ASPECTS OF THE DEVELOPMENT OF STRUCTURAL CARPENTRY

1600 - 1800

OR :

The Origins of the King and Queen Post Roof Trusses; being a Study of their Development in England.

AND CONTAINING

a brief account of early roofing, and a comparison with continental carpentry, showing the first uses of the king post in England by notable architects, its adoption by others, a survey of books for carpenters, the development of queen post trusses and other devises and a discussion of structural knowledge.

TOGETHER WITH

Appendices on the definition of trusses and on various forms of floor framing.

THE WHOLE BEING

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Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor of Philosophy by

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ASPECTS OF THE DEVELOPMENT OF STRUCTURAL CARPENTRY 1600 - 1800

ABSTRACT

Medieval side purlin roofs had their principal rafters strutted from the tie beam with members acting in compression. By the beginning of the nineteenth century these had been superceded by the use of king post and queen post roof trusses with posts in tencion.

This study shows that the trussed king post roof was first introduced into England by Inigo Jones and traces its subsequent development. It shows that Christopher Wren derived his knowledge of the trussed roof from Bernardino Baldi's Mechanics and was important in developing the queen post truss and transmitting a knowledge of these forms to his assistants and carpenters.

Through a study of eighteenth century drawings, surviving roofs and contemporary carpenters' manuals, the study also explores the level of structural understanding during this period.

"... the House may now have leave to put on his hatte: having hitherto beene uncovered it selfe, and consequently unfit to cover others. Which point though it be the last of this Art of execution, yet it is alwayes in Intention the first, For who would build but for Shelter."

Henry Wotton, The elements of architecture, 1624

C O N T E N T S

PREFACE

Between the timber buildings of the middle ages, that relied upon traditional craft techniques, and the structures of the professional engineers in the nineteenth century, new structural forms were introduced. The period during which this development took place has not received the same attention from historians of building as the periods before and after. The circumstances surrounding the introduction of these new forms has not been investigated and their origins remain obscure.

The purpose of this study is to trace the development of the 'modern' king post and queen post timber roof trusses during the seventeenth and eighteenth centuries. Before this period roof structures relied upon members working simply in bending or compression. The forms adopted were dictated by tradition and showed marked regional variations. During the seventeenth century professional architects introduced the true king post roof truss. This true truss form, ie. one that used members acting principally in tension and compression, was, together with the queen post truss, to have completely replaced the medieval roof structures by the end of the eighteenth century.

These structures were developed and became established before the use of structural mechanics was available for their analysis. It was not until the end of the eighteenth century that the behaviour of the king post truss was explained and formal techniques of structural design were not developed until the nineteenth century. The spread of these roof forms was not therefore, necessarily accompanied by an understanding of their behaviour and a component of their history is the extent to which these structures were understood.

With the extent of the period to be covered, the scope of the study has to be limited to the major events and phases of development. The principal innovators will be identified, their sources, the forms that they used and their possible influence. Comparisons will be made between major figures of the period to give an indication of the general levels of structural understanding. The source material used is chiefly the major buildings of the period, contemporary drawings and the text books available at the time.

The choice of the period for study has been made from a consideration of the existing literature on structural carpentry. There is extensive material available on the development of vernacular buildings. The study of these has been concerned essentially with the development of their structures as constructional types and there has been little attempt to understand them simply as structures (1). Nevertheless, because many workers have concentrated on particular geographical areas or particular framing types, our collective knowledge of structures of this period is extensive and the chronology of the various types is fairly well established.

Work on the nineteenth century has been largely concerned with the development of structures in iron. This period has naturally tended to attract the attention of engineers interested in the history of their own field who are looking at the forerunners of our modern building types and the birth of civil and structural engineering as we know them today (2). While timber structures of this period were becoming less important, the forms that were in use had already become well established and the developments during the nineteenth century were less significant than those that had taken place in the century and a half before. Moreover, the wide span truss roofs built of iron owed their birth to the earlier development of timber trusses.

For the intervening period there is almost no secondary source material on the development of structures, and what there is, only peripherally touches on the problem at hand. During the latter half of the seventeenth and during the eighteenth centuries both the king and queen post trusses were established in this country. Studies of engineering history however have largely neglected this type of structure. Work has been done on the development of bridge structures, on civil engineering works and on the development of structural theory (3). Histories of architecture have been concerned with the development of architectural tastes and the lives of the architects responsible. We know very little about the process of building during this period. Jenkins (4) has dealt with the relationship between the architect and his patron but we know very little about the relationship between the architect and building tradesmen. We know a great deal about the development of building fashion but little about building construction of the time.

This absence of secondary material presents a difficulty because there is no pre-established framework from which to begin. At the beginning of this study all that was known was that somewhere between the traditional structures used before the seventeenth century and the developed trusses of the nineteenth century, the king and queen post trusses appeared. It was necessary to search for the beginning of the truss form and then to determine a point at which one could say that it had become firmly established; the time when it was being widely used and its behaviour was fairly well understood. Between these two periods a framework could then be set out describing the major features of the intervening development. The result has been that the period actually covered is about a century and a half and such a long period requires an explanation if not an apology.

The king post truss first appeared in England in the mid seventeenth century. If attention had been concentrated on this form of truss then the study need perhaps only have gone as far as the mid eighteenth century by which time the form was in fairly general use even though its behaviour was not necessarily well understood. However by the beginning of the eighteenth century the major architects had developed and used forms of queen post truss. These were used in some of the most important public buildings of the period so that the story of structural design at the time would be incomplete without some discussion of this type of structure. Its development was much slower than that of the king post truss however, and it did not begin to appear in the form in which it was eventually used until the mid eighteenth century.

At the end of the seventeenth century the architect/scientists who were responsible for the most rapid development of the king post truss were well aware of its mode of behaviour. However the following generations of architects did not have the same level of understanding, as the text books of the period show, and it was not until the end of the eighteenth century that the same level of understanding was again seen (by which time the queen post truss was beginning to rival the king post in popularity). Thus for two reasons the end of the eighteenth century provides a useful terminal point.

The absence of secondary material also presents problems of methodology;

problems that are also partly a function of the nature of the material being studied.

The studies of pre-seventeenth century vernacular architecture are concerned almost exclusively with an examination of the buildings themselves. Little documentary evidence survives and what there is, is largely in the form of building contracts (5). We know little about the process of design or the difficulties of construction except what may be deduced from an examination of the forms and constructional details of surviving buildings. Given this material one must seek one's explanations for the various forms in the light of the problems of construction (6), the availability of structural materials (7), the cultural background (8) or the social aspirations of their builders (9). The explanations given will depend almost as much on the stance adopted by the particular researcher as upon the nature of the available evidence. In the absence of sufficient documentary evidence, the explanations must be archeological rather than historical.

In contrast the nineteenth century provides a wealth of evidence for the historian. Besides the surviving structures, documents exist in the form of contracts, notebooks, accounts, drawings, and even contemporary textbooks contain material that may allow us to reconstruct the form of structures that have since been demolished. In between the two periods the nature of building gradually changed from one relying upon traditional methods of construction and design, through a period dominated by amateur architects, until architecture became an essentially professional activity. Thus not only the nature of building but also that of the evidence available changes throughout the period. The availability of drawings and other documentary evidence varies and so the nature of the explanations one can provide will depend at each stage upon the nature of the evidence available for use.

The sources drawn upon in this study vary in availability, in the quality of information that they contain and their reliability. These have all influenced the method of working. Therefore at this stage the usefulness of the sources and the problems that they present must be considered.

Tracing the development of the forms of the roofs in the surviving buildings would seem to present less of a problem for the period of this study than for vernacular buildings. Although the time intervals between the events are shorter most of the buildings can be dated with correspondingly greater accuracy. However there are some buildings where work during the period in question comprised additions or major alterations to earlier buildings. Moreover alterations and repairs may have been made to a building at any time after it was built, so that the date of building provides only an 'upper bound' to the age of the structure. In these circumstances some judgement must be exercised in looking at a structure to determine whether or not it is the original. This may be judged from the condition of the timbers, the general form of the structure and the detailing used.

In using the form of the structure as an indication of its age one is using the general pattern of structural development with which this study is concerned to make an assessment of the probable date of an individual roof. Similarly the use of carpentry details as an indication of age depends upon a chronology of jointing techniques developed during the study. There may thus appear to be some circularity in the argument but the use of these dating methods is simply to identify cases where there has been a re-roofing of the building. It relies upon the much larger number of cases where the structure can be accurately dated and has only been used to separate events of about fifty years apart (10). Whether or not increased knowledge will enable these methods to be used to separate closer events is doubtful (11). A chronology of the development of roof forms and carpentry detailing will be discussed in chapter 1.

Drawings might provide more surely dateable source material than the building structures but taken alone they are an unreliable guide to the development of structural ideas. While to some extent earlier drawings are less available today than later drawings this pattern is affected by the collections of notable architects which affect not only the rate of survival in a given period but also the nature of the material that has survived. The collections that have survived may not be representative of the kind of structures nor even the kind of drawings being generally produced at the time. The earlier drawings (in fact most of the drawings examined in this study) tend to be project drawings rather than design drawings and in a number of cases they can be shown to differ from the structure as built. The design of the building may simply have changed, the carpenter may have had different ideas from the architect or the drawing may only include a notional indication of the structure rather than a well considered and serious proposal.

If these problems make the interpretation of architects drawings difficult, similar problems occur in using the drawings in the available books of the period. Some of these are measured drawings of structures 'as built', while others are suggested designs for carpenters to follow in the framing of their roofs. However the former may be inaccurately drawn and the latter are often impractical. Thus both architects drawings and text book drawings have to be interpreted in the light of what is known about the actual techniques of construction of the period, and discussion of the reliability of particular drawings will occur in a number of cases. However, in spite of the difficulties that they present, it is cearly desirable to use both sources of drawings to supplement the survey of surviving roofs. The losses of earlier roofs would make tracing their development a daunting task if there were no drawings available, and in the later period of the study, when the drawings are more reliable, they enable a larger 'sample' to be obtained, thus simplifying the problems of personal inspection.

Written documents must be considered as of largely secondary importance in this essentially visual subject. However they are by no means unimportant. The material occasionally, if rarely, provides a description of a structure which is sufficiently detailed to enable its form to be reconstructed. More often one may be able to date a structure or identify the craftsmen involved. Sometimes documents show the method of working, indicating whether the design is to be ascribed to the carpenter or to the architect. There are also instances where the degree of structural competence or interest in the problems of construction generally is shown in architects' notes.

The selection of buildings for study deserves some consideration. Initially it was assumed that the new forms of roof truss might have made their appearance in the work of Elizabethan architects. The survey of buildings thus began with the work of Robert Smythson and was then extended forward, through the seventeenth and into the eighteenth century. The survey of buildings of the middle and late eighteenth century was needed partly to provide a parallel study to complement work on the text books of the period, and partly to deal with questions that arose in the course of the work. For the earlier buildings the choice lay naturally among those large enough to have long spans, ie. spans which would require abnormally large timbers if simple bending in the tie beam was relied upon. They were thus buildings where the trussed roof offered advantages and so might have been used. This limited attention to the larger country houses, to public buildings and churches. However by the time when church building provides an important source of material, (after the fire of London and into the early eighteenth century) some of the more important figures were emerging and a more careful selection of buildings was possible. The early indications were that the centre of the new structural ideas was among the London architects and carpenters, and work has thus been confined to English examples (12).

Once the initial building surveys had established that during the seventeenth century the use of the trussed roof was confined to the major architects, their buildings and the works of their known associates were selected for examination. The direction given by the study of this early part of the period also influenced the material selected from the later part of the eighteenth century. The focus remained upon the work of professional architects. This was partly encouraged by the increasing availability of contemporary drawings. However such a direction raises the problem of whether it has been possible to provide adequate general coverage of the buildings of the period in a study which, of necessity, must be carried out in a limited period of time. There must be some selection among the questions that can be asked as well as among the buildings chosen to provide answers. Confining attention to professional architects has meant that there has been almost no attention paid to the work of anonymous carpenters in order to trace their adoption of the new roof forms. To attempt a study of this kind would require a much more extensive study than was possible here (13).

Even confining attention to professional architects involves some selection and this naturally means that more light will have been shed on some areas than upon others. The result is that the picture presented is of varying depth. However in a single study of this kind it is not possible to cover all the ground at the same depth and the quality of the overall picture depends upon the areas that have been selected for closer examination and the depth to which these have been taken. The selection has been a matter of judgement and the correctness of this will only be determined in the light of any future work that may be carried out on this subject.

It is customary at this point to acknowledge the help one has received. To mention all those who have helped me in carrying out this study would mean providing a long and tedious list and I must confine myself to generalities. There are those who have helped with my field work, the owners of buildings who kindly allowed me to crawl round in their roofs (14) and often provided the services of their staff to assist me, the administrators of publicly owned buildings who also welcomed me and the caretakers or clerks of works and architects who accompanied me in my vertiginous expeditions and often shared my interest in the subject. There are those who helped in my searches among the documentary evidence, the staff of a number of record offices, the staff at the R.I.B.A. and other collections of drawings and those who helped in searching for or identifying particular records. And there are those who helped with the writing, who offered initial advice and guidance, directed me towards particular pieces of evidence, provided translations, helped in interpretation and finally read what I wrote, made corrections and offered suggestions for improvement. Recognising my debt to all these I have attempted wherever possible to acknowledge particular contributions in the footnotes.

Notes

1. For a review of the structural aspects of vernacular carpentry see Yeomans (1975).

2. Much of the recent work in this area is to be found in Transactions of the Newcomen Society. However, for a concise review of early work on structural iron and concrete see Sutherland (1976).

3. Reviews of this development are to be found in Straub (1952) and Mainstone (1975).

4. Jenkins (1961).

5. The documentary evidence for this period is given by Salzman (1952).

6. Howard (1914).

7. Clifton-Taylor (1972).

8. J T Smith (1957)

9. Mercer (1975).

10. An example may serve to illustrate the use of this method. Brackley Town Hall is dated in Pevsner's Buildings of England to 1706. The roof depends upon queen post trusses, unusual for this date but possible. However, the way that the purlins are carried over the backs of the principals and the type of metal fixings used at the feet of the posts shows that the present roof cannot be earlier than the end of the eighteenth century although no records survive to show that the building has been re-roofed.

11. Hewett (1974) suggests a date before 1700 for the nave roof based upon the type of bolts used in the roof trusses. However, the Victorian County History shows the roof to be built in 1720. As one type of fixing replaced another, it did so over a period of time and not as a single event.

12. I recognise that some of the architects of the period were Scottish and that major buildings were built in Scotland but for convenience the survey was limited to the much larger number of English buildings available.

13. It was thought desirable to look at one area in greater detail to see whether anything resembling a regional style had developed in the use of the new truss forms during the early eighteenth century. Buckinghamshire was chosen partly because this is close enough to both London and Oxford to have been influenced by the new structural ideas fairly early. The results were negative.

14. There were some buildings which I was unable to obtain permission to survey. In some cases this has created gaps.

METHODS OF ROOFING

A study of English roof construction must begin with at least a brief discussion of the form of medieval roofs. Not only is this the background against which the new forms of truss were developed but among the traditional roof forms are two types which are superficially similar to the new types of truss and which have to be distinguished from them. A full description of the many different traditional roofs, their structure and construction is a major subject in itself and has been dealt with by others (1). Rather than go over this ground, I propose to outline one or two of the important types of roof that have some bearing on the content of this study. It is then necessary to sketch in outline the development of the new types of truss which will be examined in detail in subsequent chapters.

Open roofs

Although this study is concerned with the development of the king post and queen post trusses, roofs which have been given these names existed in the middle ages.

The problem for a roof of any reasonable span is to prevent the rafters from sagging under the weight of the roof covering. This may be done by providing bracing within each pair of rafters. 'Single framed roofs' structured in this way seem to have remained common in France into the seventeenth century (2) but were replaced much earlier in many parts of England by side purlin or 'double framed' roofs. In these the common rafters are supported at one or more places between ridge and eaves by purlins. These members are in turn supported by roof 'trusses'. In the truss the purlins are carried by principal rafters and again it is necessary to provide some assistance to these members to prevent their sagging under the concentrated load from the purlins. This may be done in a number of ways, the simplest being to strut each pair of principals with a collar (fig. 1.1,a). Other arrangements have the principals strutted from the tie beam (fig. 1.1,b & c)

The other function of the tie beam besides supporting the struts was to prevent the spread of the principal rafters and of the wall plates, the latter restraining the outward thrust of the common rafters. Pegged mortice and tenon joints at the feet of the principals prevented their outward movement while the wall plates might be secured by lap-dovetail joints (fig. 1.2). Thus, although bending under the load from the struts produced the major stresses in this member, it also acted in tension. However, it was the only member of the roof truss to do so and all the other members were in compression or bending.

The precise details of the early form of queen post truss varied with the regional traditions of construction but it is only necessary to describe a typical arrangement here. A pair of vertical, or nearly vertical struts, supports by a collar (fig. 1.1,b). This in turn strutted across between the principal rafters. The collar was an essential element of this arrangement because without it the posts would tend to be thrust inward at their heads by the deflection of the principals. Although called a queen post truss the extent to which the load on the principal rafters is carried by these posts is questionable. A considerable proportion must be taken in the collar thus lessening the load to the tie beam. In a long span roof with more than one pair of purlins, additional support would be provided with further braces standing on the collar. At the apex both principal and common rafters were joined together without any ridge piece.

The king post truss has a more northerly distribution than the queen post roofs. In this type of structure the king post standing on the centre of the tie beam (fig. 1.1,c) carries a ridge piece or ridge purlin to support the upper end of the common rafters. Now, with no collar, the struts must be steeply inclined to resist more effectively the load from the principals and they thus rest on the tie beam close to the foot of the king post. Although both these roof structures are called trusses neither is a true truss in the sense that the tie beam is trussed up by the posts (see Appendix 1). It is quite clear that in both arrangements it is the tie beam that carries these posts and thus takes most of the roof load in bending.

Roofs could be built without a tie beam if the outward thrust could be contained in some other way. This was possible by relying upon the stiffness of stone walls but it was still desirable to stiffen the principals to assist them in carrying the purlins. This was done either with a collar, with arch braces or a combination of both (fig. 1.3). A development of the arch braced form was the hammerbeam roof although used more for its decorative than for its structural qualities (3). Although this type of structure is not of major concern to this study it should be mentioned in passing because it seems to have been the only aspect of structural carpentry that some architects thought worthy of attention. Although they are hardly structural drawings, the only drawings of roof structures that survive by both Robert Smythson and John Thorpe are of hammerbeam roofs (4).

The hammerbeam roof was the finest of the decorative roof forms for both the hall and the church. It was such a powerful decorative form that Smythson even used it at Wollaton where the ceiling was no longer the underside of a pitched roof. Instead, his hammerbeam 'roof' is a false structure suspended from the floor above (5). During the eighteenth century James

Smith (6) published a book consisting of little more than a collection of drawings of hammerbeam roofs. The Brandons (7) lavished attention on the form and it was to be used by a number of Victorian architects.

Instead of eliminating the tie beam it could become the only transverse structural member and the flat lead covered roof carried on tie beams and purlins became a feature of English churches. Salzman (8) suggests that its popularity here may have been due to the availability of lead in this country. Flat roofs are less common on the continent where there is not the plentiful supply of this matterial. Whether or not this suggestion is correct, lead roofs were frequently built as replacements on churches that originally had steep pitched roofs. This is evident from the scars left on the towers of so many churches marking the position of the original slate or tile roof.

Thus, before architectural ideas were imported from Italy and the roofs of country houses were made to disappear behind parapets, flat lead roofs had already been used in this country for scores of country churches. Some roof slope had still to be contrived to throw off the water and in church roofs a wide variety of arrangements were used. Tie beams could be cut to give a natural camber, the purlins could be notched in at different heights or they could be raised at different heights above the beam on short pieces of timber. In any event the roof timbers would be left exposed. In medieval buildings similar kinds of open roof framing, whether single framed or double framed, are found in different building types. In Kent crown post roofs were used in houses and churches as well as barns. The side purlin roof types offered greater scope for decorative treatment and the more advanced structures like arch braced roofs were confined to the hall or church. Simple king and queen post roof trusses may be found in churches and domestic buildings as well as agricultural buildings. In the latter they continued to be used well into the eighteenth century. Meanwhile in domestic buildings the hall with its open timber roof ceased to be fashionable (9). Architectural developments during the seventeenth century involved changes in both the planning and elevational treatment of buildings that created new structural problems.

Structure and building plan

The overall planning of most roofs throughout the seventeenth and eighteenth centuries was fairly simple. There was not the relationship between the planning of the house and its structure that one would expect to see in buildings of today. The outward form of the house and its internal planning were only loosely connected. In the simplest structures trusses would span between parallel external walls. In double pile houses or houses with a central enclosed staircase there might be one or two internal walls parallel to the long external walls. There would thus be two or more trusses between the front and rear elevations. The trusses might be framing simple pitched roofs with valleys between or there might be flat lead roofs or multiple pitched roofs.

Within these simple structural arrangements the internal planning could be fairly free. Transverse internal walls were non loadbearing. Those on different floors might not be aligned, hence the need for trussed partitions. Examples are also found of rooms on the same level in buildings which are of different heights. Voids would then have to be left within the building so that the floor above, or the roof, could be kept level.

The structure of most houses of the period cannot therefore be determined easily, simply by looking at their plan. Indeed the very simple structural arrangements would have allowed the plans to be changed during the construction of the house if desired. They also allowed subsequent changes to be made relatively simply, either to the roof structure or to the layout of the rooms underneath; in the latter case possibly leaving the original roof unchanged. Within the shell of the building where we may expect to find loadbearing walls there might only be partitions. Nothing can be taken for granted. Columns may be supporting nothing. At Holkham for example, the marble columns of the hall appear to be supporting the plaster vaulted ceiling whereas it is in fact simply slung from the roof trusses above.

Structurally the simplest kind of roof is a 'flat' lead roof carried by tie beams. Boarding to support the lead rests on rafters and purlins with the purlins supported on heavy principal rafters. To provide some slope these are propped up from the centre of the tie beam by a short post. The beam thus carries the ceiling and part of the roof weight as a point load in the centre. Roofs of this kind were used where the roof was to be hidden behind a parapet.

Robert Smythson used this basic layout at Hardwick Hall, although because of the deep plan of the house, the 'tie beam' is in two parts and supported near the centre of the house by the main internal load bearing wall. Thus, although the principal rafters are strutted from the beam, the latter only carries the ceiling loads. The effective span of both tie beams and principal rafters is about 35ft. At Doddington he seems to have used the same formula although no intermediate support was available and the tie beams are thus in one piece (10). Although the span (25ft) is less, the structural problem is greater because both roof and ceiling loads are taken by the beams. Presumably Smythson used the same arrangement in his other houses. Structures of a similar kind were used at Burghley

House and by Webb at Wilton over the cube and double cube rooms.

The disadvantage of this structural arrangement is the large size of timbers that it requires. The beams at Hardwick approach 18ins x 24 ins. Although Airs (11) doubts the general thesis that building timber was becoming scarce by the end of the sixteenth century, it seems clear that timbers of this girth and length could never have been readily available. Certainly they must have been becoming scarce by the end of the seventeenth century for by that time the use of imported fir (rather than oak) and scarfed tie beams in trussed roofs was not uncommon. Apart from their scarcity, the difficulty of hoisting such large timbers must have made any structurally satisfactory alternative more attractive. Eventually two structural arrangements were to appear which solved the problem, both having roofs raised sufficiently to accommodate a deeper structure but still low enough to be hidden behind the parapet. Both solutions involved trussing of some kind and a discussion of these structures is more appropriate after considering the introduction of the truss.

Apart from the flat roof, the other major change of roof form that was introduced at this time was the use of the hipped roof. Just as with the flat roof, the hipped roof had been used before but the new ideas of architectural style required a more extensive use of the device. Field and Bunney (12) in discussing the work of Inigo Jones point out that:-

> ".... when the cornice is returned in an unbroken line round the sides of the building, it is necessary if a roof is to be retained, that it should be hipped back from the angles. It is this particular feature of a crowning cornice returning round at the eaves line with a steeply pitched roof rising immediately from it, and the consequent hipping of the roof, that marked

distinctly the change in outline, which is the radical difference between the renaissance buildings ... and not only the preceding Gothic and Elizabethan houses but also contemporary Palladian buildings of a larger scale in which the roof was disguised as much as possible ...."

Field and Bunney are distinguishing between large houses where the roof is to be concealed behind a parapet and smaller houses where the roof is to be a feature. The hipped roof was made an important feature in a wide range of sizes of house, from smaller town houses like Fenton House, Hampstead to large country houses like Uppark, West Sussex. As these examples indicate, the form, while established in the seventeenth century, continued to be used into the eighteenth.

The construction of these roofs was often influenced by the need to use the roof space for attic rooms. This meant that dormer windows also had to be provided; another feature that derived from the use of the continuous cornice as Field and Bunney also point out:-

".... whenever rooms in the roof required light or ventilation it had been a simple matter to run up a gable end in which the required opening would be placed, but now if a cornice should properly perform its dual function of the finish of the wall surface and the base of the roof, clearly it would not do to break the horizontal line with a wall surface rising out of the cornice .... the use of the dormers thus became a necessity ..... such a roof treatment is not a direct outcome of the Italian renaissance, it is rather an adaptation of Gothic tradition to the new decorative ideas ....." (13)

The problem with a house with a deep plan was also keeping the roof height to reasonable proportions. In the double pile Elizabethan house the central wall dividing the two ranges of rooms could be used to carry the roof structure. Thus the simplest roof form was to use a simple pitched roof over each range. This kept down the overall height of the roof although it did result in a central valley that had to be drained by gutters through the roof space to the outside walls. The Vyne, Hampshire is an example of such an arrangement, and has simple king post roofs.(14). Ham House, near Richmond, a later house with hipped roofs, uses much the same device although here there are attic rooms lit by dormers. This is not apparent externally because the dormer windows look inward on the central valleys. To provide for the attic rooms the roof is framed with collar braced principals; the collars giving minimum obstruction to the rooms.

Arranging the roof in this way does not give the maximum space in the attics and a much better layout is achieved by carrying the central wall up to the height of the collars. Greater overall height is achieved in the rooms but now the dormers have to face outward for light. This is the arrangement proposed by Webb for Lamport Hall (fig. 3.9) and used in a number of other houses. The principle could also be adapted for smaller town houses. The roof plan of Fenton House, Hampstead is basically a square. Attic rooms face outward on all four sides of the house and the walls are brought up on the inside to enclose the staircase, form the rear walls of the attic rooms and carry the inside member of each pair of rafters, commons as well as principals. In cross section this basic arrangement is fairly adaptable. In the examples given so far the joists of the attic rooms are carried by the wall plate and fixed to the feet of the common rafters. (fig. 1.4). A purlin carries the ceiling joists. Thus the tie beam to the principals also forms part of the floor structure.

The amount of roof space taken for the upper rooms could vary. At Forty Hall, Enfield, the attic storey borrows very little volume from the roof. There is simply a raised tie beam supporting the ceiling structure providing slightly increased height in the rooms whose windows are in the main walls of the house. Principals which had either raised tie beams or just collars could thus be used to allow rooms on the top floor to have raised, or occasionally vaulted, ceilings.

The disadvantages of multiple pitches was that they too left a central valley, or a central well if the building had a square plan. To avoid the problem of draining these, many buildings have since had their roofs altered with timbers spanning across between the ridges to carry flat lead tops (15). At Ashdown this was done at the time of its building in order to provide a platform to surround the cupola. However a more common way of providing such a flat top was simply to arrange pairs of beams spanning between the principal rafters (fig. 1.5). This is the basis of the structures at Hall Barn, Buckinghamshire, in part of the roof of the pavilions at Wotton House in the same county, at Stanford Hall, Leicestershire and at Sudbury Hall, Derbyshire (16). Although a widely used layout, the weakness of the structure for large buildings is the reliance placed on the bending strength of the beams.

It should be made clear that, although new architectural ideas were widely adopted, similar architectural forms might be built using quite different structures. Abingdon Town Hall and the Customs House, Kings Lynn, both use the flat topped roof with attic rooms, slopes hipped at the corners and dormer windows. The Customs House roof is structured like that of Hall Barn with pairs of beams carried by the principal rafters, while at Abingdon, deep trussed partitions have been used (17) which support the roof and cupola and separate the rooms of the attic.

The new architectural ideas both increased the span that was later required of roof structures and reduced the slope that was fashionable. Sir Roger Pratt discussed the new forms of roof that were being used by the end of the seventeenth century (18):-

> "..... the most comely, useful and strong .... is called a la Cantelavra; the most comely because the depth of it is most proportionable to the whole, and the slope of it is more artificial than what was formerly known....
>
> "These I find none so graceful as when those of a double pile are made both into one, the tops of both becoming one flat ...."

<u>The new trusses</u>

Framing the simple pitched roofs could be done without difficulty using the traditional roofing methods. Using tiles or stone slates the roof pitches were steep, 45° or more, and simple collar braced principals were often adequate for the short spans. The pedimented roof with its much lower pitch requires some other form of structure unless it is to rely upon strutting from the tie beam. The new structure was provided in the form of the king post roof truss. In this the struts which assist the principals in carrying the load from the purlins rest on the foot of the king post rather than upon the tie beam. To carry these the king post was widened at its foot to form 'joggles'. (fig. 1.6) The thrust from the struts tends to push the post downwards. However joggles are also formed at the head of the king post so that it is trapped by the principals and so supported by them. The king post is thus in tension. With this arrangement no force from the roof comes onto the tie beam which thus only has to act as a tie restraining the outward thrust from the principal rafters and as a beam to carry the ceiling load.

The king post truss may be seen as a timber arch. Indeed this is how it may have been seen at the time. The arch comprises just two main members standing on the tie beam with the joggled head of the king post forming the 'key stone' of the arch.

Inigo Jones used this type of truss, or variations on it, for the Banqueting House, Whitehall, for St Paul's, Covent Garden, and for the pavilions of the house at Stoke Bruerne. Only the last of these survives but we know of others from later measured drawings. Inigo Jones' own drawings suggest that he may well have used variations on the same basic theme for all his buildings. The drawings of his pupil and assistant John Webb show that he also knew of and used the king post truss. However any further influence that these two architects may have had was curtailed by the civil war. After the restoration, when quite different architectural tastes prevailed it was Wren who was to develop the use of trussed roofs and who, through his assistants and carpenters, was responsible for its dissemination. Wren developed the basic form to include the addition of secondary posts; pairs of tension members supported by the inclined struts which allowed the trusses to span much greater distances because additional support was given to the tie beam (fig. 1.6b).

Where the roofing was carried on common rafters, the purlins were butted against the side of the principal rafters and fixed with mortice and tenon joints. These were commonly staggered although 'in line' purlins are also found. The advantage of staggering the purlins was that two mortices were not cut out of the principal at the same point which would weaken the member. However,if the purlins could be framed into the principals close to where the struts from the king post supported them, there would then be almost no bending in the principals.

At this time close spaced purlins of light scantling were also being used. These spanned between the trusses and carried the roof covering without the use of common rafters. This arrangement was used by Inigo Jones and Wren and was to continue in use into the first half of the eighteenth century. For substantial buildings the roof covering consisted of a layer of diagonal boarding over the common raters (or close purlins) with slates over.

The other structural form used by Wren was the queen post roof truss. This works in much the same way as the king post truss except that the arch of timbers is composed of three members, the principal rafters and a 'collar' or 'straining beam' supporting between them two posts (fig. 1.7). The queen posts truss up the tie beam and may also carry inclined struts that help the principals and the straining beam to carry the roof load. Wren used the device to form roofs with flat lead tops, supported by the straining beam, with steep slated sides. This arrangement was used on a number of London churches and for the roofs of the Royal Hospitals.

These king post and queen post trusses were not traditional roof structures nor is it easy to see how they could have been developed from the earlier forms since they work on completely different principles.

We have thus to ascribe the new designs either to the invention of

Inigo Jones and Wren or assume that they copied the forms from elsewhere. The origin of these structures will be discussed in subsequent chapters but it must be noted here that these two architects were not the only ones to introduce trussed roofs into the country.

Both king post roofs and crown post roofs were built during the middle ages with the heads of the posts widened to receive the principal rafters, or braces to the crown posts. The king posts carried ridge purlins, the crown posts collar plates. This widening of the posts was almost certainly to enable mortices to be cut to accommodate both the longitudinal member (ridge purlin or collar plate) and the inclined members.

Superficially, the inclined members might appear to be trussing up the post but even if such a truss action were developed it is very doubtful that it was intentional. Certainly the earlier use of this form might have made it easier for carpenters to adopt the new king post truss but these early structures are an improbable source for the later type. The widening of the head of the posts in the medieval form was achieved by a gradual splaying rather than by a sharply defined joggle. Moreover the new king post truss appeared in areas where collar braced principals or queen posts were the more common traditional forms.

Following the work of Wren, trussed roofs continued to be built and the structural forms were further developed by Hawksmoor and the carpenters who had worked on buildings by these architects. However knowledge of the roof truss in the later seventeenth century seems to have been confined to relatively few architects and craftsmen: only those who had some direct contact with the innovators of the forms. Meanwhile the traditional types of roof framing continued to be used.

A boost was given to the development and spread of the king post truss when James Gibbs used the form in his buildings and illustrated it in his Book of Architecture (19). Gibbs had trained in Italy and had come to England with a knowledge of the king post truss rather than having acquired the knowledge from the work of English architects.

Gibbs' book was not the only one to contain drawings of roof trusses. After the first quarter of the eighteenth century a number of text books on carpentry appeared (20). These provided instructions on the setting out of carpenters' work and gave details of framing arrangements for roofs. However they were not always reliable and some care must be taken in assessing the value of the material they contain. They contain illustrations of roof trusses and trussed girders which may be either drawings of roofs as framed, recommendations as to what was good practice or simply inventions of the author which may or may not be practicable; more commonly the last of these three.

These text books do however show the kinds of roof that might be found. The truss was not always used to frame simple pitched roofs. The use of the queen post truss by Wren to form a flat topped roof was not the only way of covering a building which had a deep plan. Moreover as in earlier years there were buildings where the architectural requirement was that the roof be hidden behind parapets. For these buildings king post or queen post trusses could be used to form either flat lead roofs or roofs with multiple pitches.

To form a flat lead roof, king post trusses of relatively shallow pitch could be used. These spanned from external walls onto internal structural walls (or possibly between internal walls). Beams then spanned between the heads of the king posts, in the same direction as the tie beams of the trusses. (fig. 1.9) Joists to support the roof covering were framed into these beams. Examples of roofs of this type are found at Chicheley, Buckinghamshire; Ditchley, Oxfordshire and Badminton, Gloucestershire. Shugborough, Staffordshire has a flat lead roof on a basically square plan, carried on queen post trusses which span between the external and internal walls (21).

Multiple pitched tile roofs could be formed with simple coupled rafters. Long spanning trusses, either king post or queen post types carry beams which span between the trusses at right angles to the tie beams. These beams are carried on the heads of the king or queen posts or on the straining beams of queen post trusses. The beams then act as plates on which the rafters stand. The internal gutters formed by this arrangement are thus higher than the outside gutters over the external walls and commonly drain to the ends of the roof where the multiple pitches are completed with hips. An example of this type of roof is found at Claydon House, Buckinghamshire but a variation on this theme found at Osterley Park House uses trussed girders instead of simple trusses. Another example is shown in fig. 5.1.

Trusses were being used in multiple pitched roofs not for the shape that they provided for the outer covering but simply for their capacity to carry loads over a long span. The truss was just another form of beam, albeit a beam of much greater than normal depth, capable of spanning further than a simple solid section of timber and certainly capable of carrying much greater loads. An extension of the use of the truss in roofs as a support to the ceiling below was its use in supporting floors. The truss as a self supporting partition was widely illustrated in eighteenth century text books, although because they are now hidden within the fabric of the building it is difficult to know how common these trusses were or what form they normally took. The illustrations in the books show such trusses based upon both king and queen post forms. Eventually such partitions were also used to carry the floor structures but it is not clear how early this practice was introduced (22).

By the nineteenth century the queen post truss was being used to frame simple pitched roofs of the same external form as those framed with king post trusses. To achieve this, long principal rafters were placed above the principal rafters of the truss (fig. 1.8). These might carry a short king post standing above the straining beam. Although there were some developments towards the use of this arrangement during the first half of the eighteenth century, it did not appear extensively in the form described until late into the second half of the century. Its development was naturally slower than that of the king post truss because by the time it was being developed the king post was already established and provided a satisfactory solution for most problems.

By the end of the eighteenth century the scope of structural problems was increasing. Structures were being needed for greater spans and to carry greater loads. By this time also there were a number of architects with the structural knowledge and understanding not only to use the truss forms that already existed but also to develop them further. At the same time there were other architects whose drawings showed either an ignorance of, or a lack of concern for, structural matters. There were no developed theories of structural behaviour which would have assisted in the understanding or the design of these structures. The published text books for carpenters offered no explanation of the behaviour of roof trusses and it was not until the works of Peter Nicholson that a scientific approach was adopted to the design of structures and a satisfactory explanation provided of the mode of action of the king post truss.

Carpentry details

While there were developments in the overall form of trusses there were also changes in the details of the carpentry throughout the period. The essential features of the king post truss are the joggles at the head and feet of the king post, the joints between the principal rafters and the tie beam and the fixing of the tie beam to the king post. It is convenient to treat the variations of each of these in turn.

At the foot of the king post simple splayed joggles were commonly used but an alternative was to use square cut shoulders to receive the ends of the struts (fig. 1.10). These allowed the joggles to be cut from a smaller section of timber. For both forms of joggle the struts were tenoned into the post.

At their feet the principals must transmit the outward thrust to the tie beam. This could be achieved by the timber joint alone but some carpenters arranged the ends of the principals to kick against a metal strap which was in turn bolted to the tie beam (fig. 1.11b). Where the force was to be carried by the timber alone a problem was to hold the principals down to the tie and prevent them from kicking up. A simple way of preventing this was simply to bolt the principals down. This detail is difficult to see because the top of the bolt is covered by the roof and the nut at the bottom by the ceiling. The alternative was to have a simple metal strap, and this has been the most commonly used detail in the roofs examined. (fig. 1.11 a & c).

From the introduction of the king post truss almost to the end of the eighteenth century, the only way of trussing up the tie beam to the king post was by using a metal strap. The top of this strap was normally fixed to the king post with a staple, restrained by a fold in the strap. This was presumably intended only as a temporary fixing for the strap; it could after all have withstood little force. The permanent fixing was for some time made with bolts. Initially these were 'forelock' bolts (23) - essentially a long pin with a slot in the end that enabled it to be tightened with an iron wedge (fig. 1.12). This method of fixing lasted throughout the seventeenth century and into the eighteenth when it was eventually replaced by simple carriage bolts. However, the existence of one fixing or another cannot, unfortunately, be used as a way of dating a roof precisely. Wren was using carriage bolts in the roof of St Paul's in the late seventeenth century while forelock bolts were used in the reroofing of the nave of Tewkesbury Abbey in 1720. Thus there was some overlap of these two details (24)

A bolt is not a particularly satisfactory device because it cannot be used to tighten the strap against the underside of the tie beam. It is essentially passive. Towards the end of the eighteenth century a more active fixing was introduced that allowed the tightening of the strap. This used folding wedges. By forming the strap with rectangular holes wedges or cotters could be driven in from either side against gibs (fig. 1.13b & d) in order to tighten the whole assembly. This involved an improvement in metalworking. Previously the hole for the bolts had been formed by heating the rectangular metal strap and driving a spike through to open out the hole. Now a purpose made strap had to be made, which was widened to accommodate the rectangular slot.

This device was eventually replaced with a simpler fixing. A rectangular hole was formed at the base of the king post to contain a square nut. A bolt passing up from the bottom of the tie beam and into this 'caged' nut could then be used to tighten up the joint (fig. 1.13a). This became the commonly used arrangement during the nineteenth century.

Occasionally trusses are found without any metal strapping at the foot of the king post but these are unusual. They must rely for the trussing of the tie beam on the soundness of the mortice and tenon joint. However, even where a metal strap is used the truss may be relying more upon this joint than upon the strap. A difficulty occurs where the tie beam is wider than the king post used. A strap simply passing round both has to be bent inward from the top of the tie beam to the fixing at the post. Any tendency for the joint to open out would tend to straighten the strap whose stiffness is almost certainly less than that of a properly made timber joint. A much more satisfactory arrangement was to prepare the mortice so that the strap could be let in through the tie beam (fig. 1.10). Clearly for this to work the mortice hole must be blind.

At its head, the king post must be shaped in such a way as to receive the ends of the principal rafters and transmit the downward force to them. This can be achieved by simply cutting a recess in the head of the post. It seems that this was a detail used in Italian roof structures because it is illustrated by Daniel Barbaro (fig. 2.7). The arrangement is also shown in nineteenth century English text books when we know that the intention was for the principals to support the king post. However a similar detail can be found in a number of seventeenth and early eighteenth century structures which otherwise give no indication that the post was designed to be in tension. It seems more likely in these cases that the detail was adopted simply to provide a bearing for the principals which are being supported by the post.

In the first trusses by Inigo Jones wide splayed joggles were used at the head of the post so that it might be supported by the principals. However, later architects were to use joggles with a much narrower splay. This might have been either to save timber (since the post could then be cut from a smaller piece) or possibly to facilitate assembly. The principals were tenoned into the joggles.

A seemingly unnecessary addition to the joist at the head of the king post was metal strapping which appeared in a number of forms. The simplest was merely a curved metal strap joining the two principals. More positive fixings however joined the king post to the principals, the simplest way of doing this being to reverse the curved strap to form a shallow V. This was the arrangement commonly used by Gibbs. An early device was to cut a slot in the top of the king post and the ends of the principals to let in two metal straps to form a V. These were fixed by bolts. This rather complex arrangement can be seen in roofs at Blenheim Palace. Hawksmoor seems to have favoured Y shaped straps which passed over the top of the principals. By the nineteenth century a whole range of different pattersn of strap was being used (fig. 1.14).

The process of construction of roof trusses changed with the introduction of the new form of truss. The evidence suggests that the traditional forms of roof frame were assembled while laid flat. If the widths of different members varied then they were always brought to line up on one face. During assembly this face was uppermost because it was from this side that the pegs which secured the mortice and tenon joints were driven. Carpenters' marks on the timber commonly numbered the trusses ie. different pieces of timber in the same truss would have the same number.

In the new king post trusses however, if timbers varied in width, they were arranged to have common centre lines. The two techniques shall be distinguished by the terms "face framing" and "centre line framing". The trusses were almost certainly assembled while vertical because examples can be found where the fixing pegs were driven from both sides. The only reason I can imagine for this change of technique was that it would facilitate the fixing of the metal straps. Not only was it necessary to reach both sides of the truss to do this but a king post narrower than a tie beam would result in an awkwardly shaped strap if the truss were face framed (25).

In contrast with earlier frames the carpenters' marks in the eighteenth century numbered members rather than trusses. Thus the mark showed exactly which principal was which and which strut was which (fig. 3.2). There seems no obvious reason for doing this since the position of individual members can be uniquely determined simply by cutting the number on the same face of each member (which was done anyway). Whether or not members were interchangeable within a group of trusses can only be determined by more careful measurements than have been made so far. There is some suggestion that trusses might not have been tailor made to their positions in the building. In examples where king post trusses carry beams at their heads to frame flat topped roofs, struts are needed on the sloping faces of the roof to prop the principals. However, these struts are redundant on the inside faces so are omitted and yet the king posts could still be formed with symmetrical joggles to receive struts from both sides.

Traditionally the structural timber in England was oak but toward the end of the seventeenth century imported fir began to be used, eventually replacing oak as the major structural timber (26). A problem for the carpenter was to prevent the roof from sagging. In traditional roofs this depended simply upon the stiffness of the beam. A properly framed truss on the other hand ensured that the roof would not sag - properly framed both in the design of the structure and the proper fitting of the joints. However, compression of the timbers, particularly the king post of the truss, would allow it to sag and this would be more likely in a structure of fir which has a lower resistance to compression across the grain than oak. For this reason the king post often continued to be made of oak even when the other members of the truss were of fir (27).

The carpentry of the ceiling and roof covering changed during the period being considered. Initially ceilings were supported on longitudinal girders spanning between the tie beams of the trusses. Ceiling joists were then carried by these girders. This arrangement was adopted even with fairly close spaced trusses but during the eighteenth century it gradually became common practice simply to have joists spanning between the tie beams.

In the early roofs using trusses two different arrangements were possible for carrying the roof covering (as noted above). Either purlins and common rafters could be used or close spaced purlins of small scantling without any common rafters. The latter practice, almost certainly of Italian origin, was used by Inigo Jones, occasionally by Wren, was popular with Hawksmoor and with Gibbs and indeed seems to have been fairly common practice among London architects at the beginning of the eighteenth century. However it later lost popularity and carpenters returned to using heavy purlins and common rafters. Where re-roofing of early eighteenth century roofs has been carried out there is sometimes evidence of the initial use of close spaced purlins even though the replacement uses common rafters (28).

Common rafters might be tenoned into the purlins or carried over their backs. Both arrangements were used. Initially purlins were always butted against the side of the principal rafter but gradually this was changed. The purlins were first raised to be carried over the backs of principals which were trenched to receive them. This was a common medieval practice in some parts of the country and considerably simplifies the carpentry necessary. Eventually purlins were to be carried right over the tops of the principals and supported in place by blocks of timber. Not only does this further simplify the carpentry but it enables smaller timbers to be used for the principal rafters and became the standard technique at the beginning of the nineteenth century. This arrangement may have been adopted following French practice where butt purlins do not seem to have been used (29).

Nothing has been said about floor structures or trussed partitions. Naturally these are more difficult to examine than roof structures and most of the available evidence about their development comes from contemporary text books. These structures are dealt with only briefly in this study. A note on floor structures is given in appendix 2.

Footnotes - Chapter 1

1. A typology of roofs has been provided by Cordingley (1961). The logic of their construction was examined by Howard (1914).

2. Both the early editions of Jousee (1627 & 1650) and its revision in the eighteenth century by De la Hire (1751) show single framed roofs, as do other contemporary French books.

3. The origin of the hammerbeam roof is questionable because there is such a wide variety of forms that a single explanation does not seem likely for all. For a discussion of this see Yeomans (1975).

4. The Thorpe drawings have been catalogued by Summerson (1966) and the Smythson drawings by Girouard (1962). For a description of the Thorpe drawings see Chapter 3. The Smythson drawing for the Riding House Welbeck Abbey, Nottinghamshire, is less carefully drawn and in less detail. Another structural drawing by Smythson showing a trussed roof will be dealt with in Chapter 3. An earlier 'structural' drawing showing a hammerbeam roof for Chester Castle is reproduced in Colvin, Ransome and Summerson (1975), plt. 18.

5. The floor above this 'hammerbeam' is interesting in itself, being a 'geometrical flat floor'. See Appendix 2.

6. Smith, James (1787). An earlier edition of 1736, once in the British Library, was destroyed by enemy action.

7. Brandon (1849).

8. Salzman (1952) p.262.

9. 'Danny' in Sussex provides an interesting example of this transition. The house was originally built with an open timber roofed hall. The decorative trusses still survive but they are now concealed above a ceiling. The insertion of this presented the builders with some difficulty because to be low enough to be below the roof structure it had to be below the top of the tall windows of the hall.

10. The roof structure of Doddington is at present inaccessible and I rely on a sketch kindly supplied by the owner, Anthony Jarvis, for this information. He was able to see the roof during recent repairs.

11. Airs (1975), pp. 108-11.

12. Field and Bunney (1905), p.15 et seq.

13. Ibid.

14. The roofs of this building employ both king and queen post framings, although the former predominate. The use of queen posts is confined to the roof over the long gallery and may be accounted for by the employment of a different carpenter.

15. This has been done at Fenton House, London, to roof in a central square well. At Emmanuel College, Cambridge, the valley between king post trussed roofs by James Essex has been roofed with joists spanning between the ridges. At Chelsea Hospital a similar arrangement covers the valley in the centre of the roof over the wards.

16. These structures vary considerably in size. At Wotton the roof only has to span about 20ft, while at Hall Barn it is double this. At Sudbury Hall a structural wall provides some support to the centre of the roof structure although the layout of timbers is similar to the other buildings. Both Hall Barn and Sudbury have been extensively repaired and the nature of the original structure has been deduced from the early timbers that survive.

17. These are clearly shown in the Ministry of Works photographs taken during the restoration of the building.

18. Gunther (1928), p.68.

19. Gibbs (1728).

20. References to the carpenters' manuals will be found in the notes to Chapter 6.

21. A roof layout for a small house with a square plan and slopes up to a flat lead top is given in Price (1759), fig. F*G*G. This work is a revision of Price (1733).

22. The trussed partitions of Abingdon Town Hall carry floor girders. The floor joists span parallel to the lower chord of the trusses and are framed into the girders. The available photographs do not make clear how the lower chords were fixed to the posts. This is an unusual building and the use of trussed partitions to carry floors may not have been common at the time.

23. The term 'forelock bolt' may be found in contemporary carpenters' contracts.

24. The use of the forelock bolt persisted in the United States until the beginning of the nineteenth century and may be seen in the roof of Old West Church, Bolton.

25. In spite of this, a truss with metal strapping has been found in the United States which is face framed, resulting in a strap bent over on one side.

26. For a history of the timber trade in this country see Latham (1957).

27. Roofs may be found with the tie beam and the principal rafters of softwood and the king posts of oak. The survey carried out for this study has not been sufficent, however, to provide a quantitative measure of the increasing use of softwood nor the persistence of oak.

28. This can be seen in the re-roofing of Stoke Bruerne (Inigo Jones) and that of the library at Christ Church, Oxford.

29. See for example Le Muet (1647).

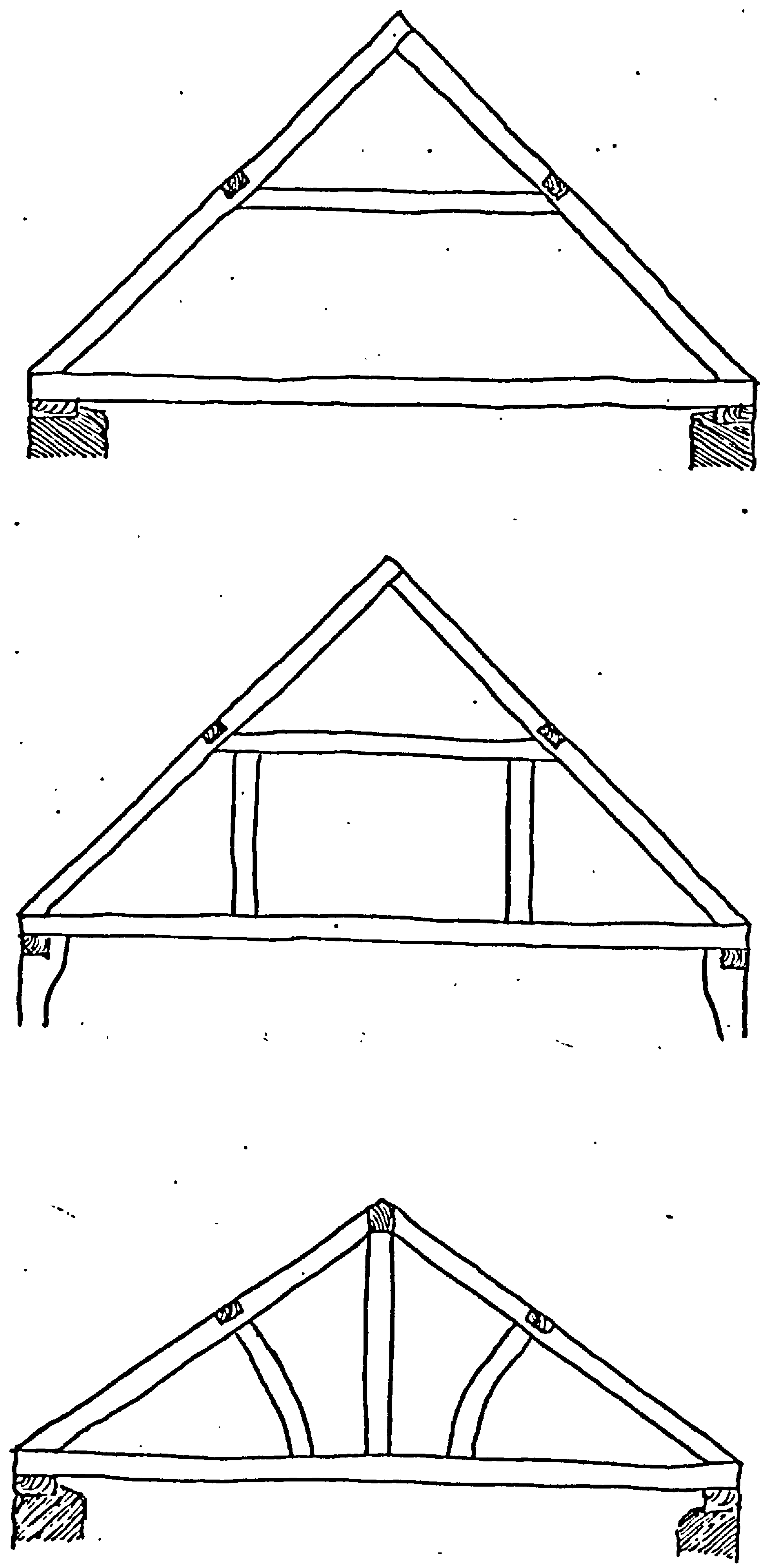


Fig. 1.1 Traditional roof 'trusses'

a) Simple frame with collar braced principals.
b) Queen post framing
c) King post framing

These are intended as diagrams only rather than as drawings of particular trusses. Common rafters have been omitted for clarity.

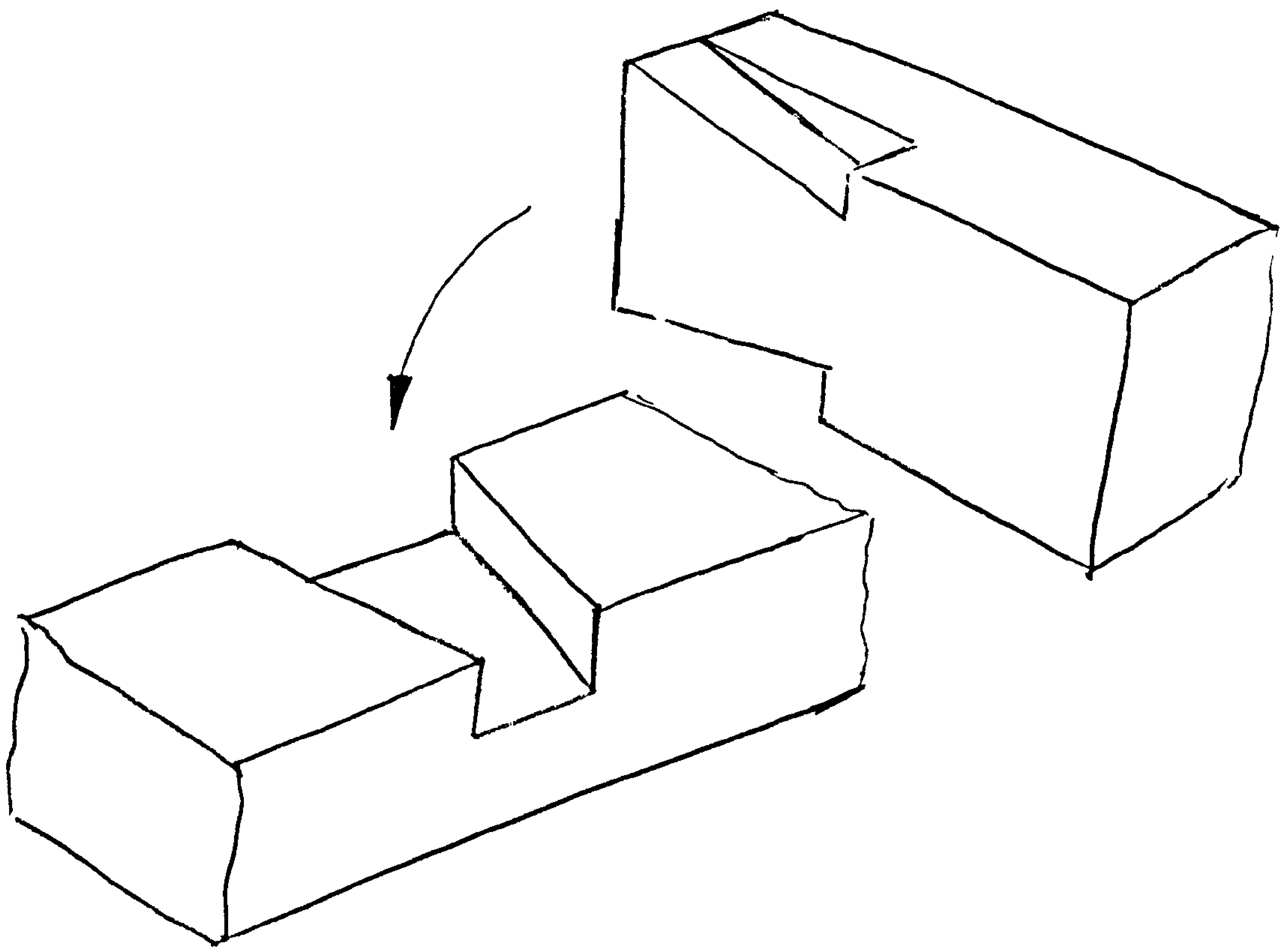


Fig. 1.2
Lap-dovetail joint used for fixing tie beam to wall-plate.

