of their practical value in design. Is it not equally appropriate to ask about the social circumstances of those who carry out analyses of historic structures? It seems to me that there are a number of examples that use sophisticated techniques, including finite element analysis, in circumstances where they appear to be of dubious historic value. Presumably it is the position of their authors within engineering departments that inclines them not only to ask purely structural questions but also to use the most sophisticated techniques available to them. This is where I divide from many engineers who turn their attention to historic structures because I want to place their analysis in a wider context. I want to consider how social and economic considerations affect the design and wish to use analysis as an aid to answering these questions and not simply an end in itself. Nevertheless some of
the remarks that I make about the appropriateness of various techniques are equally applicable to the more limited exercises.

**REFERENCE LIST**


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