Fig. 1.3

Side purlin roof with arch-braced collar.

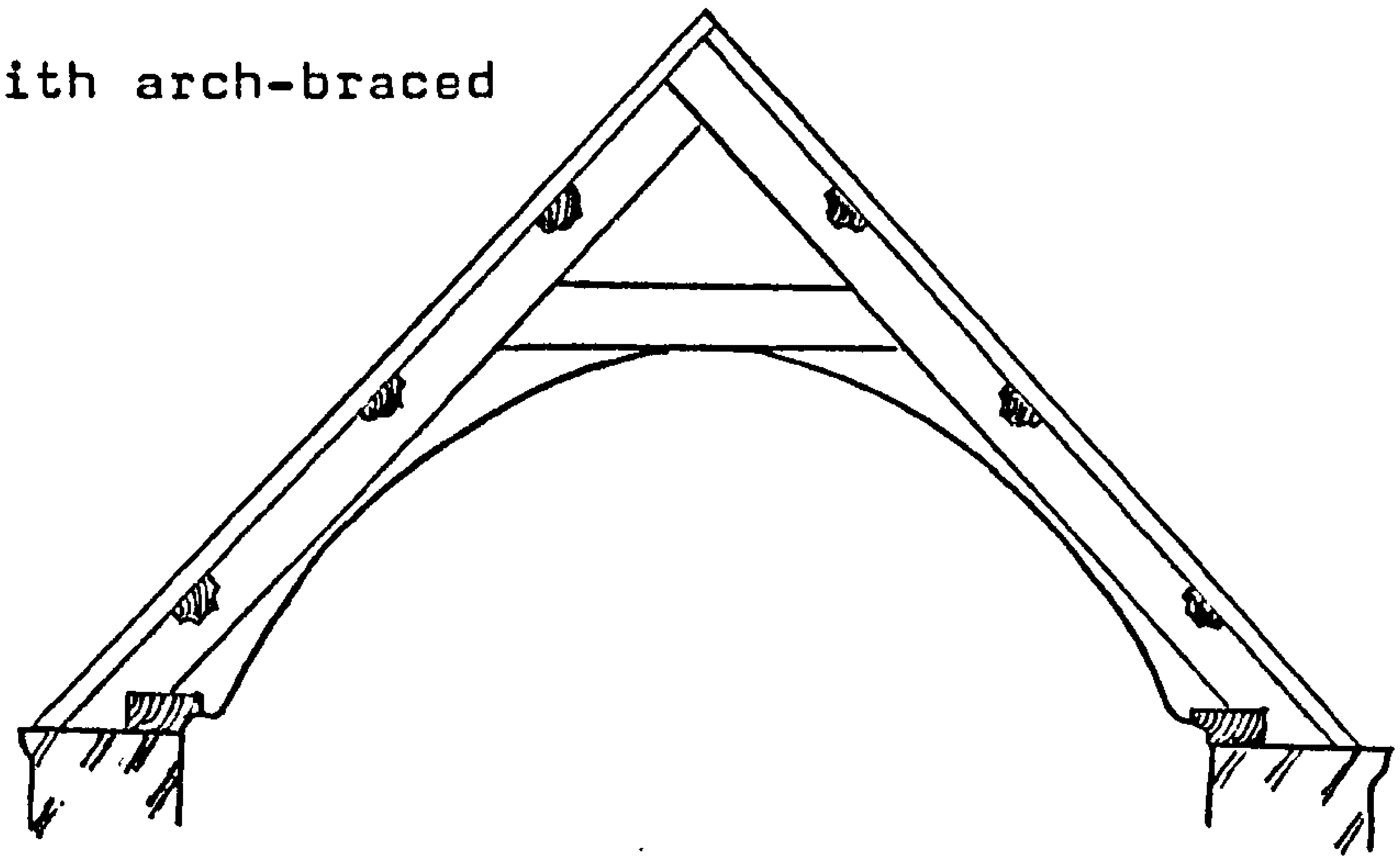
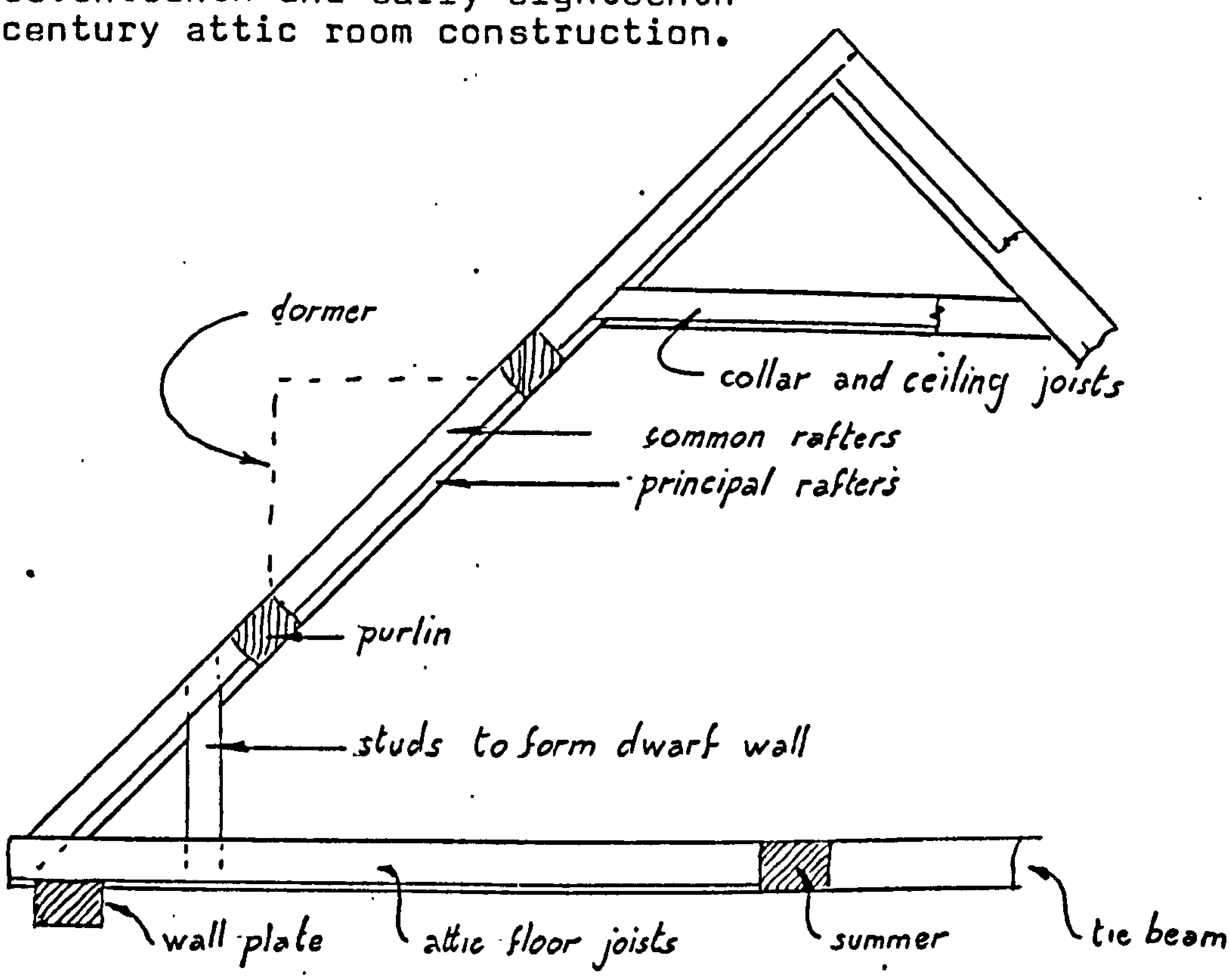


Fig. 1.4

Part section through typical late seventeenth and early eighteenth century attic room construction.



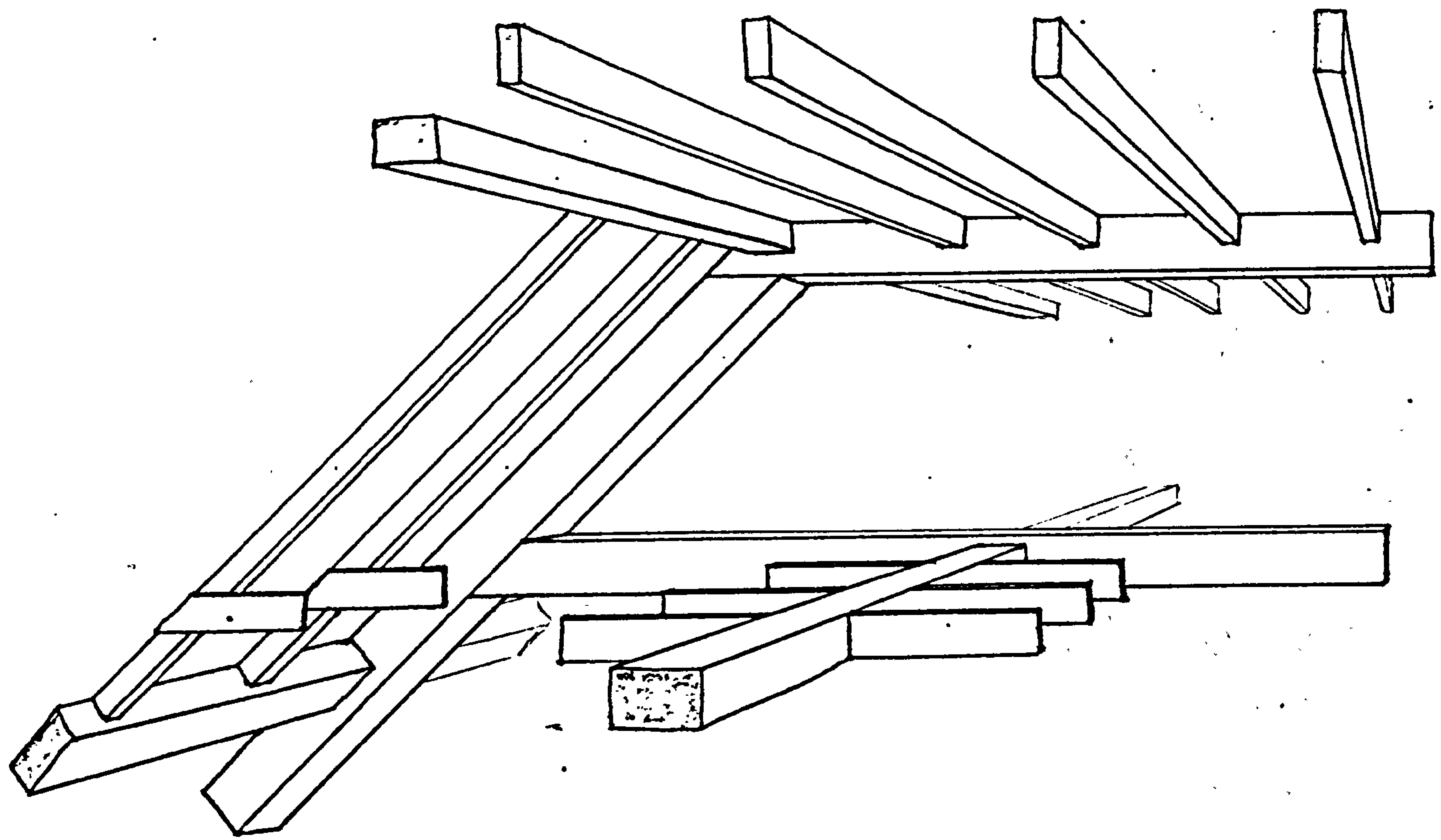


Fig. 1.5

Structural arrangement to provide 'flat' roof over attic rooms.

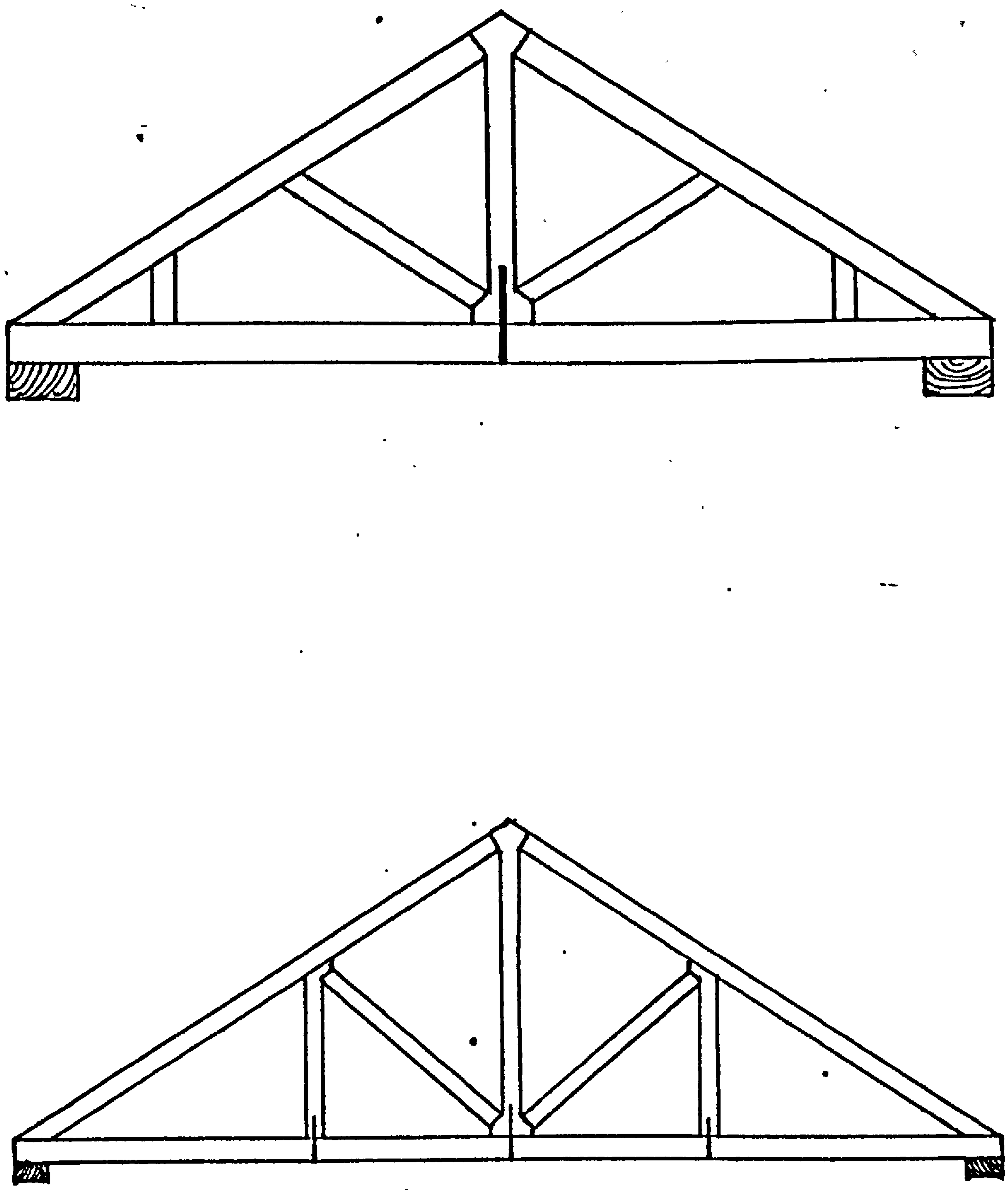


Fig. 1.6

King post trusses
a) with puncheons
b) with secondary posts.

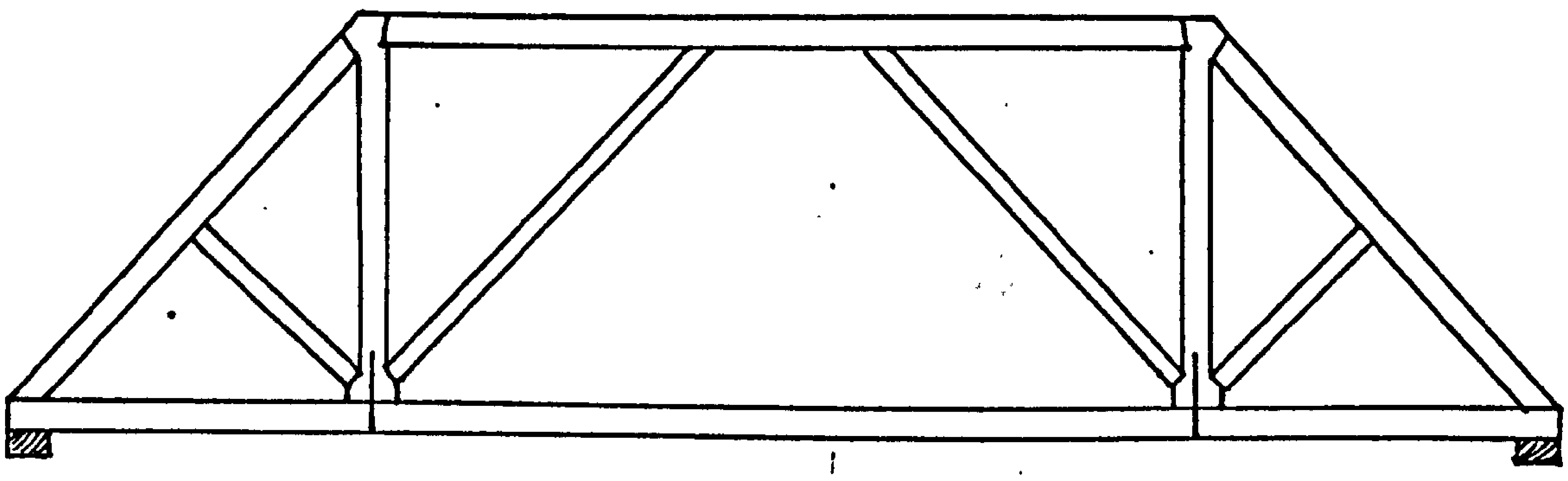


Fig. 1.7

Queen post truss forming 'flat' roof.

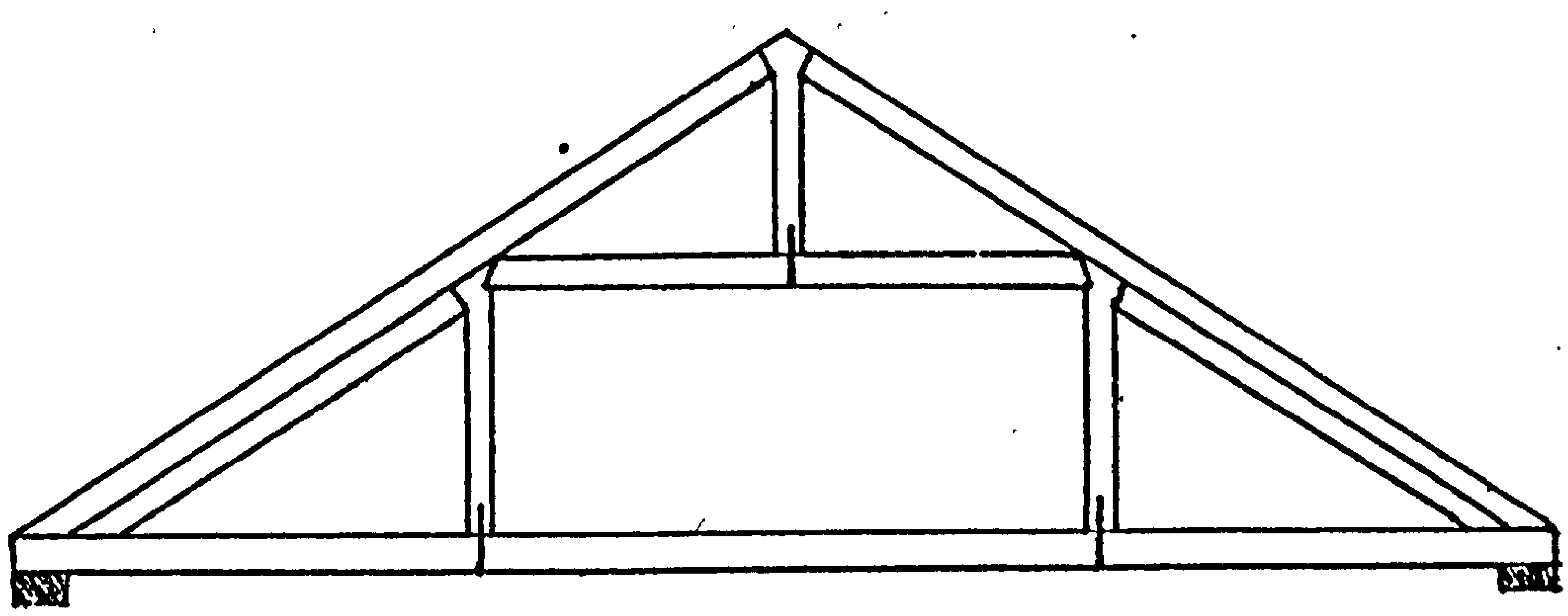


Fig. 1.8

Queen post truss with short king post.

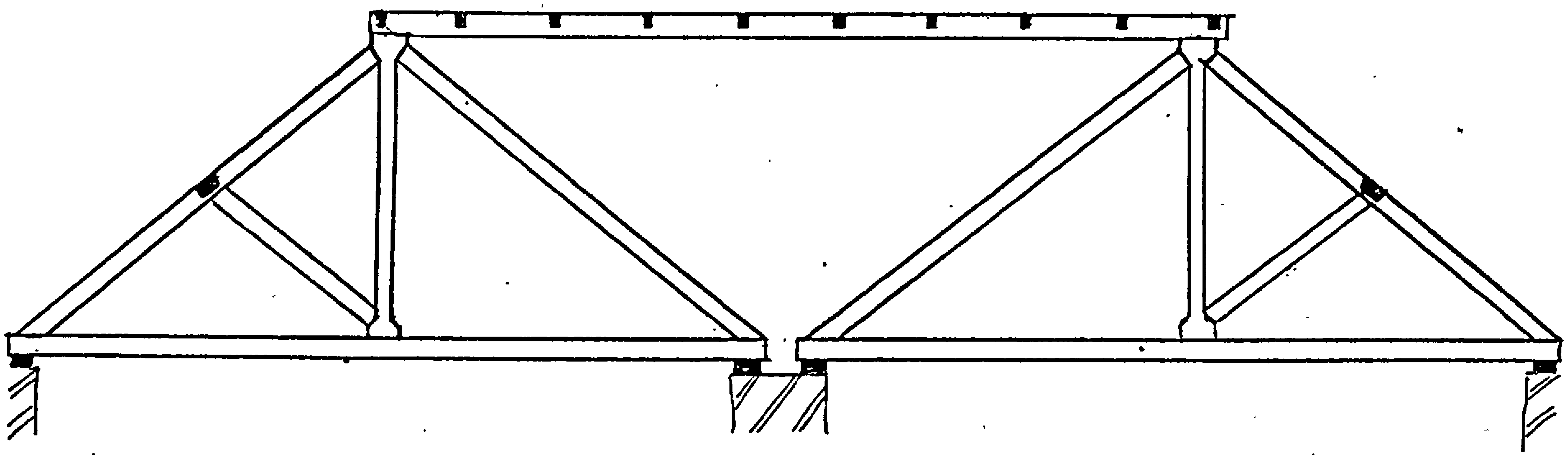
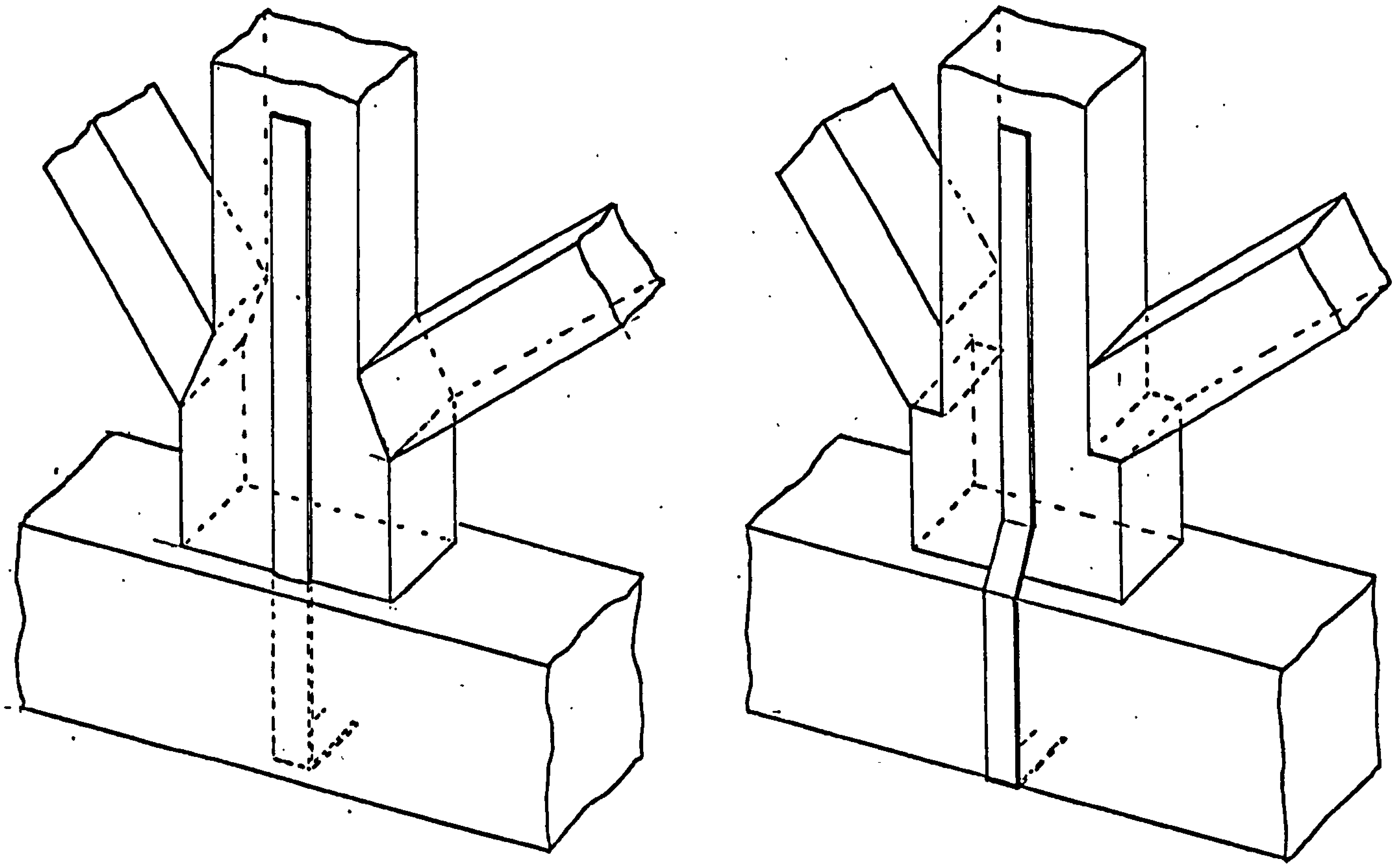


Fig. 1.9

Method of framing 'flat' roofs with king post trusses. Note the joggles which carry no struts.



(a) (b)

Fig. 1.10 Variations in detail at the feet of king posts. Joggles to receive the struts might be splayed as (a) or cut square as (b). The latter enabled a smaller piece of timber to be used for the post.

Where the post was narrower than the tie beam (it was not always), the metal could be let into the tie as at (a) or bent outward as (b).

Mortice and tenon joints have been omitted for clarity.

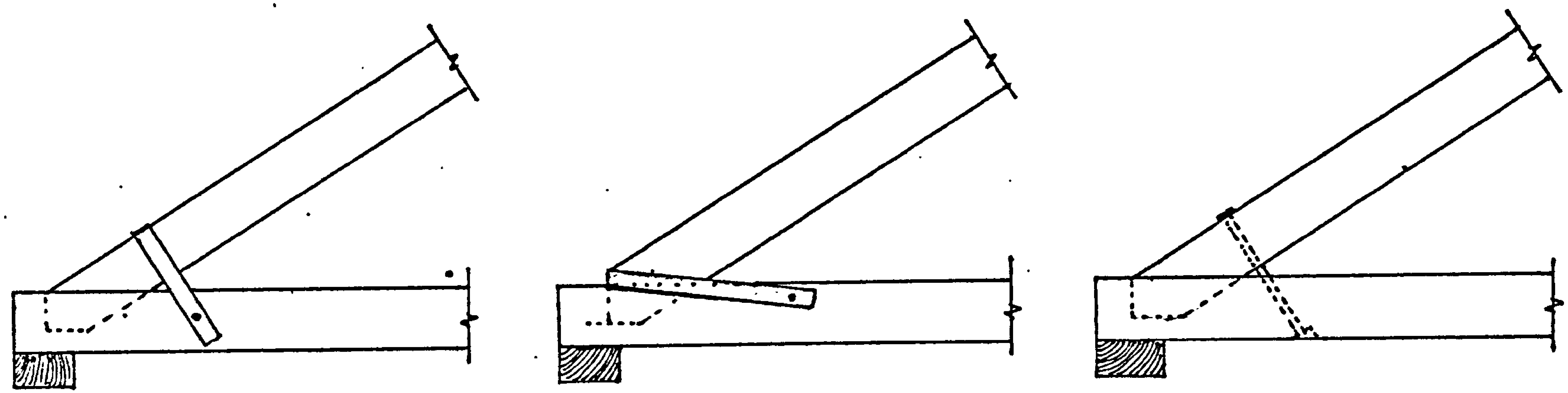


Fig. 1.11

Alternative metal fixings for the feet of principal rafters.

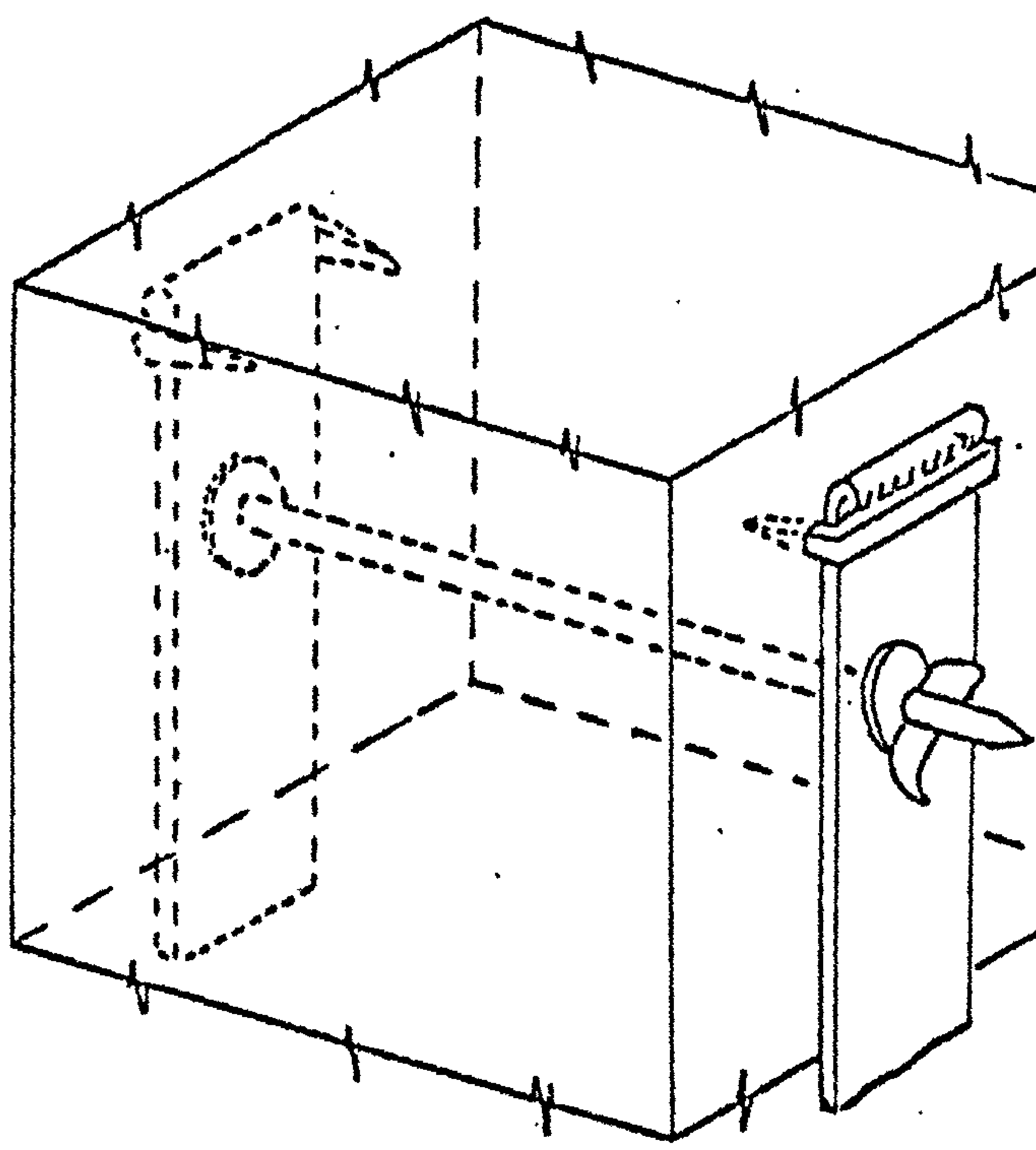


Fig. 1.18

'Forelock bolt'

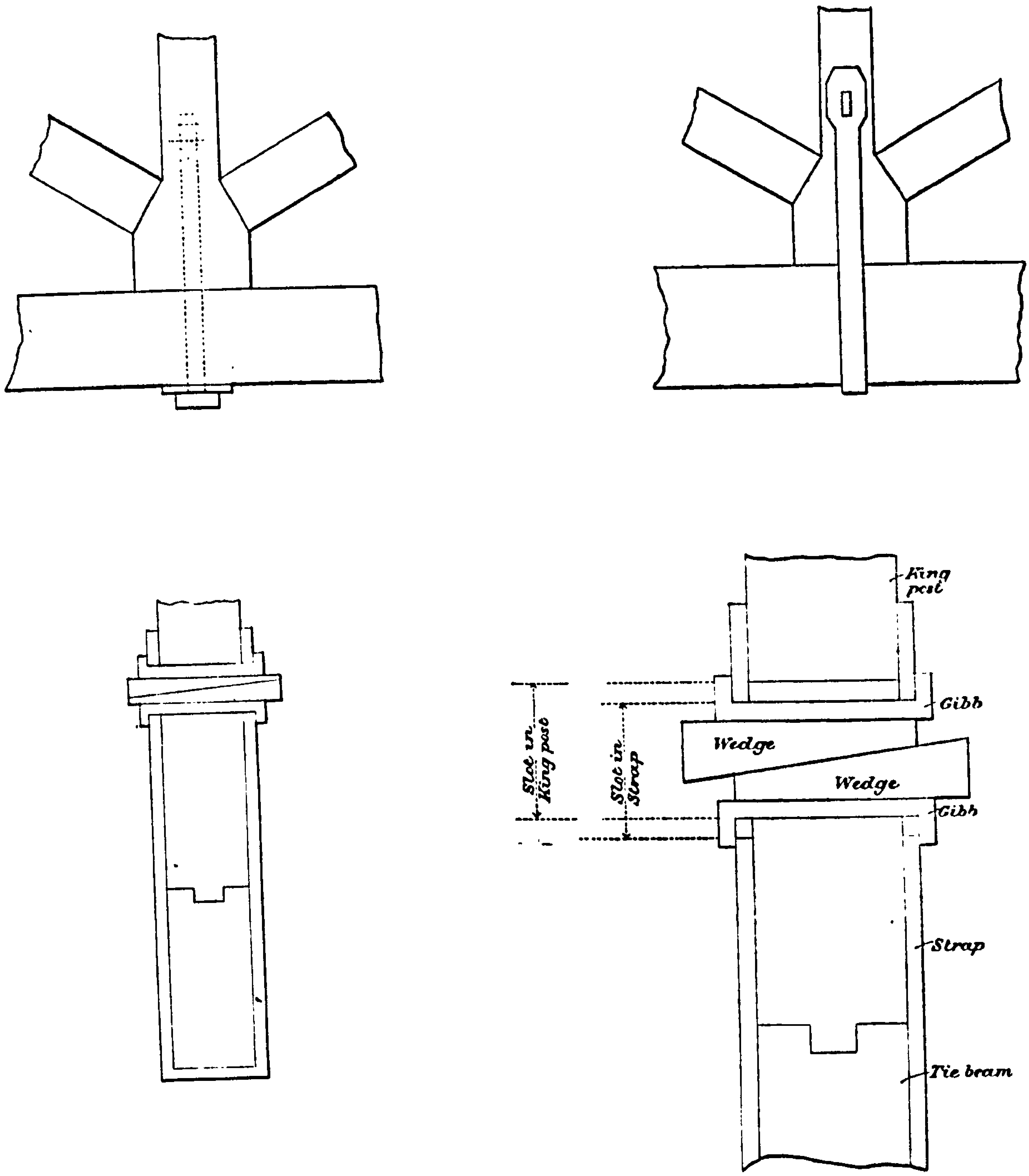


Fig. 1.13

Illustrations taken from a nineteenth century book on carpentry showing later methods of trussing up the tie beam (a) by a bolt, (b-d) metal strap with folding wedges.

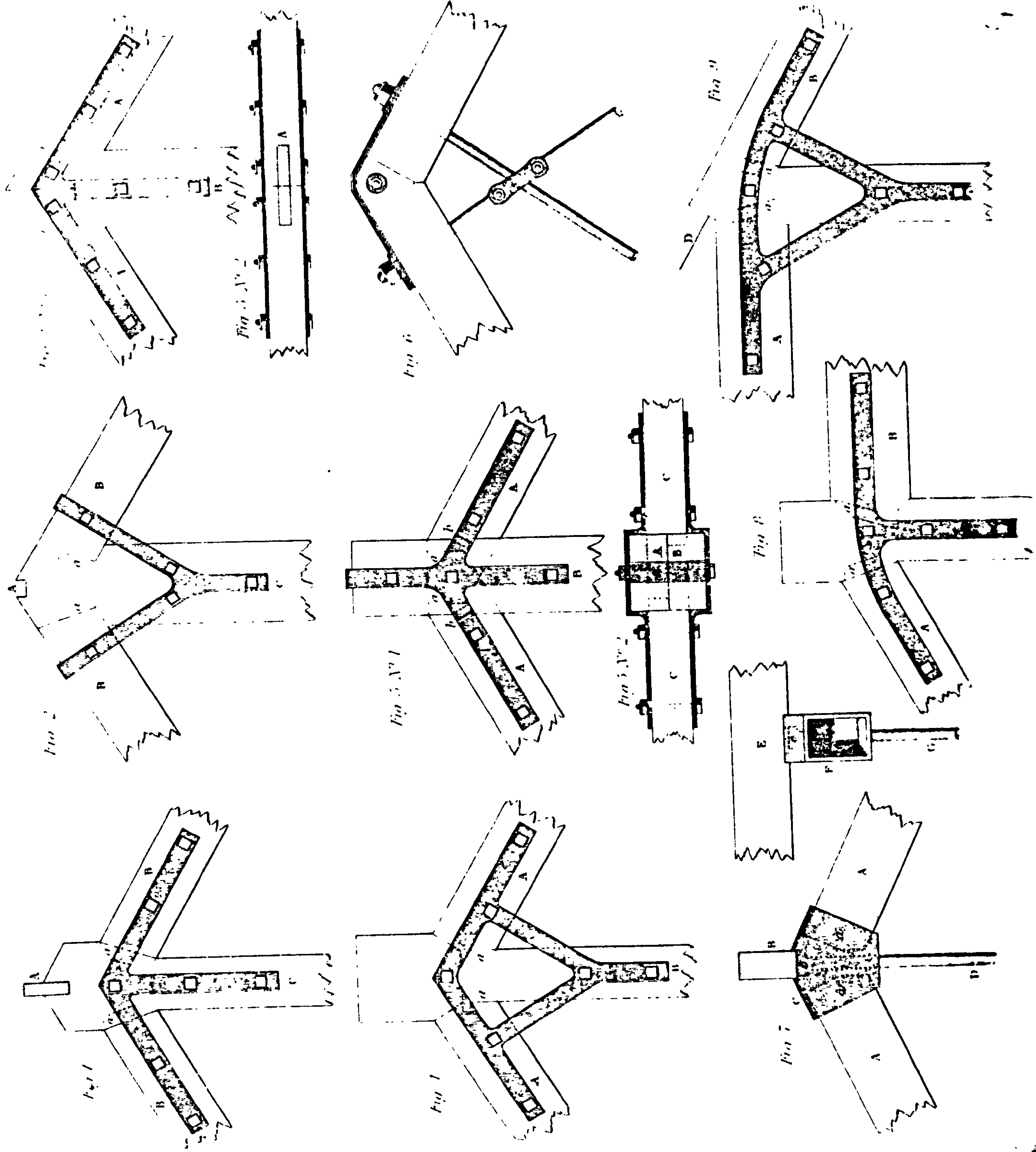


Fig. 1.14

Designs for metal strapping to
king and queen posts.

From Newland J. <u>Carpenter and</u>
<u>Joiners assistant</u>.

CONTINENTAL INFLUENCES

If we look to Italy for the source of architectural ideas in seventeenth century England, then it is perhaps natural to look to the same source for the origin of the structural forms that appeared here. Superficially there is an obvious similarity between roof structures in the two countries. Both king and queen post roofs are commonly found in illustrations of Italian buildings of the sixteenth and seventeenth centuries and both were to become widely adopted in England. Their origin here cannot be reasonably accounted for by a development from medieval roof forms. One must therefore assume that either they were independently invented here or that the ideas were imported; and there is ample evidence to support the latter view. The sketch books of English travellers in Italy include drawings of roof trusses, (fig. 2.1) (1) as do the Italian text books used by English architects. But the use of Italian text books raises the possibility of other continental influences. Italy was not the only source of architectural books and if one were looking at those available at the time specifically for their possible influence on structural carpentry, then France would also seem a likely source of ideas.

Although Philip de l'Orme's work is the best know today, a few books dealing with more conventional carpentry techniques had appeared in France before the end of the seventeenth century, showing roof construction in some detail. France also prcvided a refuge for the Catholic nobility in times of Protestant persecution and a source of artists and craftsmen when they returned to build in England. While Inigo Jones brought Palladian ideas from Italy, Wren travelled to France to look at the building of the Louvre. Thus, if structural ideas are traceable to Italy, it is necessary to ask also what influence there may have been from other, nearer continental countries, and in their absence to explain why it should be that Italian, rather than French or even Dutch or German, forms were adopted here.

English and neighbouring continental roofs

The most obvious characteristic of a roof is its pitch. While roof pitches in England vary depending upon local traditions and building materials, they tend in general to be more moderate than the steep pitches of France, Germany or the Low Countries. Climatic differences as well as the availability of building materials must be a major influence on the choice of pitch and this steepness of northern roofs compared with those of Italy was noted by Palladio (2):-

> "In Germany, by reason of the great quantity of snow that falls there, they raise their roofs to a very great pitch and cover them with shingles which are small pieces of wood or of thin slates or tiles, for if they should raise them otherwise they would be ruined by the weight of the snow."

As well as this difference in pitch the construction of roofs on the continent differed radically from that adopted in England. The common rafter (or single framed) roof had been replaced in England by the side purlin (or double framed) roof well before the seventeenth century. Thus, by the time renaissance ideas of architecture were being introduced into this country, the use of some kind of 'truss' to carry purlins was already well established. The use of large timbers in England allowed the use of butt purlins, ie. the purlins were tenoned onto the side of the principal rafters. Such an arrangement requires the use of timbers of sufficient scantling to enable mortices to be cut in the rafters without their being unduly weakened. However, it appears that in France it was common to use timbers of much lighter scantling, as will be shown below, so that quite different forms of construction resulted.

One of the best known of the early French texts dealing with carpentry is that by Philip de l'orme (3) although known more for its pioneering exploration of the possibilities of laminating timber than for its description of the normal carpentry techniques of the time. De l'Orme invented ways of assembling small pieces of timber jointed side by side and fixed together with keys or wedges. He 'demonstrated' the practicability of this technique with designs for a variety of roofs and bridges which were to be made of timbers assembled in this way. However a technique designed to utilise small pieces of timber was hardly likely to have been of much interest to English carpenters who were used to handling large scantlings of oak. Nor, I suspect, would the decorative effects possible with this technique have been of much interest in England. However there were French text books which dealt with more conventional carpentry methods.

In 1805 Krafft published a book (4) containing illustrations of roofs built in several countries. Even as late as this it is quite noticeable from the examples that he gives that the design of English roofs tended to rely upon timbers of larger scantling than those in France. Le theatre de l'art de charpente by Jousse in 1650 (5) contains a large number of drawings of roof structures. All these are of single framed roofs using only timbers of light scantling. The intention of the book seems to be to show how to adapt this simple form of construction to a wide variety of roof shapes. When de la Hire revised the book in the eighteenth century he added no other kinds of roof (6).

By this time the single frame roof of small timbers was no longer being used in this country (except perhaps for small buildings). It is possible that this difference in building tradition reflected the different availability of timbers in the two countries. However side purlin roofs had appeared in France by the end of the seventeenth century.

The roof structures illustrated in le Muet's Maniere de bien batir (7) show that there were differences between English and French roof structures even when the latter used the 'modern' form of roof truss with side purlins. The king post truss is not well adapted to steeply pitched roofs. The most convenient pitch for roofs of moderate span with one pair of purlins is clearly about 45° because then the struts from the root of the king post (which take the purlin load) will be at right angles to the principals (8). As the roof becomes steeper and more than one pair of purlins is required, it becomes more difficult to arrange satisfactory strutting relying upon struts from joggles at the foot of the king post. The king post trusses illustrated by le Muet have two pairs of struts to accommodate the steep pitch. There are no joggles and the struts are presumably tenoned into the post.

The combination of steeper pitches and the use of lighter scantlings than those commonly used in England would have made it difficult for the kind of roof structures used in France to have been adopted in this country. However one detail of French side purlin roofs was eventually adopted here.

In the king post trusses illustrated by le Muet the purlins are carried on the backs of the principals rather than being tenoned into them in the English way. Presumably this is again because small timbers were being used; two small to accommodate mortices. To prevent the purlins from sliding down the principal rafters they were held in place by blocks of timber. This practice was eventually to be adopted for English roof construction. The first example that I have found of an English architect adopting this technique is in a design for a roof at Wilton by William Chambers (9). However it seems unlikely that he derived this from a text book illustration. In the collection of drawings at the house there is also a drawing by Chambers of a French roof using this method of fixing the purlins and it thus seems more likely that Chambers was copying the technique from this structure which he had presumably seen for himself (10).

Le Muet does show examples of roofs using timbers of large scantling. Where attic rooms were to be formed within the roof space a frame of heavy timbers was constructed to carry the walls and ceiling. The roof structure was then built up on the ceiling beam using lighter timbers. The effect was not unlike the medieval base cruck used in this country (fig. 2.2). Examples of roofs framed in this way have been found at Boughton, Northamptonshire and at Moor Park, Hertfordshire. In both cases however, connections of the owners of the houses with France offer a more likely explanation for the presence of these structures than possible copying from any French text book. (see chapter 5).

The differences between Dutch and German roof construction and English roofs were even more striking. Post (11) shows roof construction as part of sections taken through houses but Johann Wilhelm (12) gives detailed drawings of the type of roof structures used in these countries. Steep pitched roofs were formed with common rafters and side purlins but, instead of trusses to support the latter, they were carried on trestle like arrangements of heavy timbers (fig. 2.4). I know of no English roofs that adopt this arrangement.

It may be noted in passing that, while these roof forms were not adopted here, they were 'exported' to America with emigrating carpenters and examples of these roofs still survive there.

Italian roofs

In view of the differences between English roofs and those of our near neighbours was there any direct transmission of carpentry techniques from Italy to England? The king and queen post trusses being used there were not unlike traditional English forms. Moreover, it would not have been difficult for English carpenters with their moderate roof slopes to have adopted the low Italian pitches.

It is not clear from the illustrations in the text books how well an understanding of the roof truss had developed in Italy by the seventeenth century. In his Engineers and Engineering in the Renaissance Parsons (13) illustrates a number of truss structures both for roofs and for bridge centering. The latter are generally able to rely upon arching action so that superficial resemblances to king post structures are not structurally significant. However the drawing for the falsework for the Santa Trinita Bridge uses a central king post in tension (fig. 2.5). This was needed because of the flatter form of the elliptical arch.

Two roof trusses which Parsons illustrates (fig. 2.6) have the posts stopped short of the tie beam, a device that demonstrates that the architect, carpenter or engineer recognised that they were in tension. Parsons complains however that this

> "illustrates the lack of mathematical knowledge by which a strain sheet could be drawn ... When a truss is fully loaded there is a

balance of forces, and there is no need to connect the post and braces with the chord. But with an unbalanced load, such as heavy snow on one side, the stresses are unbalanced, and if the connection is broken secondary stresses will be set up that under extreme conditions may be serious. The same error is found repeated in many trusses; for example in the peculiar queen post truss, as reproduced from the sixteenth century manuscript. Since the roof structure was very heavy, being composed of tiles or sheet lead, uneven loading to a great extent did not occur in practice." (14).

While undoubtedly true, Parsons' comments on secondary stresses detract from a recognition of the clear superiority of Italian roof structures over others in Europe at that time. However, although roofs were certainly built in this way, Italian text books also show trusses built with the posts standing on the tie beam and it was this latter practice that was to be adopted in England.

Barbaro's Vitruvius (15) has a clear drawing of a king post truss (fig. 2.7) with the post standing on the tie beam although other details of this particular structure differ from those that were to be commonly adopted here. The joints at the head and foot of the king post are formed by letting the principal rafters and struts into the post rather than the latter having wide splayed joggles. This arrangement has the advantage of enabling the post to be formed from a smaller piece of timber but it appears to have been used in England only for poorer quality work (e.g. stable buildings). The illustration also shows the principals notched to receive the ends of the struts. Examples of this refinement over here are rare although they do occur (see chapter 5). A more commonly adopted feature is the use of close spaced purlins shown in this roof.

While metal strapping at the foot of the king post is not shown in this particular illustration, Barbaro does include another drawing of a roof truss with this feature. This other truss also uses secondary posts (16).

The principal illustrated Italian texts were Palladio and Serlio (17). Both these works show roof structures included in sectional drawings of buildings. Of the two, Palladio's drawings are at a larger scale and hence clearer. Serlio's illustrations are too small to have provided any useful information. Palladio's Book II plate XXX (fig. 2.8) has a simple king post truss which, while having the struts notched in at its feet has a splayed joggle at the top. Other trusses that he illustrates (fig. 2.9) however, have quite different detailing with all the indications of their having been made from metal plates rather than timber. These trusses also have secondary posts (18).

Illustrations in these books show that the queen post roof was also being used in Italy. One of Barbaro's drawings is of a section through a building which uses a queen post truss (19). The majority of Palladio's drawings of buildings show queen post trusses although they are rather vague, not only being rather small in scale but also apparently differing in the arrangement of posts and straining beam. However these drawings were clearly not intended to show structural details but Serlio set aside a page of his Libro Settimo to give detailed drawings of both king and queen post trusses that purport to show details of carpentry and iron-work used (20) (fig.2.10).

These illustrations are not very helpful. The king post trusses all have their posts trapped by the principals but one of these is poorly detailed. The queen post trusses do not appear to have the straining beams drawn correctly at their ends. The impression given is either that Serlio had not copied these trusses very carefully or that he had copied trusses that were poorly made. We know from other drawings that the Italians were capable of making satisfactory queen post trusses but I am not aware of any work that shows how well developed these trusses were generally. Certainly these drawings could not have served as a useful model for English carpenters.

(Both Palladio and Serlio show bridge structures but these will be discussed in a later chapter).

The Influence of continental books

A comparison of eighteenth century structural forms in England with continental countries shows that it was the Italian types of roof truss that were used here rather than those of our nearer neighbours. Comparing traditional English roof construction with continental roofs shows why this should be so. However, while English architects draw upon Italy for their decorative details, most were to rely upon traditional English forms of roof throughout the seventeenth century. We know for example that Lady Wilbraham used a translation of le Muet's Palladio (21) in the building of Weston Park. The book is still preserved at the house and contains her notes on building. However there are no examples of 'modern' roof trusses in the buildings then erected.

English text books showing carpentry details did not appear until the 1730s so that if the modern form of trussed roof was used before then, either it was taken from some Italian source or copied from an earlier roof built in England. It is difficult to establish any positive connection between Italian book illustrations and built structures here. Apart from the ambiguity of the illustrations which makes them of doubtful use to the carpenters, one would need to establish not only a similarity between built structure and drawing, but also a connection between the builder and the assumed source; either ownership of or at least access to the book in question. It is unlikely that such links will be established for many roofs. For a builder to have successfully designed a roof structure he would need to have had both an interest in the practical aspects of construction, an interest occasionally, but by no means commonly, found at the time, and an interest in mechanics, a subject then in its infancy. For anyone with these interests Wotton indicated a suitable text (22). For the structure of arches and for roof construction he refers to Bernardino Baldi's commentary on Aristotle's mechanics (23).

Wotton makes his sources clear. He draws largely on Vitruvius, possibly Daniele Barbaro's version, Alberti, de l'Orme and Palladio. He also makes reference to Philander, Jacobo Boroccio and Durer's Geometry as well as Bernardino Baldi (24). We may surely assume that an English architect would have read Wotton and thus been directed to these sources even though there were probably few who would have been sufficiently interested in the problems of roof construction to have consulted Bernardino Baldi to find out how to frame a roof. The one notable exception which can be clearly demonstrated - Dean Christopher Wren - will be discussed below.

Henry Aldrich in his work (25) seems to have relied mainly upon Palladio and Serlio. He cites Vitruvius on roofs but the form of roof structure that he illustrates seems to have been taken from le Muet (fig. 2.3). Aldrich was an amateur architect but while he took the trouble to include a drawing of a roof structure in his book, in practice he was probably content to leave such details to his craftsmen. The design of the heavy queen post roof trusses used in his All Saint's Church in Oxford High Street were almost certainly produced by his carpenter and through him we can trace the form back to Hawksmoor rather than to any book illustration.

Apart from English writers drawing on European texts in this way, there were also English editions produced which would have made their contents available to a wider audience. Richards' translation of Palladio (26) is important partly for this reason and partly for the additional material that it contained. There were sufficient editions to suggest that it was fairly popular. The later translations of the Four Books are hardly likely to have had any structural significance.

As Richards used le Muet as his source, there is presumably some connection between the production of this book and the appearance of a translation of le Muet's own book on construction (27). This is mainly a book of plans but it does also include a drawing showing the framing of a timber building and several drawings of roof construction. Curiously these construction drawings were redrawn, rather poorly, for the English edition (fig. 2.2).

The trussed roof was developed in this country from those first used in the seventeenth century by a few professional architects. In these cases they can be shown to have used sources other than the illustrations in the books on architecture. The use of similarly detailed king posts suggests that Barbaro may have been used as a guide by some carpenters but any influence is likely to have been slight however, because the drawing in question only appeared in the early editions. When the extended seventeenth century edition was published in Antwerp (1649) the drawing was omitted. It is possible that drawings in Palladio were used by Inigo Jones for his design for the roof structure of the Banqueting House (see following chapter) but the connection is not certain. There are however two books whose influence on English workers is known.

Ironically the one carpentry form illustrated in a continental work on architecture that seems to have made an impression in this country had nothing to do with roof construction. Serlio illustrated an ingenious form of floor construction which he claims as his own invention (28). This structure was copied and further developed in this country. (Perhaps to add to the irony Serlio is not referred to by Wotton).

The form known as the 'geometrical flat floor' was characterised by having none of its timbers as long as the overall span. (fig. 2.11). The best known example of this arrangement in England formed the exposed ceiling structure in the tower of the Schools Quadrangle, Oxford. Unfortunately the timbers of this structure have been lost following recent reconstruction work and the only satisfactory record of it that survives is a drawing made when it was taken down. This shows the arrangement of the timbers but gives no details of the joints which must have been critical to the performance of the structure. However a floor using a similar construction survives at nearby Kelmscott Manor and Smythson built a floor of this type at Wollaton (29). Drawings and reference to arrangements of this kind appear in a number of eighteenth century books, but the most ambitious development of the idea was by John Wallis who published an analysis of the forces in a floor of this design (30). Details of this form of construction and the story of its adoption are not central to the argument here, but later, when discussing the development of structural understanding it must be asked why it was this floor design rather than roof construction that should have exercised the imaginations of the time. A more detailed discussion of this form is given in Appendix 3.

The other influential work was not directly concerned with architecture. The structural principles of the roof truss were dealt with in a book on mechanics by Bernardino Baldi (31) who both illustrated the king post truss and described the forces acting on it. The drawing is sufficiently clear to show the way the principal rafters support the king post, how they are to be butted gainst the tie beam so as to transmit their outward thrust and how the tie beam may be suspended from the king post. It may also be noted that Baldi says that the post was called 'monarchus' suggesting that the English term 'king post' was taken from this Italian term. (31A)

It is known that Bernardino Baldi's book was influential in this country because, as noted above, it was cited by Wotton in his Elements of Architecture. Moreover I shall show that the extensive use of king post roofs in this country can be traced to this source. Referring to roof timbers Wotton (32) says that Bernardino Baldi "doth firmly and mathematically demonstrate the firmest knittings of the upper timbers which make up the roof". However he gives no further details so that anyone wishing to follow this up would have to turn to Baldi himself.

Dean Christopher Wren, father of Sir Christopher Wren, owned a copy of Wotton's Elements and in the margin beside this reference to Baldi he noted his own design for the roof of the chancel in his church at East Knoyle (33).

His sketch for this (fig. 2.12) shows it to have a joggled king post which was clearly designed as a tension member because the tie beam is formed in two parts 'trussed' together. Unfortunately the roof does not survive but its construction is attested to in Parentalia (34). This is thus one of the earliest records we have of a 'trussed' roof structure in this country; designed by an amateur architect and using an Italian source - albeit a text on mechanics.

The design of the roof is interesting in that it makes no attempt to copy any of the roof forms illustrated by Palladio or Serlio nor indeed is Wren's design similar to the sketch provided by Baldi (fig. 3.13). The intention seems to have been to provide an open timber roof very much in the tradition of English medieval church building, simply drawing on the books available for structural advice. We might well conclude that this design and its reliance upon a text on mechanics indicates an ignorance on the part of Dean Wren of the principles of structural carpentry of the time. A knowledge of mechanical principles was used to make up for a lack of experience in traditional practice.

As the work of an amateur architect, known only in association with this one building, a unique use of a trussed roof in this way might have had no effect on the general development of structures in this country. Indeed, but for his more famous son, Dean Wren's roof design might have passed unnoticed. However we can only speculate on any possible influence the design and building of this roof may have had on the younger Christopher. Nevertheless it suggests an early acquaintance with mechanics. We know that Wren the Professor of astronomy owned a copy of Baldi's Mechanics and the influence of this on him as a structural designer will be discussed in the next chapter.

Footnotes - Chapter 2

1. eg. the sketchbook of John Talman recording his journey in Italy with William Kent in 1709.

2. The translation of Palladio's Four Books of Architecture from which this quotation is taken is that of Richards, G. (1668) who provided the first English version of the First Book.

3. De l'Ormer (1561).

4. Krafft (1805) was followed by a more extensive work on the same subject in 1819.

5. Jousse (1627). There were subsequent editions of 1650, 1664 and 1702 before the later revisions of De la Hire.

6. De la Hire (1751)

7. Le Muet (1647).

8. English and Italian roofs used pitches shallower than 45°. With these the struts to support the principals have to be arranged to meet the latter at an acute angle. This results in a component of the strut force acting parallel to the rafter. This force is normally resisted by the mortice and tenon joint although in some cases a notch might be formed in the principal to receive the end of the strut.

9. Copies of a drawing showing this survive at Wilton House and in the RIBA Drawings Collection. The existence of several copies is presumably because they were made by assistants. The only other case of multiple copies that I have found is of drawings made by draughtsmen of the Office of Works - now in the PRO.

10. The building is not clearly identified on the drawing.

11. Post (1715)

12. Wilhelm (1650) figs 2-12.

13. Parsons (1979) - illustrations to chapter 29.

14. Parsons (1979) pp. 486-7

15. Barbaro (1556). The drawing referred to in the text and fig. 2.6 does not appear in the revised version of 1649.

16. Barbaro (1556) p.219

17. Palladio (1570) and Serlio (1566)

18. The roof of the portico fo the Pantheon, Rome, is said to have originally been made of bronze plates. Mainstone (1975), p.150 discusses the possible details of this structure. I know of no evidence to suggest that other buildings had similar structures.

19. Barbaro (1556) p.214.

20. Book Seven appears in the 1619 edition of Serlio's Tute l'Opera d'Architettura.

21. Richards (1668). This is the second edition of the work and I have not been able to trace a copy of the first edition. Le Muet had translated the work into French from a Dutch edition. At the same time he added his own designs for doors and windows. It was this version that Richards translated into English, copying Le Muet's plates. An extensive discussion of the ownership and possible use of continental text books during the sixteenth and early seventeenth centuries is given by Airs (1975) pp. 25-9.

22. Wotton (1624) p.79.

23. Baldi (1621)

24. The authors Wotton cites are Vitruvius, p.2; Alberti, p.3; De l'Orme, p.13; Barbaro, p.14; Palladio (Book 1), p.16; Baoccio, p.33; Philander, p.44; Baldi, p.49; Durer, p.50; Pliny, p.84. The page numbers refer to the first mention of each of the authors.

25. Aldrich (1789). The translation of the original Latin text is by Smyth (1789).

26. Richards (1668). Further editions appeared in 1676, 1683, 1693, 1700, 1708 and 1729.

27. Le Muet (1623) was translated into English by Pricke (1675) with new plates.

28. Serlio (1566) Book 1.

29. Insall (undated) shows a photograph of the floor uncovered at Kelmscott during restoration work. Desch (1958) pp.10-11 includes a plan of the floor timbers at Wollaton.

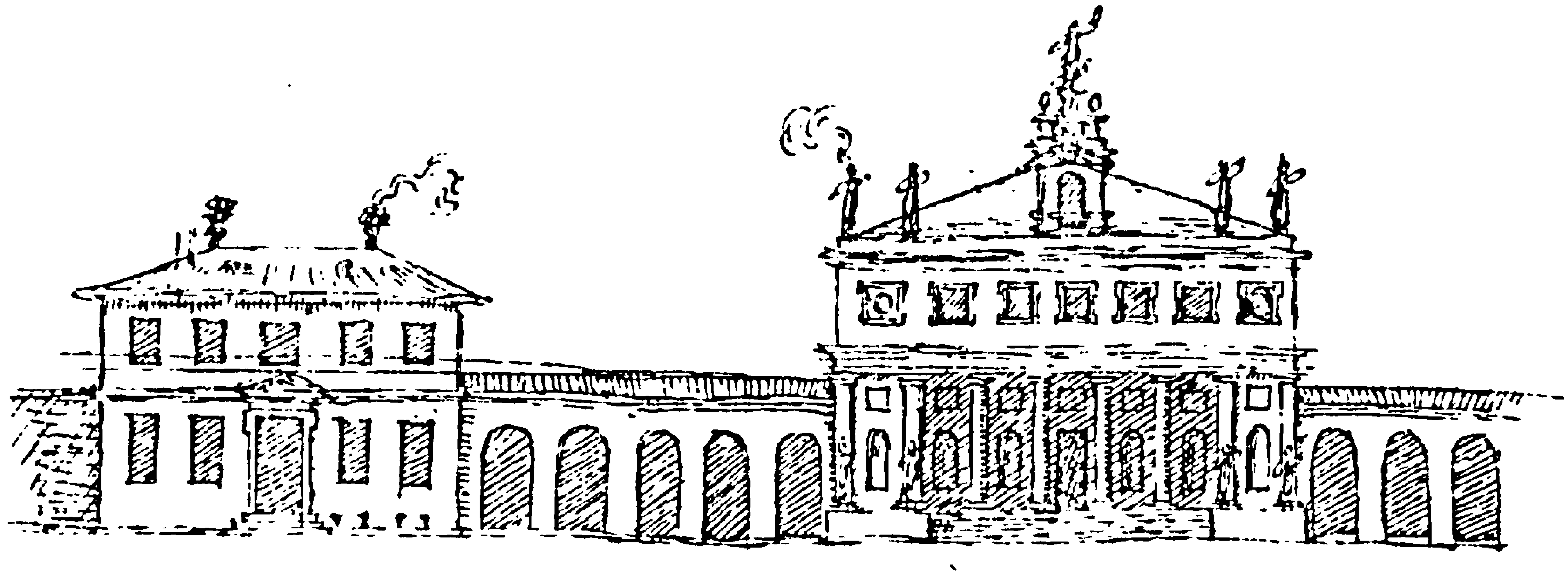
30. Wallis (1670).

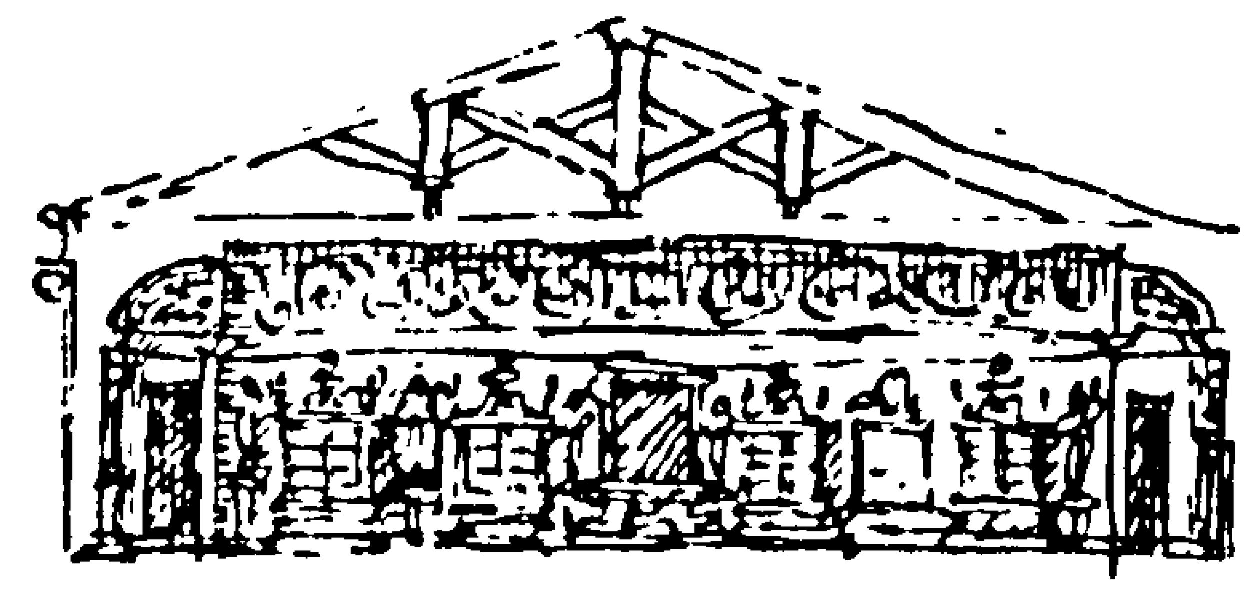
31. Baldi (1621) pp.102-3.

32. Wotton (1624) p.49 refers to Baldi's work on arches.

33. I am grateful to Sir John Summerson for both drawing my attention to the survival of these notes and for sending me a copy of the notes which he made from the book and which are reproduced here. The book is presently believed to be in the possession of Lord Macclesfield but I have not been able to confirm this.

34. Wren (1750) p.142. Unfortunately the roof no longer survives.





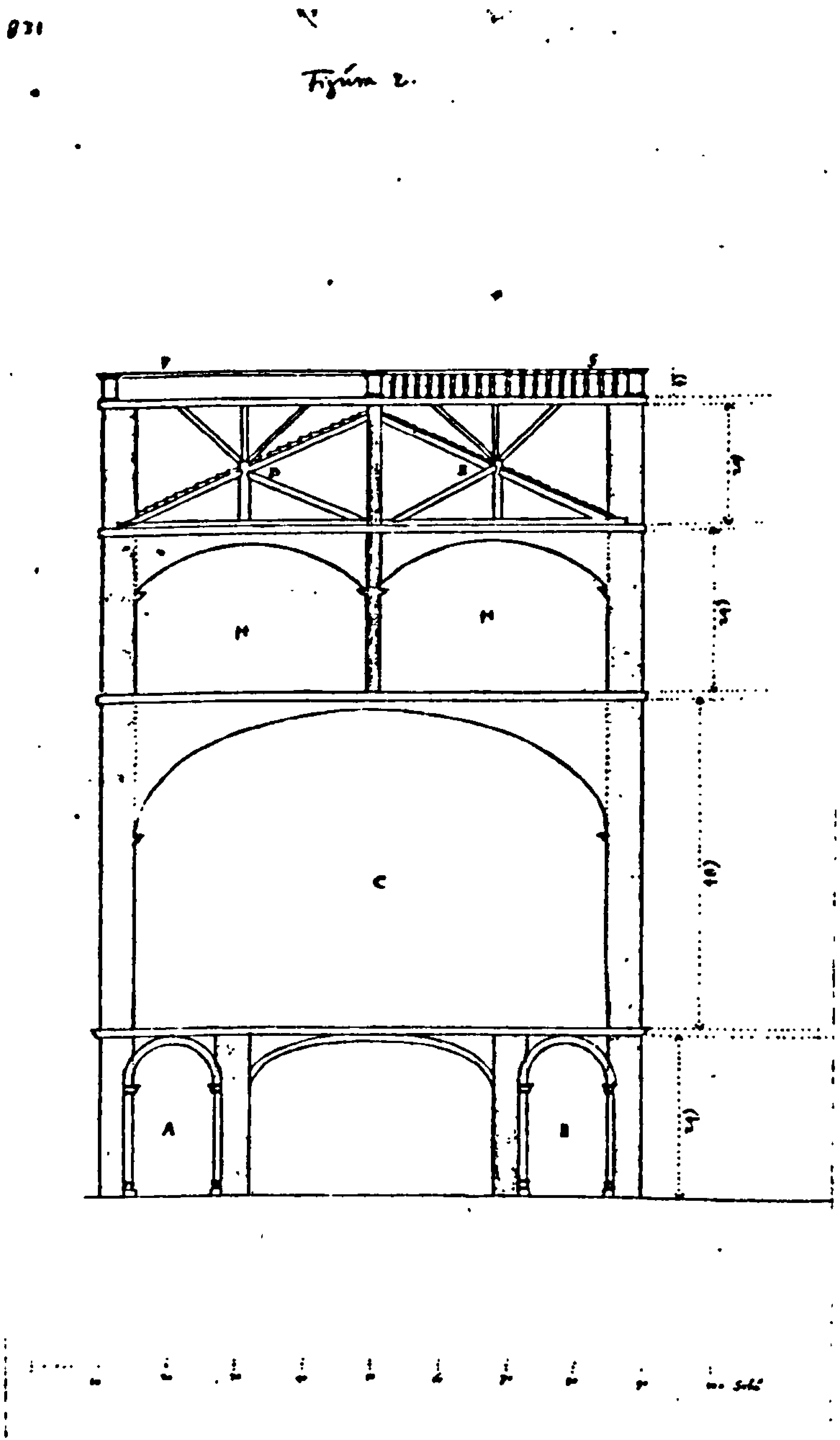


Fig. 2.1

Sketches made by John Talman during his journey in Italy with William Kent-Courtauld Institute Phots.

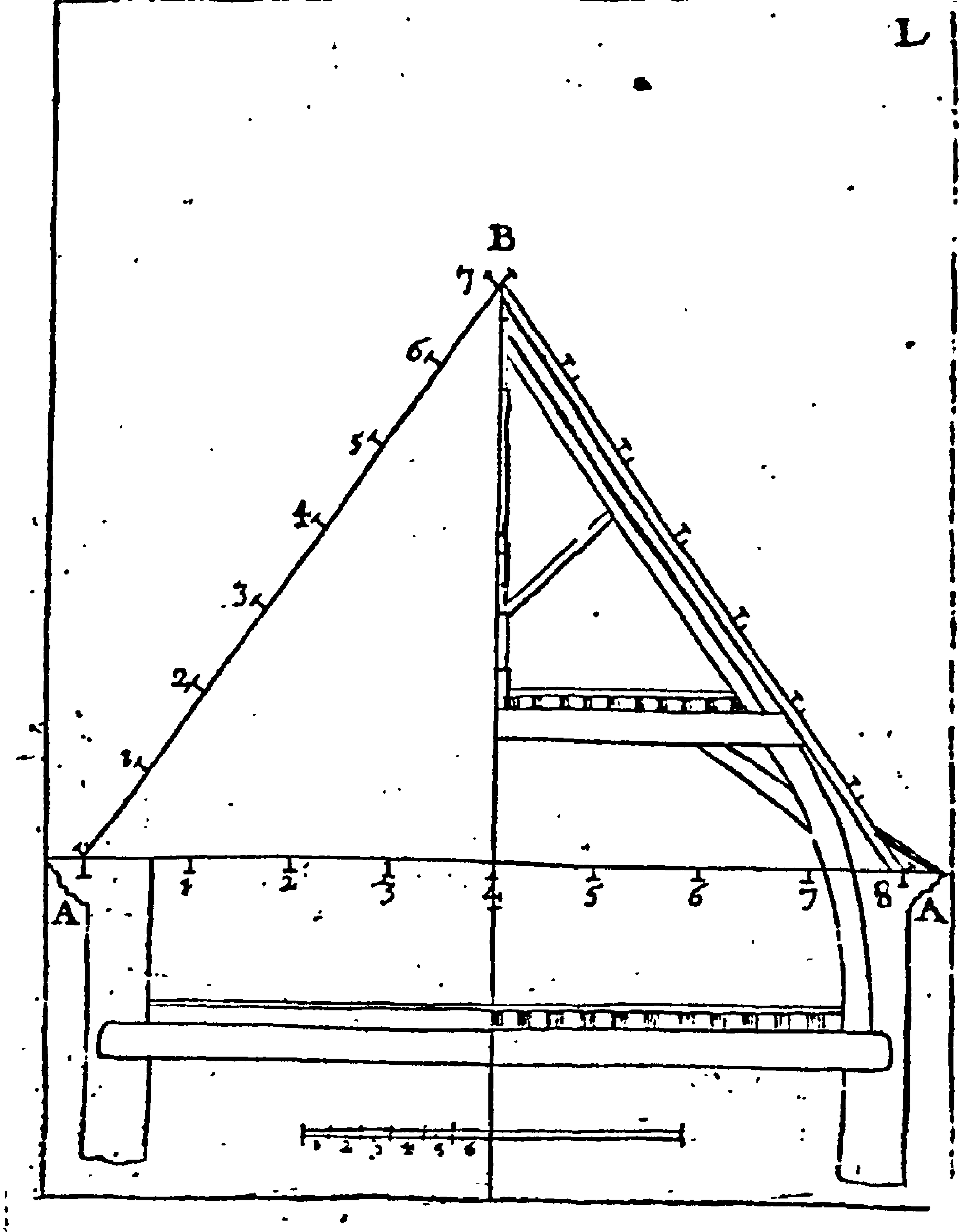


Fig. 2.2

Roof structure from the English edition of le Muet's book on construction. The plates on roof construction were redrawn for this edition with modifications to conform more with English practice. This method of forming an attic however is French.

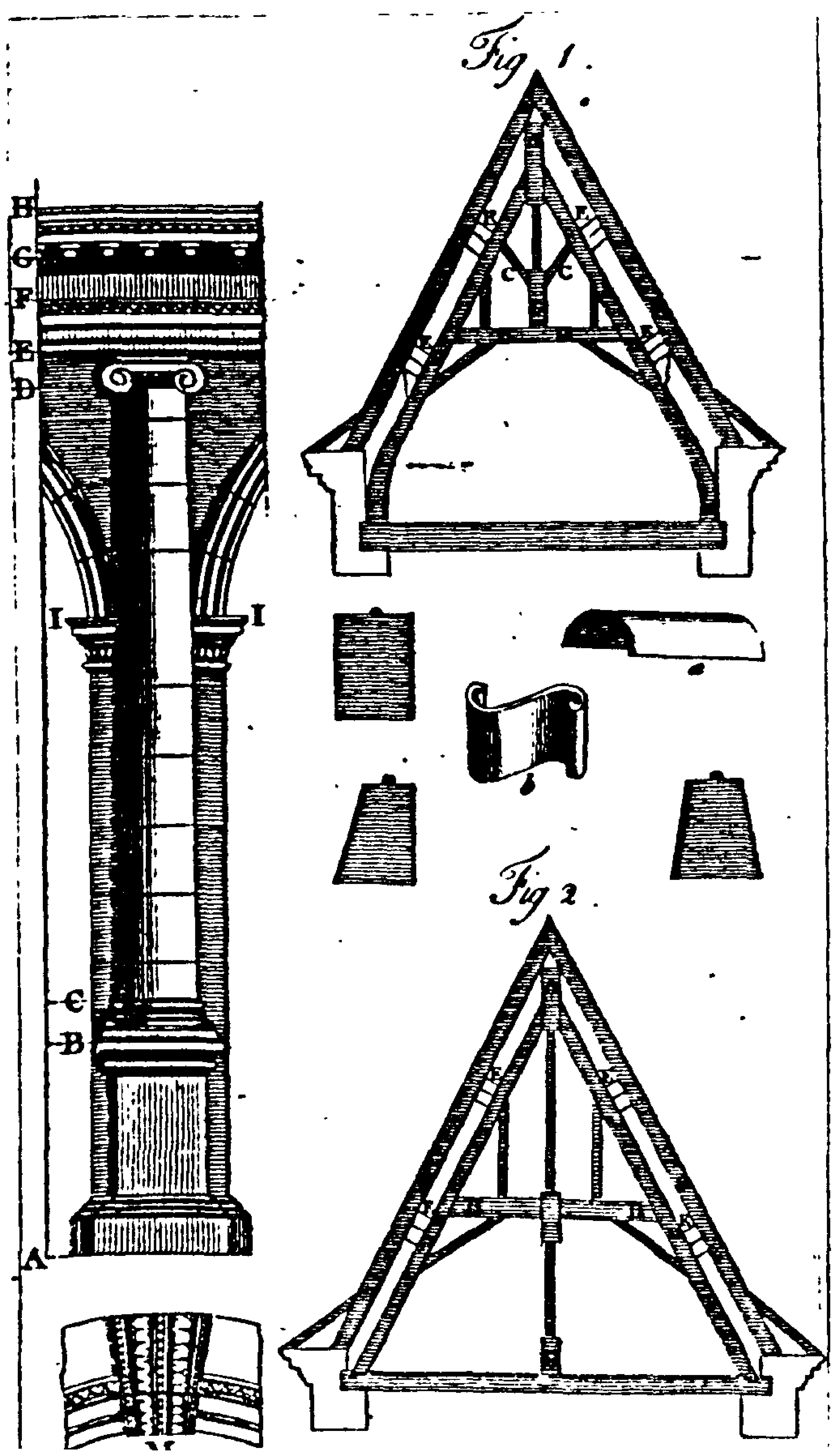


Fig 2.3

Roof construction shown by Henry Aldrich. This appears to have been influenced by le Muet (and possibly Johann Wilhelm).

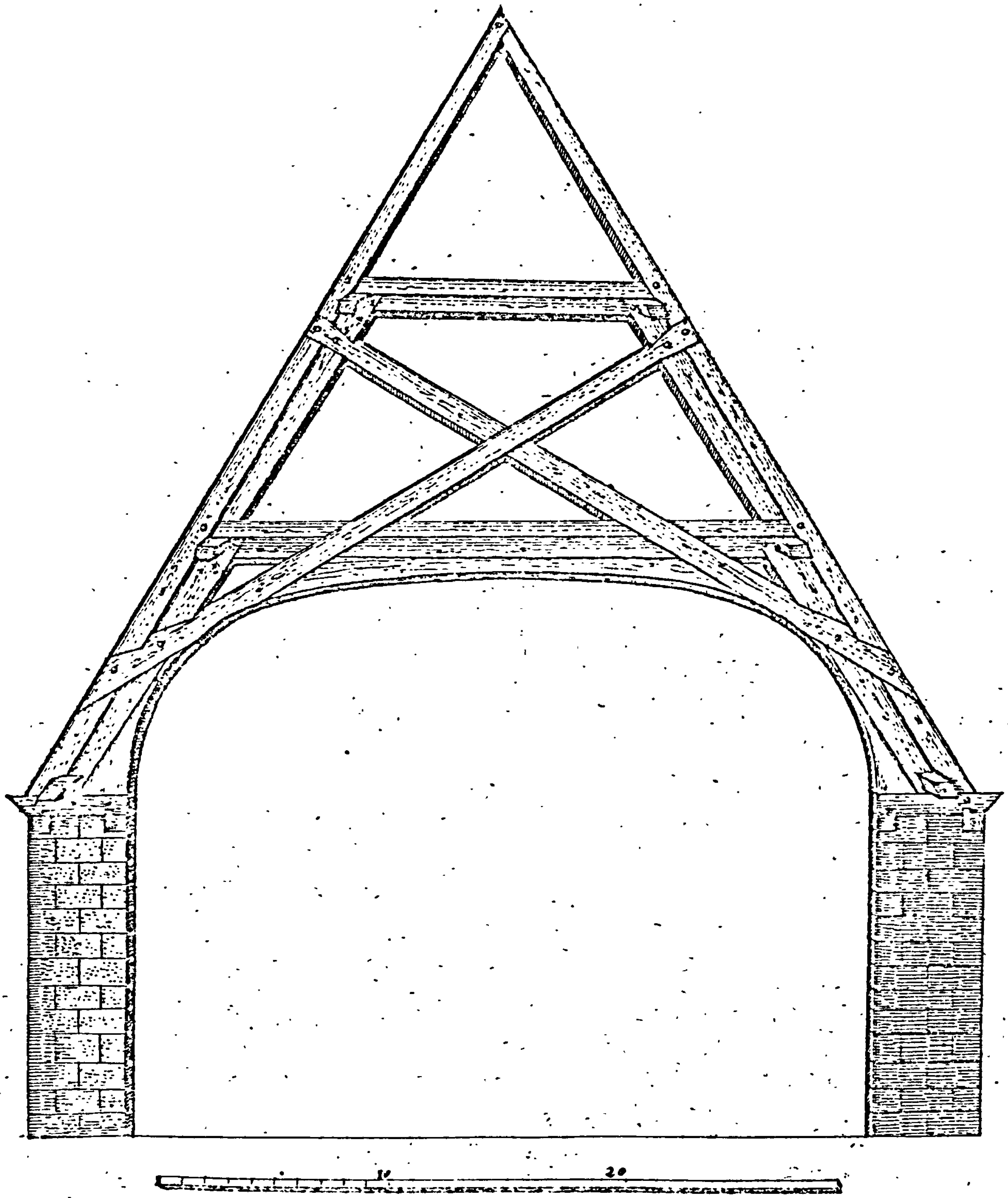


Fig. 2.4

Roof truss from Johann Wilhelm - Architecture Civilis c1650. The method of supporting the purlins is typical of this form of construction The scissor bracing is unusual (and may be of Wilhelm's own design.

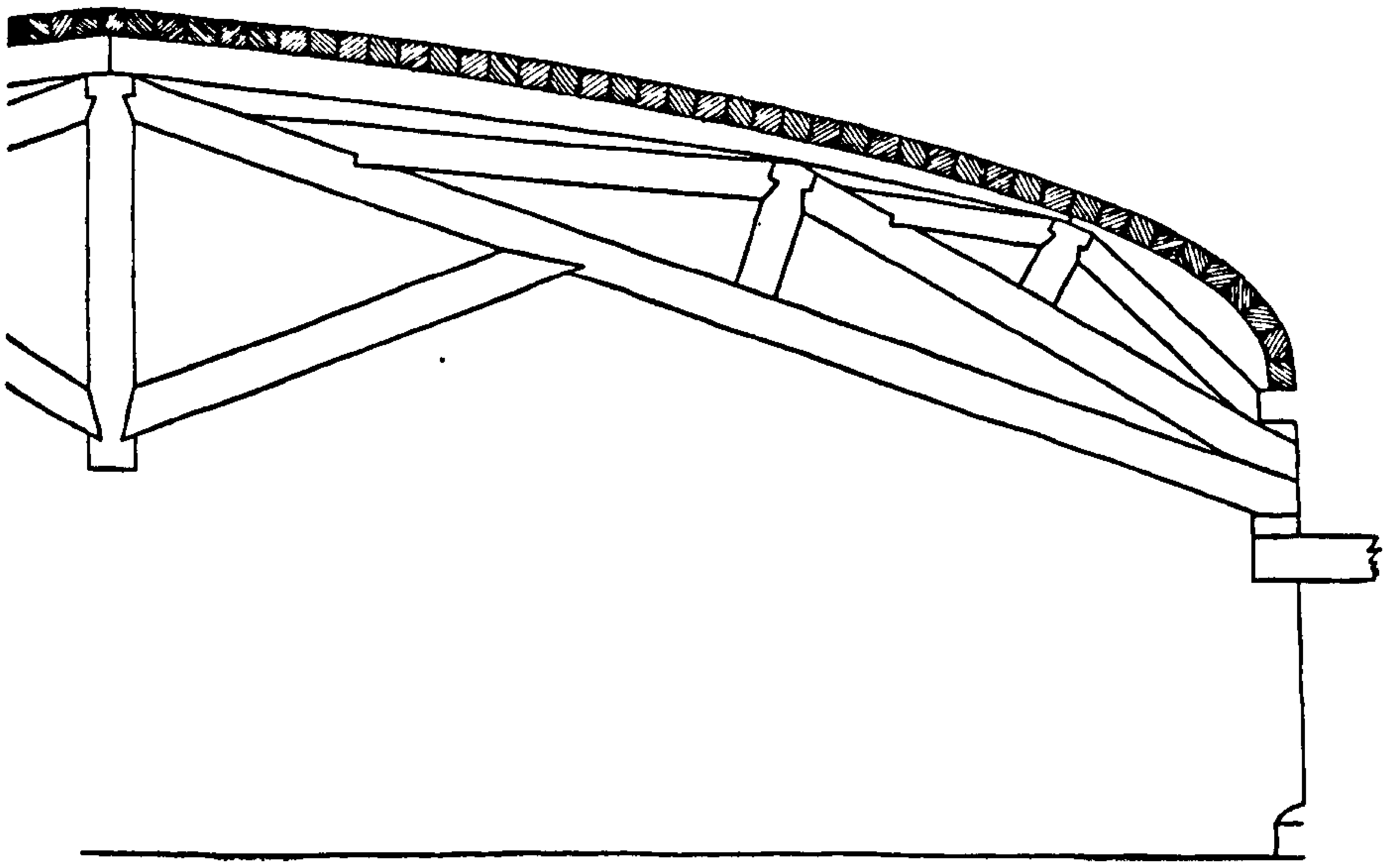
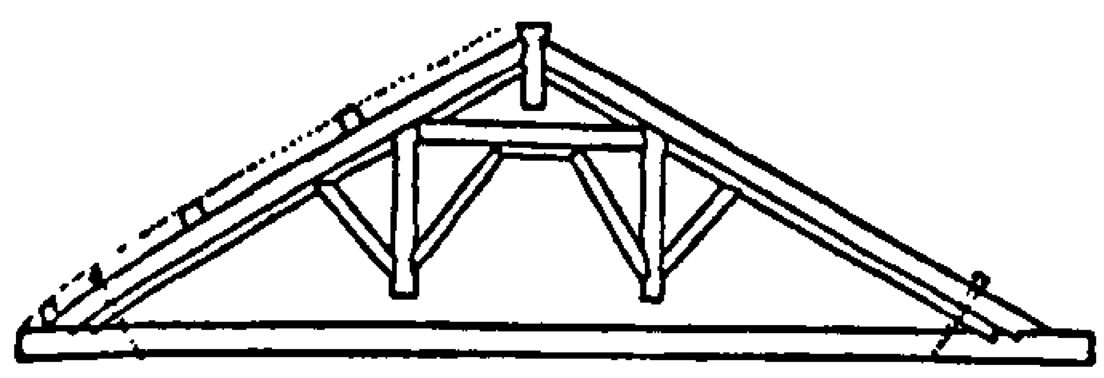


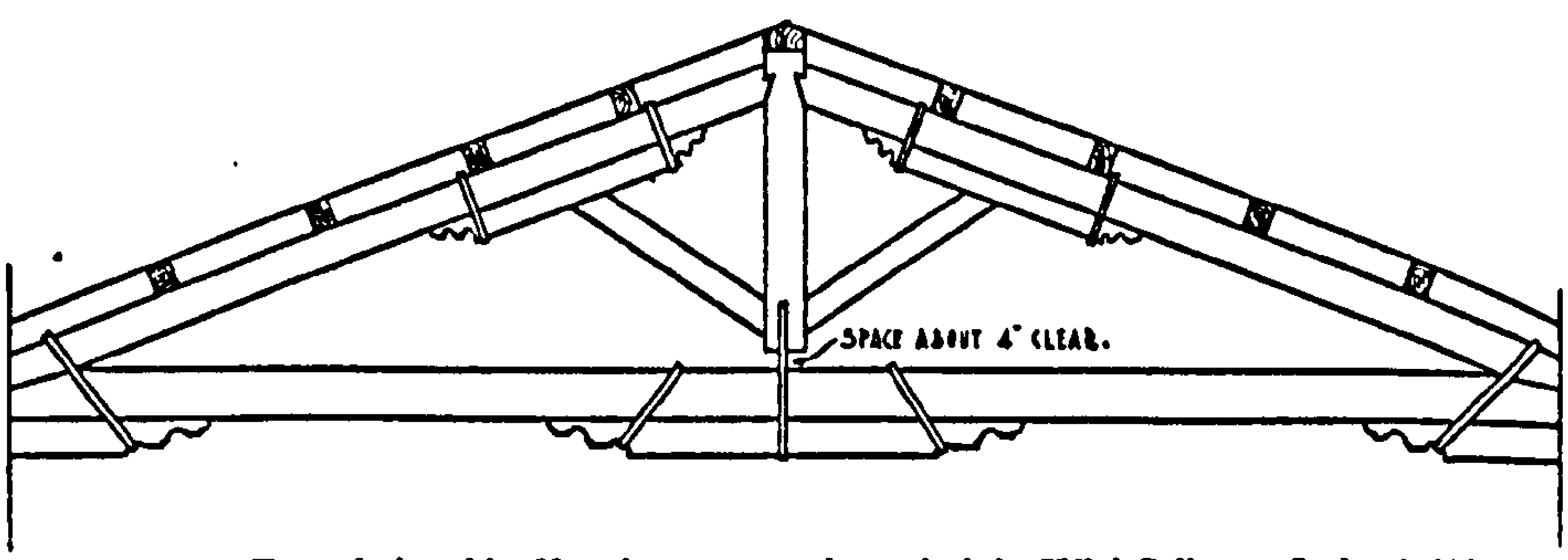
Fig. 2.5

Falsework for Santa Trinita Bridge
Design by Parigi redrawn by Parsons



A queen-post truss. From a sixteenth century manuscript.

a



Truss designed by Vasari to support the roof of the Uffizi Gallery. Scale: 1:100.

b

Fig. 2.6

Italian roof trusses illustrated by Parsons
- Engineers and engineering in the renaisance.

a) Design by Vasari for the Uffizi gallery.
b) A queen post truss from a sixteenth century manuscript.

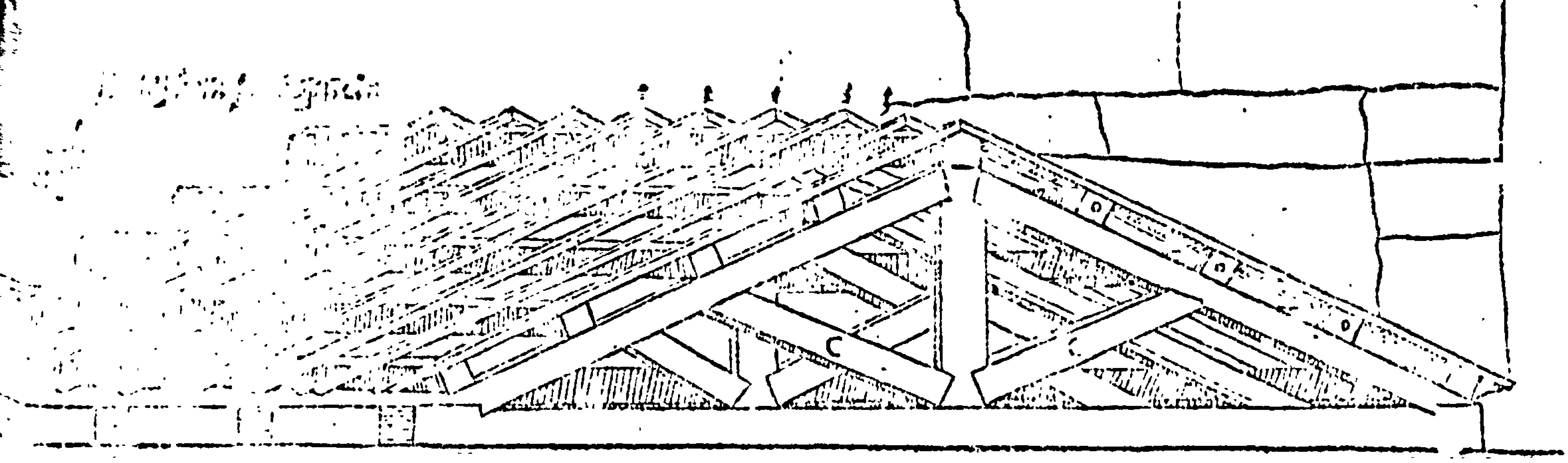


Fig. 2.7

This king post roof in Danielle Barbaro's 'Vitruvius' has the necessary joggles in the post to ensure truss Behaviour. In this example the post stands on the tie beam and there is no metal strap.

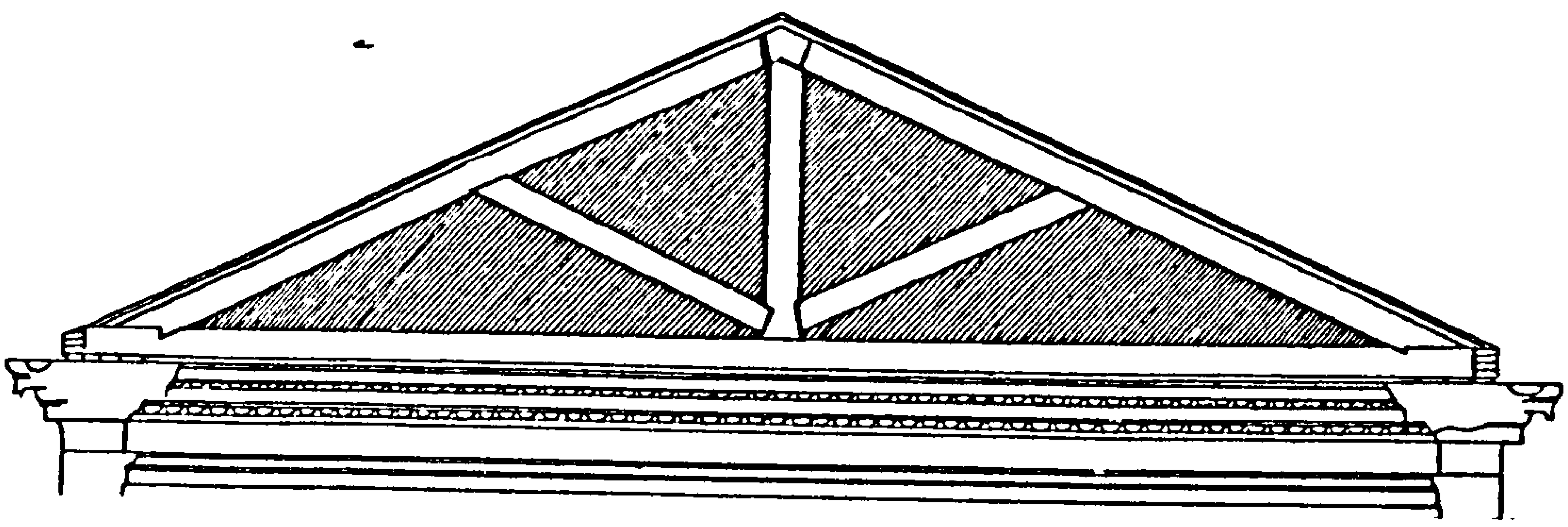


Fig. 2.8

Palladio, Book II plate 30

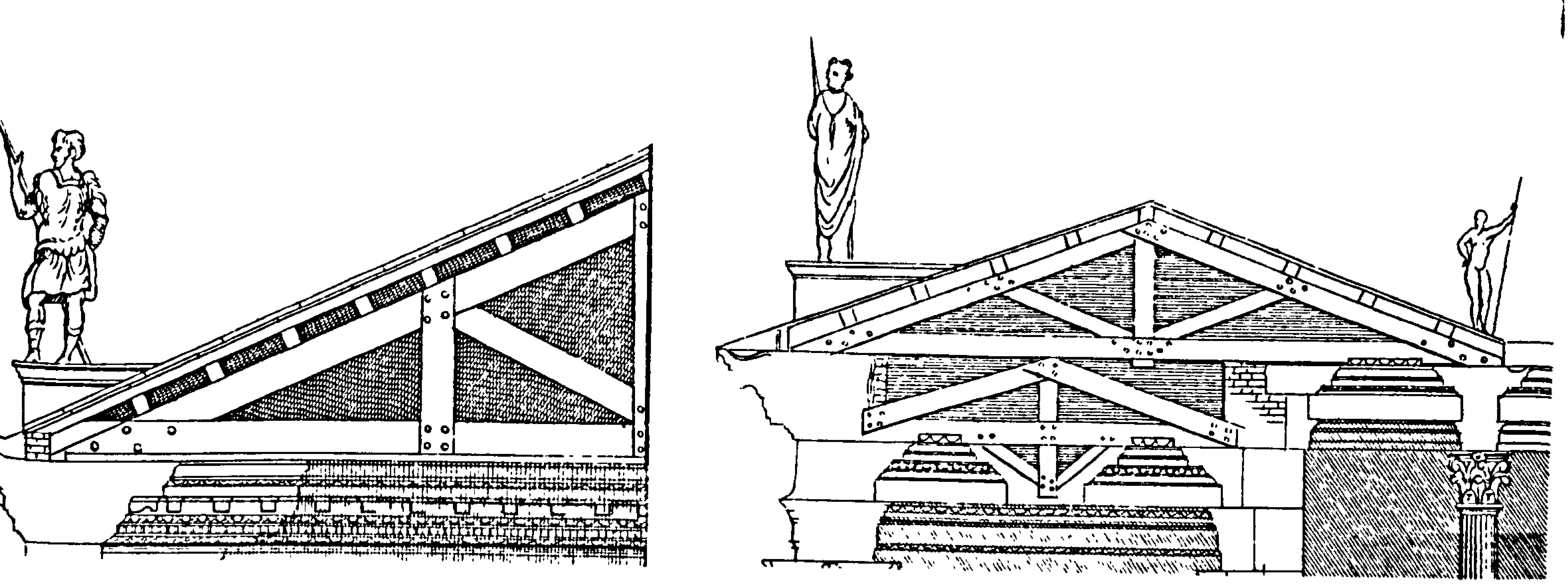


Fig. 2.9

These roof trusses illustrated by Palladio appear to be made of flat plates of metal as was the roof of the portico of the Pantheon.

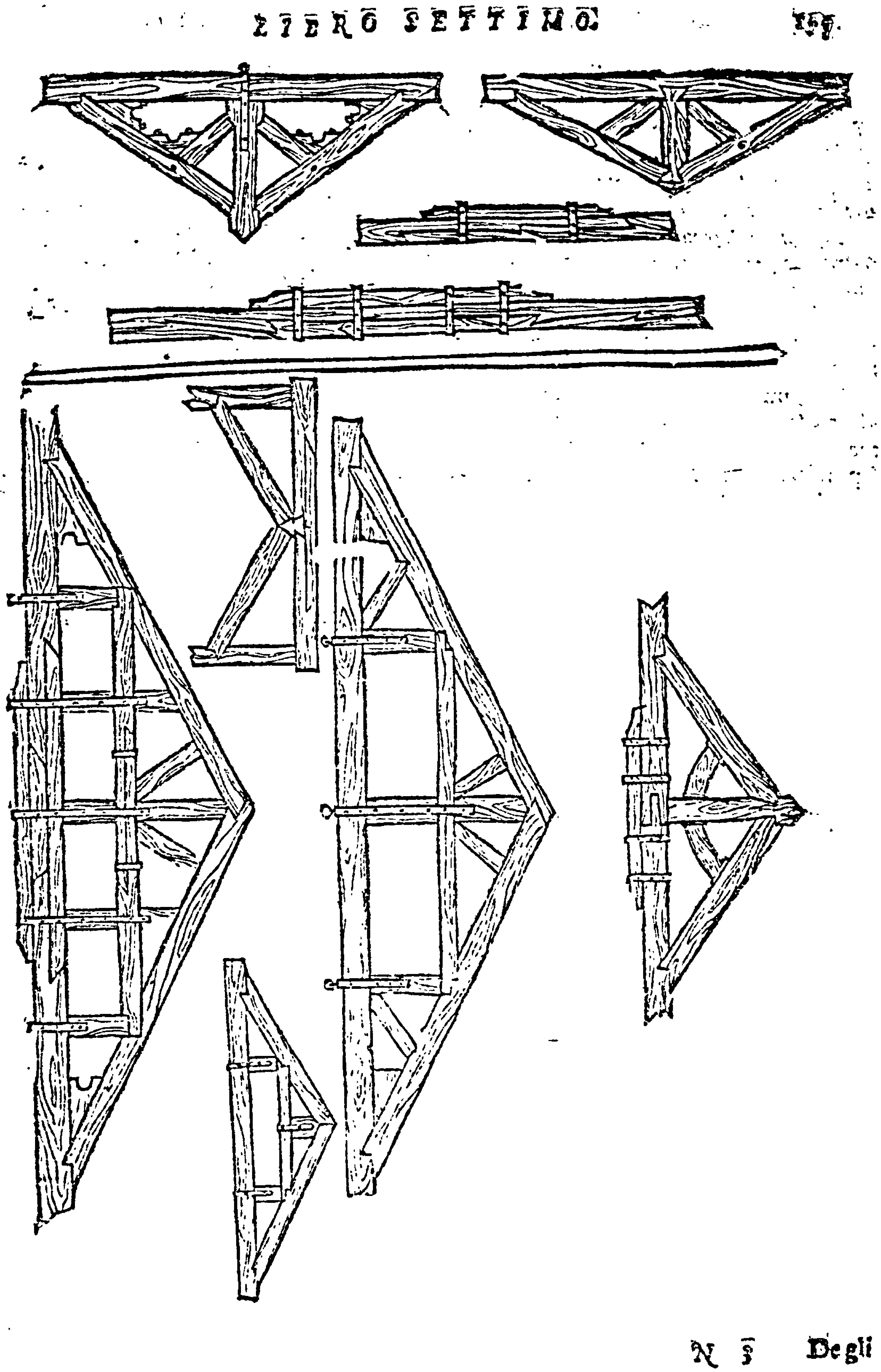


Fig. 2.10

Roof truss designs illustrated by Serlio. These show variations in detailing of the king posts and struts and of the queen posts and straining beams.

Diuersi accidenti vengono alle mani dell'Architetto, come saria questo, che volendo, essempi gratia, fare vn palco, ò solaro, ò tasello, che dir lo vogliamo; il luogo del quale sarà di piedi quindici, ma hauerà vna quantità di trauicelli, liquali non saranno di tanta longhezza, ma glie ne mancherà vn braccio a ciascuno; nondimeno egli se ne vorrà seruire. In tal bisogno non hauendo altro legname in quel luogo, potrà tenere il modo quì a canto dimostrato, & l'opera sua sarà fortissima, mettendo vn trauicello nel muro da vn lato, & l'altro capo sospeso, come quì si vede espresso.

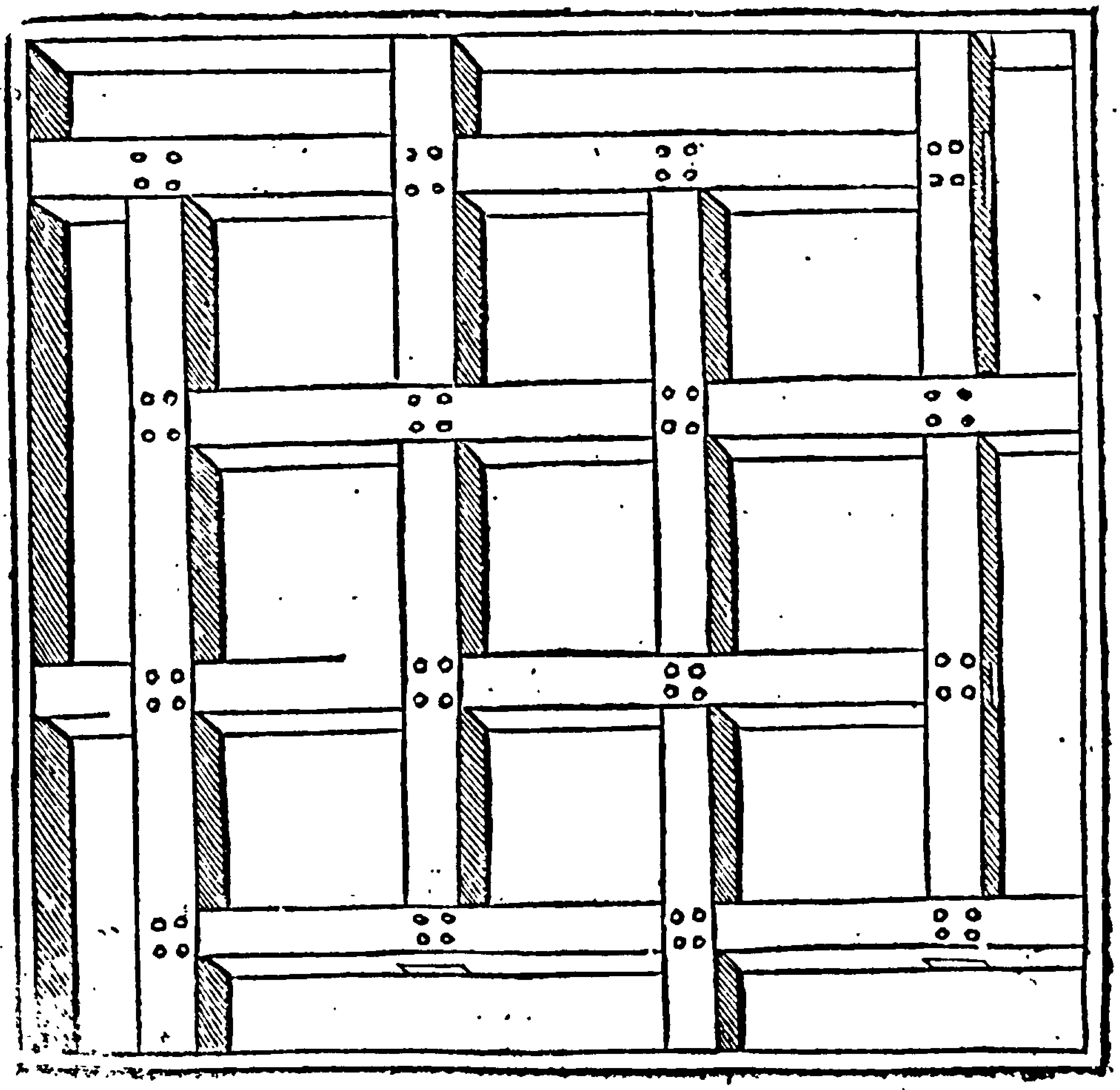


Fig. 2.11

'geometrical flat floor' by Serlio. It is not clear, from either text of illustrations how this was constructed. See appendix 2.

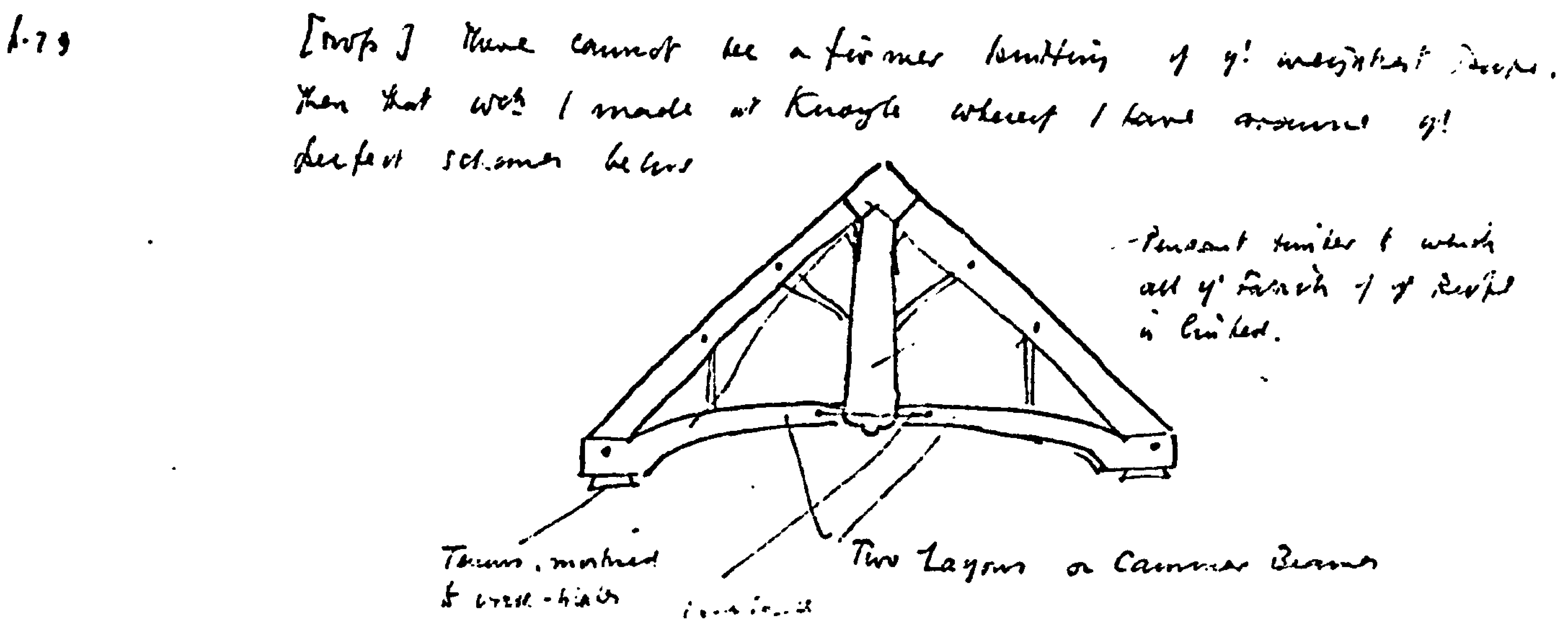


Fig. 2.12

Roof of East Knoyle Church.
From Dean Wren's copy of Wotton's
Elements of architecture. These
notes were made by Sir John
Summerson.

THE ORIGINS OF THE KING POST TRUSS IN ENGLAND

The earliest surviving examples of the modern type of king post truss are those by, or associated with, Inigo Jones. Unfortunately his longer spanning trusses have been lost in later re-roofing of the buildings but original structures still remain at Wilton and Stoke Bruerne (1). In both cases the buildings have been altered, but enough remains of the original structures to show their design. For the longer spanning structures we have to rely upon the few drawings which were made before their destruction. These drawings are important in confirming Jones' knowledge of the king post truss because without them it would be uncertain how extensive was his knowledge of this form. However the combination of drawings which show that Jones knew of and used king post trusses and the little evidence that exists for his contribution to Wilton and Stoke Bruerne suggest that their roofs may be his design.

The Italian origin of Jones' structural ideas can be identified and his influence on his pupil and assistant John Webb can also be seen although this in itself presents a problem because there can be no certainty that it was not Webb rather than Jones who better understood the structural forms that they both used.

The work of Jones and Webb was eventually to be overshadowed by that of Wren, whose work will be discussed in greater detail in a later chapter. However it is important to discuss Wren here as an originator of the king post truss because events were to make his influence on the development of the technology far greater than that of Jones. Moreover the source of Wren's ideas was quite different and, based on an understanding of the theoretical principles of the truss rather than the copying of previous forms, led to greater structural invention in his roofs.

Wilton and Stoke Bruerne

The roofs at Wilton illustrate the difficulty of interpreting structures of this date. Whatever the original structures over the famous cube and double cube rooms may have been, they were lost in the fire of 1647 or 1648 (2). In restoring these rooms on the south front, Webb used simple beam structures although it is possible of course that he copied what had been there originally. Roof structures elsewhere in the house appear to be eighteenth or even nineteenth century re-roofings or repairs. However what appears to be an early roof structure is now buried among the later framing of the clock tower over the East, and originally the entrance, front. It is possible that these timbers include some of the earliest now surviving at the house. The general condition of these timbers indicates that they are of seventeenth century origin but they may not have all been built at the same time because there are considerable variations in the detailing adopted for the different trusses. Repairs or changes may have included re-use of original timbers and perhaps also the building of new trusses and this makes the attribution of any one part of the work largely a matter of judgement. In spite of these difficulties the presence of a king post truss here requires some discussion.

Inspection of the timbers in this roof is difficult because of the later timbers inserted to support the clock tower above. Carrying out this work involved removing some of the rafters and purlins. The roof surface is no longer in its original place and the trusses now only support the ceiling. The simplest of the surviving forms are 'king post' arrangements carrying a ridge piece and side purlins (fig. 3.1). There are two arrangements where the principal rafters bear on the head of the strut or post, one where the post has shoulders cut to receive the principals as shown and the other without. Neither detail suggests that the posts were seen as being supported by the principal rafters. Within the same space is a more complete king post truss with struts to the principal rafters carried on square cut joggles at the foot of the king post and a joggle formed at its head. This truss is assisted by short struts, or puncheons, between the tie beam and the principals. The post of the truss is narrower than the tie beam and the truss is framed on centre lines with the strap at the foot of the king post being let into the beam (fig. 3.2). Metal straps have also been used at the foot of the principals to tie them to the beam.

It seem curious that there should be so many different trusses within the same space. It can hardly be accounted for just by assuming that more than one carpenter was employed (3). It is possible that the differences represent a development of structural ideas during a single building sequence but a more attractive idea is that the different trusses were built at different times (4). Carpenters marks are visible on the 'true' king post truss (fig. 3.2) but the numbers refer to the separate members of this truss and give no indication of its intended location or how many similar trusses there may have been. Whether the trusses were built at the same time or whether there were later alterations is difficult to determine without at least a more thorough inspection of the timbers; a task made difficult by the confined space.

At Stoke Bruerne the picture is much clearer. Early drawings show that the pavilions originally had pedimented gables (5) but these were removed during re-roofing in the eighteenth century when the present hip roofs were built. Nevertheless the surviving timbers show that although there were some changes made to the layout of the structure, the original trusses were re-used. These are king post trusses with wide splayed joggles at both the heads and feet of the king posts (fig. 3.3). That the trusses are of seventeenth century origin is shown partly by the way that the lower joggle is set right at the foot of the post; a detail that was soon to change. Today the trusses carry two pairs of purlins and common rafters but empty mortice holes in the principal rafters show that the roof covering was originally carried on close spaced purlins of small scantling which spanned between the trusses. Similar mortices in the tie beams once received the tenons of the ceiling joists. The present ceiling structure comprises girders between the tie beams to carry the joists.

The trusses are spaced at 15ft which seems rather wide and because of this the upper and more heavily loaded pair of purlins that were put in are assisted by inclined struts from the tie beams. This is not a very satisfactory arrangement and was probably dictated by the wish to re-use the original trusses. Assuming that these are in their original positions (and there is nothing to suggest otherwise) then it may be that excessive deflection of the close spaced purlins necessitated the re-roofing.

The overall form of the trusses here is similar to that of the most developed of the trusses at Wilton. Puncheons are used to assist the principal rafters as well as struts from the king post, the trusses are framed to centres and metal straps are used to truss up the tie beam to the post. No strapping is visible at the feet of the principals in this roof but there may be some hidden by the brickwork which has been brought up above the wall plate. Metal straps at the apex of the trusses at Stoke are probably eighteenth century additions dating from the re-roofing (6).

There is a difference in the detailing of the metal strap at the foot of the king posts which should be noted. While the truss at Wilton has the strap let into the tie beam, at Stoke the straps on each truss are simply bent outward to pass over the wider beams; not as good structurally because they would tend to straighten out under load (7). This difference suggests that the Wilton truss may be later than those at Stoke, a possibility also suggested by the shape of the joggles at the feet of the posts. Given these doubts about the detailing of the Wilton truss, the roof at Stoke has the only surviving trusses whose design can, with any reasonable confidence, be ascribed to Inigo Jones. The notable features of his design are the use of joggled king posts to form true trusses, strutting from the base of the posts, metal straps to truss up the tie beams and the use of close spaced purlins instead of common rafters. None of these is a traditional English technique. None is found here earlier than in the Stoke Bruerne roof although Jones must surely have used these techniques in his earlier buildings whose roofs have since been replaced.

Longer spans

The roof at Stoke is of modest span and we must rely largely on drawings to see how Inigo Jones handled more difficult structural problems. The roof of the Queen's House, Greenwich, does not seem to have survived long into the eighteenth century and there are no drawings of the building showing the roof structure although some original timbers remain. The Banqueting House roof was replaced by Soane and although nothing remains of the original structure it was, in its time, illustrated more than once. The roof of

St Paul's, Covent Garden, was burned in 1795 but fortunately a number of drawings were made of it before then. However, for both St Paul's and the Banqueting House the various drawings differ and some care must be taken in reconstructing the original form of their roofs.

At the Queen's House the roof is now carried by a modern steel structure but earlier tie beams remain. Accounts for Greenwich Hospital (8) show that the roof was in such a poor condition by the end of the seventeenth century that repair work had to be carried out. Unfortunately, though, they give little detail of either the nature of the timber work or the exact extent of the repairs. Photographs taken of the roof in 1952 show queen post trusses and although these were certainly not the structure built by Jones, we cannot be certain when they were built (9). The tie beams that can be found in the roof today are also visible in these earlier photographs and show that they were not part of the queen post structure. They can only be the tie beams of the original Inigo Jones roof trusses, left in place during both subsequent re-roofings, possibly because their massive size made their removal difficult.

The beams (figs. 3.4 - 3.6) are surprising, not just for their size, but also because they are each formed from two pieces of timber joined by long scarf joints clamped together with iron straps (fig. 3.5). The beams have a number of slots cut in their upper surface whose purpose is difficult to determine but a number of regularly spaced notches presumably once carried the ceiling joists (fig. 3.6). Three deep mortices cut in the top of the tie beams (fig. 3.4) indicate the number of posts in the original trusses. These posts would be consistent with a roof of similar form to that at Stoke and also with the layout of timbers shown in the drawings for the Banqueting House roof. Given the relative spans the latter is probably a better indication of the form of the Queen's House roof.

At the Banqueting House there is nothing left of the original roof after Soane's nineteenth century replacement. Unfortunately Soane, although reporting on the condition of the roof (10), seems to have made no survey drawings before he replaced it and among the eighteenth century drawings of the building are two conflicting versions of the roof structure. The drawing in Campbell's Vitruvius Britanicus (11) shows a fairly low pitch roof relying upon a simple king post truss with puncheons (fig. 3.7). This drawing thus corresponds with the Stoke roof though the span here is very much greater. There are two features of the drawing that should be noted. The head of the king post is incorrectly drawn, possibly a drafting error by someone unfamiliar with the details of the construction, and secondly the principals are shown curiously bent down at their feet. This detail, apparently adopted occasionally (12), is shown in the roof truss illustrated in Richards' Palladio (fig. 6.2), but there is nothing to suppose that it was a feature of the roof here.

Contrasting with Campbell's drawing is Flitcroft's version of the structure. His drawing in Kent's Designs of Inigo Jones (13) shows a roof with a much steeper pitch (fig. 3.7b). The puncheons have become secondary posts and first carry a second pair of inclined struts on joggles at their feet. They then pass below the tie beam where they carry two further short struts to assist the beam. This version of the structure seems to be confirmed by a drawing by M A Nicholson published early in the nineteenth century (14) which shows essentially the truss layout drawn by Flitcroft but with the extension of the outer posts below the tie beam missing and a pair of metal tie rods from the top of the principals to the tie beam inserted into the timber work. The tie beam shown by Nicholson has the same scarf joint that is found today in the roof of the Queen's House, there is metal strapping to both ends of the secondary posts and the roof slope, though greater than shown by Campbell is less than in Flitcroft's version (fig. 3.7c). Clearly one of the eighteenth century drawings must be wrong and Flitcroft's is confirmed as being more nearly correct by Nicholson's. Flitcroft made his drawings for Kent's book from Lord Burlington's collection of originals. Differences between his drawing and that of the structure as shown by Nicholson can be accounted for by changes made between design and construction.

The design of the roof was not very successful. The secondary posts were not strutted directly by the inclined struts from the king post, a feature criticized by Nicholson in his commentary on his drawing (15). This would have resulted in increased bending on the principal rafters. Although the roof survived into the nineteenth century, extensive repairs had been required early in the eighteenth. It was in poor condition by the time that Flitcroft was making his drawings. (They were published in 1727). Shortly after Kent was taken into the Office of Works in 1726 Flitcroft became regularly employed in work at Whitehall Palace (16) and repair of the Banqueting House roof must have been one of his major jobs there.

The long tie rods were presumably added during this repair work. It seems unlikely that they would have been part of the original design. It is difficult to say when the metal straps were put on the secondary posts. Removal of the paintings and releading of the roof would have enabled them to have been added as part of the repair work but there is now no way of knowing for certain. It seems likely that they were original because a drawing by Smythson of the roof of the Riding School at St James Palace shows a similar structure (17). This roof has a steep pitch, thus tending to confirm the relative steepness of the roof in the Flitcroft drawing;

has two pairs of struts from the king post and has the same arrangement of metal strapping as shown in the Nicholson drawing. Smythson shows the king post joggled at the top but the same failure of the struts to support the secondary posts. Given the similarity between the two structures there must be a strong presumption that Inigo Jones was (at least in part) responsible for the design of the Riding School roof (18).

In 1728 a scaffold was put up in the Banqueting House to inspect the ceiling paintings and it was then discovered that the roof was in such a poor state of repair that it was thought to be dangerous (19). The Office of Works therefore requested that money should be made available to enable a scaffold to be erected to support the roof which was at the same time designed to allow services to continue in the building (20). (By this time it had become the Chapel Royal). It does not seem to have been until 1732 however that restoration work was eventually completed. This work included Kent's restoration of the paintings, the repair of the roof structure and the recasting of the lead (21).

Although of similar scale to the Banqueting House, St Paul's, Covent Garden, was a far more complex problem because of the overhanging eaves. There are three drawings of the original structure and although there are differences between them, these are slight and there can be no doubt about the general arrangement of the principal timbers. Campbell shows the roof structure at a fairly small scale in Vitruvius Britanicus (fig. 3.8a). The other published drawing is by Batty Langley; this was a measured drawing of the portico columns and the roof timbers, the latter to be subsequently redrawn for his <u>Treasury of Designs</u> (22). This drawing was to a much larger scale and shows more of the details of the structure (figs. 3.8b & c). There is also a surviving drawing of the structure made by William Newton (23). This is part of a study apparently made in preparation for the design of the roof structure for Greenwich Hospital Chapel when he assisted in the restoration in 1780-88 (24). (It is on a sheet containing four roof structures including two Greenwich roofs (fig. 8.1)). Newton's drawing is also at a large scale showing the details of the jointing and the sizes of the timbers.

Langley and Newton differ in that the former includes in his drawing an additional pair of 'discharging braces' (his term), and a pair of short vertical struts between the tie beam and the principal rafter. It might be assumed that the difference is because they measured different trusses but this is unlikely. There seems to be no reason why there should have been any differences in the framing of the trusses. Campbell's drawing leaves out the discharging braces but includes the short vertical struts and this seems likely to have been the form of the roof at that time. Repair work had been carried out on the structure by 1734 (25) and the additional braces shown by Batty Langley could well have been inserted at that time. Newton might possibly have wished to show the original design and so omitted these timbers. His omission of the short vertical struts might also have been because he assumed that these too were later additions. It is indeed possible that they could have been inserted after the original building but before Campbell made his drawing. However, without the original structure to examine, it is difficult to substantiate such an assumption.

There are other differences of detail in the drawings that should be noted. Batty Langley's 'measured drawing' has the roof at a steeper pitch. His purlins are wider apart and the head of the king post has no joggle. There is no metal strapping shown but he does include puncheons over the wall plate to help support the principal rafters. Both drawings show notches taken out of the principals to receive the heads of the secondary posts but only Newton has the tie beam similarly notched to receive the outer pair of struts. However, Batty Langley's book illustration does have this latter feature. The roof slope of this drawing also agrees with Newton's version.

The unique features of Langley's book illustration can be ignored. The joggles at the head of the secondary posts are unlikely and those at their feet could not have existed in the original structure because the struts which they support were not there originally. This drawing is thus an idealised version of the eighteenth century state of the structure. Some of the differences between the Batty Langley measured drawing and the Newton drawing may be because they were unclear about what was part of the original structure and what was added later. Newton's version is probably nearer to the original arrangement although the metal strap at the foot of the king post appears to be a later form (26).

The roof of St Paul's was essentially a king post structure with joggles at the head of the king post so that it might be carried by the principal rafters. The trusses were an improvement on those used for the earlier Banqueting House roof in that the posts to truss up the tie beam at its quarter points were more adequately strutted from the king post. However, the wide overhanging eaves presented a structural difficulty in that there could be no solid bearing for the feet of the principals which must instead rest on the cantilevered tie beam. Perhaps for this reason Jones used a second pair of struts to help support the structure from above the top of the walls. Newton's drawing raises the possibility that the short struts might have been added later and suggests therefore that the original design might not have been completely successful.

Any discussion of these structures must take into account the work of John Webb because it is now impossible to say for certain how much he might have contributed to their design and to the initial development of this form of structure. There are rather more surviving drawings by Webb that show roof structures than there are by Jones and these consistently use the king post form. Indeed it seems as if this was the standard type of roof for Webb, to be used in all situations whether appropriate or not. Among the papers for the building of Lamport Hall is a section of the house by Webb which includes a roof truss (27). In this the 'M' shaped roof framing of the attic rooms is shown carried by the spine wall of the house (fig. 3.9). The traditional way of framing a roof of this kind would simply have the principals and a collar; the latter to act as a beam to carry the ceiling joists. The addition of a king post to this, which Webb shows, is an unnecessary complication.

Unfortunately at Lamport the upper part of the roof is inaccessible but a similar arrangement was actually built at Uppark. The attics in this house (by William Talman) are on a larger scale than those at Lamport but are still of no longer span than may often be found elsewhere with simple collar braced principals. Nevertheless, here the principals carry a king post (fig.3.10). At its foot the post is halved to join the collar rather than being tenoned into it. This curious detail suggests that neither carpenter nor architect were quite sure of the form of construction. In view of the drawing from Lamport, Webb would seem to be a likely source for Talman's use of this arrangement of timbers at Uppark.

We know from the correspondence on Lamport that the detailed supervision of the building and even some of the detailed design was left in the hands of the clerk of works (28) but Webb was not unaware of construction details. His drawings of other buildings which show the roof truss do so in some detail, even though they are often at small scale. The joggles are carefully and correctly drawn and the fixing pegs indicated. Such an attention to detail, which shows Webb's understanding of construction, suggests that it may have been he, rather than Jones, the designer of scenery and costumes for court masques, who made the greater contribution to the design of the roof structures.

There can be no doubt, though, that it was through Inigo Jones that the king post truss was first brought to England. The use of both the king post truss and close spaced purlins is Italian in origin. The former is clearly drawn in a number of illustrations by Palladio (29) and eighteenth century measured drawings of Italian roofs show the latter (30). That Inigo Jones himself saw king post trusses while in Italy is confirmed by a sketch he made of one (31). Curiously this truss is part of a hoist rather than a roof (fig. 3.11) but Jones' drawing is in sufficient detail to show that he was familiar with its construction.

Although Jones knew of the basic construction of the king post truss it is difficult to assess how much he may have understood of its mode of behaviour. The size of the tie beam at Stoke Bruerne is sufficient to have carried the roof without the need for any truss action at all. If the choice of beam size had been left to the carpenter this would be expected but the fact that the trusses are framed on centre lines suggests that he received fairly explicit directions from the architect.

Whether or not Jones and Webb fully understood the structural behaviour of the king post truss, they made some developments in construction from the form as received. The illustrations in Palladio of roof trusses that use secondary posts do not show them adequately strutted from the foot of the king post, ie. there is no joggle on the head of the secondary post to receive the strut and both members are separately joined to the principal rafter. This was the weakness found in the Banqueting House roof, and it seems possible that the use of secondary posts was suggested by illustrations in Palladio (32). The extensions of these posts below the tie beam that appear in the design seem to have been taken from the same source (33). The problem of supporting the secondary posts is, as has been seen, solved in the design for St Paul's. The shape of the joggle at the foot of the king post at Stoke is also as found in Palladio and as drawn in Jones' Italian sketch. This has the weakness that a satisfactory mortice and tenon joint cannot be made at the feet of the inclined struts. However the problem was later solved by forming an extended foot on the bottom of the post as shown on the drawings for both the Banqueting House and St Paul's.

A question which is difficult to answer is whether the knowledge of the king post truss was passed on directly from Inigo Jones and Webb to anyone else. The use of the king post at Uppark is however a clear indication of the dissemination of these ideas and a Thorpe drawing which shows the use of a joggled king post in a hammerbeam roof (34) suggests a similar connection. However the evidence is only circumstantial. Other examples may come to light but, with so few practising architects, any dissemination of the idea can only have been limited and, in the light of subsequent events, can have had little significance.

Early Wren roofs

The line of development begun by Jones was effectively ended by the civil war. Any dissemination of his ideas that might have occurred was prevented by the decline in building during the interregnum. Following the Restoration, with Webb out of favour, any development through his buildings remained restricted. It is possible that other architects may have known of and used the king post form. Pratt was certainly aware of this kind of structure, describing it in his essay on architecture (35). But the work of all the other Restoration architects was overshadowed by that of Wren. He became the most important figure in the development of structures at the end of the century both because of the large volume of work for which he was responsible and because of his clear understanding of the structural principles involved.

Wren's first two buildings show his immediate grasp of structural technique. The model for the chapel at Pembroke College, Cambridge has carefully made king post trusses (36) showing that, like Jones, Wren was aware of this structural device. The trusses here differ from Jones' structures in omitting the puncheons but otherwise have no particular structural improvement. The introduction of secondary posts and even a second pair of inclined struts was to appear in Wren's later roofs.

The roof of the Sheldonian Theatre, Oxford introduced a quite new structural form. The drawing of this in Parentalia (37) shows that each truss had three posts with the principal rafters between these arranged in an arch like form (fig. 3.12). The detailing of the joints shows that the posts were suspended from the timber 'arch' and the tie beam was in turn supported by these posts. It was the construction of the tie beam however that attracted so much attention at the time. Rather than using a single piece of timber which would have had to have been more than seventy feet long, Wren built up the tie beam from several pieces. These were not simply scarfed together like Jones' tie beam at the Queen's House but were instead arranged to interlock. Four pieces were first carried on notches cut into the sides of the posts. These were then formed into a continuous tie by three timbers passing under the feet of the posts and jointed into the four upper members in such a way as to allow tensile forces to be transmitted between them.

We may, like the writers of the eighteenth century, admire the detailed design of the carpentry of this beam, but the significance of the roof is that it shows that Wren must have understood the fundamental principles involved in a roof truss. The posts were clearly designed to be in tension. There is no question of their standing on the tie beam which could hardly have acted as a beam and was also clearly designed with tensile forces in mind. As it was an early building, he could not have experimented with this form or developed it from earlier structures, perhaps simpler or of smaller span. Instead he immediately recognised that he was hanging the attic floor from the timber arch above. Furthermore the difference between the structures of these first two buildings by Wren shows that, unlike Jones and Webb, he was not restricted to variations on the simple king post form.

While Jones obtained his ideas on trusses from having seen them in Italy, Wren could not have used the same source. He did not leave England until 1665, after the buildings at Oxford and Cambridge had been started, and this journey was only to Paris. Nor as has been noted were Italian architectural books sufficient in their illustrations to have given much guidance on roof construction. The simple king post roof might have been taken from Serlio or Palladio but neither has anything that could have inspired the Sheldonian roof.

It has been seen earlier that Wren's father drew upon Bernardino Baldi's mechanics for the design of a roof structure and that Wren himself owned a copy of this. There can be little doubt that this was the source of his structural understanding and his innovations in design (38). Following Aristotle's method, Baldi examined a number of common everyday problems in mechanics and discussed the forces acting. For the roof truss he provided a drawing and described the arch like action of the principals. The king post truss illustrated has wide splayed joggles at its top and is cut short of the tie beam (fig. 3.13). An iron strap supports the latter and Baldi showed how loads on the beam may thus be carried by the king post. The joints between the beam and principals to contain the outward thrust of the latter were clearly drawn. A second sketch has an alternative truss layout with struts and secondary posts added.

Whatever the influence of his father's design on Wren, the importance of Bernardino Baldi's book was that it provided not simply a description of the roof truss but an explanation of its mode of behaviour. Wren like his father was not confined to the slavish copying of a form that he had seen built. Whilst Inigo Jones and Webb did little more than adopt the simple king post layout Wren's father was able to produce a unique open timber roof and Wren himself the elaborate design for the Sheldonian roof as well as other novel structures that will be examined in the next chapter. In the text book they used, the theory as well as the form appeared together and the understanding of the theory gave the designer greater freedom in the development of satisfactory structures.

A translation of the relevant passage in Baldi is given in Appendix 4.

Footnotes - Chapter 3

1. Stoke Bruerne cannot be definitely attributed to Inigo Jones. A summary of the evidence for this attribution is given by Colvin (1978), p473. Hill and Cornforth (1966), p.61, opine that "the pavilions are almost certainly by Inigo Jones".

2. Hill and Cornforth (1966), p.75.

3. Examples do occur where different roof structures in a building may reasonably be accounted for by the employment of different carpenters during one continuous building operation.

4. The relative positions of the trusses in this roof space hardly suggest a layout planned as part of the original building of the house.

5. Shown in the drawing in Vitruvius Britannicus. Hill and Cornforth (1966), p.61, reproduce an eighteenth century drawing showing this roof, apparently covered in lead.

6. Other roofs with later repairs have similar metal straps. The use of coach bolts rather than forelock bolts on such straps indicate a later date.

7. In fact the beams on the trusses would be sufficient to carry the whole of the roof and ceiling load without any trussing action.

8. Wren Society VI p.59

9. Photographs in the Ministry of Works (D of E) Photographic Collection show queen post trusses with pairs of timbers forming the posts. This suggests that they are either nineteenth century trusses or earlier trusses with repairs.

10. The drawing by Soane, now in the Soane Museum, shows the replacement roof which he designed.

11. Vitruvius Britannicus I, plt. 12. Campbell says of this - "after much labour and expense I have at last procured these excellent designs of Inigo Jones for Whitehall from that ingenious gentleman William Emmett of Bromley ... from whose original drawings the following 5 plates are published ...."

12. I am informed by Dr Brunskill that this was a common detail. It has been suggested that it was either to give the joint greater protection or to provide more timber where the mortice was cut. Sir Roger Pratt appears to be describing this arrangement when he says "The principal refters were all made of knee pieces because that by their crookedness ... much of the weight of the roof is by that means taken off from the walling." - Gunther (1928), p.251.

    The only trusses on which I have seen this arrangement are in the roof of the Quaker Meeting Room, Merion, Pa.

13. Kent (1727), plt. 51.

14. Nicholson (1826), plt. xx. The plates of this are by M A Nicholson who made many of his father's illustrations. The measurements may have been by either of them.

15. Ibid.

16. The first mention of Flitcroft in the minutes of the Office of Works appears in May 1726. There are then frequent references to work to be carried out by him. PRO.

17. The drawing is J/14 in Girouard's Catalogue - Girouard (1962). He notes that this is "probably dating from Smythson's visit to London 1609." He also reproduces from James Sheppard, <u>Memorials of St James' Palace</u>, the information that "In July 1604, directions were given for buildinge such conveniente stabling and barne room as shall there (at St James' Palace) be founde needful for the Prince's (ie Henry's) service."

18. Jones returned from Italy in 1603 and his involvement in Prince Henry's works is chronicled in the <u>History of the King's Works III</u>, pp.120-7 where it is also recorded that he was under the Queen's patronage at least from 1605. He was certainly present during the building and we may readily imagine how ideas and advice would have been sought from one who had so recently visited Italy.

19. The events can be followed in the minute book, the letter book and the accounts of the Office of Works. The original warrant for the erection

of a scaffold was made on 25 October 1726, for an estimated £145. At that stage it was "ordered that Mr Flitcroft, Mr Kynaston and Mr Joynes be acquainted therewith but not to proceed until further ordered." PRO. works 4/3.

20. "We humbly crave leave to represent to your Lordships the decayed conditions of the roof over the Banqueting House at Whitehall which upon examination we find to be so very bad that it is dangerous for people to congregate there.

"And whereas the reason is too far advanced to do the necessary repairs, we humbly propose that a scaffold be forthwith erected in such a manner as will secure the roof for the present and enable us to see better what repairs will be wanting, and will be no hindrance to Divine service when it is set up; this scaffold will be absolutely necessary for the making the repairs may be set up in a month's time and will cost about the sum of 185 pounds and is most humbly submitted by Thos. Ripley, Westby Gill, Wm. Kent.

"Whitehall Office of Works. 30 July 1728" PRO. Works 6/15 p.172.

21. In spite of the above it was not until the paintings were taken down that the true condition of the roof was discovered:-

"We think it our duty to inform your Lordships that upon taking down the pictures in the Banqueting House, we found the ends of the beams which bear a great length so very much decayed by the badness of the covering that we are of the opinion they should be thoroughly repaired and the lead new cast. If it be your Lordships' pleasure that the same be done the expense may amount to the sume of six hundred and fifty pounts. Ripley, Gill, DuBois, Kent. Aug. 29 1732." PRO. Works 6/15 p.258.

22. Langley (1736), plt. 27. Also Gough Maps 22 f.65 and Langley (1740). Note the difference between the two drawings. Either Langley was careless in making his later drawing or he delegated the work to a poor draughtsman.

23. RIBA. Drawings Collection.

24. Newton assisted James Stuart and then completed the work when the latter died - Colvin (1978), pp.591-2.

25. Survey of London 36 p.108

26. One would expect a strap at the foot of the king post to be original. The strap joining the feet of the struts could have been added during the repairs.

27. Northamptonshire County Record Office.

28. Letters from Sergeant, the Clerk of Works, with recommendations for building details are in the Northamptonshire Record Office.

29. See figs. 2.7 & 2.8. However, in the sections of the buildings in the Four Books queen post trusses are more common.

30. The best of these are those collected for Henry Holland. See Chapter 8.

31. Inigo Jones' Roman Sketch Book. The illustration here is taken from a photograph in the Courtauld Collection.

32. Palladio (1570), Bk. iv, plts. 6, 11, 19 & 97.

33. Ibid. plt. 27.

34. T.115 of Summerson's catalogue - Summerson (1966) - is an elevation of a house but with two wings shown in section. The care with which these are drawn suggests an interest in carpentry. One wing is a service wing of two storeys, the upper floor roofed with collar braced principals. The structure is carefully drawn, shows wall plates and has the principals reduced at the collar. The other wing is a high open hall with double hammer-beam roof, again carefully drawn. The use of a joggled king post here is unmistakable and Thorpe was certainly familiar both with this device and with carpentry details generally.

35. Gunther (1928), p.212. The passage here refers to the structure of St Pauls.

36. Wren Society V plt, xi.

37. Wren (1750).

38. Baldi (1621). Wren's copy of this is now in the Bodleian Library, Oxford.

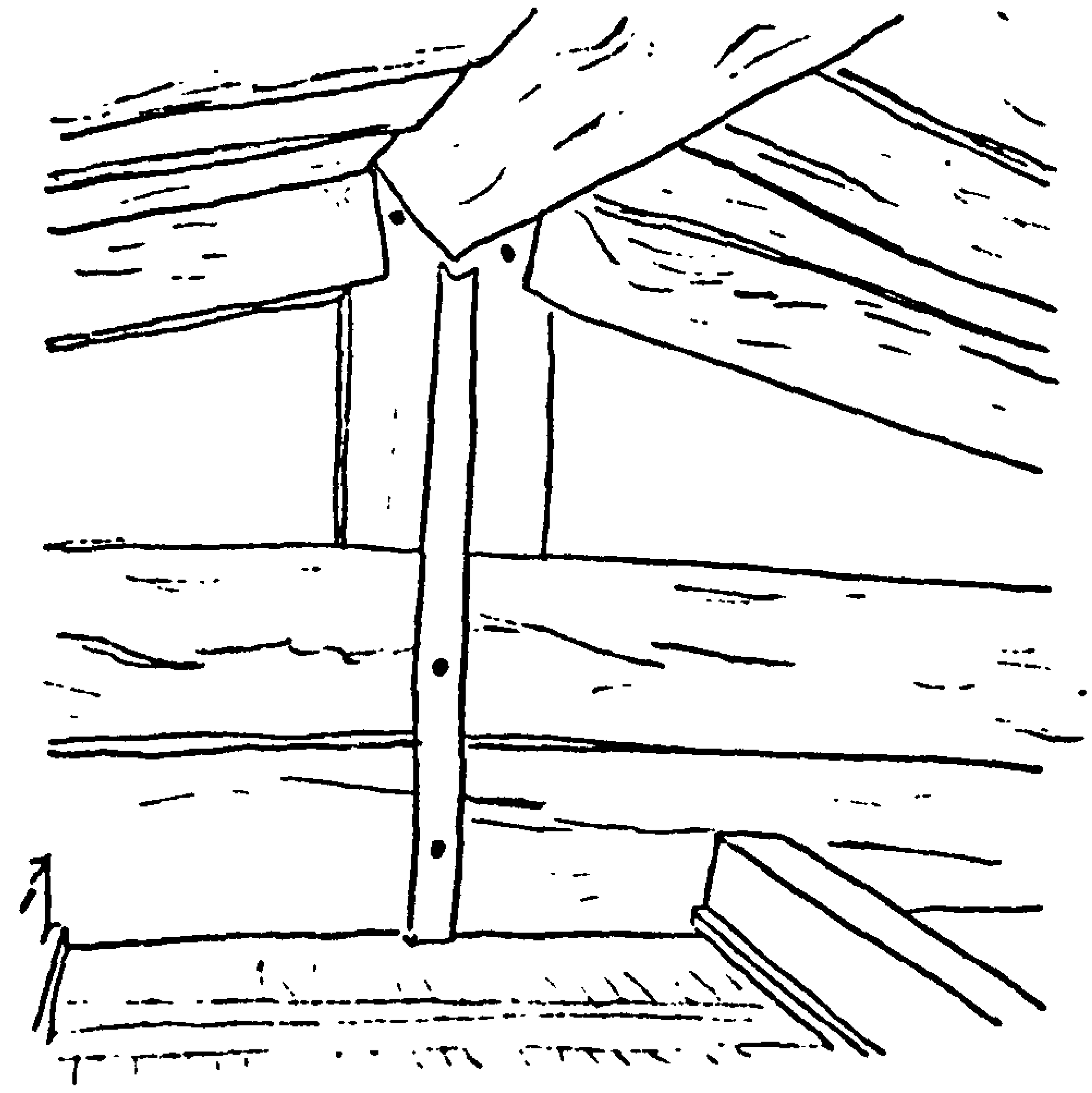


Fig. 3.1

Wilton House

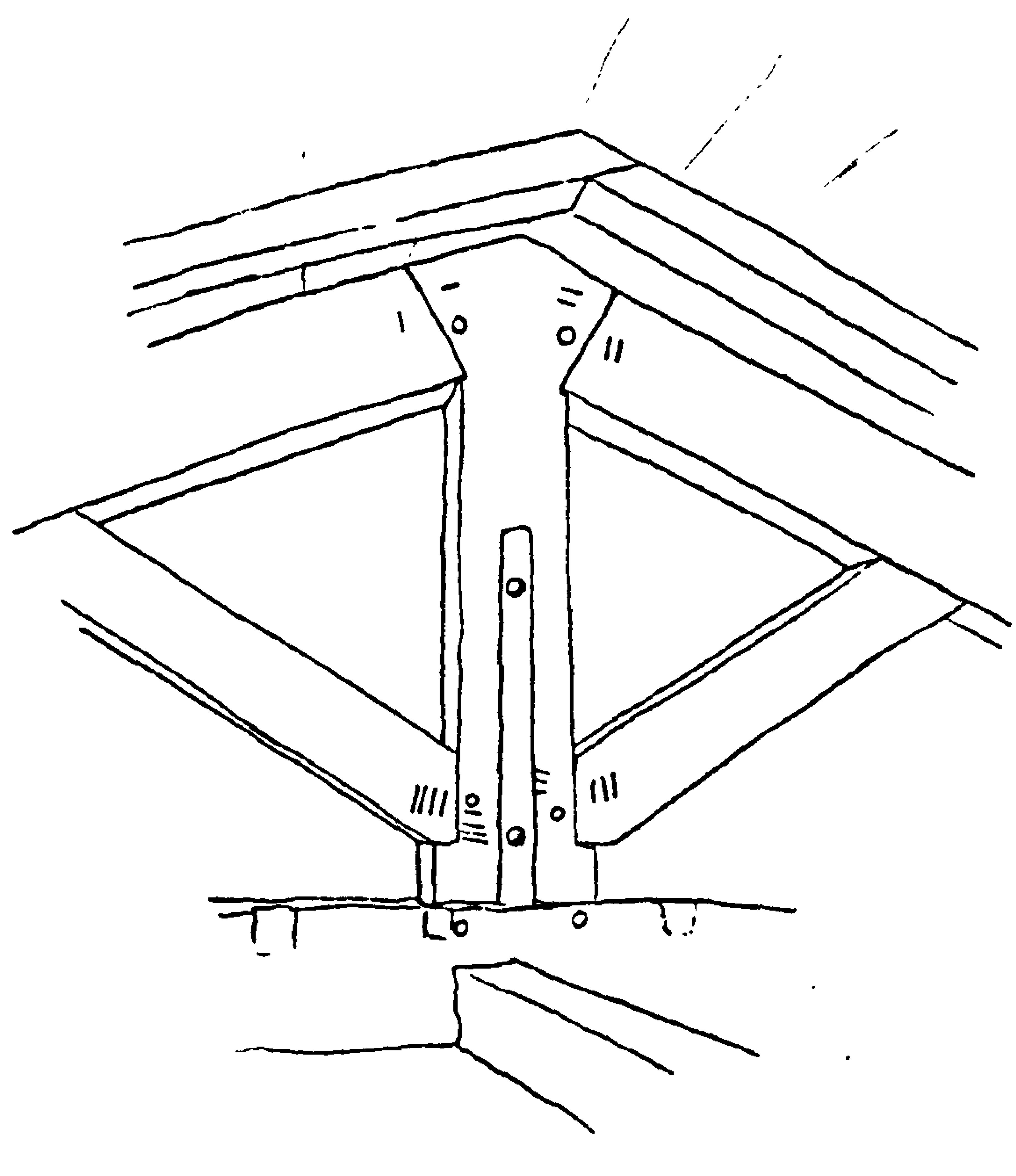


Fig. 3.2

Wilton House

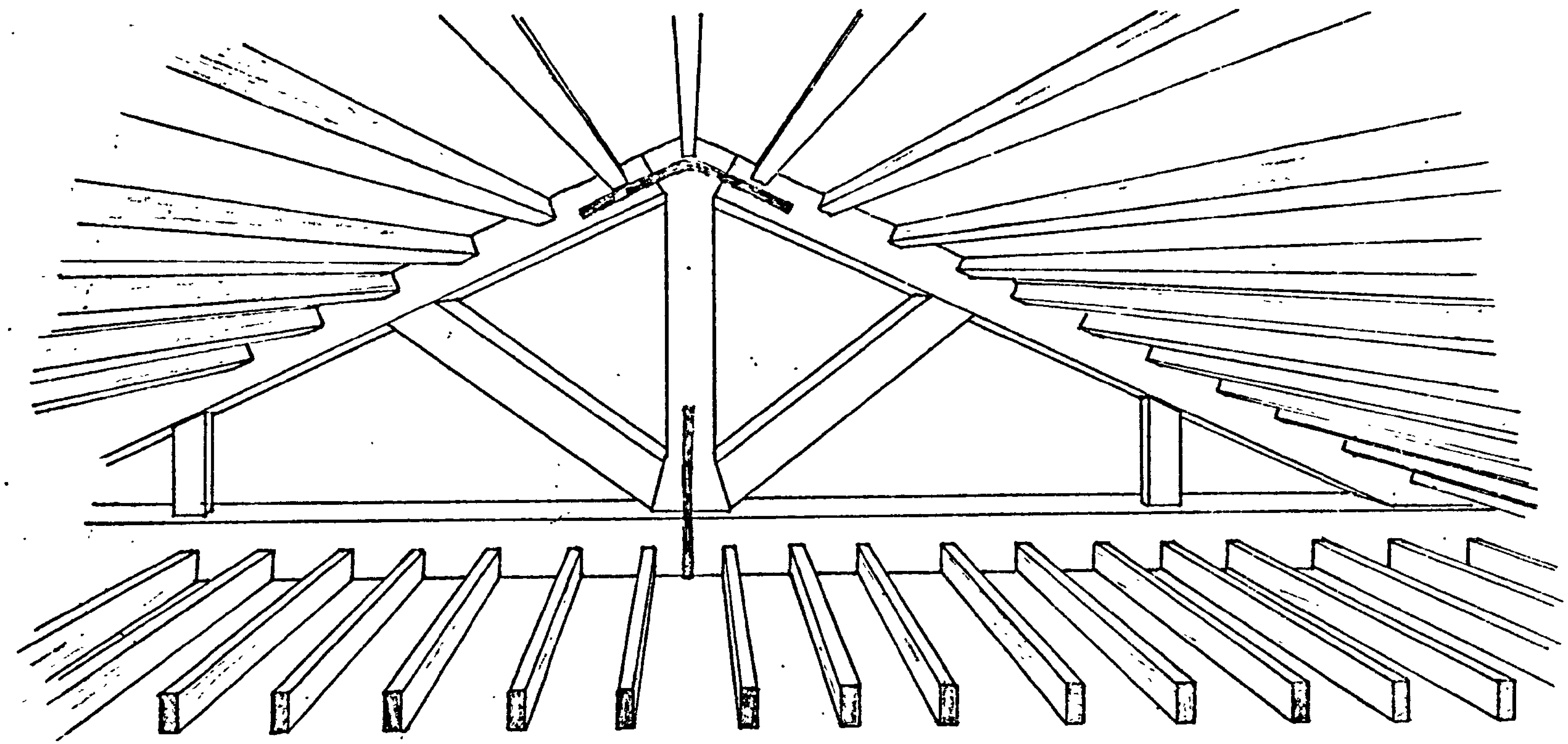


Fig. 3.3

Stoke Bruerne reconstruction
of original roof structure.

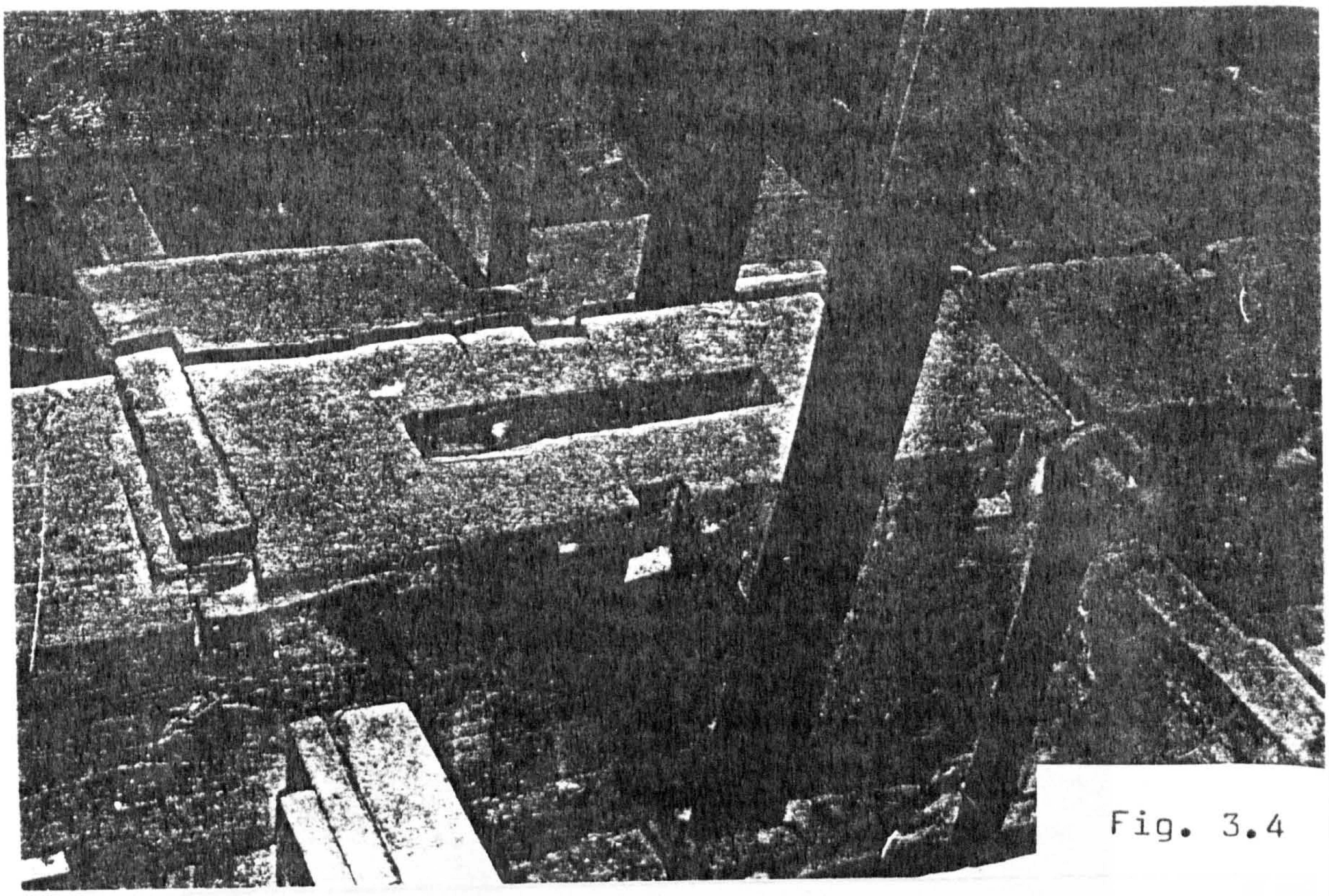


Fig. 3.4

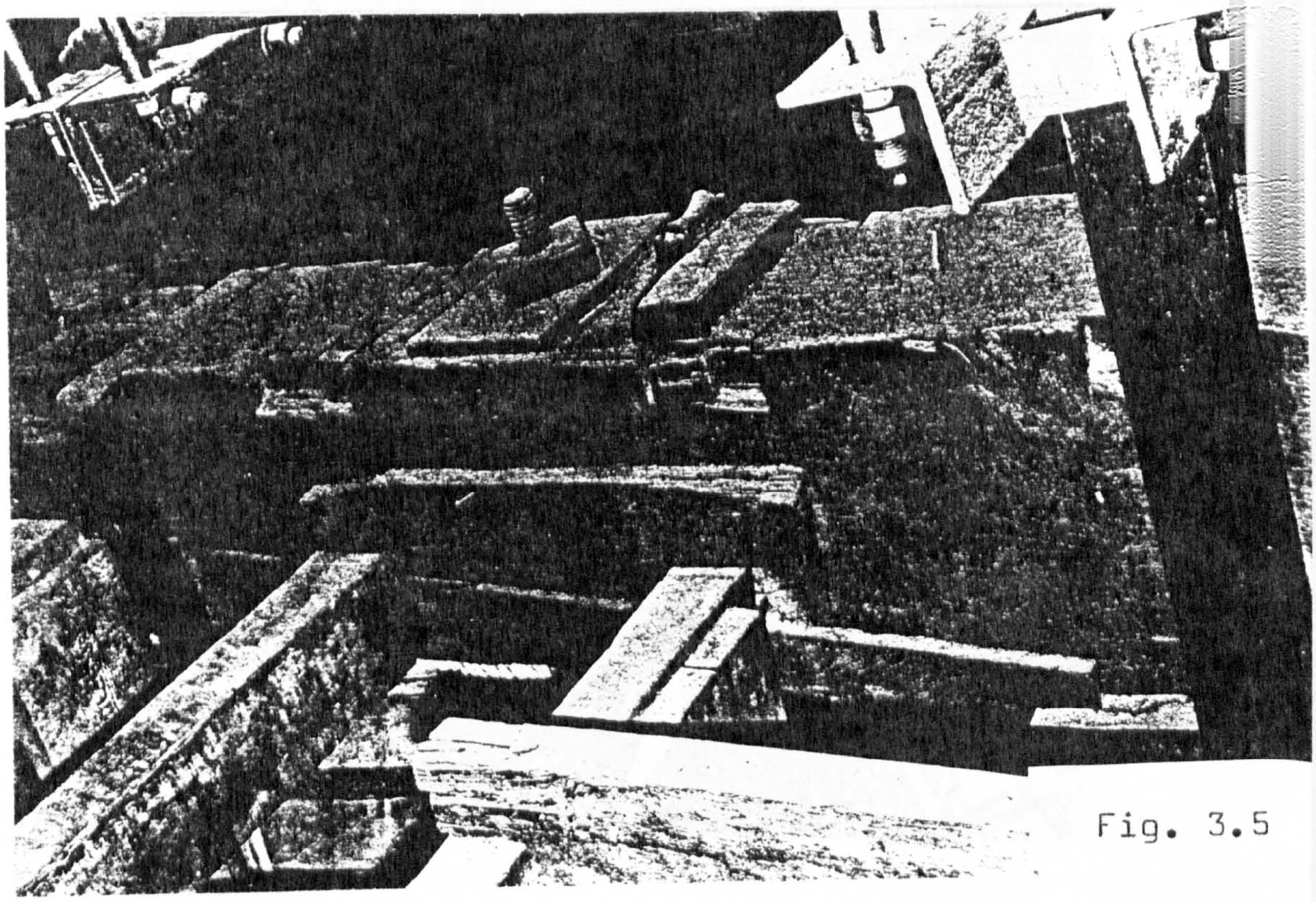


Fig. 3.5

Fig. 3.4

Queens's House, Greenwich. Tie beam showing mortice.

Fig. 3.5

Scarf joint in tie beam. Note that the tie beams are now suspended from the more recent replacement roof structure.

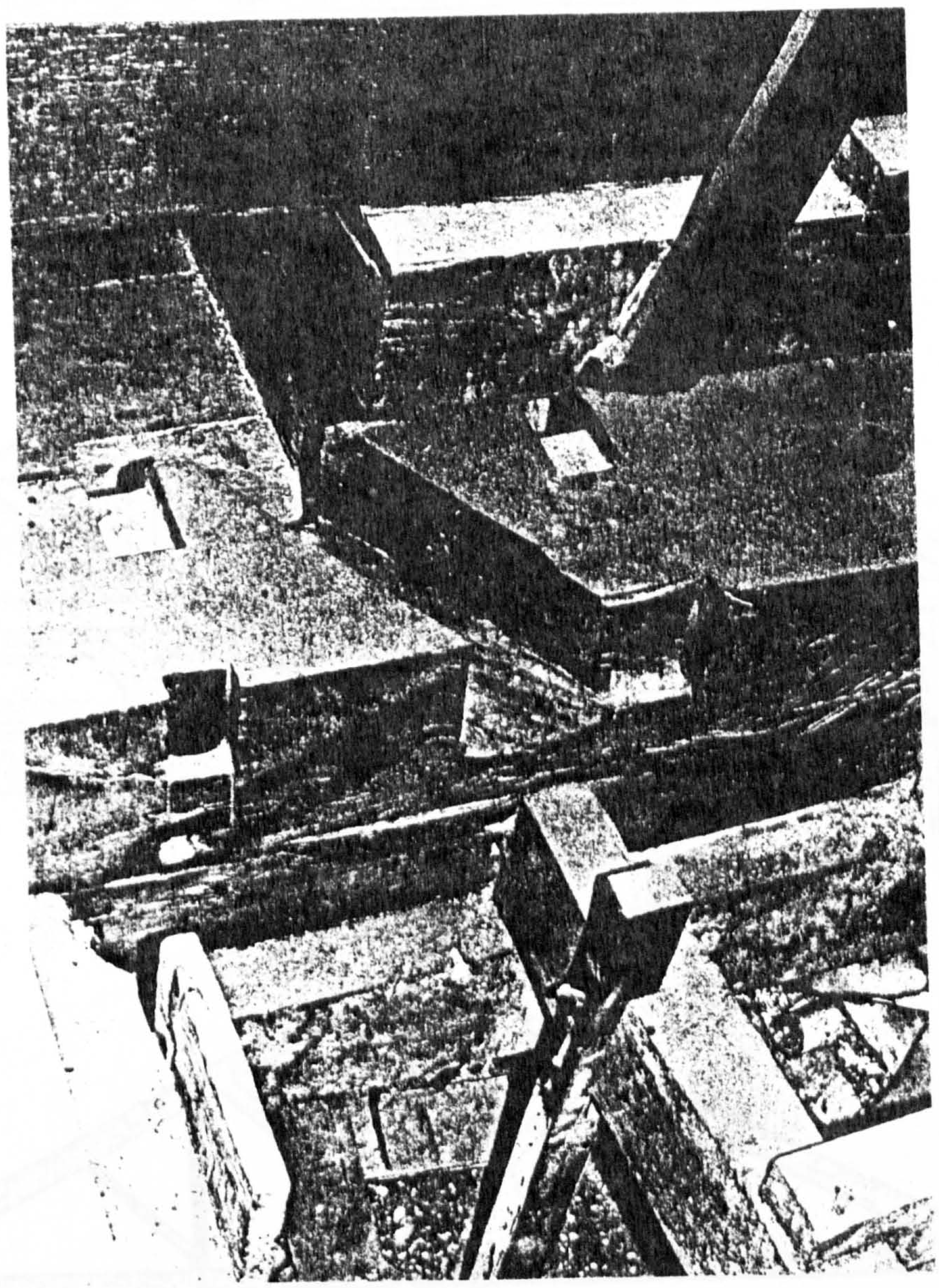


Fig. 3.6

Queen's House, Greenwich.
Diagonal slot cut into
the top of the tie beam.

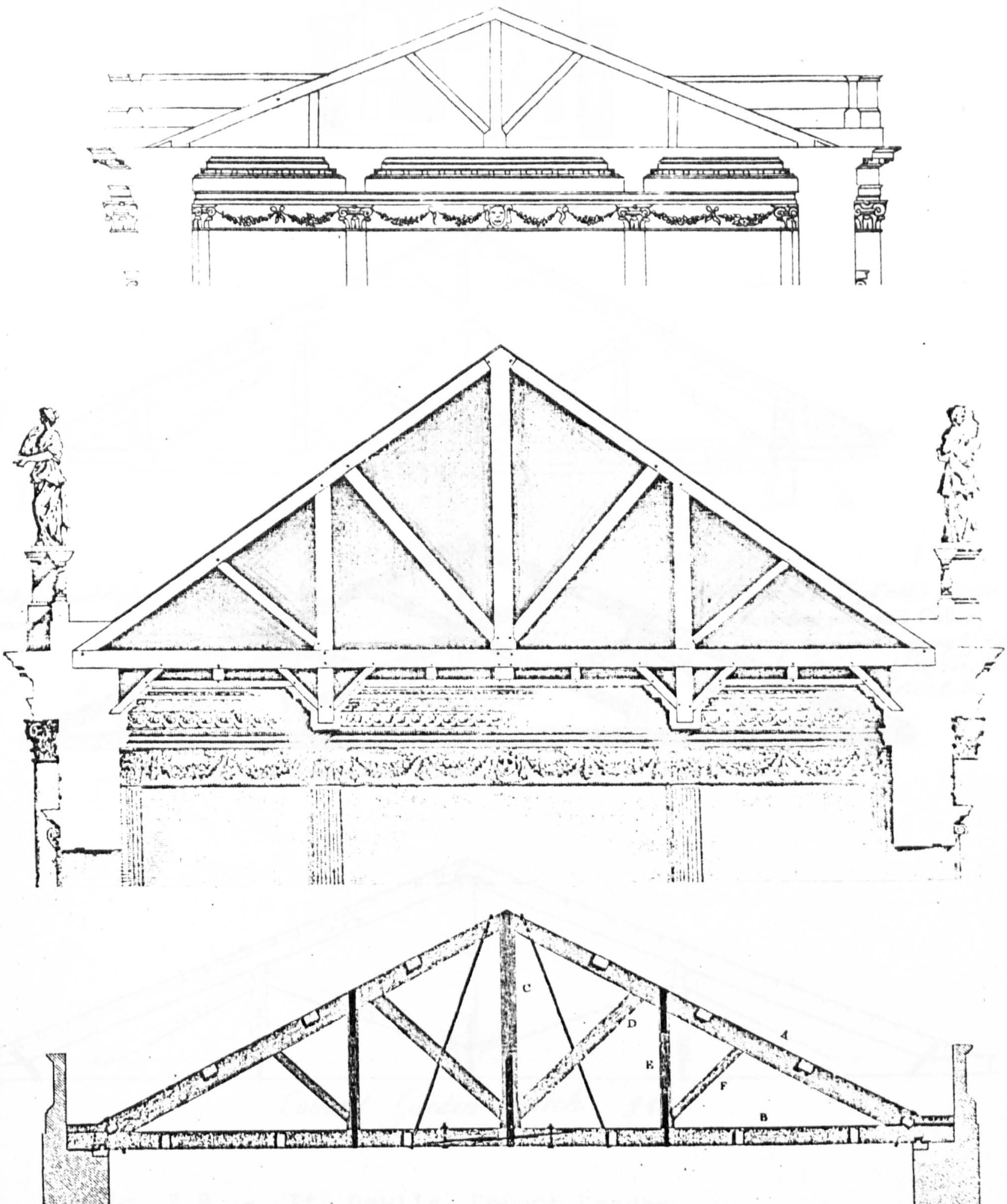
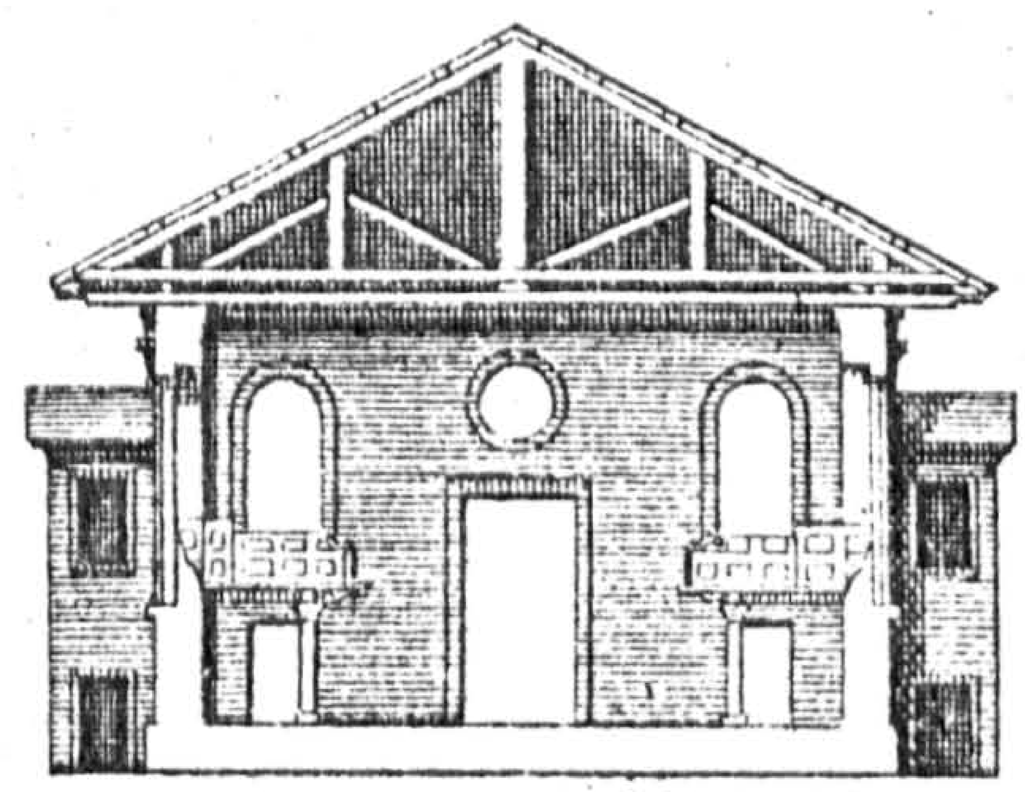


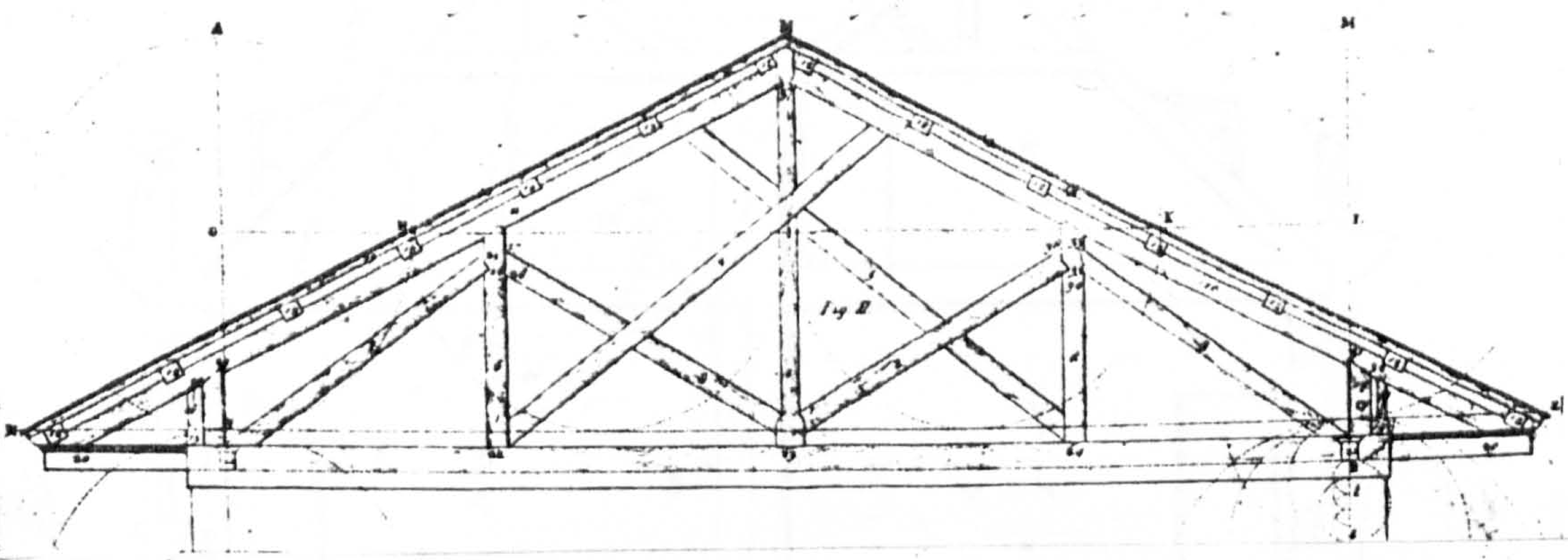
Fig. 3.7 - Banqueting House, Whitehall

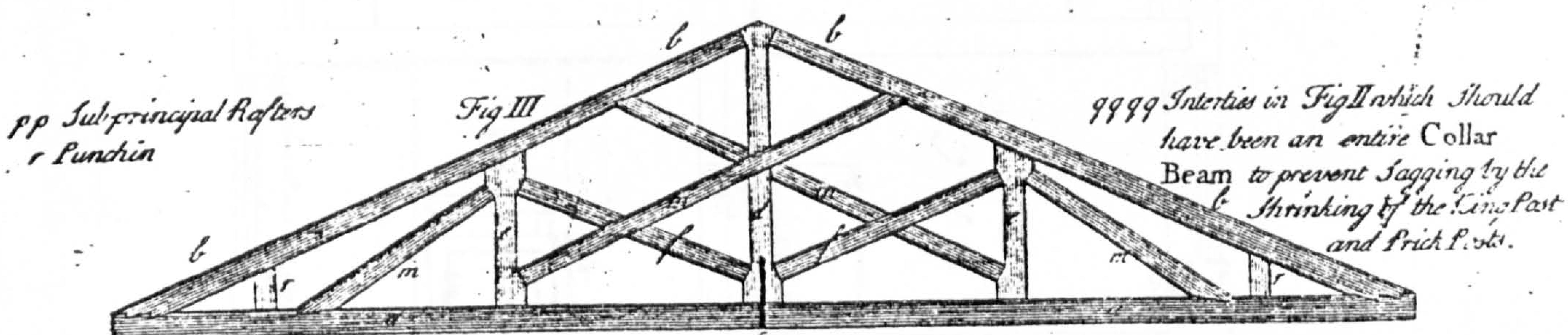
The available drawings of the roof of the Banqueting House, Whitehall.

a) Vitruvius Britanicus I, plate 12.
b) William Kent Designs of Inigo Jones, plate 51. The drawing was made by Flitcroft.
c) Nicholson's Practical Carpentry, Joinery & Cabinet Making 1826, plate XX. The drawing is by M.I.Nicholson. The roof was replaced by Soane during the nineteenth century.

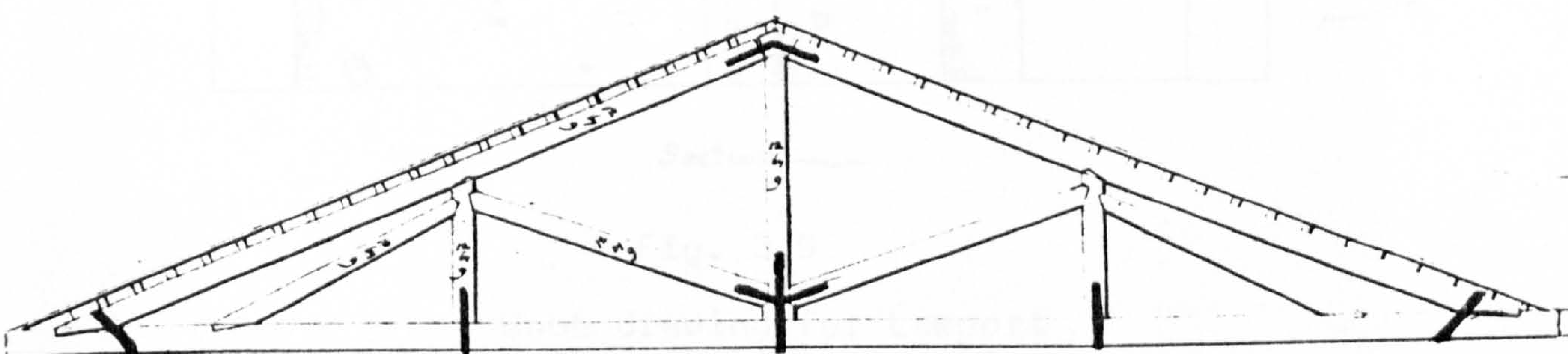


The Section.





At St Paul Covent Garden in the Liberty of Westminster. Extent 60 Feet

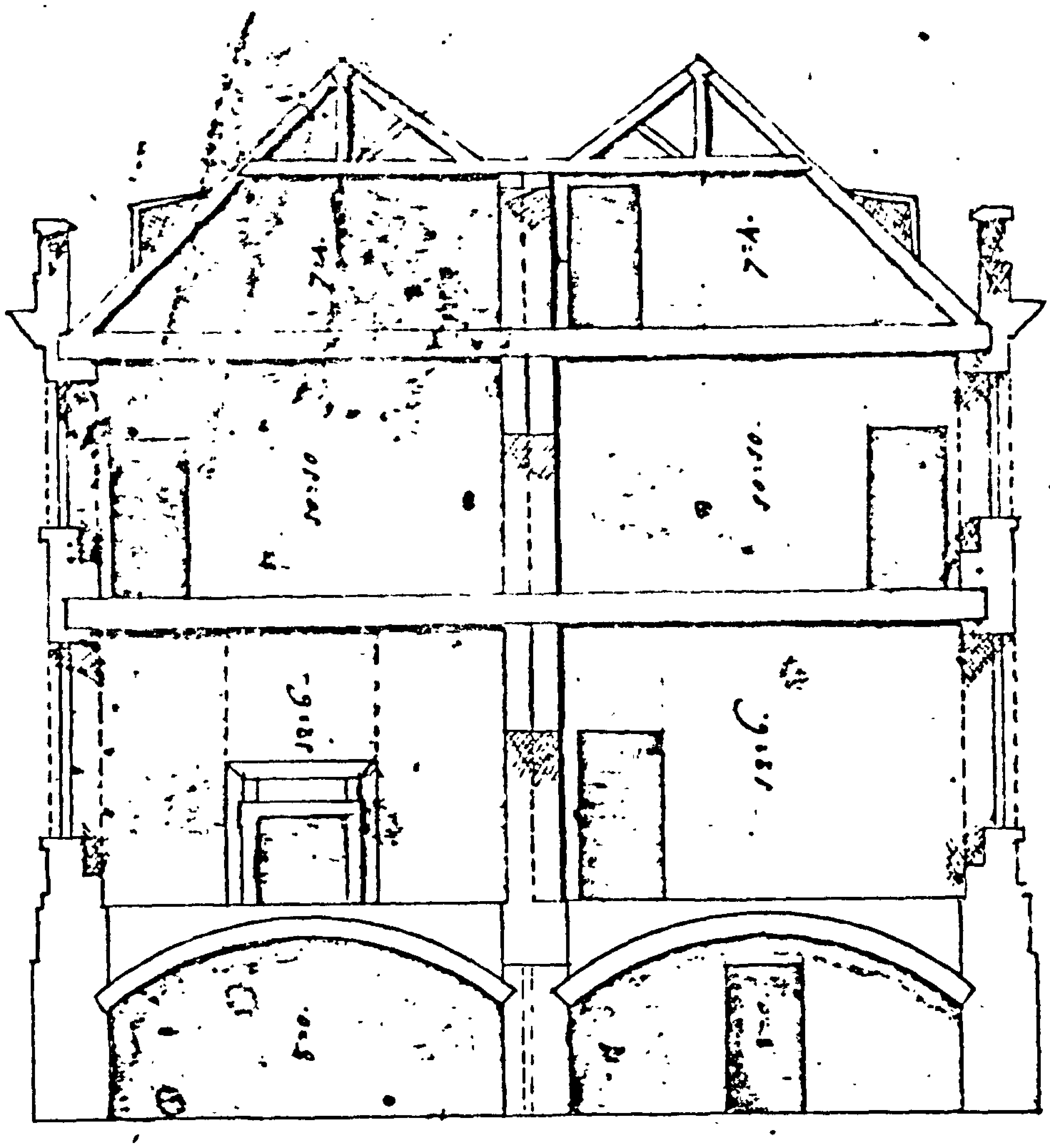


Covent Garden Church. 54

Fig. 3.8 - St. Paul's, Covent Garden

Alternative versions of the roof structure

a) Vitruvius Brittanicus
b) Batty Langley - measured drawings
c) Batty Langley - Treasury of designs the members marked 'm' in this drawing and the equivalent members in the drawing above are additions made during repairs.
d) William Newton - measured drawing (RIBA drawings collection).



Section

Fig. 3.9

Webb drawing for Lamport Hall. (Northamptonshire Record Office). Although a king post with joggles is shown this member is unnecessary.

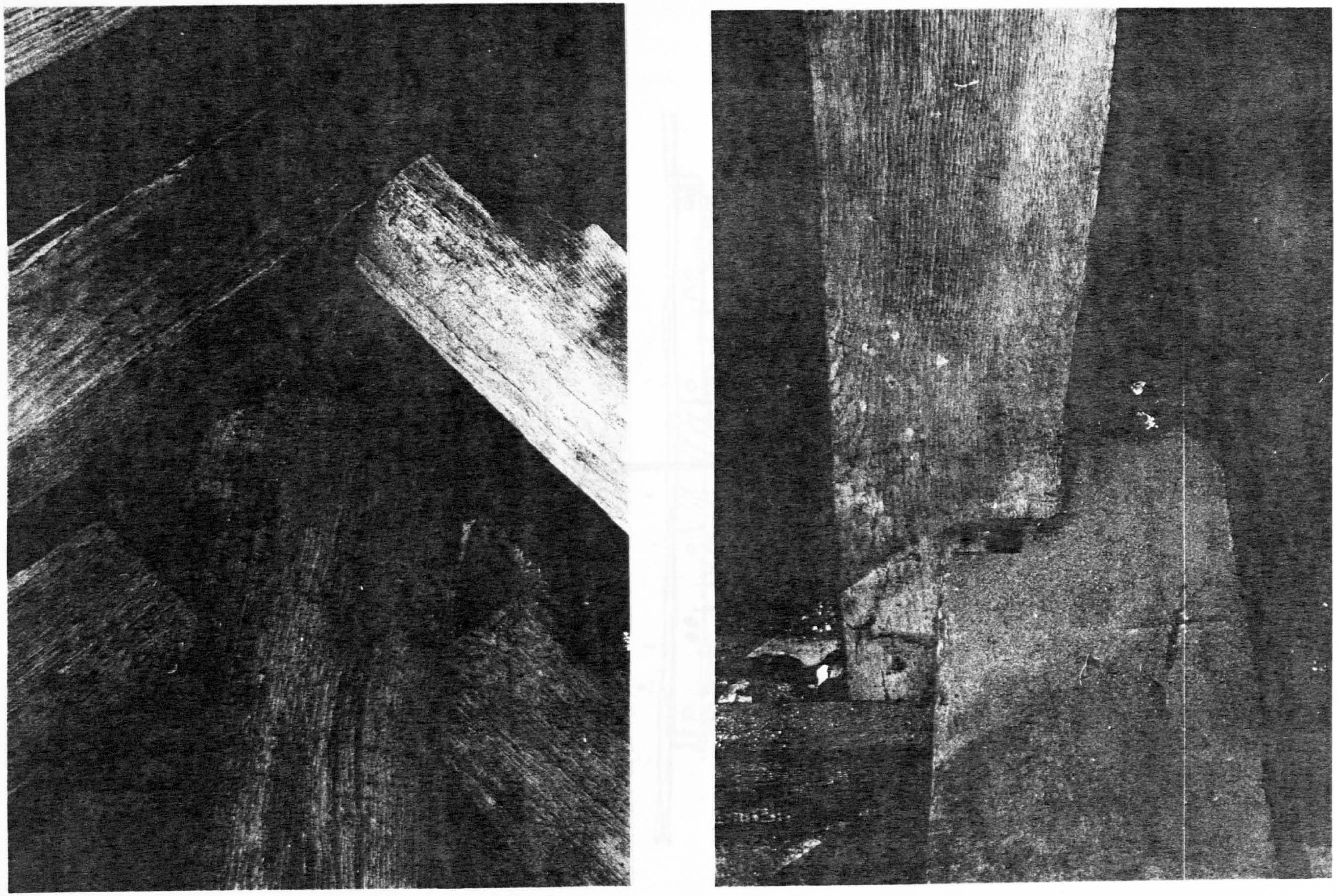


Fig. 3.10 - Uppark

Roof principal front over attic rooms.
Details of head and foot of king post.

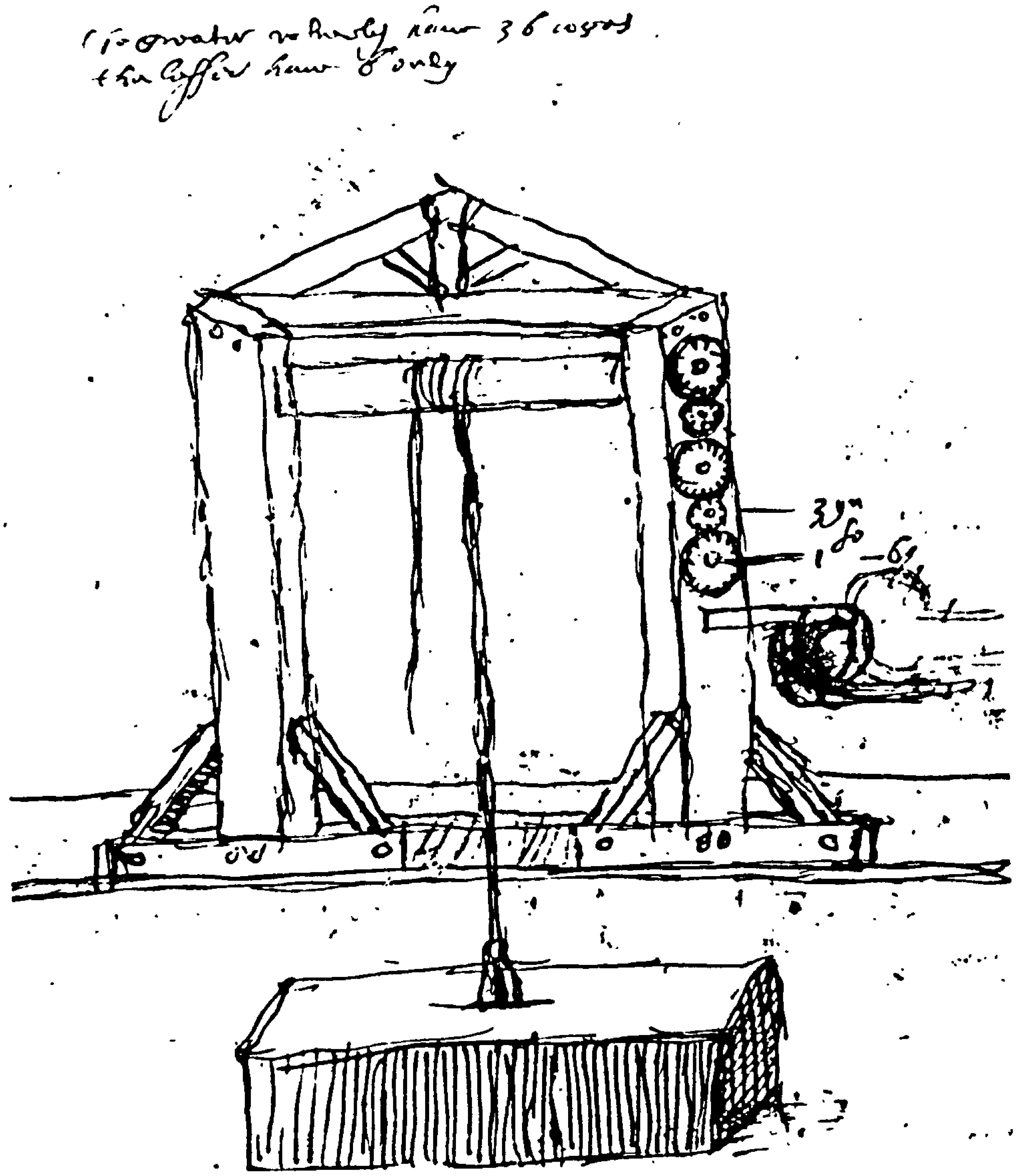


Fig. 3.11

Drawing of a truss from Inigo Jones Roman sketch book. (Photograph Courtould Institute) Although not part of a roof the joggle at the head of the king post is clearly shown.

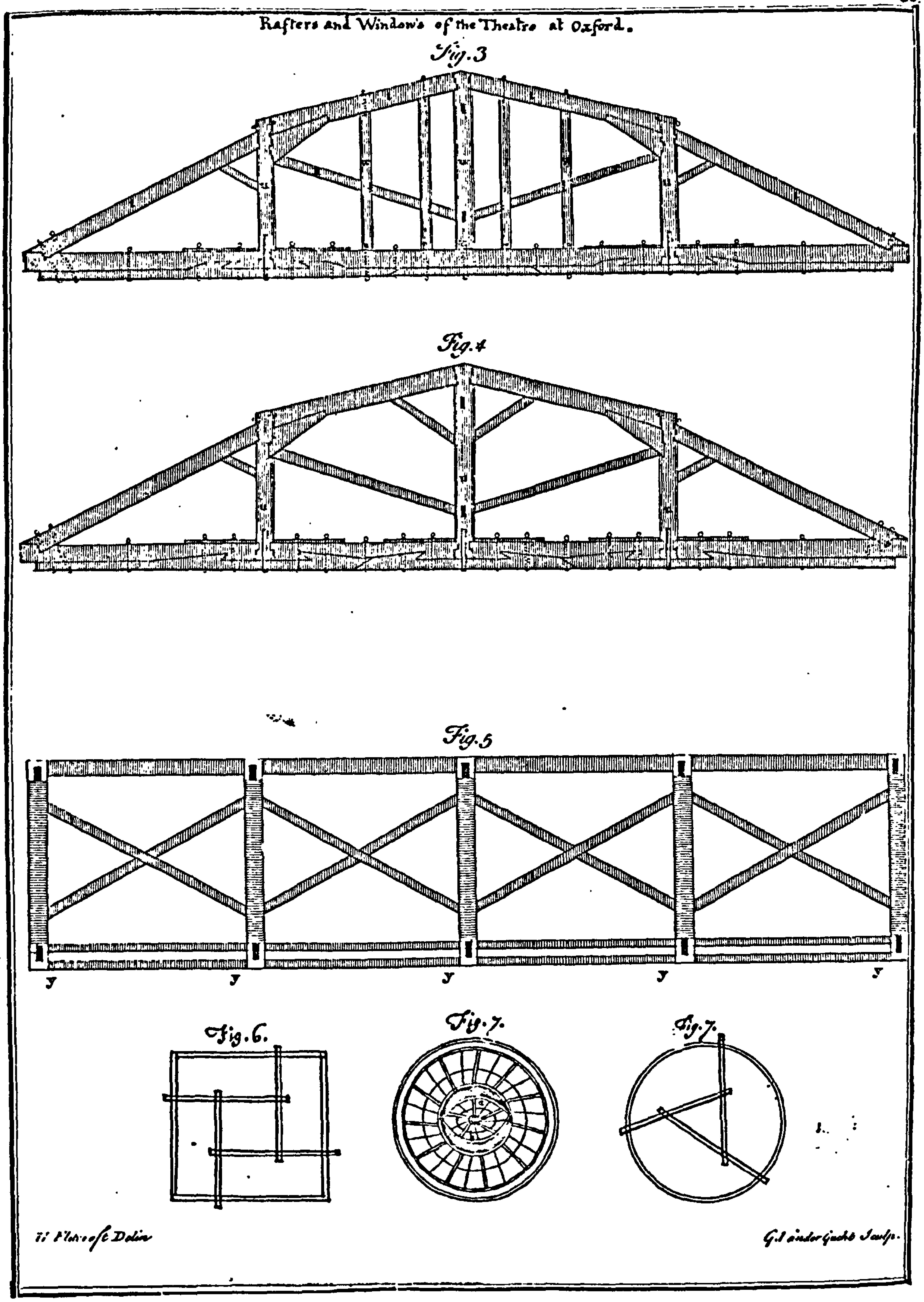
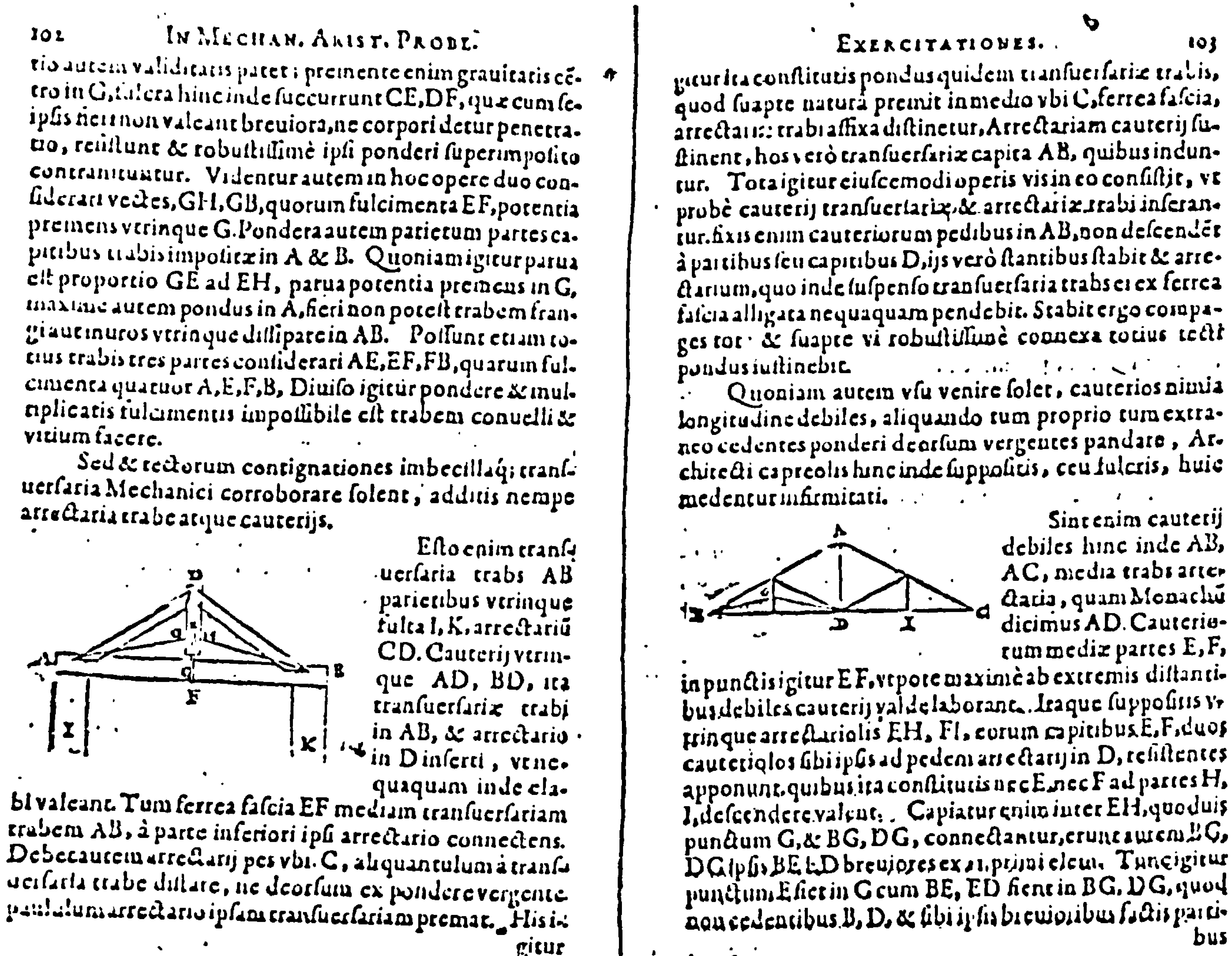


Fig. 3.12

Sheldonian Roof
<u>Parentalia</u>



102 In Mechan. Arist. Probl.

tio autem validitatis patet; premente enim grauitatis cẽtro in G, fulcra hinc inde succurrunt CE, DF, quæ cum seipsis neutiquam valeant breuiora, ne corpori detur penetratio, resistunt & robustissimè ipsi ponderi superimposito contrantuntur. Videntur autem in hoc opere duo considerari vectes, GH, GB, quorum fulcimenta EF, potentia premens vtrinque G. Pondera autem parietum partes capitibus trabis impositæ in A & B. Quoniam igitur parua est proportio GE ad EH, parua potentia premens in G, maxime autem pondus in A, fieri non potest trabem frangi aut muros vtrinque dissipare in AB. Possunt etiam totius trabis tres partes considerari AE, EF, FB, quarum fulcimenta quatuor A, E, F, B, Diuiso igitur pondere & multiplicatis fulcimentis impossibile est trabem conuelli & vitium facere.

Sed & tectorum contignationes imbecillaq; transuersaria Mechanici corroborare solent, additis nempe arrectaria trabe atque cauterijs.

Esto enim transuersaria trabs AB parietibus vtrinque fulta I, K, arrectariũ CD. Cauterij vtrinque AD, BD, ita transuersariæ trabi in AB, & arrectario in D inserti, vt nequaquam inde elabi valeant. Tum ferrea fascia EF mediam transuersariam trabem AB, à parte inferiori ipsi arrectario connectens. Debet autem arrectarij pes vbi C, aliquantulum à transuersaria trabe distare, ne deorsum ex pondere vergente paululum arrectario ipsam transuersariam premat. His igitur

Exercitationes. 103

itaque constitutis pondus quidem transuersariæ trabis, quod suapte natura premit in medio vbi C, ferrea fascia, arrectario trabi affixa distinetur, Arrectariam cauterij sustinent, hos verò transuersariæ capita AB, quibus induntur. Tota igitur eiusce modi operis vis in eo consistit, vt probè cauterij transuersariæ, & arrectariæ trabi inserantur. fixis enim cauteriorum pedibus in AB, non descendẽt à partibus seu capitibus D, ijs verò stantibus stabit & arrectarium, quo inde suspenso transuersaria trabs ei ex ferrea fascia alligata nequaquam pendebit. Stabit ergo compages tot & suapte vi robustissimè connexa totius tecti pondus sustinebit.

Quoniam autem vsu venire solet, cauterios nimia longitudine debiles, aliquando tum proprio tum extraneo cedentes ponderi deorsum vergentes pandare, Architecti capreolis hinc inde suppositis, ceu fulcris, huic medentur infirmitati.

Sint enim cauterij debiles hinc inde AB, AC, media trabs arrectaria, quam Monachũ dicimus AD. Cauteriorum mediæ partes E, F, in punctis igitur E F, vtpote maximè ab extremis distantibus, debiles cauterij valde laborant. Itaque suppositis vtrinque arrectariolis EH, FI, eorum capitibus E, F, duos cauteriolos sibi ipsis ad pedem arrectarij in D, resistentes apponunt, quibus ita constitutis nec E, nec F ad partes H, I, descendere valent. Capiatur enim inter EH, quoduis punctum G, & BG, DG, connectantur, erunt autem BG, DG ipsis BE, ED breuiores ex 21. primi elem. Tunc igitur punctum E fiet in G cum BE, ED fient in BG, DG, quod non cedentibus B, D, & sibi ipsis breuioribus factis partibus

Fig. 3.13

Explanation of the king post truss from Bernardino Baldi

THE STRUCTURAL CARPENTRY OF WREN

While the careers of Inigo Jones and John Webb were interrupted by the civil war and the development of their ideas curtailed, Wren's career flourished in the years following the Restoration. The public buildings commissioned by Charles II and the rebuilding of the London churches after the Fire produced a milieu in which his structural ideas could be developed. Wren used a variety of roof forms on his buildings, treating the roof not merely as a covering but also as an important element of his architecture; sometimes using a simple low pitch while on others using a high roof as a major visual element. Providing such a variety of forms also required a variety of structural arrangements although these were nearly all based upon two major types: the king and queen post trusses.

Wren's designs were advanced for his period. Amateur architects continued to build using traditional techniques of roof construction and even his friend and fellow scientist/ architect Hooke failed to show the same skill at structural design. In the absence of any text books the only methods for the dissemination of new structural ideas could have been through direct contact with those using the new techniques or by copying from completed buildings. The knowledge of these new structural forms would be acquired and passed on by Wren's collaborators; his assistants and the craftsmen employed on his buildings.

Sources

Although Wren built far more buildings than Inigo Jones, the percentage of his original roofs that has survived is not very high and this does present a problem if a complete picture of his work is to be built up. There have been alterations and replacements of his roofs and some complete demolitions of his buildings, but the most serious losses were caused by enemy action during the Second World War. Of over fifty London churches built by Wren, only a handful survive intact and a number of these have been re-roofed. For those that have been lost, drawings have to be used to obtain some idea of their original structure and here there are two main sources.

In the mid-nineteenth century Clayton published a folio of measured drawings of forty-six of Wren's London churches (1). These are invaluable in showing the structures of a number of roofs that have since been lost but unfortunately they provide a less than complete picture. The measurements and drawings in the collection are not all by Clayton himself (2) and there is some variation in the detail to which they have been taken. The roof structures are not shown in the drawings for all of the churches. Where they are, scantlings of timbers are sometimes given, but not sufficiently often to enable useful comparisons to be made, and the details of construction are not always clear. In spite of these deficiencies the drawings give an indication of the structural arrangements used in fourteen of the buildings for which there are no other data. Moreover they are important in providing data to enable comparisons to be made between the completed buildings and the design drawings which show roof structure.

Drawings from Wren's own office provide the remainder of the data that we have on the lost structures. Of these the major collection is at All Souls College, Oxford, but there are a number in the RIBA drawings collection and a few elsewhere (3). These drawings also cover buildings other than the London churches.

There are a number of differences between Clayton's measured drawings and the surviving Wren drawings for the same building. St Clement Danes for example, bombed during the war and now roofed with steel trusses, has a different arrangement of timbers shown in the two drawings that we have (figs. 4.1 & 4.2). The profile of the roof is similar although not identical and although they do not conform exactly there are similarities in the two structures. Clayton shows no diagonal struts in the aisle roof framing. It is possible that in this roof the carpenter deviated from the design drawings. The two structures are not greatly dissimilar and this explanation would account for the absence of diagonal struts, a feature unique to this church.

It is clear from other drawings, however, that some of the differences must have originated in the design office, and that Wren explored alternative roofing arrangements, changing the profile of the roof and the structure at the same time. St Benets, Paul's Wharf has a high flat top roof, as shown in Clayton's drawing (fig. 4.7b), whilst a surviving Wren drawing for the building shows a simple pitched roof with a very much lower profile carried by king post trusses (fig. 4.8). The roof structure in a Wren drawing for St Antholins (fig. 4.9a) is incompatible with the roof profile given by Clayton where a domed ceiling is contained within the roof space.

The design drawings show something of the working methods within the office. Differences in the way that structural details are handled suggest more than one hand at work and point to quite different levels of understanding of structures among the different draughtsmen. All the structures drawn by Clayton have joggles at the head and feet of the king posts (with the exception of St Clement Danes noted above) and it is reasonable to suppose that this detail was found on all the other Wren roofs using king posts.

Secondary posts, where used, also have joggles for the diagonal struts to bear against. The consistency with which these details were used in practice is not however shown in the surviving design drawings. Some trusses have no clear joggles at the head of the post but rather have recessed shoulders for the principals to bear upon (fig. 4.1 to 9b). These trusses also have no joggles at the feet of the post to carry the struts. Trusses may have the struts bearing directly upon the tie beam rather than upon the king post. Such details suggest draughtsmen drawing upon a knowledge of traditional construction although with a knowledge of the form of the king post truss. Somehow these differences and inadequate details were eliminated by the time the roofs were constructed, and sound, although by no means uniform, details were actually built.

Changes in design can be followed in successive drawings made for Westminster dormitory (4). An early drawing shows a simple ridged roof. A later design has the roof truncated to reduce the height but a king post was still used for this which meant that it was unsupported by the principal rafters. A drawing made shortly afterwards, however, used a correctly detailed king post truss.

Clayton's drawings show that the carpenters did not rely upon traditional details and it seems reasonable to suppose that they were provided with drawings for the framing of the trusses. There is a surviving drawing by Hawksmoor of a roof truss for the building of All Souls College, Oxford (fig. 4.21). No similar drawings survive for the London churches (5) but Hawksmoor presumably learned to produce this kind of drawing while in Wren's employ. Details of the roof framing, specifying the scantlings of timbers, are included in surviving carpenters' contracts (6) and carpenters were also on some occasions asked to provide models of the roof frame for approval by the architect (7). However with only fragmentary records surviving one can only speculate on the relative importance of each of these methods for instructing the carpenters. With the same carpenters being employed over a number of contracts they must have developed some experience of Wren's structural forms and we may suppose that the degree of instruction they required changed as they acquired this experience.

* * * * * *

One must not expect to see the same dramatic developments in the later structures of Wren as we have seen in his Sheldonian roof and in the sudden introduction of the new structural type by Inigo Jones. The king post truss had arrived with these early buildings and the only major developments were the addition of secondary posts and a second pair of struts for the longer spans. Wren did introduce the queen post form of roof, not as it was used in Italy but instead to form a flat topped profile. However the seeds of this structural type were already present in the Sheldonian Theatre. Although the later Chelsea Hospital roofs are far more visually dramatic today than one can imagine the (now lost) Sheldonian attic to have been, they are structurally similar.

The structures by Wren show the consistent use of a simple structural device with simple variations on the main theme. There is little inventiveness to be found or explained but the variations between the structures do present questions. There are differences in the metal work used in the roof, in the supporting of the roof covering and in some of the details of the carpentry of the trusses (8). Many of these are most likely attributable to the many carpenters used. For the roof of St Andrew's, Holborn, Longland, the carpenter, contracted to supply the iron work (9) and he must therefore have issued the smiths with instructions. If this practice was repeated for all the churches then differences in design would be inevitable. Not all differences in the structures, however, can be attributed so easily to the employment of different carpenters and it seems more likely that there was some experimentation with different designs by Wren's office.

The London Churches

Wren's churches comprise a surprisingly complex group of structural types because of the variety of external forms that were used. Some of the roofs required special structural arrangements because domes or vaulted ceilings were carried above the wall plate. The majority of the buildings however had king or queen post trusses, or variations on these forms, with king post types predominating. The simple king post truss, ie. with the post and one pair of inclined braces was sufficiently versatile to enable it to be used in St Paul's Cathedral for both a 'small' span of 26ft and the 45ft span over the nave (10). For smaller churches it seems to have been limited to spans below 40ft. Pitches varied and most of these trusses carried purlins to support common rafters although a few had close spaced purlins.

Variations on the king post truss had puncheons added as at Christ Church, Newgate; secondary posts carried by the diagonal struts as at All Hallows, Thames Street; and secondary posts carrying a second pair of struts as at St Lawrence, Jewry. The only general rule that seems to emerge from these variations is that churches with spans much above 40ft all had some members in addition to the simple king post form. St Nicholas, Cole Abbey (span 44ft) had puncheons, All Hallows with its secondary posts had a span slightly greater than 40ft, whilst a drawing for St Antholin shows a roof of 44ft span with two pairs of diagonal struts. This arrangement was also used at St Lawrence Jewry with a span of 50ft.

An explanation of the wide variety of roof trusses is hardly possible because we cannot be sure how representative the drawings may be of all those that were built. Longland is the carpenter for the largest number for which we have drawings and it will therefore be convenient to look at his work, although what strikes one immediately is that his roofs seem to be the poorest detailed. The most sensible way of carrying the purlins is to arrange for the principals to be strutted at just where they have to bear these point loads. Longland's roofs however do not always follow this simple rule. His roof for Christ Church, Newgate, has two pairs of purlins with struts from the king post to carry the upper and puncheons to carry the lower pair (fig. 4.8c). At St Nicholas, Cole Abbey, however, the struts are brought too far in toward the centre to effectively prop the principal under the lower pair of purlins (fig. 4.6c). At All Hallows, Thames, there are secondary posts to provide additional support for the tie beam but no second pair of struts so that the principals receive no assistance in carrying the lower purlins (fig. 4.6a). At St Brides, Fleet Street, the steepness of the roof results in the struts arriving at the principal rafters mid-way between the two pairs of purlins (fig.4.5a). Longland did not always have joggles at the head of his secondary posts for the struts to bear against. At St Andrew's metal straps were used instead to supplement the secondary posts (11).

The weakness of the St Brides roof was solved in the roof for St Benet, Gracechurch. The similar pitch might have presented the same problem but in this later church the roof is carried on close spaced purlins. Clayton shows these set vertically, an arrangement that must have been inconvenient for the carpenter. It would clearly have been easier for him to have had them perpendicular to the principals but one can imagine the young Hawksmoor perhaps taking care to ensure the strongest disposition of the timbers. We cannot be certain that it was Hawksmoor who was responsible for this detail but he frequently used close purlins in his own later roofs. They are unlikely to have been Longland's idea (12).

The difference between the two churches raises the question of whether St Benet's indicates an improvement in structural design or simply better control by the architect over the carpenters' work. Do the weaknesses perceived in Longland's other roofs originate in the design office, and thus reflect some of the weaknesses seen in the drawings, or did they occur because Longland was allowed some discretion over 'minor' details? In either case we should note that the later church was built after Hawksmoor was taken into Wren's office and it is tempting to assume that the employment of Hawksmoor improved the position and he may therefore have made an important contribution to the high standard of design and construction to be found in Wren's roofs.

St Lawrence, Jewry, for example does not show the weakness of detailing seen in Longland's other roofs nor in the early study for the building (fig. 4.8b). In the roof as built the principal rafters were assisted by two pairs of struts, each strutting the principals close to the purlins. To ensure that the inner struts were close to the upper purlins they had to be carried high on the king post which thus needed a longer than usual foot. The secondary posts in this roof had joggles formed at both ends to receive the struts. A queen post truss was used to carry the slope of the hip over the chancel end. The structure of this roof was the most developed of Wren's king post trusses. Today his only surviving roof of comparable scale and level of detail is that at Trinity College Library, Cambridge (13).

The aisled churches all have king post framed trusses over their naves but again framing arrangements differ slightly in all of them. For churches without clerestories the columns of the nave were brought up to carry the roof framing. In each case the tie beams were assisted by diagonal struts from the columns. The omission of inclined struts in the truss at St Clement Danes did not therefore constitute a serious weakness because the purlin load would have been transferred by the secondary posts directly to this lower strut and so to the column. In all cases the lean-to aisle roof was structurally separate from the nave roof. The principal rafter of the former was framed into the columns a little below the tie beam of the main truss. This produced a break in the slope of the roof over the line of the columns; a feature that was to disappear in the work of later architects, who used a continuous slope over both nave and aisles. (Of the Wren churches, St Andrew's in the Wardrobe has a gable wall with a continuous slope but the roof line is still broken in the same way as in the other aisled churches). This framing has the advantage that it reduces the continuous length of rafter necessary at the expense of some complication in the carpentry at the top of the column. Judging by the frequency with which one finds tie beams in Wren's roofs formed by two lengths of timber scarved together it may have been a shortage of long timbers that led to the need to break the roof slope.

Queen Post Trusses

The largest of the Wren roof structures, after the roof of the Sheldonian, are those of the Royal Hospitals at Greenwich and Chelsea. These, together with the roofs of a small number of churches and roofs at Hampton Court were framed with queen post trusses, providing steep slopes at the sides and flat tops. Survival of these roofs is little better than for the king post trusses. Four of the five church roofs shown by Clayton have been lost as has the chapel roof at Greenwich. However the roof of the Painted Hall at Greenwich and the magnificent roofs at Chelsea Hospital do survive.

Clayton shows St Mary's, Somerset, with a simple queen post roof truss with a flat top. Compared with the other queen post roofs (fig.4.7) it is remarkably simple. There are no additional braces and the queen posts have simple joggles. The remainder of the queen post roof trusses are more complex.

The surviving church roof is that of St Benet's, Paul's Wharf, which differs in design from the others in having a very high roof with unusually steep pitches. The roof contains only two large trusses. The tie beams of these are each formed in two lengths, scarf jointed together. The high queen posts are clasped between principal rafters and straining beam and in addition have cross-bracing between them (fig. 4.7b). The high roof of this church makes it unreliable as an indication of the possible detailing used in the other queen post church roofs. This is a pity because there are variations in the detailing of the other surviving roofs which may well have appeared also in the church roofs. Clayton's drawings are tantalizingly difficult to read in this area.

Not unexpectedly there is little consistency in the design of the truss framing with the disposition of bracing struts being different in each of the roofs. We have seen this kind of variety in the king post trusses and the queen post form if anything offers more scope for differences of design. However the differences are not confined simply to the overall layout of the timbers. Unlike the king post trusses, the queen post roofs have differences in detailing at the head of the posts which suggest some experimenting with this form before a satisfactory design emerged.

In Clayton's drawing of St Clement's, Eastcheap, (fig. 4.7c) the heads of the queen posts appear to be trapped between the straining beam and the principal rafters, as at St Benet's. The roof of the former also has the same arrangement of struts from the base of the posts, although trusses support light purlins rather than heavy purlins and common rafters.

At All Hallows (Fig. 4.7a) in spite of an apparent similarity in the arrangement of the struts, the detail at the heads of the posts seems to have been different. The straining beam appears to run through the heads of the posts with its ends projecting at either side. Below this it does seem as if the queen posts may be joggled so that the arrangement of the roofs looks something like a combination of two intersecting king post trusses with the straining beam added to form the flat top.

The trusses of St Michael, College Hill, have yet another detail with metal strapping down both sides of each post apparently fixing them to both straining beam and principal rafters. Although this roof has been destroyed we can see how it was probably built because roofs using a similar detail survive at Hampton Court and over the hall at Greenwich. The overall layout of the Greenwich roof is shown in William Newton's later study of roof trusses (fig. 8.1). Of this we only need to note that because of the wide span the tie beam receives additional support from a central tension member - a combination of timber post and metal straps. The most curious feature of the roof is the detail at the heads of the queen posts. Each is cut out at the head to form a saddle to carry the straining beam (fig. 4.10). This enables the ends of the principals to butt directly against the ends of the beam. To enable the posts to act in tension they are hung on metal straps from the arch of timber so formed.

It can be seen from figs. 4.10a & b that each post has a metal strap in the shape of an inverted 'U' passed over the projecting end of the straining beam. We may assume that the roof of St Michael's was similarly detailed but with additional straps on the inside faces of the posts.

The arrangement can hardly have been used just to ensure a continuous arch of timber, uninterrupted by the posts. The possible advantage was rather that it simplified construction. During assembly the posts could have been stood on the tie beam when in position on the walls and the straining beam then carried temporarily in the saddles while the principals were brought up. Truss action could then have been ensured by the addition of the metal straps before any loading came on to the truss. It could thus have been assembled in place with comparative ease. However metal strapping was not used in this way at Chelsea where the queen posts are incorporated into the timber arch and thus carpentry details are relied upon to ensure that posts act in tension.

The roof of the hall at Chelsea is astonishing in its size - its grandeur would perhaps not be an overstatement. The first impression of the space is of a barn or hall like structure with two long rows of columns down either side standing on the floor and supporting the roof. It is only with difficulty that one adjusts to the fact that one is in the roof and the floor is hung on these two rows of posts. The illusion is helped partly by the height of the space. This attic was originally used as accommodation for the nurses and the space is as large as that in the wards, although there are no windows. Plaster work to form the walls and ceiling has been removed leaving marks of the plaster on timbers and exposing the rafters to view, thus giving the barn like quality to the space. The illusion is heightened also because, although the roof has a flat top, it is higher than the straining beam and so is not immediately visible.

The overall structural layout of the roof can be seen in fig. 4.11. In addition to the members of the queen post truss, tie, principal rafters, straining beam and posts, each post carries two struts, one to the principal rafter and one to the straining beam. These struts are framed in, not at the foot of the posts but just above head height. Two pairs of longitudinal members run along the roof between the trusses. The lower pair, jointed to the queen posts at the same point as the struts carries longitudinal bracing to the roof surface. The upper pair, set into the straining beams where the latter are strutted was originally intended to carry the roof surface although the arrangement here has been altered.

The longitudinal beams have notches (fig. 4.11) into which transverse beams would have been framed to carry the flat roof surface. A number of short rafters to form an inward facing slope are still fixed to these beams (fig. 4.14). Thus the original design of the roof had a wide internal 'gutter' with the roof rising above the heads of the queen posts. A roof of this design was proposed by Hawksmoor for Sir John Moore's Writing School (fig. 4.19). The rather curious arrangement can be explained by a need to have the roof at a certain height while at the same time wishing to keep a useable interior. Moving the posts inward so that they come under the 'ridge' would leave a narrower central space.

Today there is no central gutter on this roof. It simply has a flat lead top and slated sides much like the Greenwich roofs (14). This is carried on beams set above the straining beam on short puncheons (fig. 4.14). It is not clear however when this alteration was made and although there are still some of the inner facing rafters in place I suspect that the design change occurred during original construction of the roof. This is because the adjoining chapel roof has a flat topped roof carried by the straining beam. It could never have been designed to have anything rising above the heads of the queen posts or it would not have been at the same height as the hall roof.

The main difference between the hall and chapel roofs is that the latter has a raised tie beam. It uses a similar queen post layout as the basic structure but the space enclosed within the attic is smaller. This is because the chapel has a vaulted ceiling rising above the wall plate and the tie beam has thus to be raised to clear this. Below the floor of the attic the tie beam butts against the inside faces of the principal rafters to which it is fixed with iron straps. The feet of the principals are each restrained against spreading by pairs of timbers from the middle of the tie beam. These clasp, and are bolted to the tie and principal at each end. Access to these is difficult but they appear to have been tightened with timber wedges (fig.4.16).

The metal work of Wren's roofs varied considerably, as Clayton's drawings of the London churches show. At Chelsea the principal rafters over the hall are restrained by straps which, instead of being bolted to the sides of the tie beam in the usual way, are dogged down into the top face (fig.4.15). Unfortunately the detail at the bottom of the upper face of the principal is inaccessible.

One would expect queen posts to be strapped to the tie beam in the same way as king posts. This is so over the hall roof but the chapel roof trusses have straps on the other faces of the posts. These are twisted just above the floor presumably to pass through slots in the tie, but how these are fixed cannot be seen (fig.4.18).

Hawksmoor's possible contribution to the design of these roof structures has to be considered. That Hawksmoor was an important figure in Wren's office can be seen from surviving records but these do not make clear the extent to which he might have contributed to the structural designs. Hawksmoor was trained by Wren and so must be considered as the principal heir to his structural knowledge but was he simply taking over Wren's own ideas or did he have the ability to develop these himself? Assuming the latter is true - and I hope to show that it is - then how much did he contribute to the structural designs of Wren's own buildings? To attempt an answer one must first look at Hawksmoor's own work.

Hawksmoor

There can be no doubt about Hawksmoor's ability to design satisfactory roof structures. Roofs designed by him survive at Blenheim and Oxford and these alone are sufficient to show a competent use of the king post form. His long span roof of St Alphege, Greenwich, appears to have been a development of the queen post type of structure used in the Hospital to suit the provision of a ridged roof. Unfortunately this roof was lost by fire during the war and no original drawings survive, and measured drawings made during the eighteenth century must be relied upon for any knowledge of this structure. However a full discussion of this structure can wait until a later chapter when I shall be looking in more detail at the development of the queen post truss form. It is sufficient to note here that Hawksmoor used an arrangement at St Alphege that does not appear in any Wren structures.

Drawings for some of his London Churches survive (a drawing for the structure of the dome at Greenwich Hospital has been identified as being by Hawksmoor) but perhaps his best known drawing is that for the roof structure for All Souls College, Oxford, part of the Worcester College collection. This drawing shows the construction of the roof in some detail, including purlins and ceiling joists and specifying the scantlings of timbers (fig. 4.21). This is not only the most detailed drawing of a roof structure by Hawksmoor that is known, it is also the most detailed drawing of the period that has survived.

This is almost certainly the drawing supplied to the carpenter. Not only does it detail the structure but the notes at the bottom give instructions for the preparation of the bill. In the absence of similar drawings of the period one can only speculate as to how typical such a drawing was at the time. As will be shown, whether or not such drawings were prepared must have depended upon the working relationship between the carpenter and architect and their relative skills at structural design.

The details shown in this drawing correspond fairly well with the structure as built. There are two major differences between the roofs as built and the drawing. The ceiling joists are set lower on the tie beam than shown and the purlins are at a much wider spacing. Otherwise scantlings are all within ½" of those specified and the metal strapping provided is much as shown, although the straps actually used are much longer than those drawn. The shoulders (joggles) at the foot of the king post to receive the struts are cut square as shown in the sketch in the upper right corner of the drawing and not splayed as shown on the original truss drawing. This sketch looks very much like a modification agreed during work and supports the view that this was a'working drawing'.

This is the only drawing known for the first half of the eighteenth century which appears to be a working drawing which might have been supplied to a carpenter, and as such its survival has to be accounted for. It has already been suggested that, in general, if drawings were supplied to craftsmen they would in all probability have been used and then discarded. But then might not record drawings have been made and kept by the architect? If so one would have expected some of these to have survived. There is thus the possibility that this Hawksmoor drawing is not typical of many that he made but a unique example. This seems unlikely however. It is difficult to see how the carpenters were instructed to build the new forms of roof truss for the London churches if not through either drawings or models, possibly both. The records show that carpenters were sometimes asked to build models of the roof structures but it seems likely that they would at least have been provided with a drawing of the roof truss from which to work. Contracts survive which specify in some detail the structure to be built and it was these that must have fulfilled the function of the contract drawings which are used today. Thus we should not be surprised if only one copy of the working drawing was made. The survival of the All Souls drawing must therefore be due to the presence of Clarke, the amateur architect, into whose possession it came. His interest in architecture seems to have been sufficient to collect a number of preliminary drawings and sketches and he would thus have been quite likely to take the trouble to save this working drawing after it had been used.

Less detailed structural drawings exist for the London churches. Structural drawings survive for the roof of St George in the East, St Mary Woolnoth and St Giles in the Fields. Of these the last (fig. 4.20) are simply project drawings, the church eventually being built by Flitcroft. However, sufficient design work was carried out for alternative schemes to have been prepared and the sections of these show the roof structures. For St Mary Woolnoth the drawings include a section showing a king post roof truss. The church has a square 'pyramid' shaped roof which relies essentially on one large king post truss, but the king post has to carry struts to the hip rafters as well as the normal struts to the principals. The drawn section is not sufficient to have shown the carpenter how to build this unusually complex form and presumably more detailed instructions must have been given.

The drawings for St George in the East include a sketch (fig.4.22) showing roof timbers over a domed ceiling. A note on the drawing reads:-

> "The roof is intended in pyramidal form .... If what Mr Grove has provided for Wapping St John's cannot serve at Limehouse then we must be content to put it upon Wapping Church".

This note seems to suggest a change of mind by Hawksmoor. Having had a roof constructed for one church he is now proposing, if possible, to put it upon another. The outcome of this is of no concern here. What is more interesting is the implication behind this comment.

The drawings for St Giles in the Fields show that Hawksmoor might well consider the structure of the roof of his churches at the preliminary design stage, certainly before there was any firm undertaking that he would be the architect appointed for the building. The All Souls drawing shows that he might provide detailed drawings for the carpenter. Here at St George however he was proposing to use a roof that had already been built to go elsewhere. The use of the word 'provided' also raises the question of the exact contribution that Grove was making to the structure. He might have been simply carrying out work to Hawksmoor's design or he might have been providing the design as well as the construction of the roof. The latter would suggest some variation in Hawksmoor's method of working, sometimes providing instructions for the structure and at other times relying upon the skill of those he employed when this was adequate. The possibility that Grove worked for Hawksmoor in this way is suggested by his structures for Hawksmoor's Christ Church, Spitalfields, and Archer's St P aul's, Deptford, which will be discussed in the next chapter.

Two features of Hawksmoor's roof designs should be noted. He appeared to favour the use of close spaced purlins to support the roof covering rather than common rafters, and he made use of metal strapping at the head of the king posts. Close spaced purlins appear in his roofs at Blenheim, at All Souls College and the Clarendon Building, Oxford, and in his London churches of St George's, Bloomsbury, and St Mary, Woolnoth. The advantage of close purlins is that they avoid point loads on the principals from the heavy purlins and this may be the reason for the choice of this form of support.

At Blenheim Palace the metal ties at the head of the king posts take the form of pairs of simple flat bars let into slots cut into the king post and the ends of the principals. These are then fixed with iron pins. At St George's, Bloomsbury, simple curved straps fixed to the face of the timbers were used for joining the ends of the principals and again fixed with iron pins including a pin through the king post. His most elaborate arrangement however, used in the All Souls roof, is the 'Y' shaped strap shown clearly in his drawing. The straps of this device pass over the backs of the principals and the arrangement appears to be designed to assist, or perhaps even replace the joggles in transmitting the load from the king post.

Hawksmoor's structural ability and his presence as an important figure in Wren's office presents a real problem if we wish to determine the precise authorship of the structures of the Wren buildings. Are we to conclude, for example, from the similarity between Hawksmoor's design for Sir John Moore's Writing School and the roof structure of the Hall of Chelsea Hospital that he also designed the latter? This seems unlikely because of the clear differences between this roof and that provided for Greenwich. We know that Hawksmoor was responsible for supervising the construction of the roof of the hall of Greenwich Hospital for the minutes of the building committee record that:-

> "(Grove) is to make a model of the roof frame ... according to the manner give him by Mr Hawksmoor..." (15).

It seems quite possible then that the design might also have been Hawksmoor's. He had been working in Wren's office for some time. This roof relies upon metal strapping of which Hawksmoor seems to have been fond and the strapping to the queen posts resembles that used in his roof for St Alphege.

However, if the use of metal strapping at the heads of the posts is a Hawksmoor characteristic it is not a Hawksmoor innovation. Clayton shows it used on the king posts of St Nicholas, Cole Abbey (1671-7), built before Hawksmoor entered Wren's office. The queen post design cannot be attributed to him either because All Hallows (1677-83) was also built too early.

This leaves the possibility that the use of close spaced purlins may have been a Hawksmoor 'innovation' and their use possibly an indication of his hand as designer. The two churches shown by Clayton to have close purlins, St Clement's (1683-87) and St Michael (1686-94) and the king post roof church

St Benet, Gracechurch (1681-86) are all late enough for Hawksmoor to have possibly made some contribution to the design. St Michael's, College Hill, also seems to have used a similar strapping arrangement to that adopted at Greenwich.

The evidence for Hawksmoor's involvement in the design of these structures is largely circumstantial but it seems likely because it accounts for the introduction of the use of close spaced purlins for which there otherwise seems no apparent reason. But where did Hawksmoor acquire the idea? The answer is surely from a study of the structures of Inigo Jones. Possibly for example, the Queens House, Greenwich, but more likely St Paul's, Covent Garden, which was to be studied and drawn by later architects. The sketch book of the young trainee (16) shows how he learnt by drawing existing buildings and in the study of existing structures he would have been doing what other architects did later and for which there is much clearer evidence.

The remainder of the structural devices which Hawksmoor used he would simply have acquired from Wren although it is possible that he may have made some contribution during the design of later structures like the roofs at Chelsea Hospital. Two clear developments which may be attributed to Hawksmoor, seen in the roofs of St Alphege, Greenwich and Christ's Church, Spitalfields, will be discussed in detail in later chapters.

Footnotes - Chapter 4

1. Clayton (1848). Clayton's drawings have been reproduced by the Wren Society, Volume XI.

2. The names of the other draughtsmen are given on the drawings.

3. The most useful current source are the reproductions of the drawings in the Wren Society volumes from which the illustrations here have been taken.

4. Gough Maps 23.

5. Drawings from St George in the East (Kings Maps) are at much less detail, being only preliminary drawings, while his drawings for St Giles in the Fields is a general scheme drawing and does not show the construction in the same detail.

6. Scantlings were, for example, specified for St Andrews, Holborn. Wren Society X p.99.

7. Grove was required to built a model of the Hall roof of Greenwich Hospital (see 14 below). He was also asked to make a model of another roof at Greenwich. Wren Society VI p.42

8. These details may be seen in the drawings by Clayton of the roofs as executed but there are also differences in the carpentry shown in design drawings. The latter can be seen in the All Souls' collection. While we may attribute the differences in actual roofs to different carpenters, differences in the drawings may be due to the work of inexperienced assistants. However, being only project drawings, the details would not necessarily have been carried through to 'working drawings'. Chapter 5 gives examples of churches by Flitcroft and Gibbs where the construction of the roofs differs from that shown in the project drawings.

9. Wren Society X p.99

10. Here I rely upon the measured drawings published by Poley (1927) and a perspective of a truss in St Pauls by Hewett (1974). Project drawings of St Pauls

also show king post trusses - reproduced in Wren Society XIII pts. 23-25 and VIII pt.8.

11. The use of metal strapping in the original construction of a roof cannot be determined with certainty from a later measured drawing because there is evidence from the inspection of a number of roofs that straps have been added in later repair work.

12. The possibility that close purlins are due to Hawksmoor will be discussed later. Elsewhere Longland used common rafters and purlins. He is unlikely to have suggested an arrangement himself that complicated the carpentry.

13. A measured drawing of this is in the National Monuments Record

14. The roof over the wards was originally 'M' shaped. The central gutter drained to a brick shaft within the building. A flat roof has since been built spanning across between the original ridges.

15. From the minute book, quoted in Wren Society II p.40

16. RIBA Drawings Collection

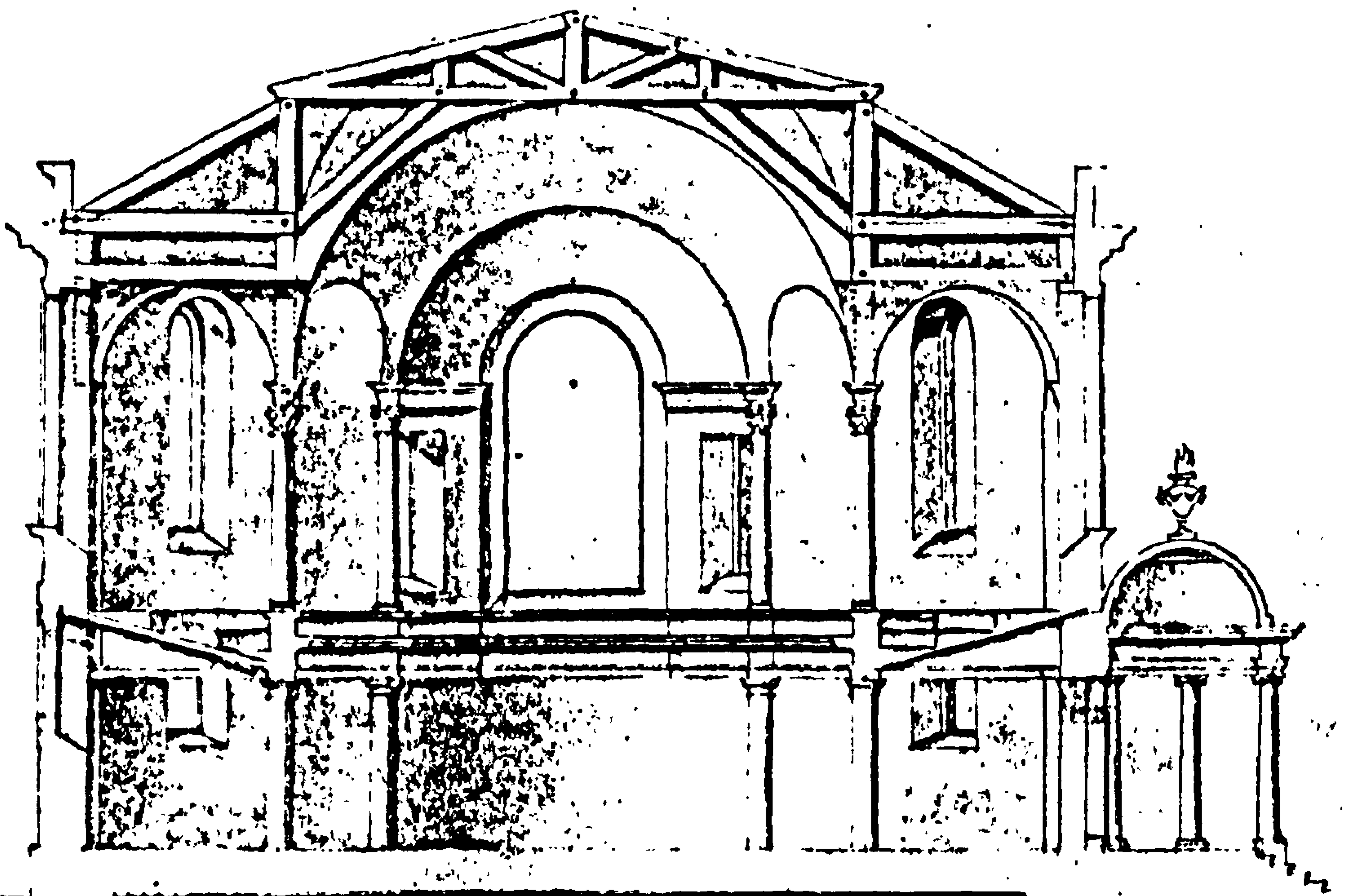


Fig. 4.1

St. Clement Danes, A.S. 11.56

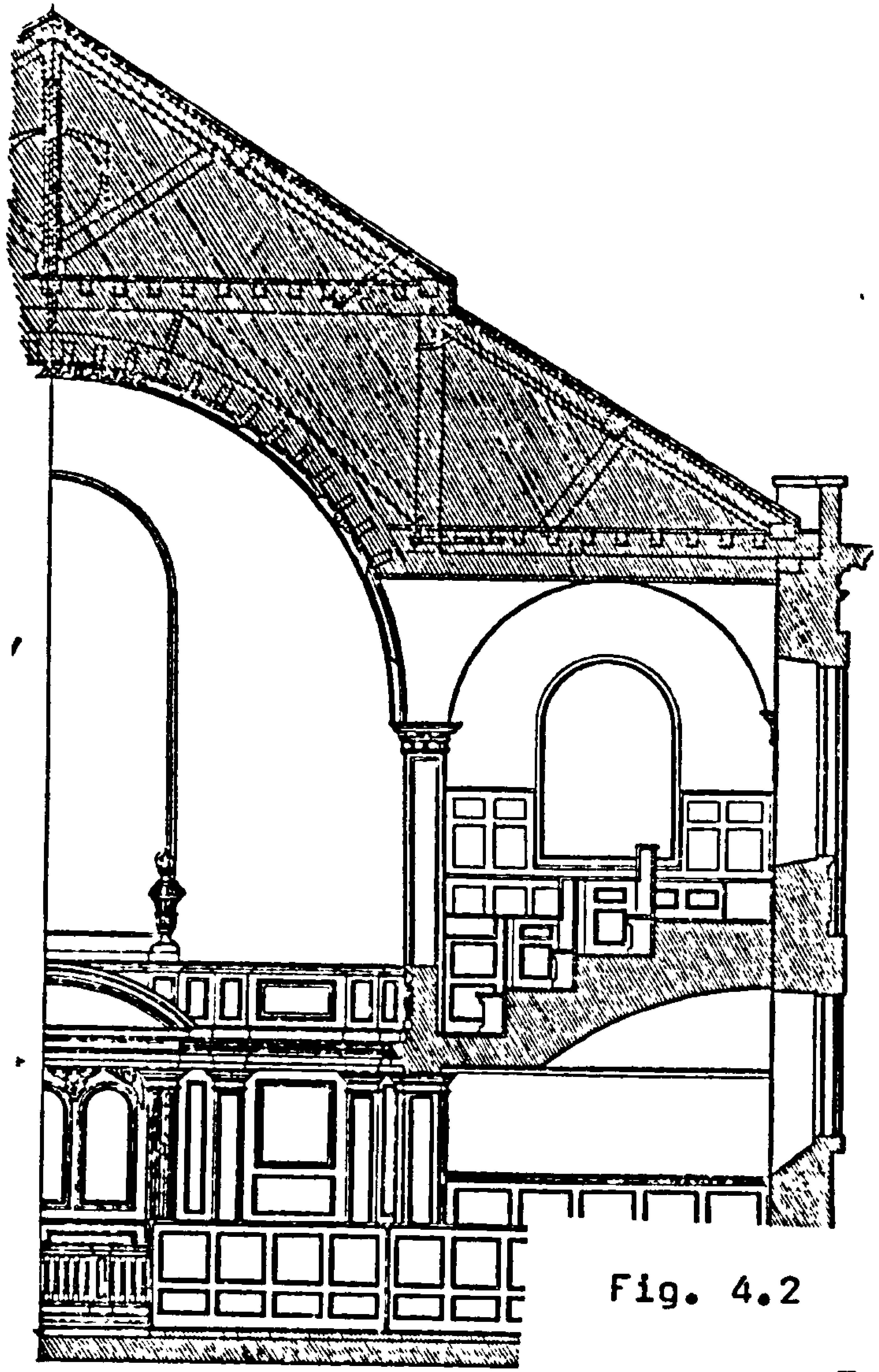


Fig. 4.2

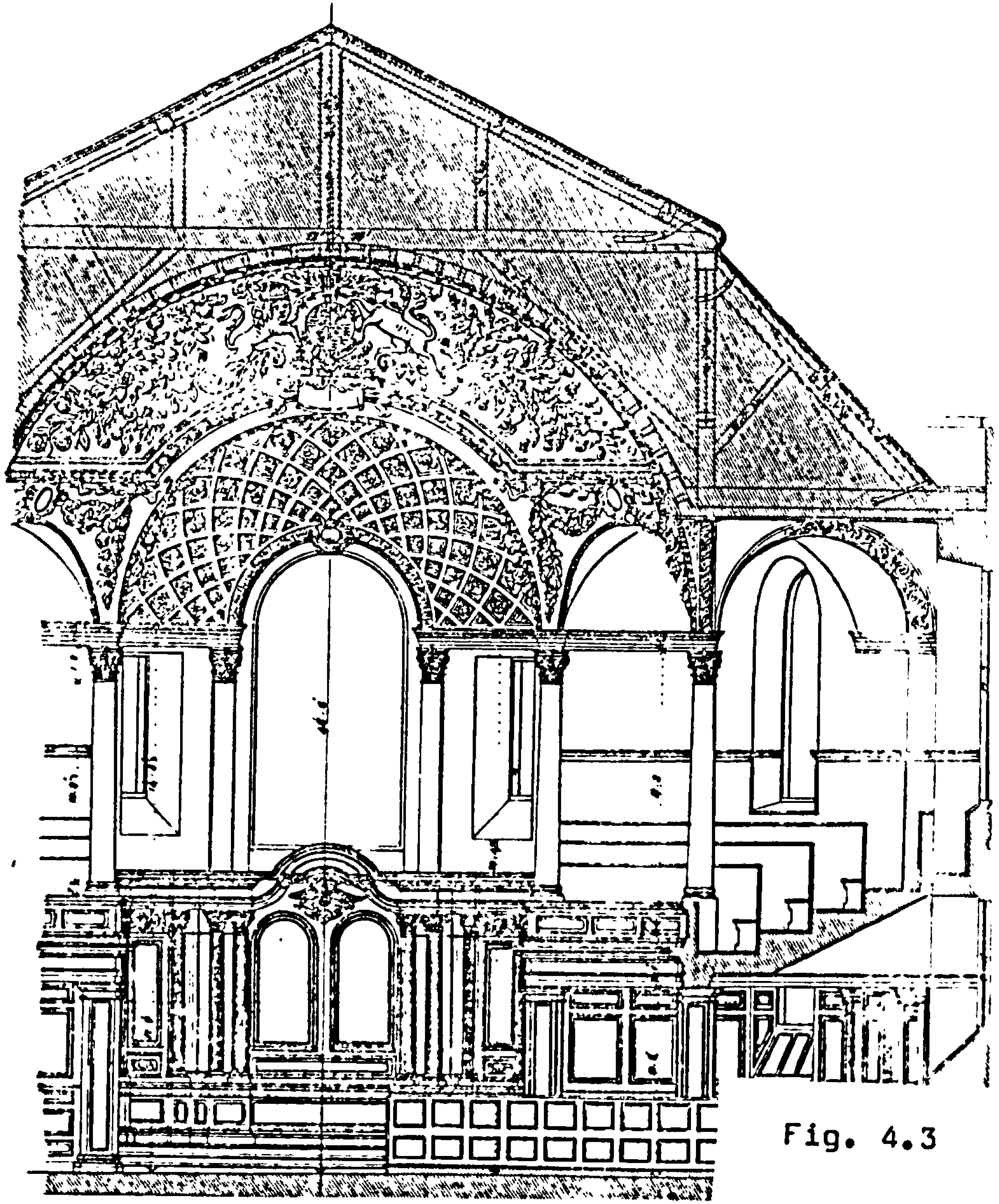


Fig. 4.3

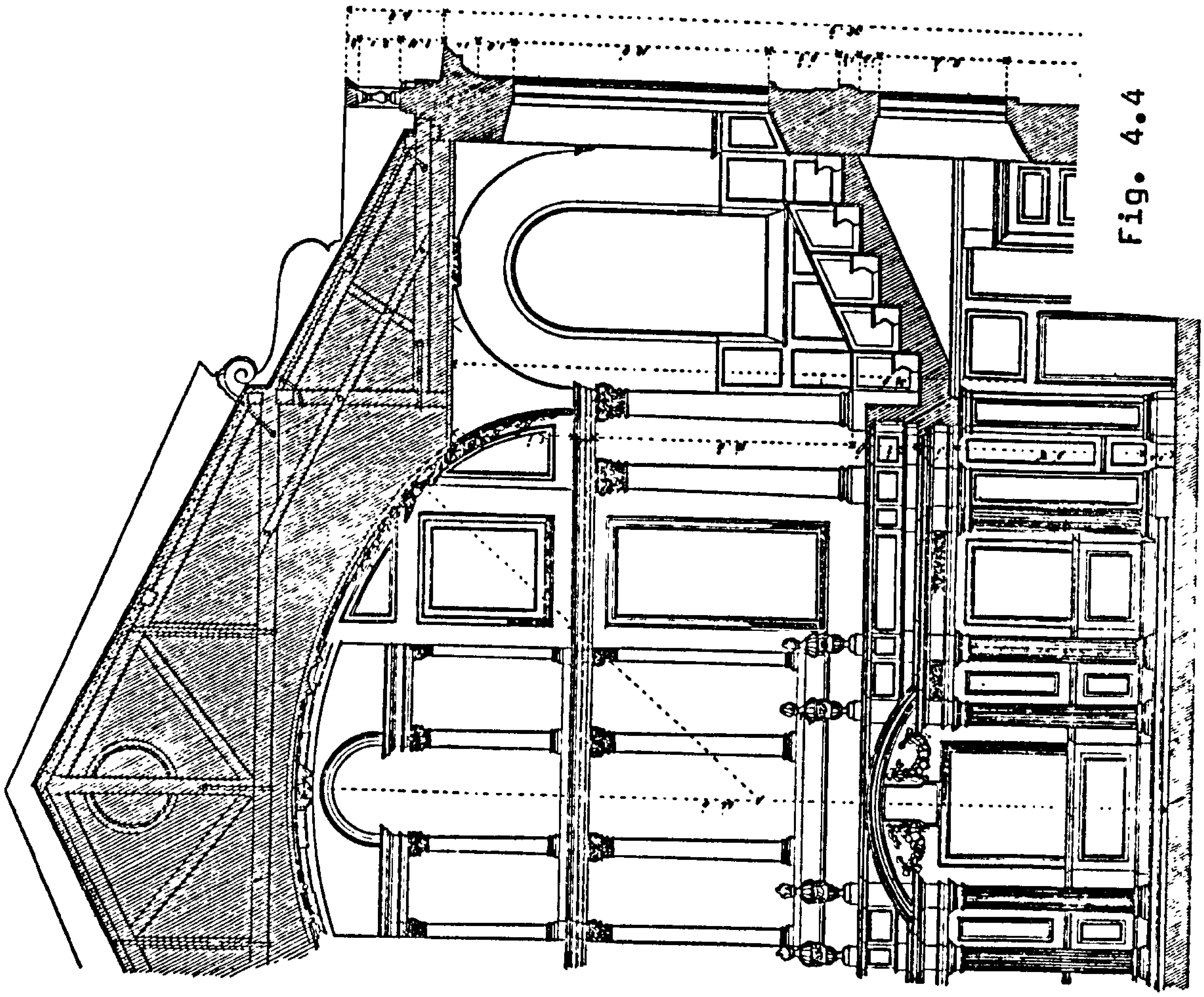
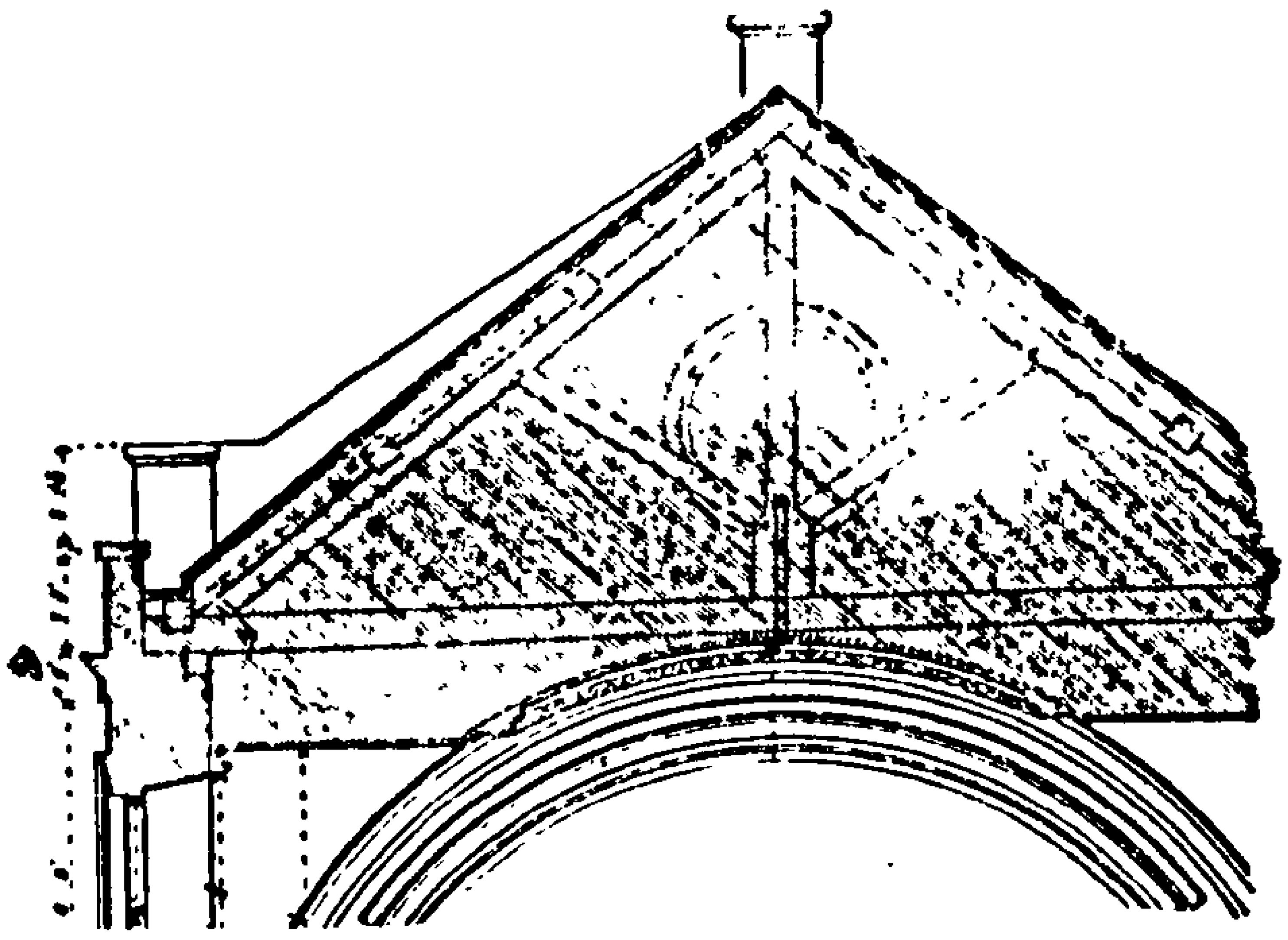


Fig. 4.4

Fig. 4.2 St. Anne's, Blackfriars

Fig. 4.3 St. Clement Danes

Fig. 4.4 St. Andrews, Holborn



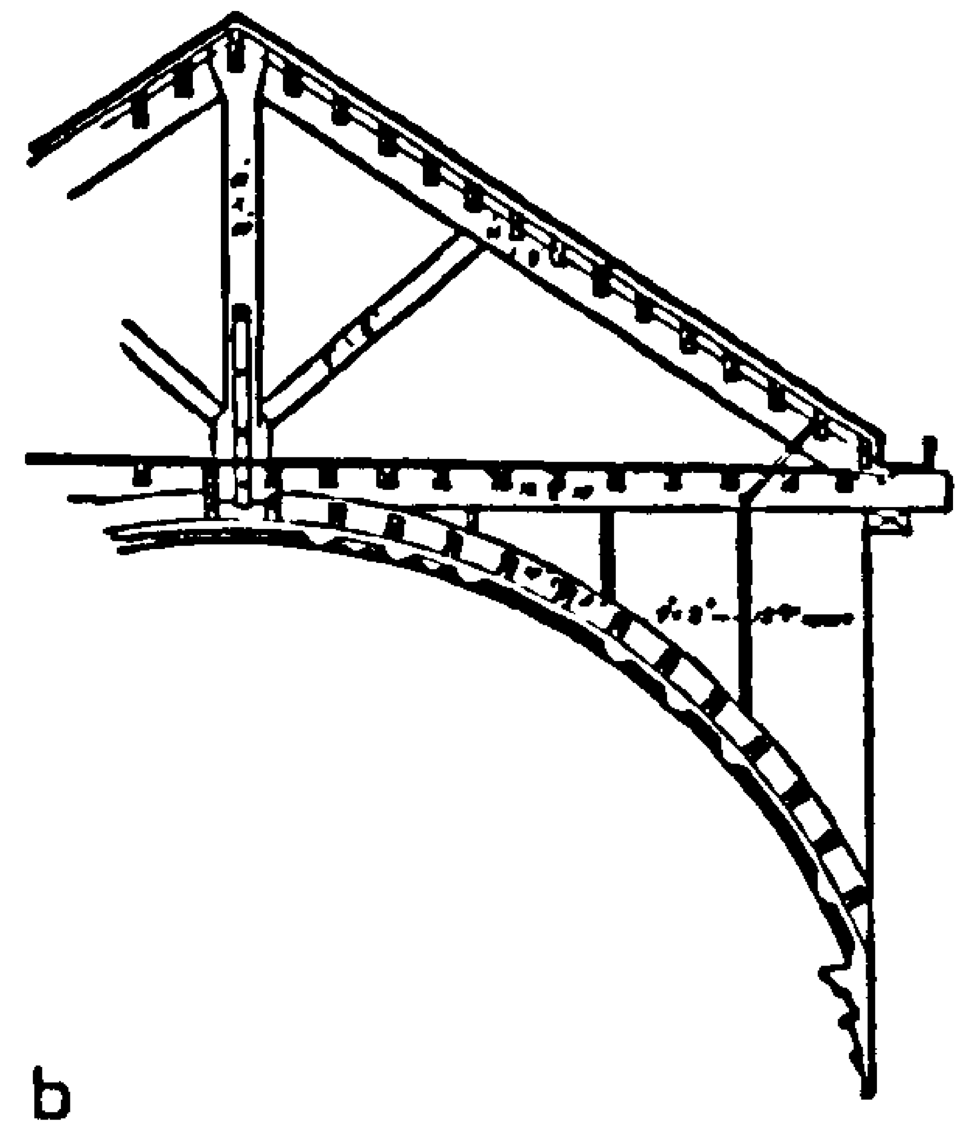


Fig. 4.5 a b

Fig. 4.5

a) St. Bride's, Fleet St.
b) St. Benet's, Gracechurch Street.

Fig. 4.6

a) All Hallows, Thames St.
b) St. Edmund the King, Lombard St.
c) St. James, Garlick Hill
d) St. Mildred, Bread St. There are two trusses with raised ties and trusses with ties at wall plate level in this church. The raised ties were to accommodate domed ceiling.
e) St. Vedast, Foster Lane
f) St. Nicholas, Cole Abbey

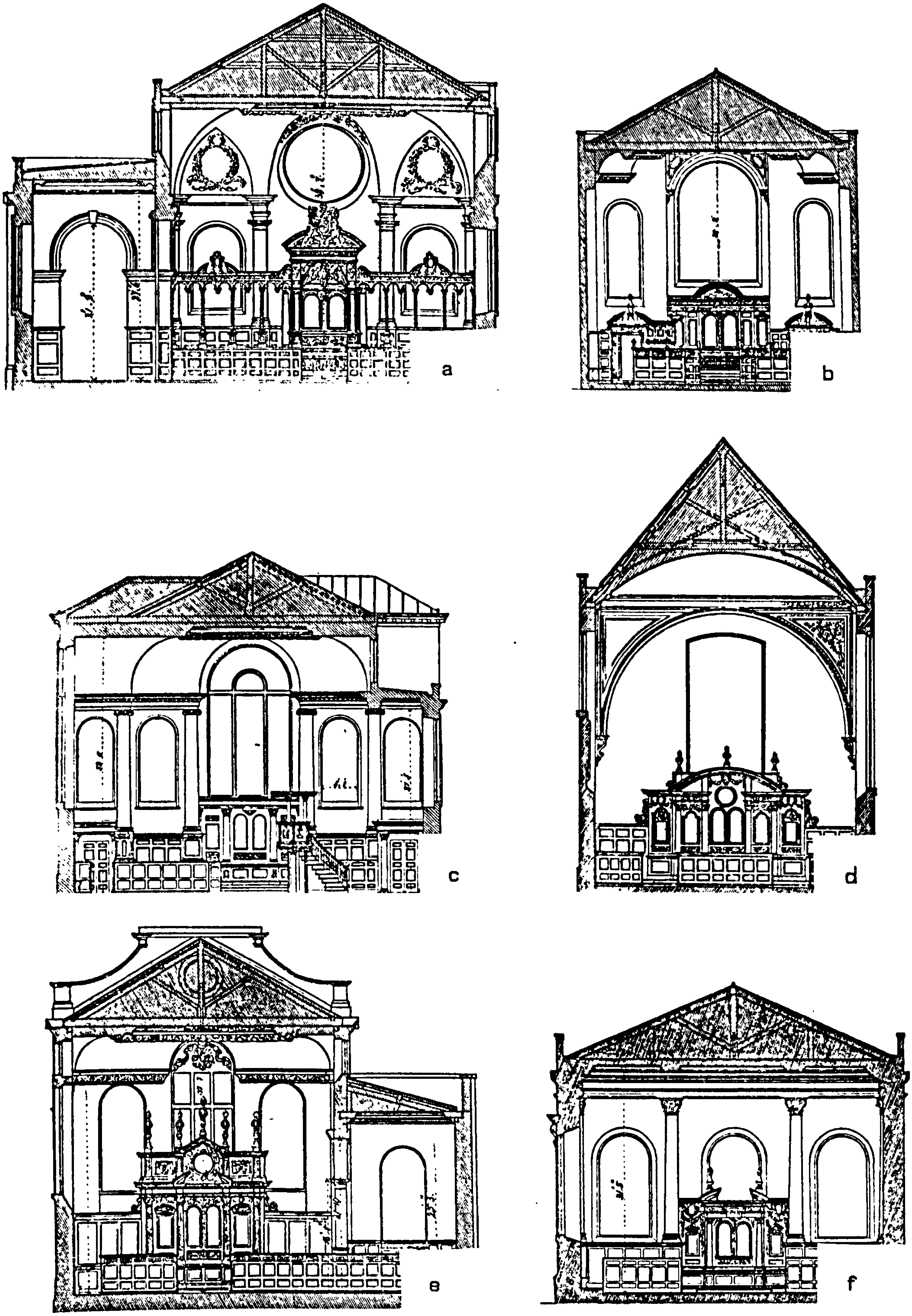


Fig. 4.6

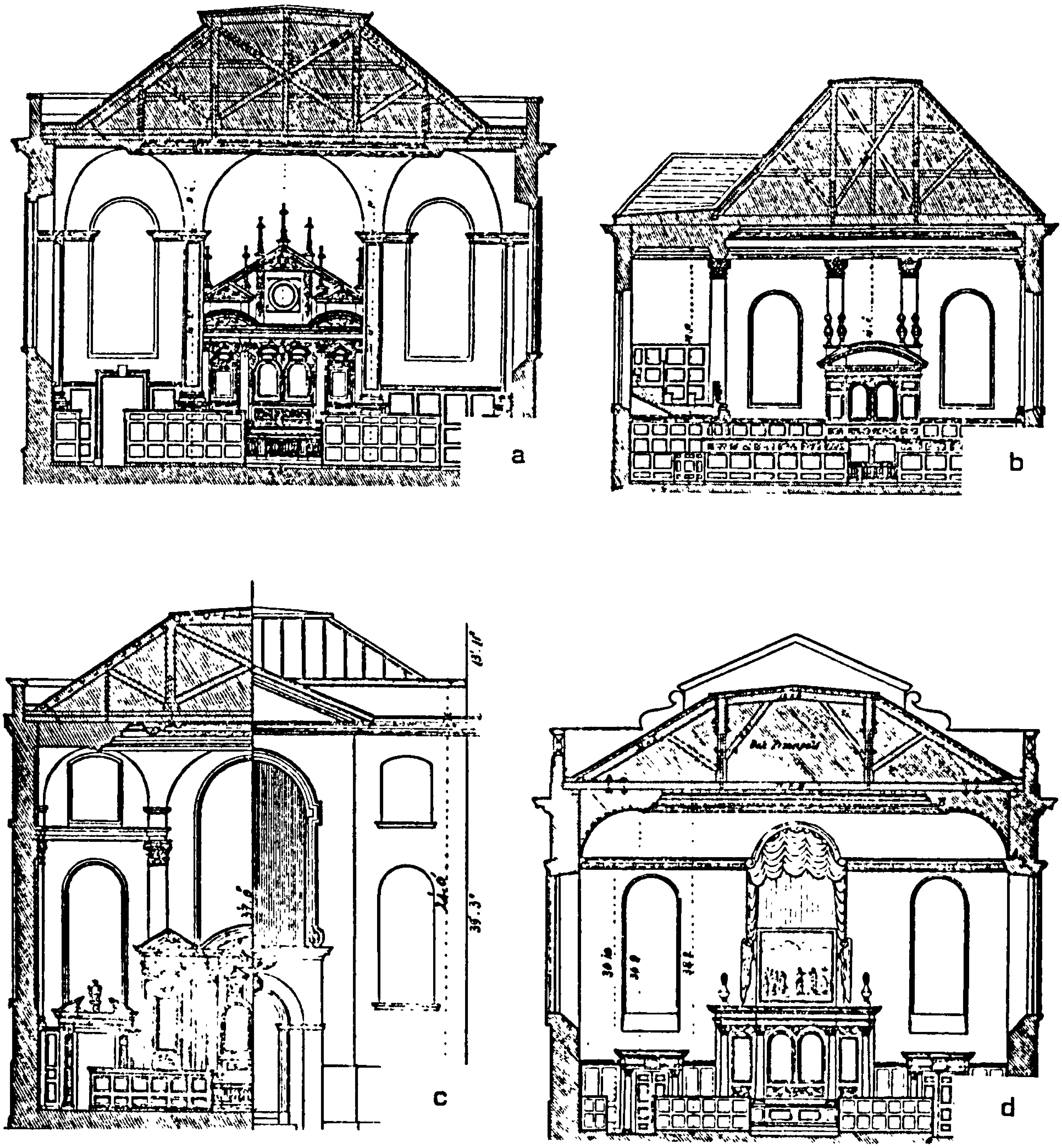
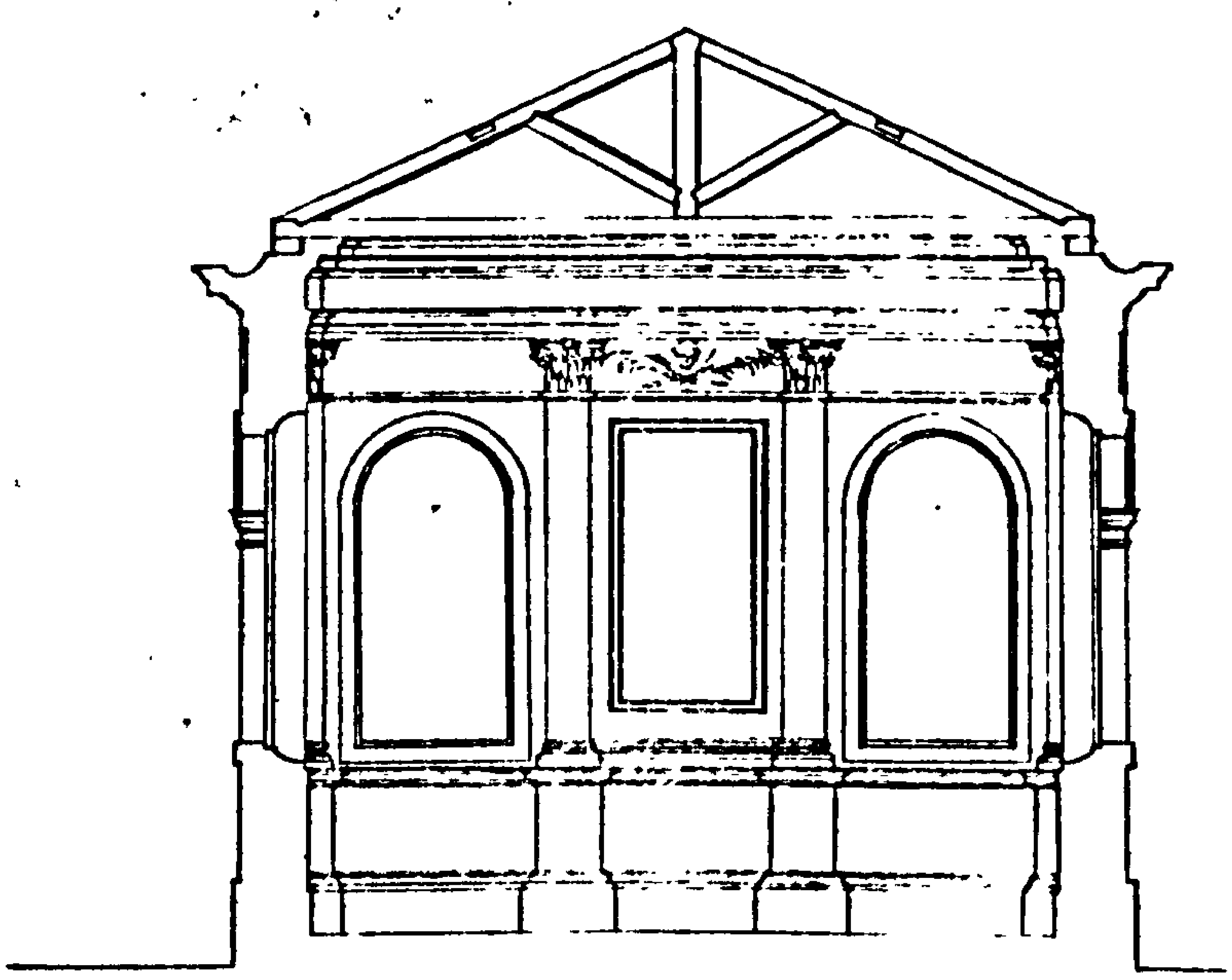
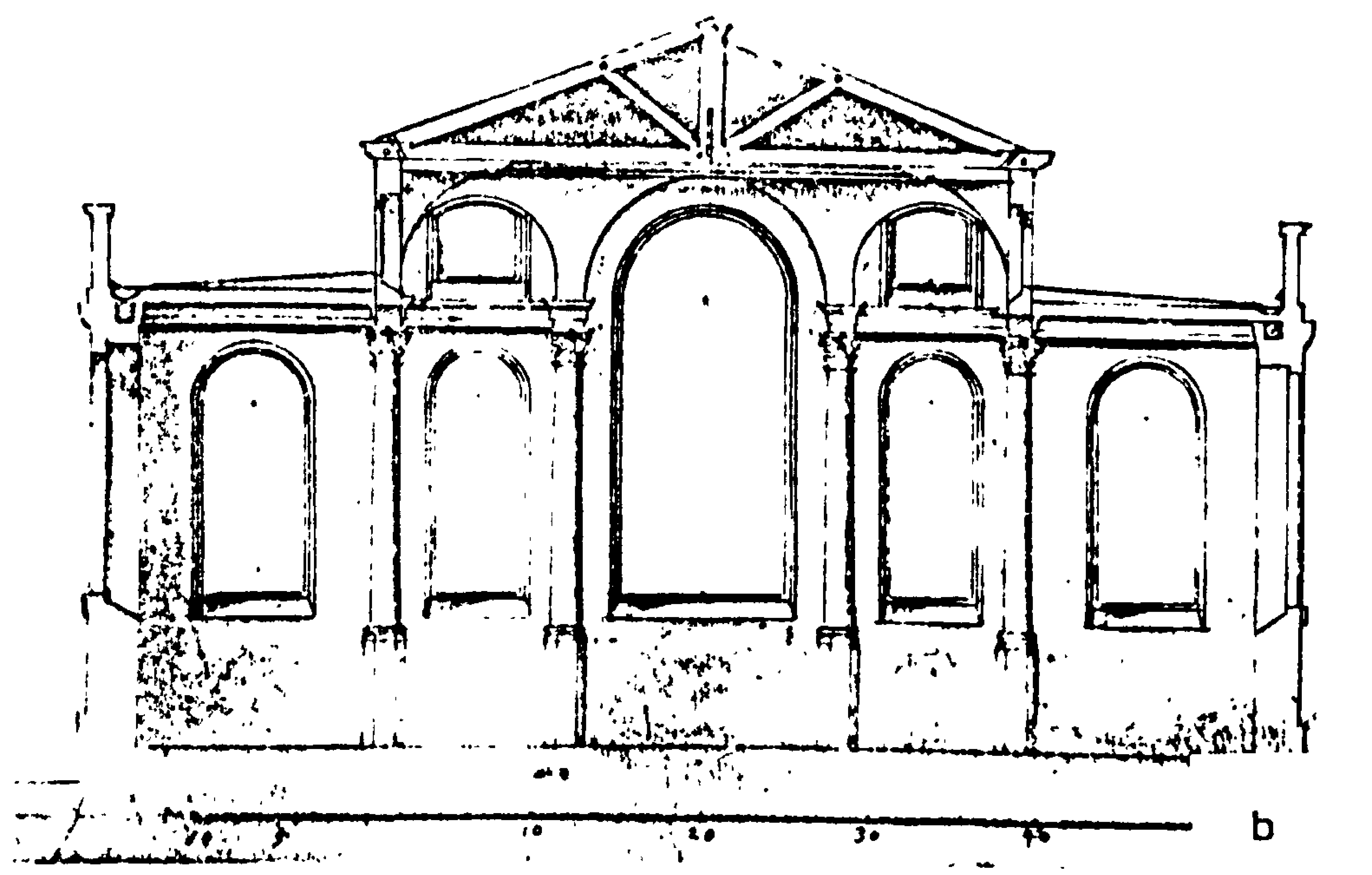


Fig. 4.7

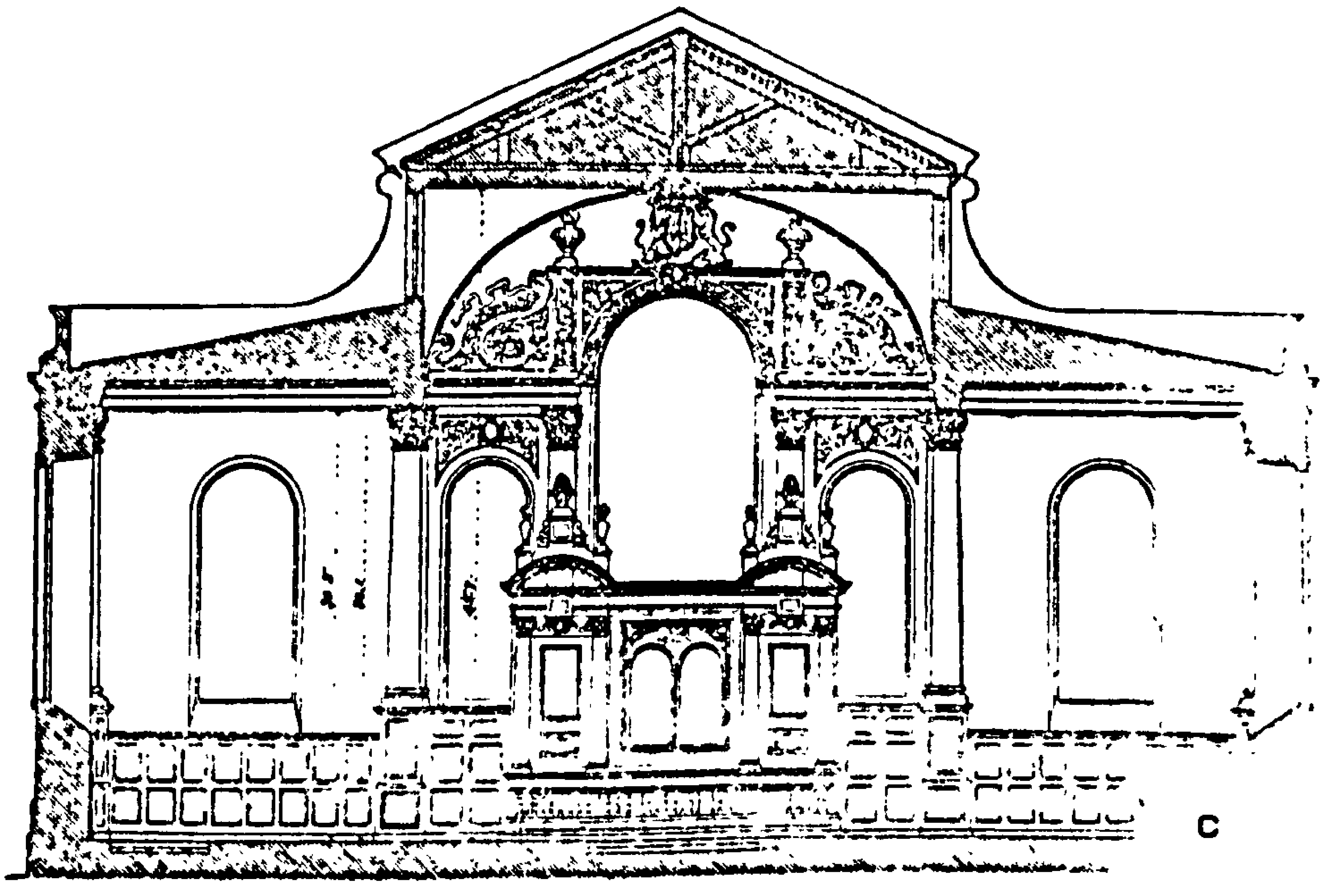
a) All Hallows, Lombard St.
b) St. Benet's, Paul's Warf
c) St. Clement's, Eastcheap
d) St. Michael's, College Hill



a



b



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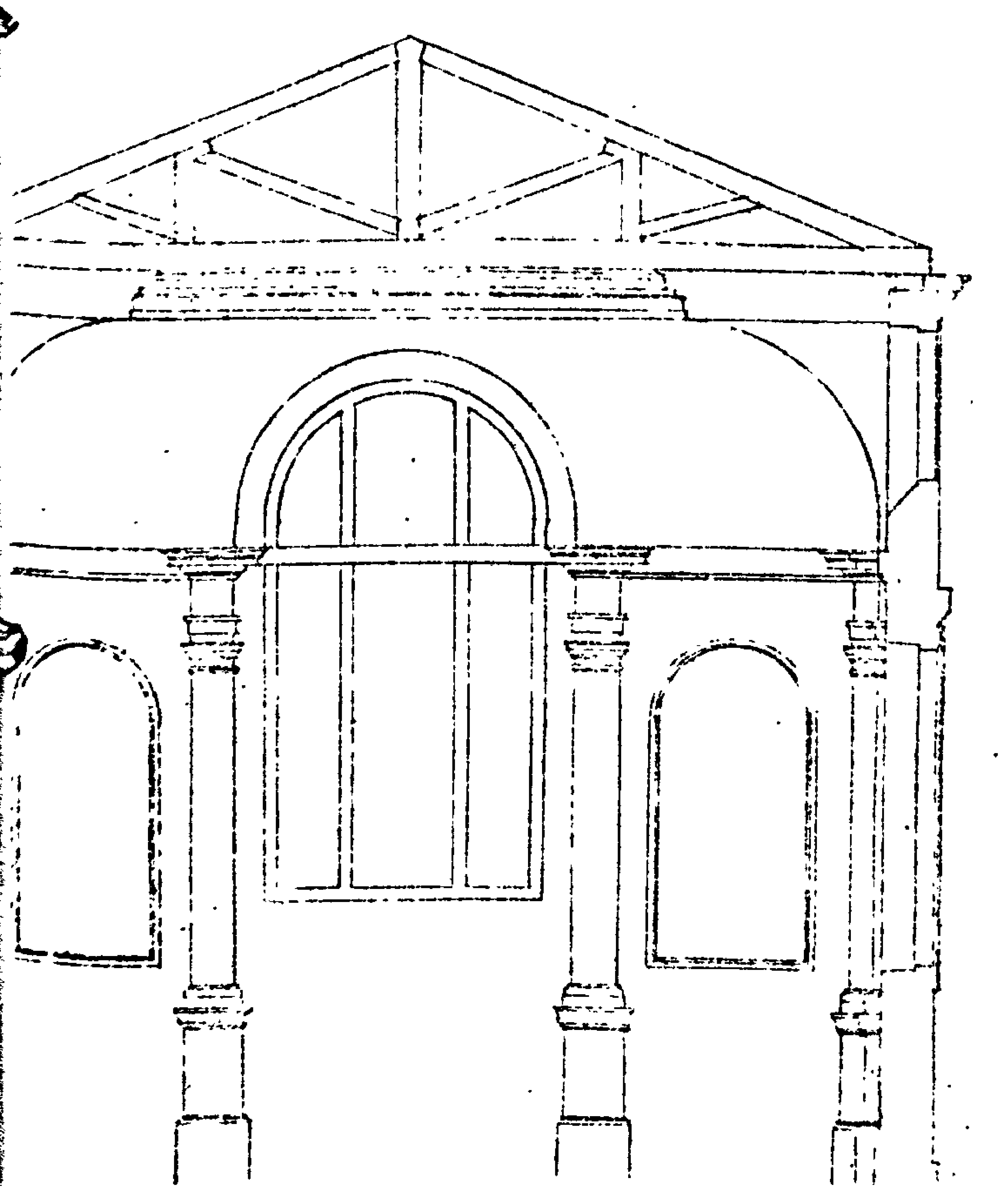


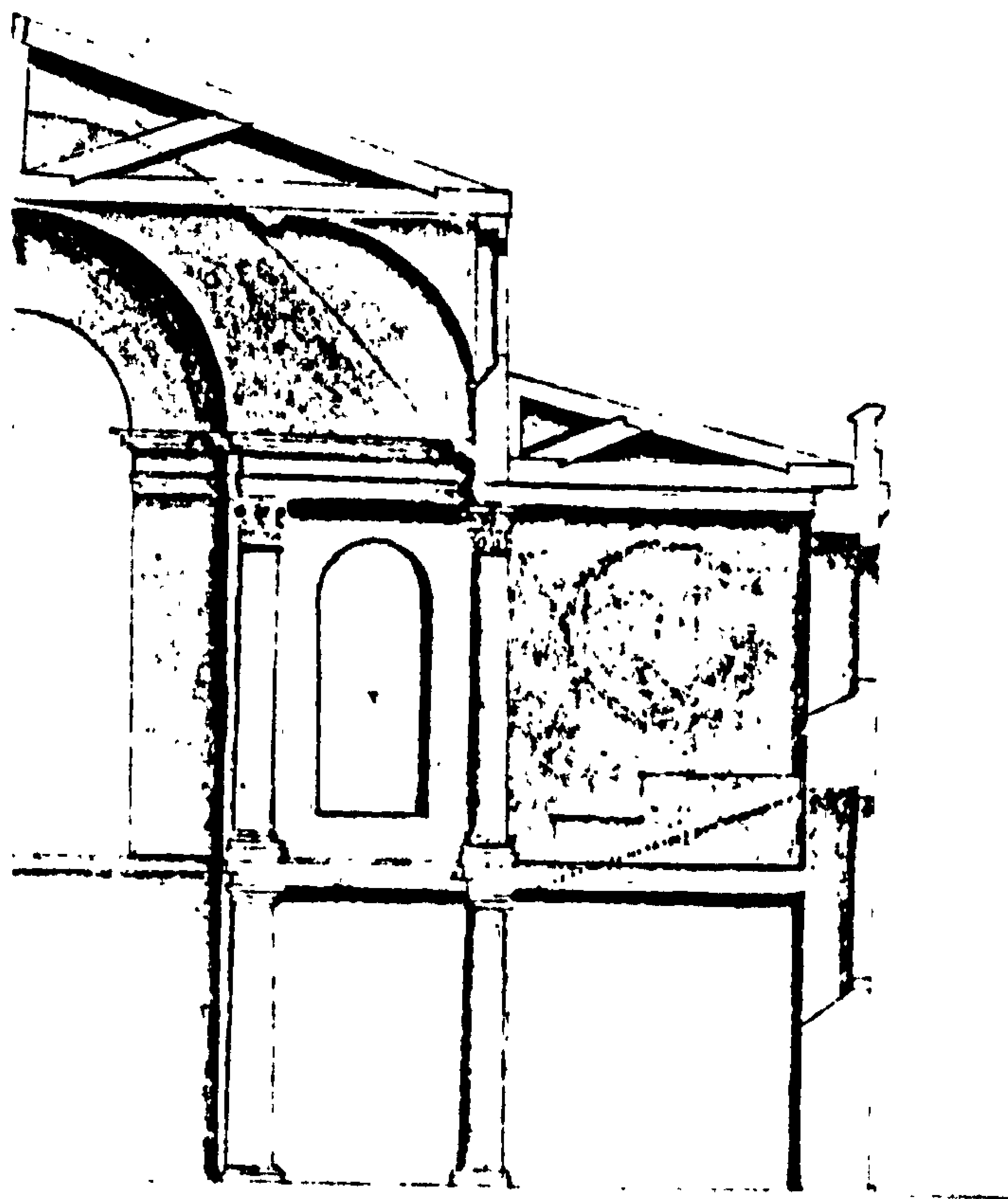


Fig. 4.8

a) St. Benet's Paul's Warf. A.S. I,94.
b) St. Lawrence, Jewry. A.S. I,61
c) Christ Church, Newgate St.

Fig. 4.9

a) St. Antholin Study A.S. II,51
b) Study identified in W.S. as being for St. Lawrence Jewry. A.S. I,74

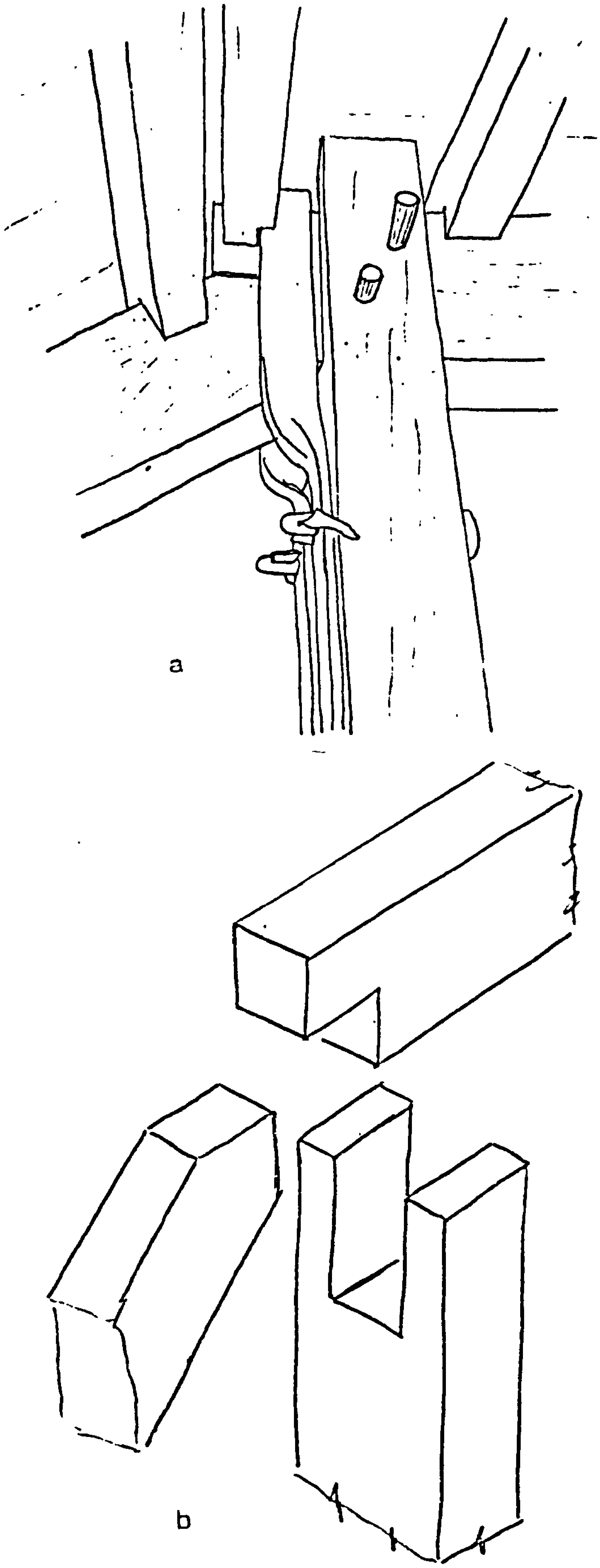


Fig. 4.10

Greenwich Hospital - Roof over Hall -
Detail at head of queen post.

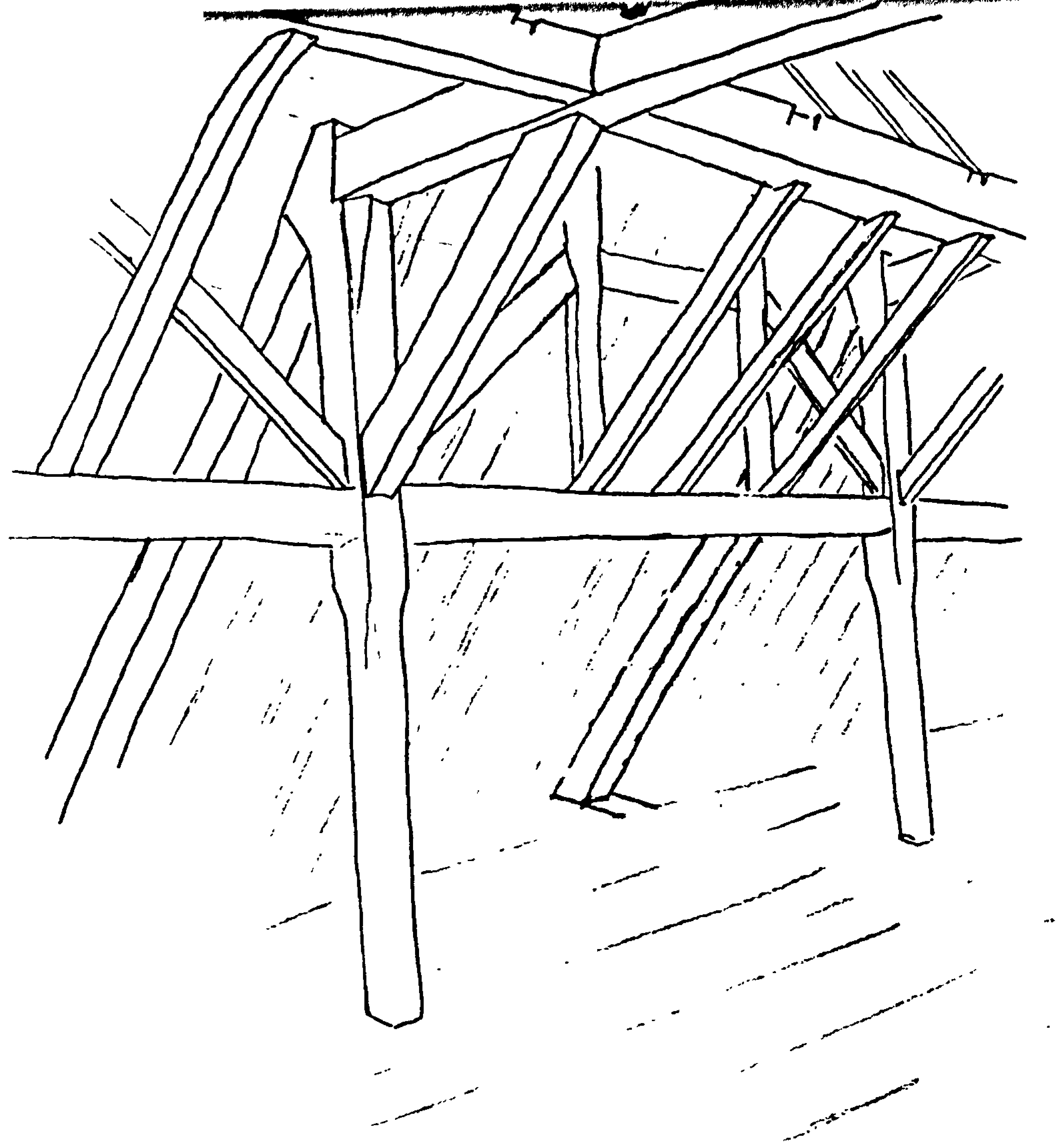


Fig. 4.11

Chelsea Hospital Roof over hall - general arrangement of queen post trusses.

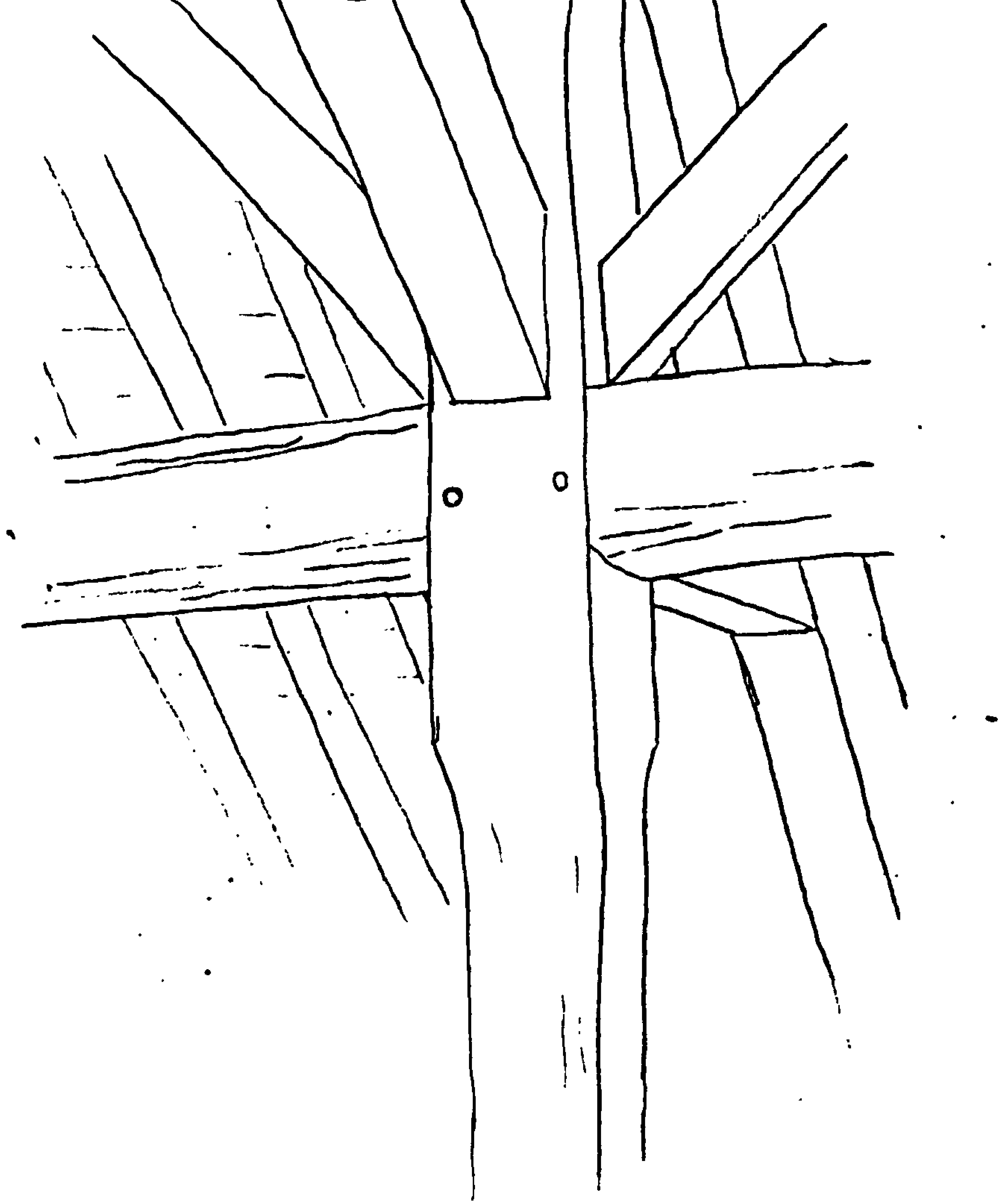


Fig. 4.12

Detail of bracing

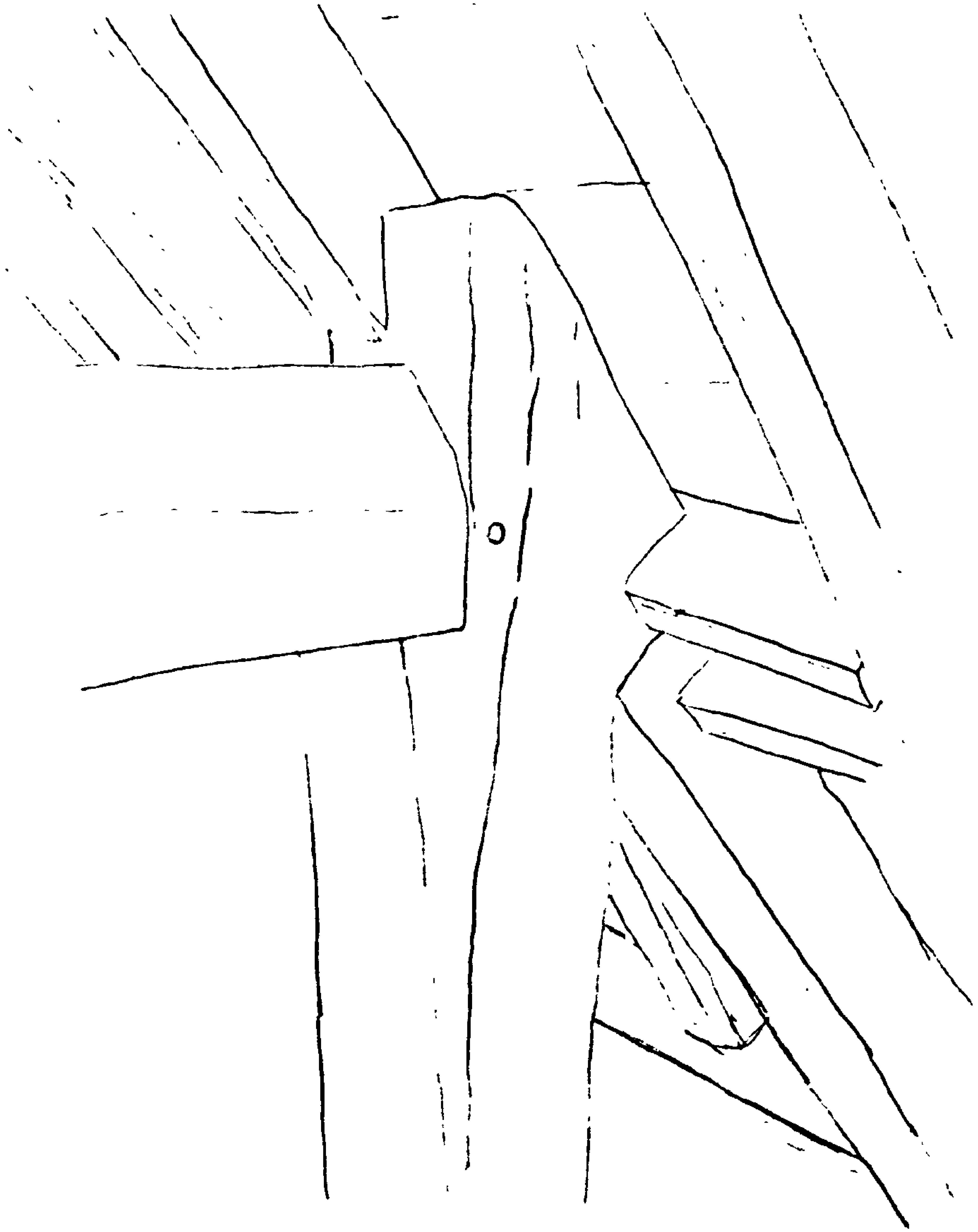


Fig. 4.13

Detail of head of queen post

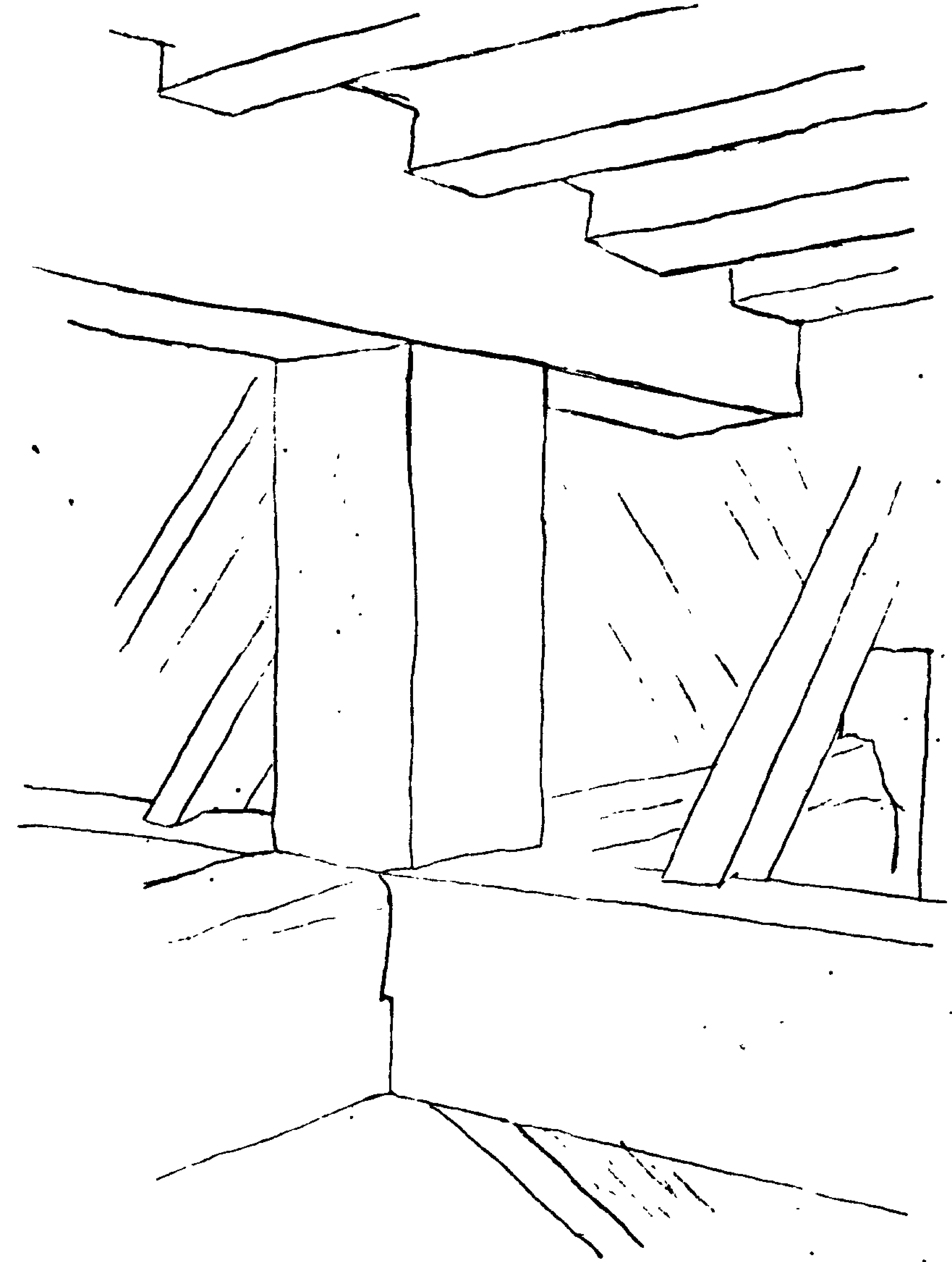


Fig. 4.14

Post supporting upper beam. Note the short 'rafters' to the longitudinal plates which support nothing.

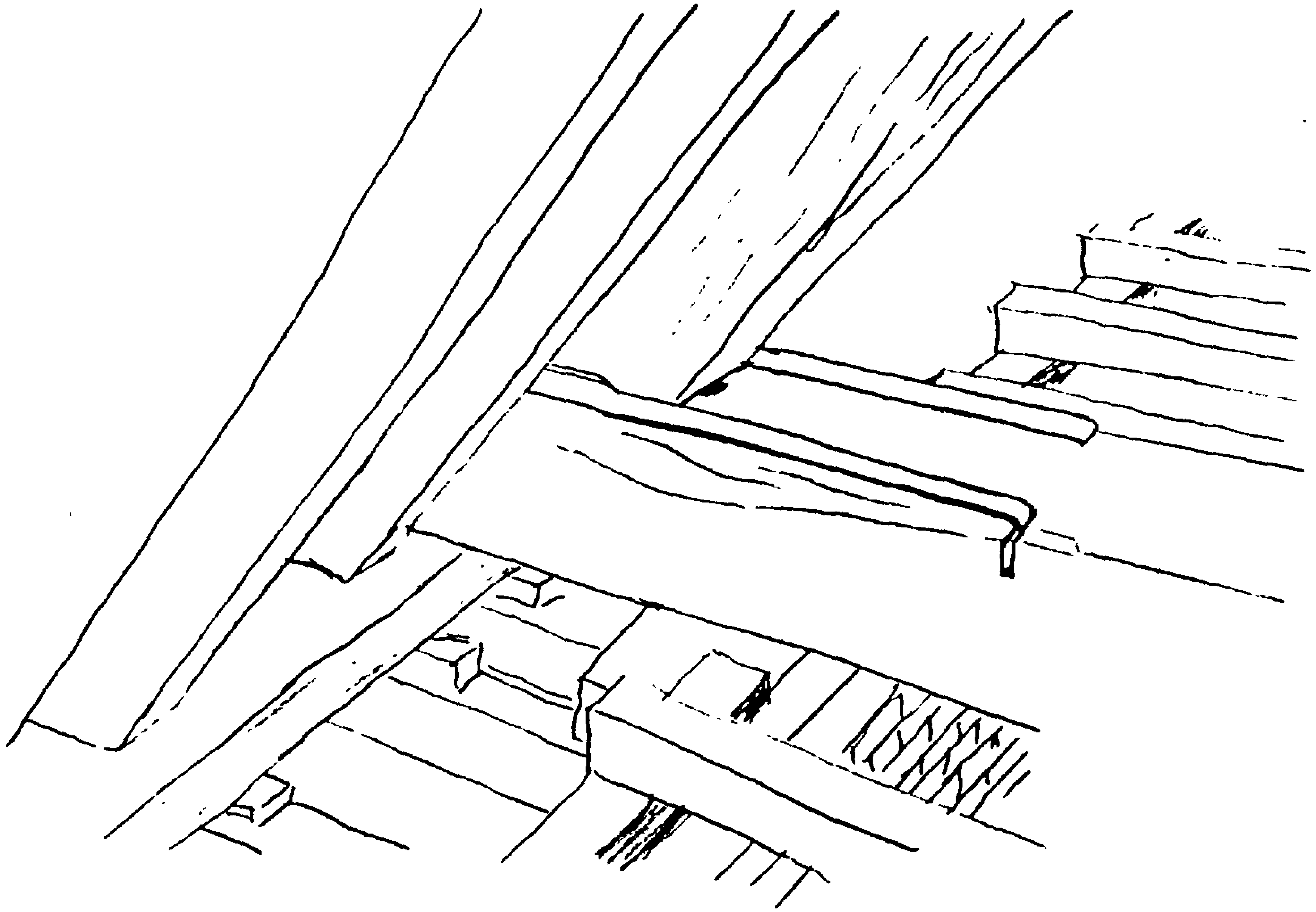


Fig. 4.15

Chelsea Hospital Hall roof. Metal straps to resist the outward thrust of the principals.

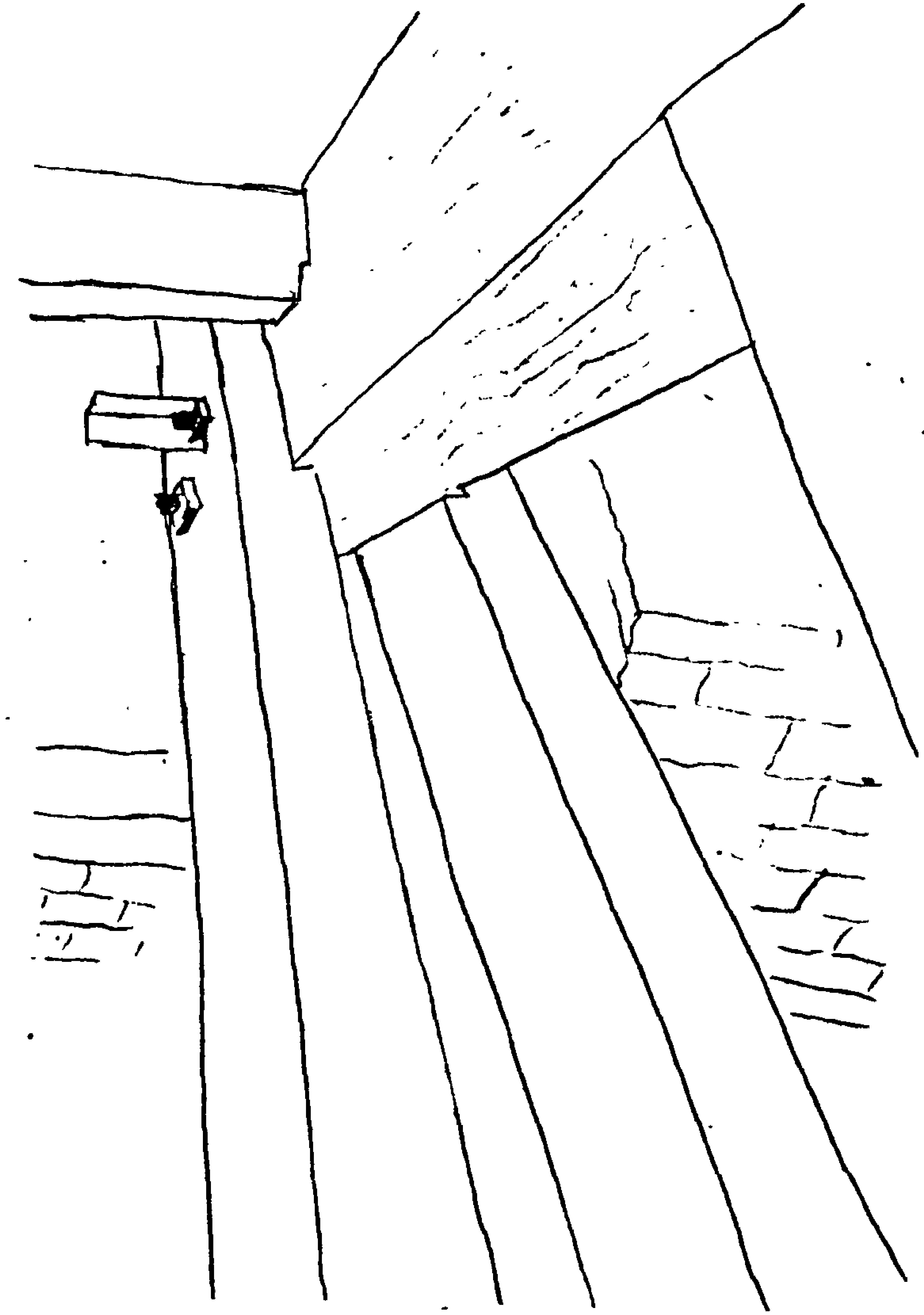


Fig. 4.16

Chapel Roof. Pair of timbers clasping the feet of the principals. The raised tie is just visible at the top of the drawing.

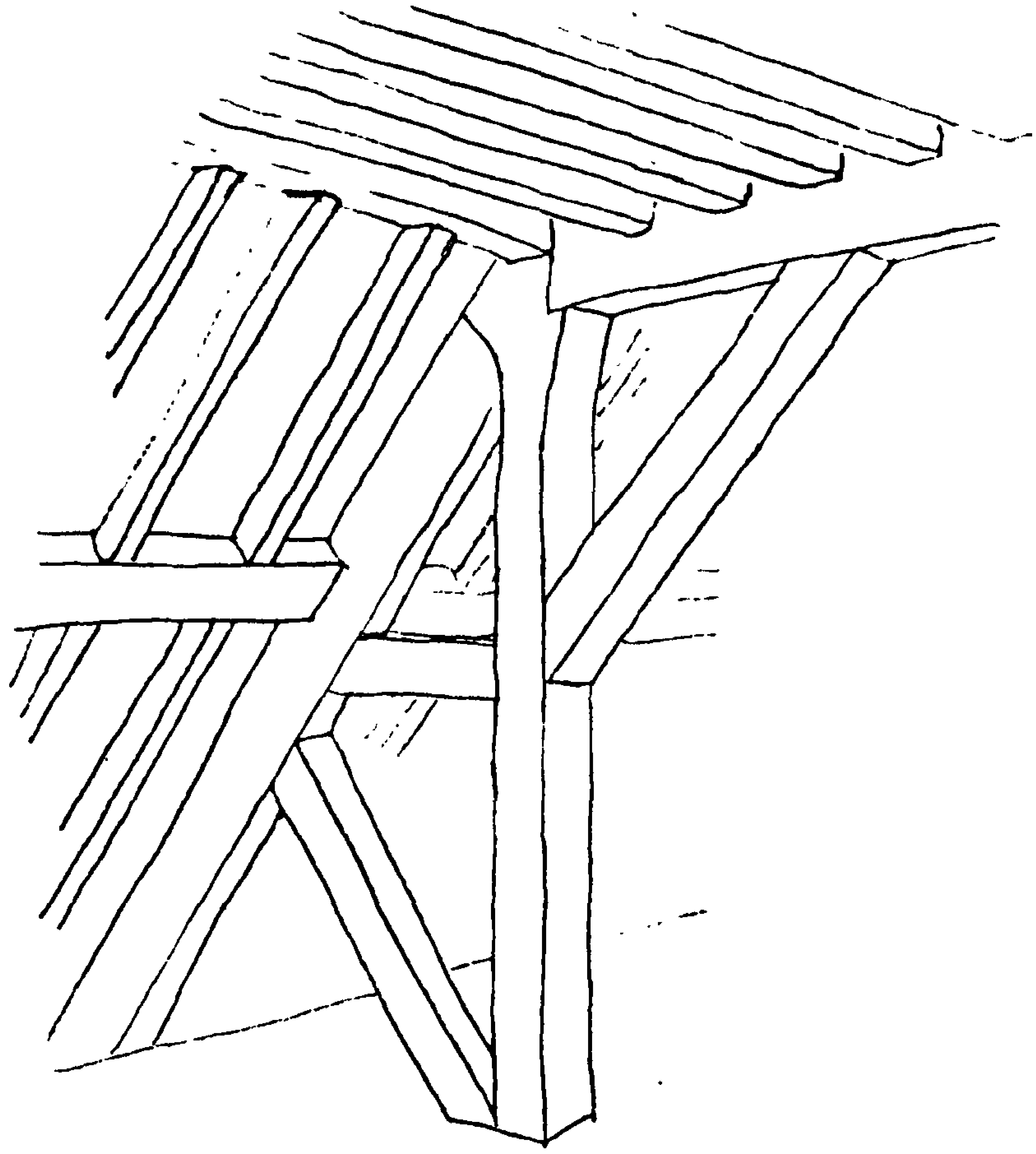


Fig. 4.17

Chelsea Hospital Chapel roof.
General arrangement of queen post truss.

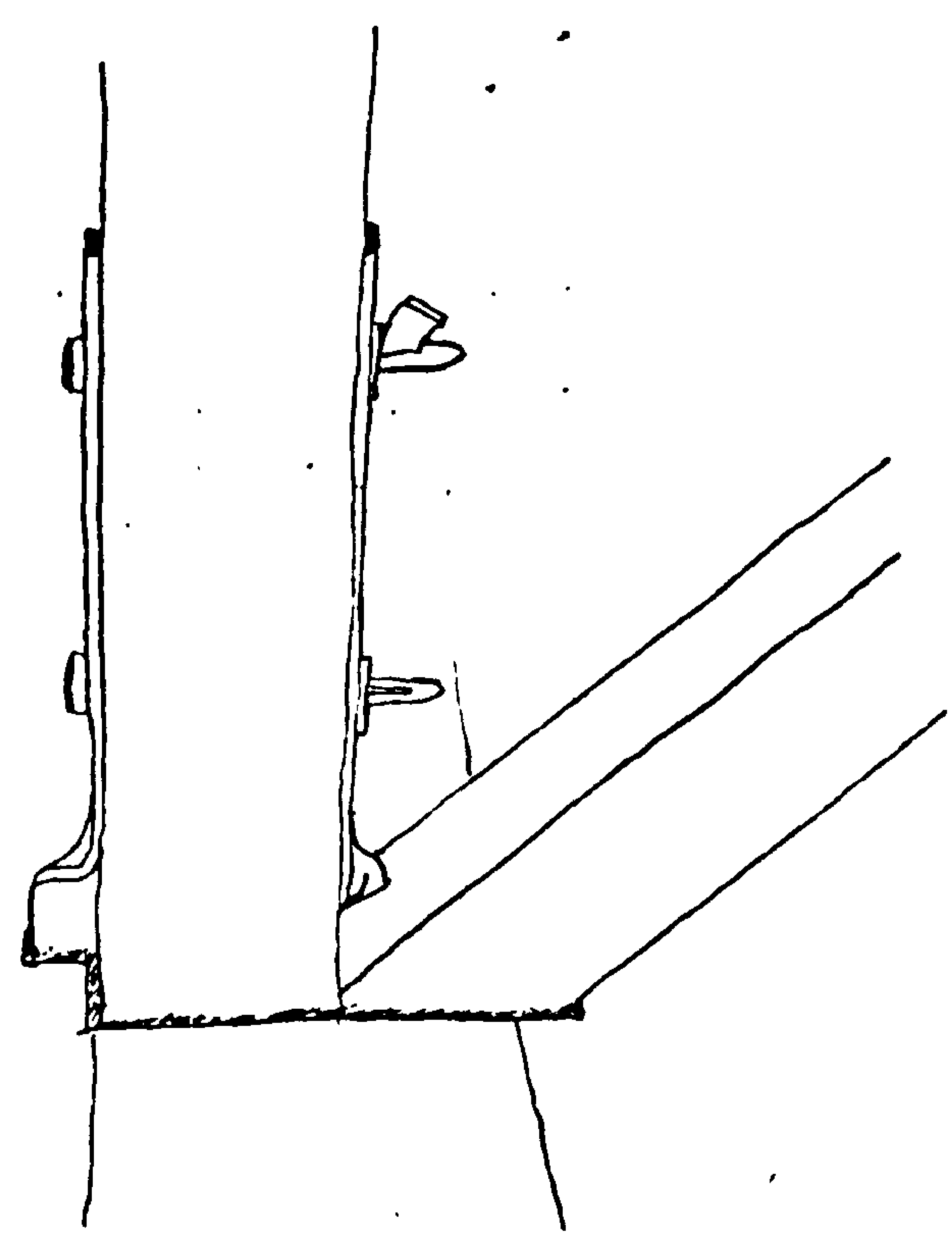


Fig. 4.18

Detail of metal straps at the foot of queen post.

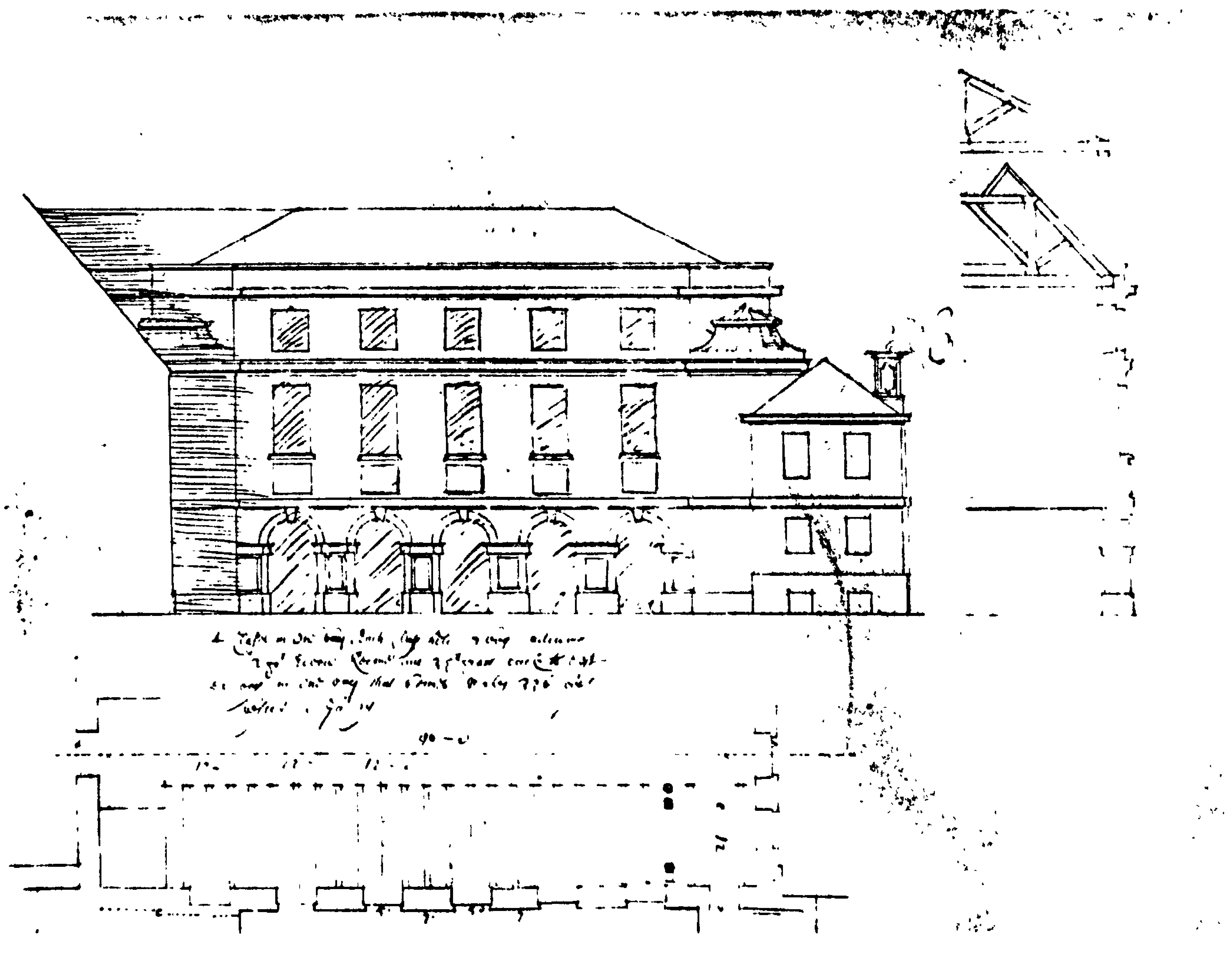


Fig. 4.19

Sir John Moore's Writing School.
AS IV, 29
One of a number of studies for this building. AS IV, 28 has a section with a king post roof only. AS IV, 31 has a section with the queen post only.

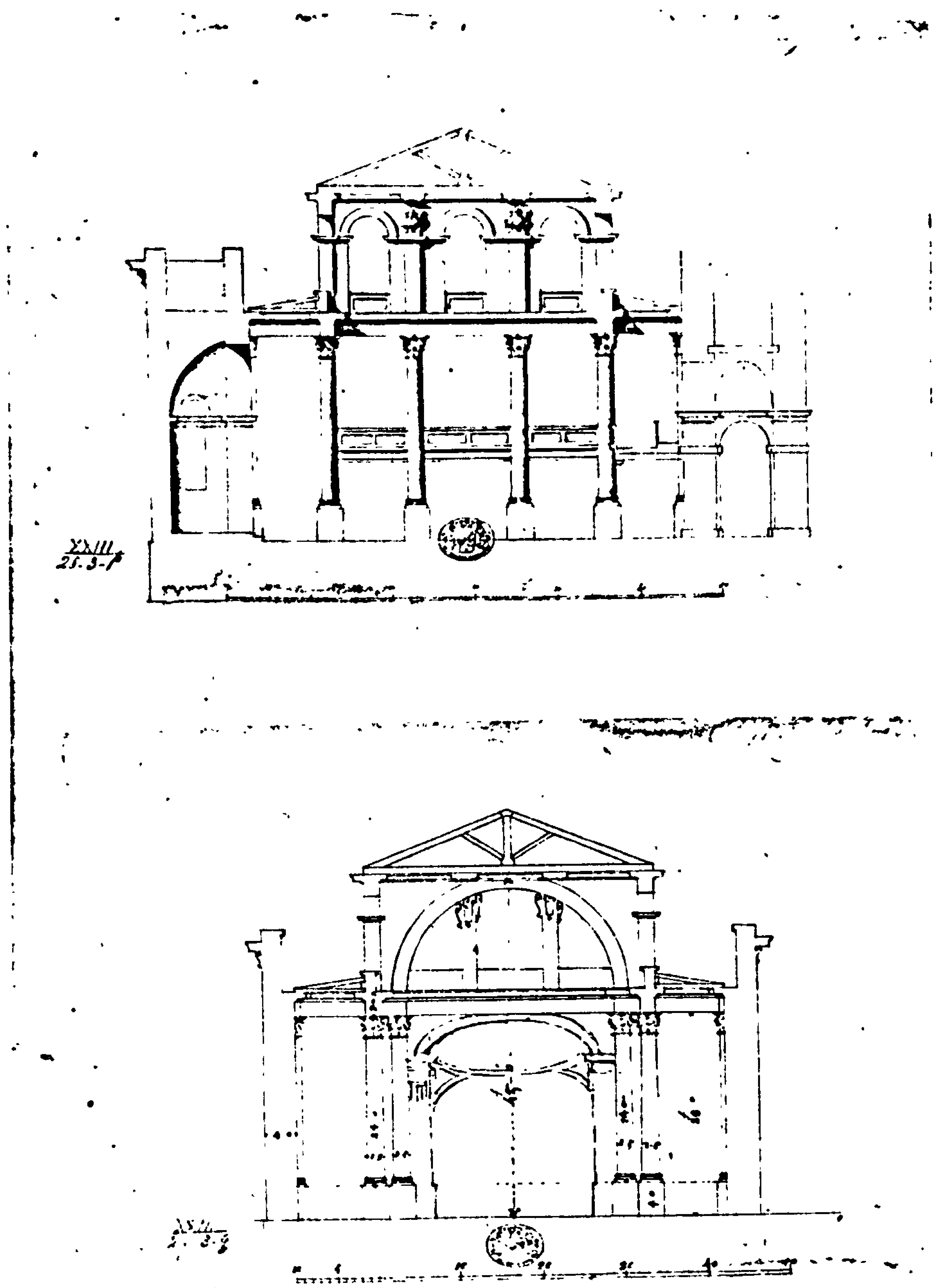


Fig. 4.20

St. Giles in the Fields.
Project drawings by Hawksmoor.
Kings Maps 23.28, 3p & q.

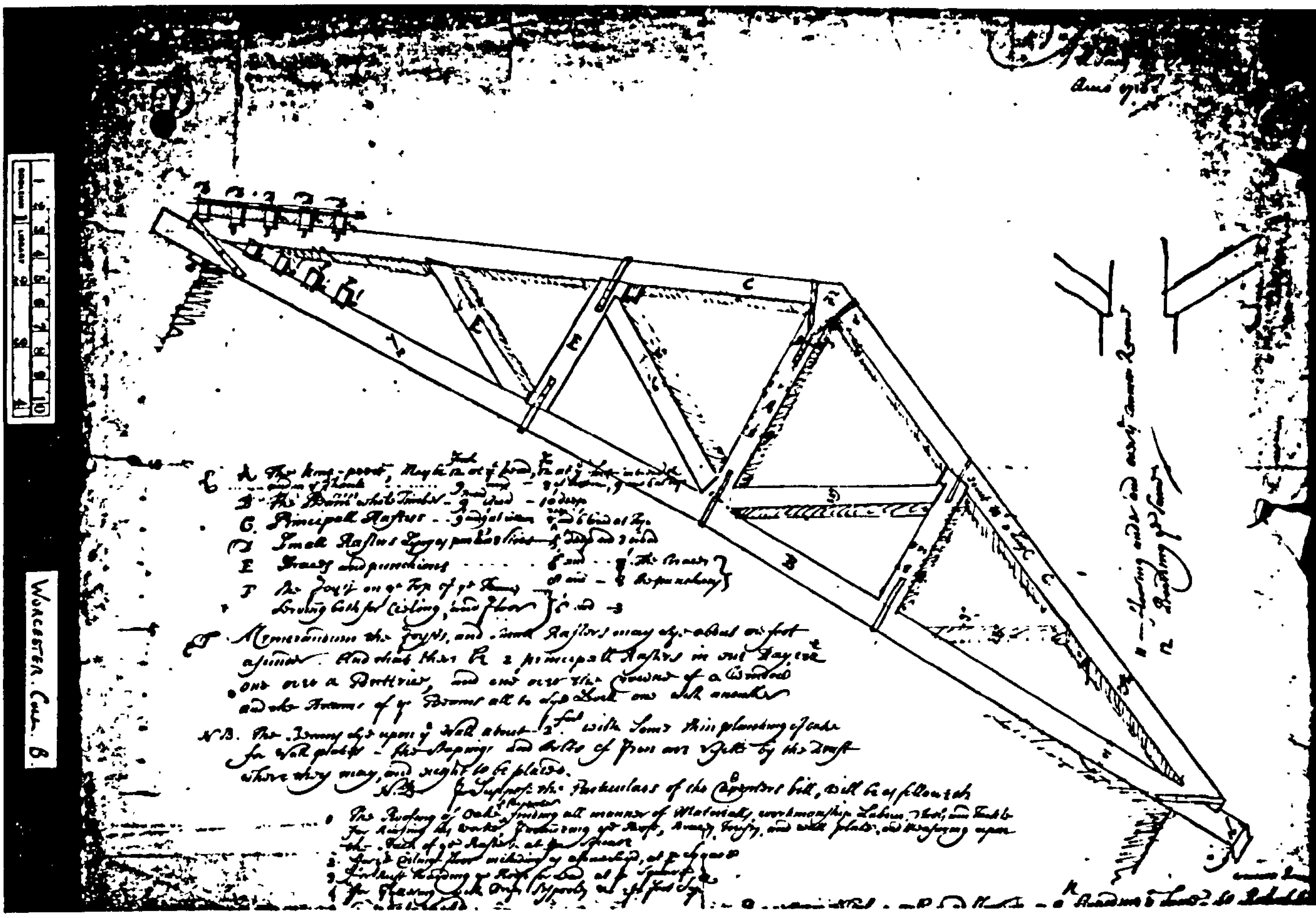


Fig. 4.21

Drawing by Hawksmoor for the roof structure of All Soul's College, Oxford (Clerk Collection, Worcester College). This drawing corresponds well with the roof over the hall.

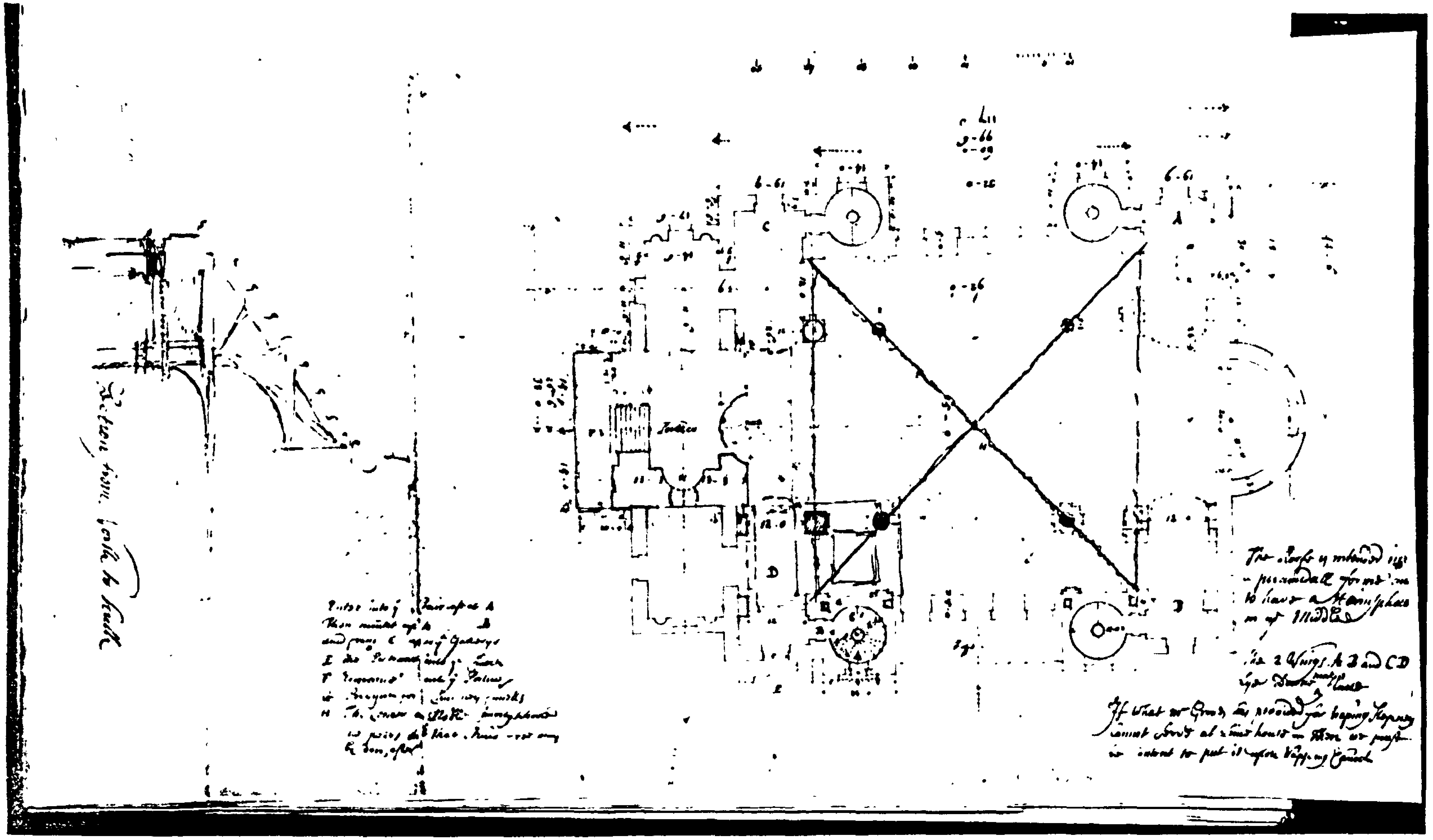


Fig. 4.22

Hawksmoor sketch for St. George in the East. Note the reference to Grove in the note in the corner. (B.M. Kings Maps)

THE EARLY 18th CENTURY; FROM WREN TO GIBBS

Towards the end of the seventeenth century Wren's structural techniques were far more advanced than those of most other contemporary architects. Only a few builders of the period were using other than simple 'traditional' structural types. Even so by 1730 king post roofs of a form similar to that developed by Wren had appeared in the churches of Archer, Gibbs, James and Flitcroft and were being used in the roofs of country houses like Blenheim and Badminton. How then did the knowledge of this improved structural type become more widely known? The only illustrations of a king post roof available at the beginning of the eighteenth century were those in Richard's Palladio and Moxon's Mechanik Exercises. Whilst it is possible that some carpenters may have seen and copied these, other ways for the dissemination of knowledge are also possible and even more likely.

Dissemination of Wren's structural ideas would have been possible through those who had worked on his buildings, either as assistants in their design or the supervision of their construction, or as carpenters in the building of the roofs. Whilst Hawksmoor is the obvious heir to Wren's inventions it is quite possible that their roof forms were copied by their carpenters and used on other buildings. It is also possible that they may have been studied and copied by other architects or carpenters who had no direct contact with either Wren or Hawksmoor. Nor need their buildings have been the only possible source for designers working in this way. The major structures of Inigo Jones, like the Banqueting House or St Paul's, Covent Garden, might also have been copied.

It is difficult to say which of these possible mechanisms for the dissemination of knowledge was most important, because the evidence that each leaves must vary. If an architect designed a structure then a drawing may remain as a record. However a drawing made as a study of a structure or a drawing for an unbuilt project is more likely to have survived than one for a completed building. For the latter a sketch or a preliminary drawing may survive among the architect's collection, but one supplied to the draftsmen could well have been used and then discarded. If this were the only drawing then the effect would be the same as if the carpenter had provided a roof without instruction. Occasionally the carpenter for a building may be known from the accounts but only rarely, when more examples of his work can be traced, is this information useful. Given the difference in the material available, the approach taken here is to show that each of the different ways for the dissemination of knowledge did in fact occur by looking at a number of individual examples. Without a much larger sample of structures and more extensive documentary evidence than is at present available there can be no attempt to assess the relative significance of each of the different mechanisms.

At the same time the state of architectural practice of the period has to be considered. Without the formal structure that architecture has today, without any formal training for entrants to the 'profession', the means by which architectural status and knowledge were acquired varied considerably. The kind of training received by Webb and Hawksmoor was the exception rather than the rule. Most architects of the period were self taught and the professional might not have any advantages over the diligent amateur. Moreover, the distinction between amateur and professional was not as clear as it is today. Amateur architects not only designed and built their own houses but they might even have given advice and help to friends or relatives thus acting in a quasi-professional capacity. In building his house the amateur might be competent to carry out his own designs or he might draw heavily on the advice and skill of his craftsmen to an extent that makes it difficult to distinguish the latter's role from that of an architect.

Amateurs

The scale of Wren's roofs and their general standard of detailing are such that, seen in isolation, it is difficult to believe they are not part of a well established technology. Comparison with other contemporary work however shows that this is not so. While Wren was developing his structural designs the work of other architects in the country was still largely dependent upon the use of traditional forms. Many of these architects were of course amateurs who relied upon the skill and knowledge of their craftsmen to provide the structural details. In most cases the carpenters would be able to use the traditional structural types but occasionally they might be asked to provide a roof of unusual shape. In such instances the form of the structure that was built provides some indication of their level of structural knowledge.

Boughton, Northamptonshire, has a roof which is quite un-English. The north front of the house, built by Lord Montague after he inherited it in 1683, has a mansard roof framing attic rooms. The structure of this has curved principals supporting the ceiling structure. Over the ceiling is a roof of single framed coupled rafters of shallow pitch. This layout resembles the roofs illustrated by Le Muet (1) (fig. 2.2). Montague was ambassador to France from 1669 to 1672 and it is recognised that the design of the house was inspired by contemporary French architecture (2). The designer of the house is unknown but we may assume that Montague employed either French craftsmen or a French architect. The stable block, however, built at about the turn of the century, has a simple pitch roof. The span is sufficient to warrant a king post truss but instead it is built with simple queen strutted principals: a traditional form presumably designed by a local craftsman.

Weston Park, Staffordshire, was designed by Lady Wilbraham who used Richards' Palladio (3) as a source. In her copy of the book, still preserved at the house, are her notes on materials and prices, showing her concern with the administration of the building work. However it would be unreasonable to assume that she was capable of structural design. The simple ridged roof of the stable block (dated 1688 on the rainwater heads) uses traditional king post trusses. The struts to the principals bear on the tie beam and the principals themselves rest on notches in the heads of the king posts. Over the wings of the house a less conventional form was adopted. A flat top roof was used to provide a low profile that would be concealed behind the parapets. Wren might have used a queen post truss to structure this shape as seen at Greenwich Hospital. At Weston, however, the carpenter provided a simple structure relying upon bending in the tie beam. The design does not even use queen struts which, given the external shape, would seem more logical. Instead a central post was used to carry the upper beam as if the carpenter wished to deviate as little as possible from the traditional king post form that he knew.

At Burley on the Hill correspondence between the owner of the house, Lord Nottingham, and his employees shows that he exercised direct control over the building operations himself (4). He was clearly in close contact with the day to day progress of the work and gave instructions about the tasks that his men should be employed upon. Colvin says that he "was to a large extent his own architect" (5) but he nevertheless drew upon outside advice for the design of a roof structure. In this case however 'modern' rather than traditional roof trusses were used (fig. 5.1) and it is probable that advice was sought through Lumley, the supplier of the drawing, from a London architect or carpenter who, at the time, would have been more likely to have had knowledge of this structural device.

At Burley the employment of Lumley and the surviving correspondence shows how knowledge of the new structural forms could have been transmitted. However, where a carpenter simply copied a form that he had seen used elsewhere there may be no record and tracing the transmission of ideas in this way is difficult. With no evidence available in the form of drawings this must remain in most cases an impossible task.

The simple reproduction of a roof form for more than one building will be demonstrated in the work of James Grove (see page 105) but he is a major figure and a number of his buildings can be identified. The passing of the knowledge of such men as Grove to their apprentices or assistants cannot be traced so easily because little or nothing is known of the careers of these minor figures. However, that such copying did occur can be demonstrated in one case where a carpenter provided a 'modern' form of roof by imitating one that he had seen built previously.

In 1719 Edward Taylor offered to build the roof for Newent Church (6):-

> "Edward Taylor Carpenter of Newent, (now) in the 85th year of his age 1719 ... proferred (sic) to build the rest of the church and they should take down the pillars. They asked him how he could do it, he told them that when he was at work in London after the fire he saw at Saint Bride's and at some other places such blades as would soon run up this building. The gentlemen desired to see a draft of it which he drew and they liked it well enough but thought they had be better shew it to somebody that understood it. Old Edward desired to send it to his old master in London who was accounted the best carpenter there."

In quoting this Colvin suggests that Taylor's 'old master' might have been Longland, the carpenter for St Brides. If so this shows the difficulty of tracing such carpenters who might have also copied these London buildings. Taylor would have been about forty years old during the building of St Bride's, too old to have been an apprentice and so have appeared in the apprentice records of the London Carpenters Company (7). There must also have been many others in a similar position.

In this case it is possible to trace the transmission of the structural idea from London to the provinces even though the structure itself no longer exists. However this might have occurred in many instances where there is no documentary evidence. Girouard has pointed out that the mobility of the landed families, spending part of their time in London and part on their country estates ensured the dissemination of the architectural fashions (8). Buckingham House in London was the model for Wotton House in Buckinghamshire. Much the same form was then used for nearby Chilton House, the design of which may have been taken directly from Buckingham House or possibly from Wotton, its earlier neighbour (9).

No comparison can be made of the roofs of these houses. Chilton has the only surviving original roof and although king post trusses were used over the front range of rooms (10) they were made too shallow and have since failed. This suggests copying of the form by a carpenter who imperfectly understood it. An interesting comparison is, however, possible between the roofs of the pavilions of Chilton and Wotton.

The pavilions at Chilton House are roofed using simple collar braced principals whilst the Wotton pavilion roofs have queen post trusses. While Chilton House seems to have relied upon locally trained craftsmen for its roof structure the design of the queen post trusses at Wotton must have come either from London or from nearby Oxford (11), the only other places where they are known to have been used at that time. It seems likely then that a sound structure was also provided for the main house at Wotton. Chilton is very much the lesser of the two houses and this comparison shows that while architectural forms may be copied, technical competence is not so easily borrowed.

Architecture was part of a cultured gentleman's education and building an expression of his wealth and taste. Competent builders like Lady Wilbraham and Lord Nottingham were capable of sharing their skills with others (12) but the extent to which building round the turn of the century was being incompetently managed (and so an indication of the general lack of technical knowledge) was described by Roger North.

North was one of the most competent amateur architects. His surviving drawings (13) show that he was a skilled draughtsman and his autobiography records (14) that he dedicated himself as a young man to acquiring this skill. He is known to have designed the Temple Gate (15), he remodelled his own house at Rougham (16) and his drawings suggest that he might well have designed houses for others. His understanding of structural carpentry is not certain but it could well have matched his other skills for his autobiography contains comments on the strength of the roof trusses at Rougham.

His considerable skills were however unusual for an amateur and his notes on architecture present a rather different picture of other amateur builders. His advice to others in these (unpublished) notes is to obtain help and advice from those with some knowledge. He then emphasises the point by describing a number of cases where the failure of builders to obtain such advice or to obtain competent craftsmen resulted in poor building or failures (17). The number of these that he cites suggests that such deficient building was not uncommon.

Professionals, Amateurs and Craftsmen

The distinction between the amateur and the professional does not say very much about the method of design or supervision employed. Today we should assume that a professional architect would provide the complete design and supervise the building operations. He might also employ assistants to work under his direction. However in the seventeenth century a builder would more often than not control the building operations through his own clerk of works or surveyor, only obtaining the general design from the architect (if he employed one at all). Even well into the eighteenth century an architect might have little contact with the building operations for some of his designs.

Supervising construction presented a difficulty because the building of a large country house was a major undertaking. It could not be simply left to the local builder. The problems of managing construction on this scale and obtaining building materials were greater than for normal building. Moreover, at a time when travel was more difficult than it is today, a professional would often not be able to provide close supervision throughout the construction of the building and this might be far better done by a clerk of works more easily able to be at the site of the building.

The drawings provided by the architect would have come nowhere near the detail of today's working drawings. Plans, elevations, sometimes sections and details of major decorative elements such as fireplaces might be provided but much would still have to be determined by the man on the site who would thus have to manage the building operations, determine the constructional details and thus perhaps carry out any structural design that was necessary.

The status of these assistants varied considerably and it is difficult today to determine their contribution. Whether or not they are to be regarded as architects may simply depend upon our present attitudes and may to an extent be a reflection of the opportunities open to them to carry out other major work of their own.

Sergeant, who acted as clerk of works at Lamport had to take a number of decisions over more than just constructional details (18). Webb's drawings seem to have been little more than a general guide and even such features as the placing of windows had to be decided during building. While Sergeant defers to Sir Justinian Isham, the owner, for the final decision, he makes clear recommendations on a number of architectural matters. We know nothing of Sergeant's other possible building activities however and he probably remained as simply a clerk of works.

John Lumley who was employed by Lord Nottingham at Burley-on-the-Hill possibly obtained the roof designs but otherwise probably contributed little to the design. He does not even seem to have been able to act completely at his own discretion over structural matters for he defers to Lord Nottingham (19):-

> "I have sent a ruff draght of ye roof. If yr Ldpp likes of it, it will be ye safest to frame it arched as drew and no sag."

It seems as if this arrangement was questioned because he later writes (20):-

> "the trussed roof will expect be stronger than to lay beams over. each other to beare ye gutter Beams, for these two trusses will take but neare ye same quantity of timber as two beams ... beams if not arched will sag."

Lumley can be considered as an architect even if he did not act in that capacity at Burley. He is known to have acted as such at Ampthill and to have built the Westmoreland Building at Emanuel College, Cambridge. His relationship to Lord Nottingham seems to have been that of a specialist consultant. At other houses architects may have been employed simply to supervise the construction.

In building Ditchley, Oxfordshire, the Earl of Litchfield obtained his initial designs from Gibbs but employed Smith of Warwick to supervise the construction. Smith was more than a minor architect and carried out a large number of commissions. In correspondence (21) with the client about the purchase of structural timber for Ditchley he refers to alternative plans which the earl had before him at the time. Smith was anxious that the earl should make his choice between them because upon it depended the timbers which were needed. The earl, who was relying upon professional advice both for the design and the construction of his house, could hardly be called an amateur architect but was nevertheless making choices between alternative designs offered to him, and so was presumably taking a fairly active interest in the building of the house. Whether or not the designs in question at the time came from Gibbs or Smith is not clear from the letters. However Smith was certainly capable of making such designs and could have made a major contribution to the design of this house (22).

The problem of the credit that must be given to the executive architect became the subject of public controversy in the eighteenth century over Brettingham's contribution to the design of Holkham Hall. Brettingham's son claimed that the designs of Kent "were departed from in every shape" and believed that "he that had conducted the laying of every Brick from the foundation to the roof thought he had a better claim to the Reputation of the Fabrick than he who only gave the designs, but never once attended any part of the execution of the work" (23). This defence of his father, occasioned because the latter had claimed credit for the design of the house, (24) raises the question of how much of the detailed design Kent may have supplied.

The status of Burlington's assistants is clear even if that of Burlington himself is not. It is not certain whether he is to be regarded as an amateur or a professional. As a member of the aristocracy he certainly did not practice architecture as a 'trade' but he employed assistants just as a professional would do today and the scale of his building operations was as great as that of some contemporary professionals (25). The distinction is not important except in that he would have left the mechanics of building to his assistants who later became architects in their own right. Kent and Campbell were already aspiring architects when they attracted Burlington's patronage. More important as providers of constructional details would have been Garrett and Flitcroft, the latter raised through Burlington's interest from the trade of joiner, eventually to become an architect.

The purpose of this discussion is to point out that if the status of these 'assistants' is difficult to determine then so is the possible source of the structural details used in the buildings with which they are associated. The picture varies from building to building. At Lamport, Webb's 'structural' drawing survives and so it should be possible to distinguish a structure provided by Sergeant (26). At buildings like Ditchley where there was a competent supervising architect it may be impossible to separate his work from that of the primary designer. Elsewhere one may be able to identify the designer of a structure but there is still the problem of tracing the source of the structural ideas.

At Burley, Lord Nottingham received sound advice from Lumley but where did the latter, a mason by trade (27), obtain his ideas? He could have acted as a broker seeking advice for the building on Lord Nottingham's behalf. Alternatively, he might have been practising as an architect in his own right and have carried out sufficient work to have acquired some structural knowledge. He was forty nine at the time of writing these letters and in view of the fact that he later built the Westmorland building at Emmanuel College, Cambridge, this latter explanation seems more likely. However this still does not account for the source of his knowledge although it is tempting to suppose that it was through contacts in London where he is known to have been during his earlier career.

William Townsend at Oxford worked for more than one amateur architect. He built the library at Christ Church for Dr Clerk and All Saints Church for Henry Aldrich. For the library roof he used king post trusses carrying close spaced purlins. The ceiling of the library is lower at either end than in the centre while the roof remains at the same level throughout. The ceiling cannot therefore be carried throughout by the tie beams of the trusses and is supported at the ends on the lower chord of queen post trusses put in for just this purpose. Massive queen post trusses were also used for the roof of All Saints Church, also with close spaced purlins. These buildings were built at about the same time that Townsend was also building All Souls to Hawksmoor's designs. Townsend had earlier worked for Hawksmoor at Blenheim and then built the Clarendon Building to his designs. Thus Hawksmoor must be the source of the structural ideas at Christ Church and All Souls, either directly or indirectly. The king post roofs at Christ Church could be explained by the simple copying of Hawksmoor's trusses for All Souls College. There is some evidence, though not conclusive, that queen post trusses were used at Blenheim (28) and Townsend may have seen these and used them as a model for his own queen post trusses. The link is uncertain (29) but it seems likely that Townsend at least discussed the design of his own structures with Hawksmoor and even the possibility that the latter provided drawings cannot be discounted.

Although Brettingham was responsible for the execution of the work at Holkham his son may have made exaggerated claims. The roof structures of the house use king post trusses. Over the hall the trusses have not only to span almost fifty feet but have also to carry the ornate plaster ceiling. To achieve this they have secondary posts and two pairs of inclined struts. It is difficult to see how Brettingham, originally apprenticed as a bricklayer to his father and with a provincial building practice, could have acquired the knowledge to build such a roof. Traditional roof forms were still in common use at the time as can be seen in the roof of the barn of a farm on the Holkham estate and which is contemporary with the building of the Hall (30). Moreover, Brettingham himself is not known to have built any major structures before. It seems more likely that Kent obtained a roof design from Flitcroft by then working for him as carpenter to the Office of Works.

Professional architects

The extent to which a professional architect relied upon assistants or craftsmen to design the structural carpentry of his buildings depended upon his own knowledge of these practical issues. Few architects approached the structural competence of Wren. Of those that did, their sources varied. Contemporary work that might be expected to show a knowledge of truss forms and which might even have a resemblance to Wren's structures, is that of his friend Robert Hooke. Unfortunately there is little of Hooke's architectural work left and no drawings which show structural details. However we know from his writings that he was concerned with structural matters. He wrote more theoretical works on structures than Wren, examining the stability of arches (31) as well as providing the law of elasticity which now bears his name. Entries in his diary also show that he concerned himself actively with the process of construction. There are several references to meetings with his carpenters (32) and apart from the work that he did for others, he built a timber framed observatory at his own house.

Robert Hooke

Only two of Hooke's buildings survive, Willen Church, Buckinghamshire, and Ragley Hall, Warwickshire. Willen Church is built using king post trusses. These are to be expected since Hooke would presumably have been as familiar as Wren with Baldi's Mechanics and would thus have known of this form. The truss is unusual however in having additional, and apparently unnecessary, timbers (fig. 5.2). It is possible that these were added by the carpenter who, working at a distance from London, must have been left very much to his own devices (33). If he was not familiar with the king post truss he may have been unhappy with Hooke's design and wanted the reassurance of these extra members.

Hooke used close spaced purlins in this design thus following the Italian pattern of construction adopted by Inigo Jones and used in some of Wren's buildings. However Hooke omitted the lower joggles on the king posts of the trusses. Instead the struts of the roof trusses are tenoned into the sides of the posts.

The roof at Ragley Hall has been very much altered since it was first built. The house has a basically square plan and the original roofing appears to have been achieved by using five parallel ridges. The ends of these roofs were closed by a 'lean to' structure so that there are similar slopes on each face of the building. These slopes are set between the higher roofs of the four corner pavilions.

Nineteenth century alterations involved adding a range of attic rooms across the centre of the roof at right angles to the original ridges. This change necessitated the removal and alteration of much of Hooke's structure although many original timbers remain and some reconstruction can be attempted.

The corner pavilions which survive intact are each framed with a pair of tall queen post trusses with X bracing between the posts. These structures thus resemble that of St Benet's, Paul's Wharf, and the truss shown in Clayton's drawing of All Hallows. The relative dates for the building of these roofs are uncertain (34) but it is possible that Hooke consulted Wren or used these chruch roofs as a model.

The three internal ridges, the part most affected by later alterations, appear to have used king post trusses and are thus unremarkable. In any case it is now difficult to establish how much of this part of the roof is original without a more detailed examination of the structure. The outer pair of ridges, however, have been less altered and use a queen post design which appears to have been peculiar to Hooke at that time (fig. 5.3). On one side of the roof these are complete. On the other side there have been alterations but the remaining timbers show that the arrangement was the same on both sides. In re-roofing, original purlins have been removed but the form of the roof can easily be reconstructed.

The principle of Hooke's queen post truss is simple. In order to clasp the top of the queen posts the principal rafters are diminished at this point.

The joggles of the queen posts thus bear against the resulting shoulder and are held in place by the straining beams strutting across between the heads of the two posts. The resulting form has the general appearance of the queen post structures illustrated by Palladio and Serlio and it is possible that Hooke was attempting to reproduce their form. However these were not drawn to a large enough scale to show their construction and therefore the details of the Ragley trusses must be Hooke's own design.

Thomas Archer

Archer made some study drawings for the roof structure of St Johns, Smith Square (35). Unfortunately the original roof of this church perished in the fire of 1742 only a few years after it was built and there is no record of this structure. It seems unlikely however that it resembled any of Archer's drawings. These show a number of alternative structures for an aisled church, all of curiously flimsy looking design (fig. 5.4). His intention seems to have been to provide room for a high barrel vaulted ceiling over the nave. Although the timbers are disposed vaguely to resemble king post trusses at the crown of the roof, the overall designs are poor and suggest that Archer's understanding of structural carpentry was weak.

Archer's Church of St Philip, Birmingham (now the Cathedral) has only a small spanning roof. It is an aisled church and the design follows the form of Wren's aisled churches in having the roof of the nave and the aisles separated. At St Philip's the separation is achieved by carrying a wall on the aisle columns and it is this wall which supports the roof trusses. These are simple king post trusses and, while they show that either Archer or the carpenter he employed for this building was aware of this structural form, the span is sufficiently small to require nothing more than the simplest truss arrangement. This roof therefore throws little light on Archer's possible competence as a structural designer and does nothing to change the impression given by his poor drawings for St John's.

In contrast with these two roofs that of St Paul's, Deptford is ambitious in its span and layout and is well engineered. The church with its square cross-shaped floor plan (fig. 5.5) and roof must have presented something of a structural problem. Trusses span some 44ft across the nave but because of the cross-shaped plan, those at the centre of the church have no walls to land upon. Instead they must be carried by other trusses spanning the transepts over the line of the columns. This pair of trusses may appear to be the most heavily stressed, but their deformations and the consequent opening of their joints suggests that they are assisted by the columns below.

The basic layout of this structure has close spaced purlins resting on principal rafters. However only every other one of these rafters forms part of a truss. The trusses are spaced at about 15ft and as well as carrying the close spaced purlins they also support heavy purlins which in turn carry the intermediate rafters (fig. 5.6). The trusses are of the king post type with secondary posts and two pairs of inclined struts. The tie beams are formed of several pieces of timber as one might expect in a roof of this span. However they are not of two pieces scarfed near the centre, as was common at this time, but comprise a number of pieces joined side by side (36). This fairly sophisticated layout appears to be similar to that provided for the roof of Christ Church, Spitalfields, although the latter did not have the complication presented by the cross shaped plan. One thus has to explain not only the difference between the well designed structure at St Paul's and the amateurish drawings of Archer for St John's, but also the similarity between it and Christ Church.

No structural drawings survive for Christ Church, Spitalfields, although there are otherwise quite a large collection for this church (37). If a drawing of the roof structure was in fact made by Hawksmoor for the church then it probably went to the carpenter, Grove.

The probability is that Grove provided Archer with his design. As the carpenter for both churches he provided the construction of the roofs but we cannot be certain where the design originated. The two buildings are more or less contemporary and like Christ Church, there are architectural drawings for St Paul's (38). One possibility is that Hawksmoor provided a design for the roof of his church which Grove then copied for Archer's. The other is that Grove himself provided the design for both these churches. He certainly had the experience to have designed such a roof and there are features of the structure, the design of the tie beam and the use of secondary principals for example, that are not found elsewhere in Hawksmoor's structures. Moreover Grove had in any case the problem of carrying the ends of the trusses over the transepts at St Paul's which required some structural invention.

The first assumption involves the kind of working arrangement which would be considered normal today: the designer providing the detailed instructions for the carpenter. The alternative, with the designer of the building relying upon the carpenter to provide a roof on a 'design and build' basis would not have been uncommon at the time. Although a competent designer himself, Hawksmoor would probably have had the confidence to use Grove in this way even for major spans, having used him on other major roofs. Indeed if Grove was responsible for the design of Christ Church roof, then it was probably from Hawksmoor that he acquired the skill in the first place. That Hawksmoor may have used this arrangement on occasions is suggested by his note on the St George's drawing (quoted p.83). Whatever Grove's relation with Hawksmoor on this occasion he was to Archer both 'consulting engineer' and carpentry contractor.

Flitcroft

At any time when a technology is developing the obvious and commonly used method of learning about the new technique is to study the work of the leaders in the field - those who are developing or have used the new methods. At the beginning of the eighteenth century an architect designing his own trussed roofs, but who had not travelled to Italy, could only draw upon the designs of recently built English roofs if he wished to use built examples as a model. Of the architects of this period Flitcroft seems to have worked in this way.

A joiner by trade, Flitcroft was taken into the service of Lord Burlington as a draughtsman and architectural assistant. Although originally in Burlington's employment as a journeyman carpenter, he may not have been employed on structural work and in any case it is unlikely that his apprenticeship as a joiner provided any training in structural design. Much more probable is that he acquired his knowledge of structures in his later studies of architecture. He was employed to draw the plates for Kent's Designs of Inigo Jones and used Webb's original drawings for Whitehall Palace, which as noted earlier have simple king post trusses. Also, as has been argued earlier, his drawing for the Banqueting House roof was probably taken from a drawing for the building. These drawings would have introduced him to the design of structures but he did not simply rely upon the drawings of others for his knowledge of structural forms.

A bound volume of his own drawings is preserved in the British Museum (39). Dedicated to the Duke of Cumberland, this largely comprises studies of the five orders but included in the collection is a drawing of the roof structure of the Sheldonian Theatre. Although the collection is undated it may reasonably be assumed that this drawing is earlier than, and the basis, for, his drawing of the roof for Parentalia (fig. 3.12) (40). Flitcroft clearly examined the roof himself and may have done so early in his career. The drawings are the kind that might be made in studying architecture.

The care with which he drew these roof structures shows an interest in their construction that one would perhaps expect from a trained craftsman. The same care can be seen in his own designs. His roof of Chiswick House for Burlington had the principal rafters notched out to receive the posts (41). This is an unusual (though not unique) detail and has the mark of a joiner rather than of a carpenter. He seems to have used the structure of Inigo Jones' St Paul's, Covent Garden, as a model for his original design for St Giles in the Fields (fig. 5.7). His designs for this church include a section with the jointing of the timbers carefully shown and accompanied by a detailed description of the roof timbers. Although the design is for an aisled church, necessitating a slightly different structural arrangement from St Paul's, the layout of timbers over the nave is very similar and is almost certainly an adaptation of Jones' structure. It bears little or no resemblance to the structures of other churches built at the time. In the event, however, the roof structure used in the building does not have this form. Instead a more satisfactory layout resembling Gibbs' trusses for St Peter's Vere or St Martin's in the Fields was built, although using common rafters rather than close purlins to carry the roofing. Flitcroft seems thus to have looked at more than one structure before deciding upon a final design for this building.

Gibbs

It has been shown that the king post roofs in this country derived essentially from the earlier use of the structure in Italy, but if the idea could be imported from there once, then it could easily be brought over again. In fact later imports would have been easier as it became more common for English architects to study there. An eighteenth century architect need not have acquired his knowledge of the form from earlier English examples but might well have copied Italian models directly. Gibbs, who received his architectural training in Italy, clearly did exactly this. His roof structures all employ the king post truss or derivatives of it and he also used close spaced purlins rather than rafters to carry the roof covering in the same way that Inigo Jones had done.

Drawings by Gibbs survive in both his Book of Architecture (42) and in the collection of drawings at the Ashmolean (although many of the latter are originals for the plates of the book). However these are not necessarily drawings of the structures as they were built. Gibbs shows how this may be so in his preface to Biblioteca Radcliffiana (43). Here he is careful to note that the drawings do show the completed structure and that this differs in some respects from the original designs because of changes that were made during construction.

That such changes took place can be more clearly seen in the structure of St Peter's Vere. Comparing the drawings with the completed church shows a number of differences. The drawings show a king post truss with puncheons while the roof truss as built has secondary posts and a second pair of inclined struts. The tie beam is butted against the columns and not carried over them as in the drawings and the roof over the aisles does not have struts to the rafters (figs. 5.8 & 5.9).

Differences between these design drawings and the final structure are understandable; the drawings are only project drawings and not working drawings and one might expect the same kind of differences in buildings today. Less easy to understand is the difference between the structure and its description in the contract for the building (44). This says that:-

> "Carpenters work to be done as followeth viz:- The Bressummers and girders for the galleries to be 12" x 10" and 8 columns of oak to go up to the ceiling to support the roof. All other timber in the galleries to be in proportion. The roof to be framed in yellow fir. The beams to be 12" x 9", the principal rafters 10" x 8", the purlongs 10" x 8", the small rafters 4" x 3" and the roof to be covered by good blue slate ..."

The description and the drawing suggest that the intention was to use a purlin and rafter roof while the roof as built has close spaced purlins. Close spaced purlins are shown in the drawing of All Saints, Derby, (now the cathedral) in Gibbs' Book of Architecture (45). The roof was indeed built in this way but there is still a discrepancy between apparent design intentions and the final construction. What appears to be a design drawing for the church survives (46). This shows the form of the trusses as built but quite clearly shows heavy purlins rather than close spaced light purlins (fig. 5.10 a & b).

As noted above, Gibbs himself admitted that changes might occur. What is curious is not so much the change between design and construction but that Gibbs should have considered using common rafters at any stage - still more that such an intention should have been taken as far as a contract. All the examples of Gibbs' buildings examined use close spaced purlins. This was the form apparently in use in Italy and so would have been the arrangement that Gibbs would have learnt. It is possible that he may have considered experimenting with the 'English' arrangement or have employed an assistant who used it.

Gibbs did not stick rigidly to one structural layout throughout his designs. A feature of St Peter's, Vere, as shown in the drawings of the church, is the use of a continuous pair of principal rafters over both nave and aisles into which all the other timbers are framed. At St Martin in the Fields (fig. 5.11) and at Derby however the columns carry separate, complete king post trusses over the nave. Laid over the top of these are the long rafters which carry the close purlins to support the roof covering. While these form part of the 'lean to' framing over the aisles they are not part of the main nave truss. This arrangement is unique to Gibbs (47). It would clearly have made the structure easier to erect than the design used at St Peter's, Vere.

Gibbs seems to have paid close attention to the structural carpentry of his buildings even at the project design stage and in construction to have exercised close control over carpentry details.

His largest projected roof span, though not actually built, is his early design for St Martin in the Fields. This was to have a dome externally with a flat ceiling inside the church. Between the two a king post roof was to carry dome and ceiling (fig. 5.12). The span of this structure approaches 70ft and would have been a major undertaking, not only exceeding the span of Hawksmoor's complex trusses for St Alphege, Greenwich, but also having to carry much greater loads. A drawing in the Ashmolean collection shows that Gibbs' intention was to have a radial arrangement of structural timbers with all the load carried by a single main truss. Gibb seems to have at least recognised the seriousness of this problem because the section illustrated in his Book of Architecture shows quite clearly the use of metal strapping.

Whether Gibbs could have successfully built a roof for this span and loading is doubtful when one looks at the biggest truss that he did build.

The longest clear span actually built by Gibbs is the truss in the portico of the completed design for the same church. A simple arrangement would have been for purlins to span from the wall of the tower to the pediment in order to carry common rafters. This was a common arrangement for the portico of country houses of the time. Instead of this Gibbs chose to retain the close spaced purlin layout used in the rest of the church. To keep the purlins to a manageable size over the 25ft span, some intermediate support was needed and this was provided by spanning a massive truss between the two side columns of the portico. The truss design used, although a development of the king post, is unusually complex (fig. 513). Additional braces were added between the foot of the king post and the feet of the secondary posts to resist the inward thrust of the outer pair of struts. Two pairs of secondary posts were used and a similar but inclined braced strut between the head of these posts. At the feet of the principal rafters metal strapping is used to transmit the outward thrust of the principals to the tie beam.

It is not just in the overall layout of timbers that this truss is exceptional. The heads of the king post and the inner pair of secondary posts (these only can be easily inspected) have been cut through in order to have wedges let in (fig. 5.14). Thus the joggles at the head of the post could be tightened against the ends of the struts during construction. The effect of this would be that as the roof load came on there would be no initial sagging of the truss as these joints took up load. A further precaution was the cutting of notches in the tie beam for the outer pair of braces to bear against (fig. 5.15) and it seems as if both the layout and detailing of the truss were designed to avoid placing too much reliance on the mortice and tenon joints at the top and bottom of each post.

In spite of these precautions the roof failed and by the late 1780's was in need of repair. Excessive deflection of the portico ceiling, said to have been caused by shrinkage of the timbers, was noticed and James King was called in to carry out repairs (48). Inspection of the roof today suggests that the deflection was the result of failure of the jointed tie beam. Because of the long span this member was formed in two lengths scarfed together at the centre. This is a curious joint. The faces of the joint are vertical and the two pieces of timber are brought together in such a way that they clasp the foot of the king post (fig. 5.16). However the detail did not prove effective and the joint has opened up. King's repair consisted of inserting two king post trusses either side of Gibbs' king post but spanning at right angles to his truss, ie. from the tower to the pediment. Metal straps from these trusses support the centre of Gibbs' tie beam.

Just as the influence of Wren's structural ideas can be seen in the work of later designers it would be pleasing to be able to trace Gibbs' influence in the same way. This is less easy to do at a time when knowledge of the king post truss was already fairly widely spread from its earlier introduction but there is one building where it may be inferred. This is Grosvenor Chapel, reputed to be the design of Benjamin Timbrell who was one of those who undertook its building in 1730 (49). Timbrell was in partnership with Thomas Phillips when they contracted to build St Peter's, Vere (50). Grosvenor

Chapel has a roof differing from St Peter's in having the tie beams above the heads of the columns. However the roof is framed with close spaced purlins. This last detail may suggest Gibbs' influence but the connection is tenuous.

For both the promoted craftsmen and the trained architects, little is known about the nature of their training. The buildings discussed so far have been selected to demonstrate possible learning mechanisms relying upon direct contact between architects and craftsmen (in any combination) working together on the same job. However it would be quite wrong to draw any general conclusion from these examples about the extent to which structural knowledge was transmitted. For example, in spite of his connections with the Office of Works and the Carpenters Comapny, Isaac Ware (51) seems to have remained ignorant of the advanced techniques of roof carpentry of his day (52).

A number of architects, like John James for example, began their careers in the Office of Works where they might be expected to have received some structural training. If so one might expect such training to be conservative, limited to the teaching of proven methods, and that this would result in a standard approach to subsequent problems. However, James' roof for St George's, Hanover Square, denies this expectation. King post trusses (with puncheons) carried by the columns alternate with a king post truss with raised tie beam (and secondary posts) over the crown of the vault. These latter trusses span directly between the walls. The close spaced purlins could not span as far as the aisle column spacing (unless made inordinately large) so had to be carried on an intermediate principal rafter. James did not carry this on large purlins as Grove had done at Deptford and Spitalfields. Nor did he support his intermediate trusses on longitudinal framing as Gibbs did. Both are satisfactory and structurally simpler solutions than the one James chose.

He was possibly unaware of Grove's design, but Gibbs' London churches of St Peter's and St Martin's were contemporary with St George's and we must either assume James was ignorant of their structures as well or else preferred to use his own designs. In either case he certainly had an adequate working knowledge of roof trusses and this unusual structural arrangement hardly suggests a conservative attitude (53).

The master carpenters of the period seem to have conducted their business through the coffee houses. Robert Hooke records a number of occasions on which he visited coffee houses to meet his carpenter to discuss the buildings he was working on (54). George Dance Sr conducted his duties as Clerk of Works to the City of London from a coffee house (55). No doubt the convivial atmosphere of such establishments encouraged the exchange of ideas. One may assume that there were exchanges of ideas between members of the same trade or the same profession but such exchanges are rarely recorded even in more recent times (56). The carpenter Grove provided a rare documental example when he recorded both his prices and those of John James for their tenders for carpentry work at St Alphege (57). Certainly with the volume of work at the time there must have been a lively exchange among the London carpenters.

Carpenters working in the provinces would not be so privileged. The spread of knowledge and ideas to these areas would be dependent upon London trained craftsmen moving away and establishing businesses elsewhere, contact with craftsmen or architects engaged upon major work in the provinces or perhaps less direct and less reliable methods of communication. In the late seventeenth and the first third of the eighteenth century a carpenter or architect would only have learnt of the new forms by direct contact with others who knew of them or by seeing them for himself. Eventually the text books were to provide an alternative channel of communication.

Footnotes - Chapter 5

1. Le Muet (1647).

2. For a description and history of Boughton see Lees-Milne (1970).

3. ie Richards (1668).

4. Finch (1901) reproduces extracts from his correspondence

5. Colvin (1978) p.271, fnt.1.

6. Quoted by Colvin (1978) p.811

7. Guildhall Record Office.

8. Girouard (1978)

9. For a discussion of the connection between Wotton and Buckingham House see Lees-Milne (1970), p.15.

10. The roofing arrangement is curious. The structure of the house has a spine wall carrying floors and roof. The roof has multiple pitches. Over the front rooms the coupled rafters of these are carried on plates supported on very shallow king post trusses. Over the back rooms more use seems to have been made of internal 'cross' walls to support the roof.

11. There is no evidence at present of the flat topped queen post truss being widely known outside these two cities - but see Chapter 8.

12. Lady Wilbraham gave advice on the building of Woodhay and Lord Nottingham gave his brother advice on the building of his house at Albury, Surrey.

13. BM. Add. 23005.

14. Jessop (1887).

15. Colvin (1978). p.597.

16. Jessop (1887).

17. BM. Add. 32540. There is the possibility that North may have intended publishing this because the margin notes (presumably to be left out in a published version) identify the builders who had suffered the failures that he describes.

18. The correspondence is preserved in the Northamptonshire Record Office.

19. Finch (1901) p.64. The letter is dated 3.v.1705.

20. Finch (1901) p.65. No date is given.

21. Oxfordshire County Record Office

22. Smith also carried out work on All Saints, Derby, and the structure of this would have taught him much, even assuming that he had little previous structural knowledge.

23. Quoted by Colvin (1978) p.135.

24. Brettingham (1761)

25. We may perhaps compare the work of Burlington with that of Archer, a professional architect. Colvin (1978) lists no more work by the latter but one may also assume that Burlington would not have undertaken work of a minor nature whilst a professional architect might well have carried out many jobs for which there is now no record. The diary of Robert Hooke, for example, refers to many jobs which now cannot be identified.

26. Drawing at Northamptonshire County Record Office. I have not been able to examine the structure itself which is concealed by a ceiling.

27. Records of his acceptance into the Masons' Company are in the Guildhall Record Office.

28. In the roof over the entrance hall is a king post truss with secondary posts and 'X' bracing between these. Behind this is a lower roof, much altered, but the surviving timbers suggest that it originally included a queen post truss.

29. I have no documentary evidence to support a connection between the two men over this particular building.

30. I am indebted to Dr W O Hassall for this information and for drawing my attention to the farm buildings

31. Manuscript at the Guildhall Record Office

32. Robinson and Adams (1935)

33. There are only two references to visits to Willen in the diary

34. The building dates for Ragley are given by Colvin (1978) as 1679-83 and for St Benets as 1677-83. It is therefore possible to imagine the two men discussing one or toher of the buildings and ideas for the structure being taken from one to the other. Given Wren's use of the queen post elsewhere, he is the more likely originator.

35. Gough Maps 23

36. Unfortunately it has not been possible to see exactly how the tie beams were formed because they are now obscured by a timber floor in the attic.

37. A measured drawing of the original roof was made by Mayhew (1914). Hawksmoor's drawings are in Kings Maps xxiii, a-x and xxvii, 50, a-g.

38. Kings Maps xviii, 18, e-i.

39. BM. Kings Ms, 283

40. Wren (1750)

41. This roof has recently been replaced. Photographs of the original structure are in the Ministry of Works (D of E) Photographic Collection

42. Gibbs (1728)

43. Gibbs (1747)

44. BM. Add. 18238, f.371

45. Gibbs (1728)

46. Ashmolean Museum - Gibbs Collection II, 39.

47. All other aisled churches of the period, which have been seen so far, have continuous principal rafters from apex to eaves which form part of the king post truss above the nave. In some cases the tie beam may be raised above the head of the column posts, in others joined into the sides of the posts.

48. Colvin (1978) p.495.

49. Colvin (1978) p.828.

50. BM. Add. 18238 ff.37-39.

51. Ware held several posts in the Office of Works and was warden of the Carpenters' Company in 1761-2. Colvin (1978) pp. 844-5.

52. The lack of knowledge of king post truss design shown in his Complete Body of Architecture will be discussed in Chapter 6.

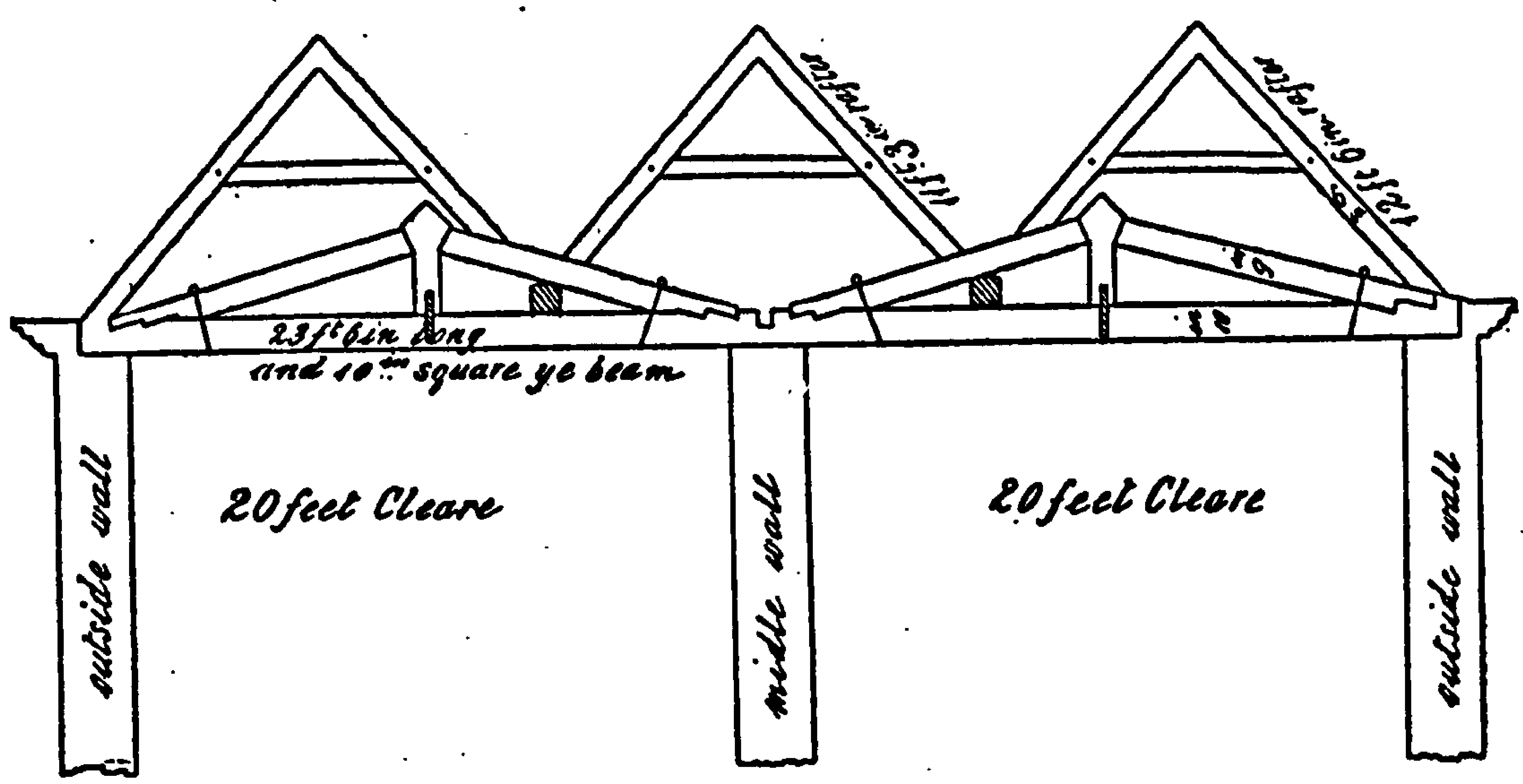
53. This is the only example that I have found of a combination of two different trusses in an English building of the period.

54. Robinson and Adams (1935).

55. Dictionary of National Biography

56. This problem is mentioned in relation to iron structures of the nineteenth century by Rosenberg and Vincent (1978) p.46.

57. BM. Add. 30092. This is dated 1713.



FROM THE ORIGINAL MSS. AT BURLEY-ON-THE-HILL

Fig. 5.1

Burley on the Hill
Drawing supplied by
Lumley.

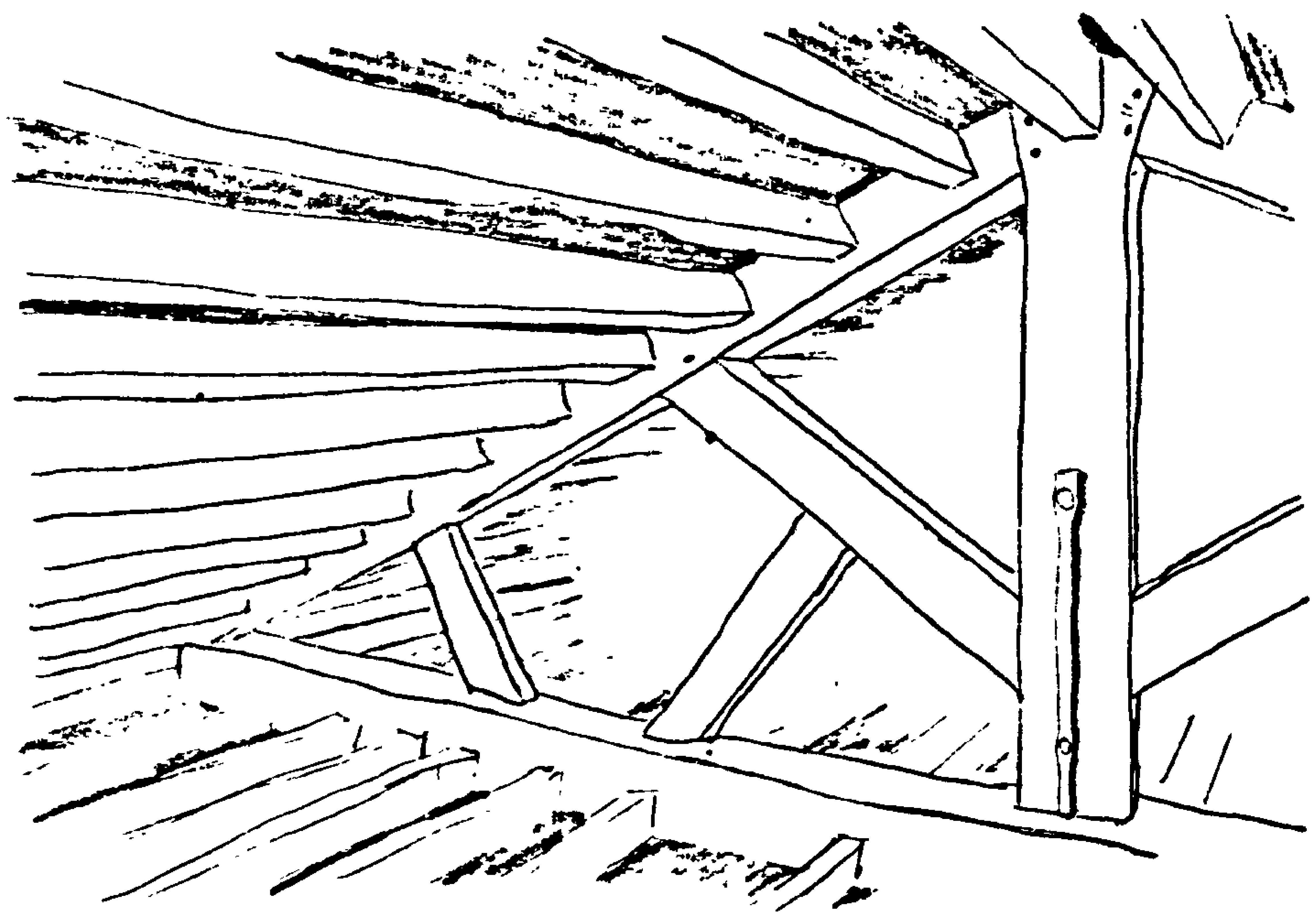


Fig. 5.2

Willen Church - Robert Hooke

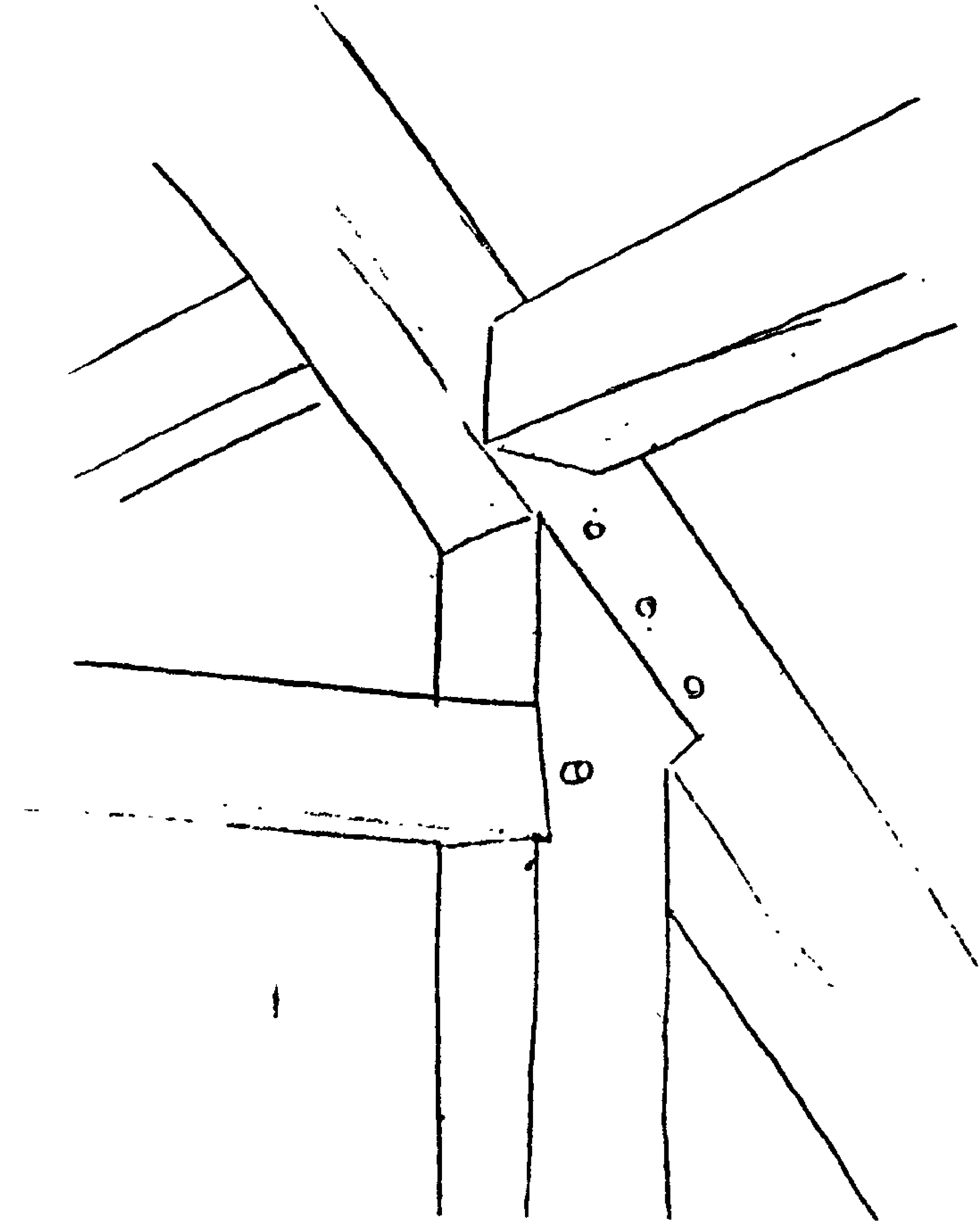


Fig. 5.3

Ragley Hall - Robert Hooke
Details at the head of queen post. Note the reduction in size of the principal rafter to receive the head of the post. Note also that the purlins are fixed to be 'upright' - an unusual detail.

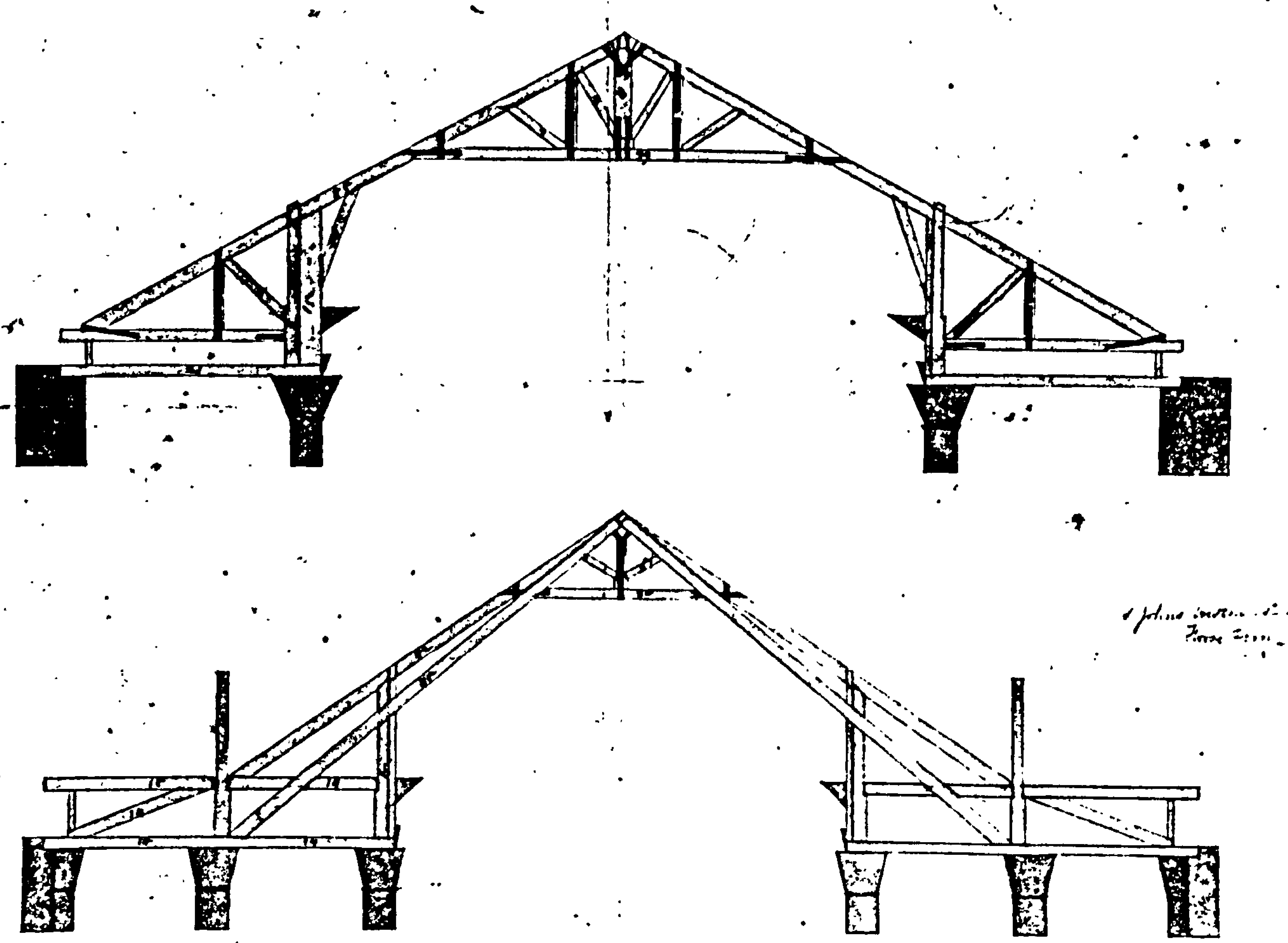


Fig. 5.4

Study for St. James Smith Square.
One of two drawings by Archer
showing alternative structures for
St. James Smith Square (Gough Maps).
There is no record of the structure
as built.

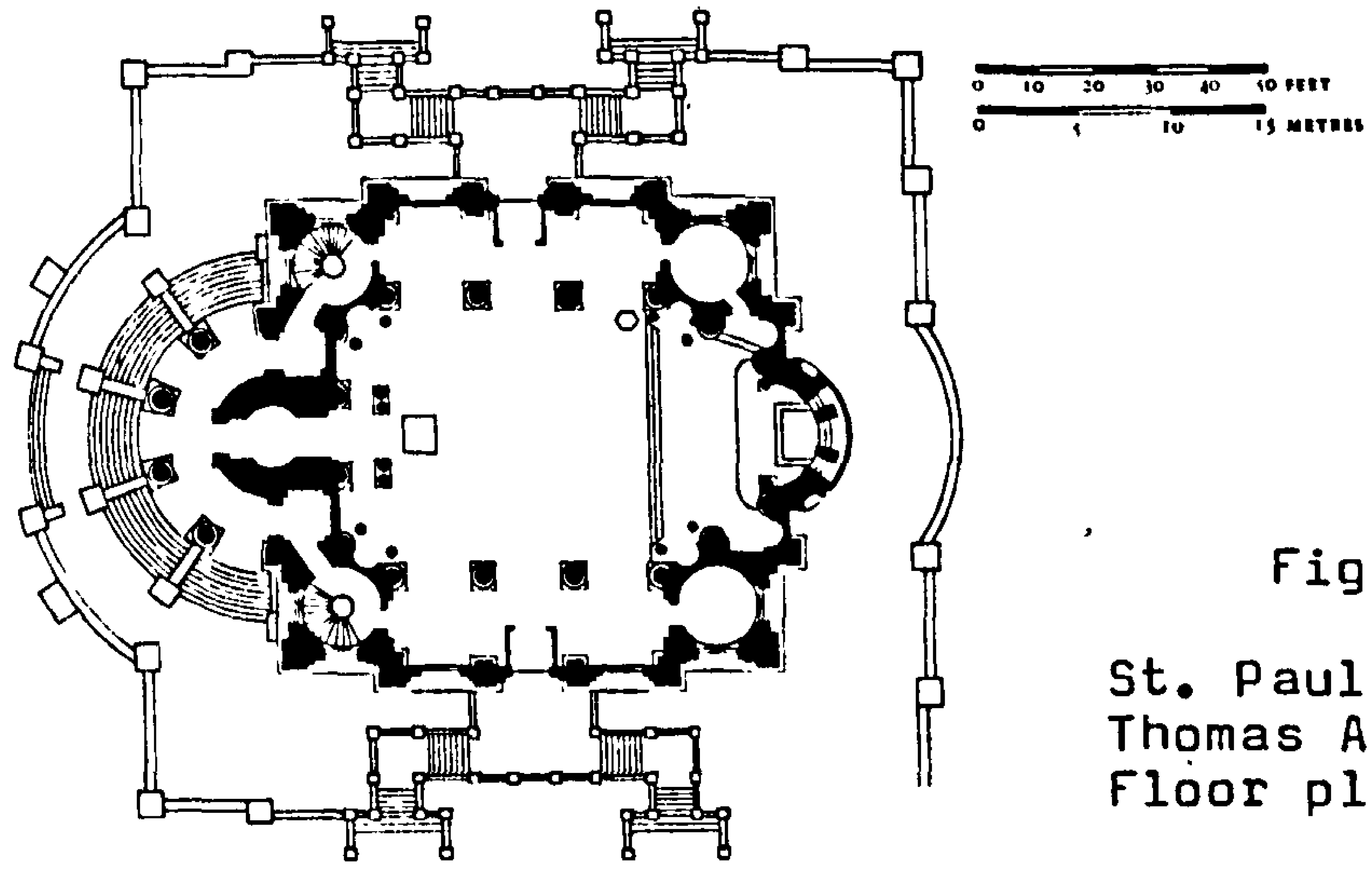


Fig. 5.5

St. Paul's, Deptford - Thomas Archer. Floor plan.

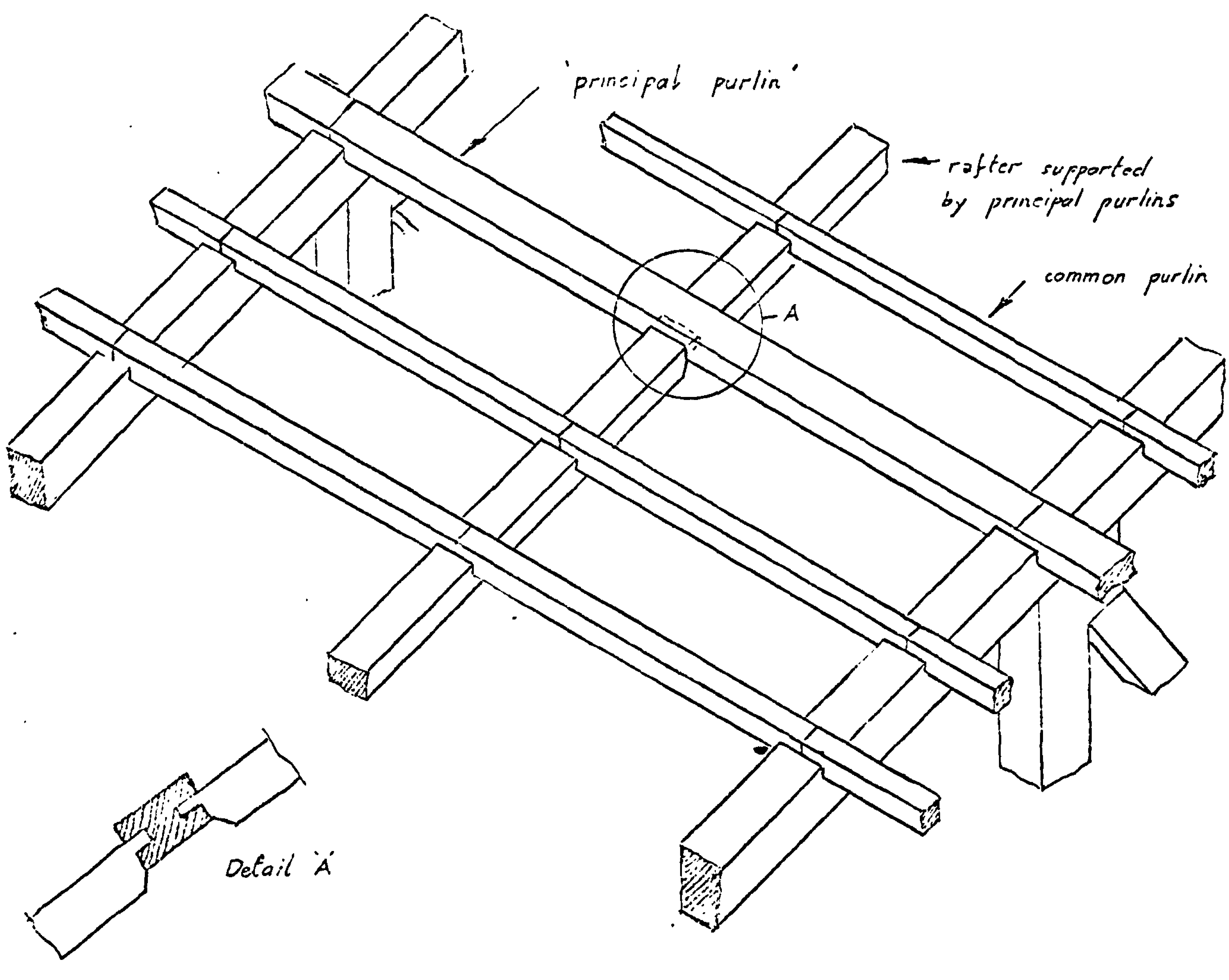


Fig. 5.6

St. Paul's, Deptford - Archer
Diagram of layout of roof timbers

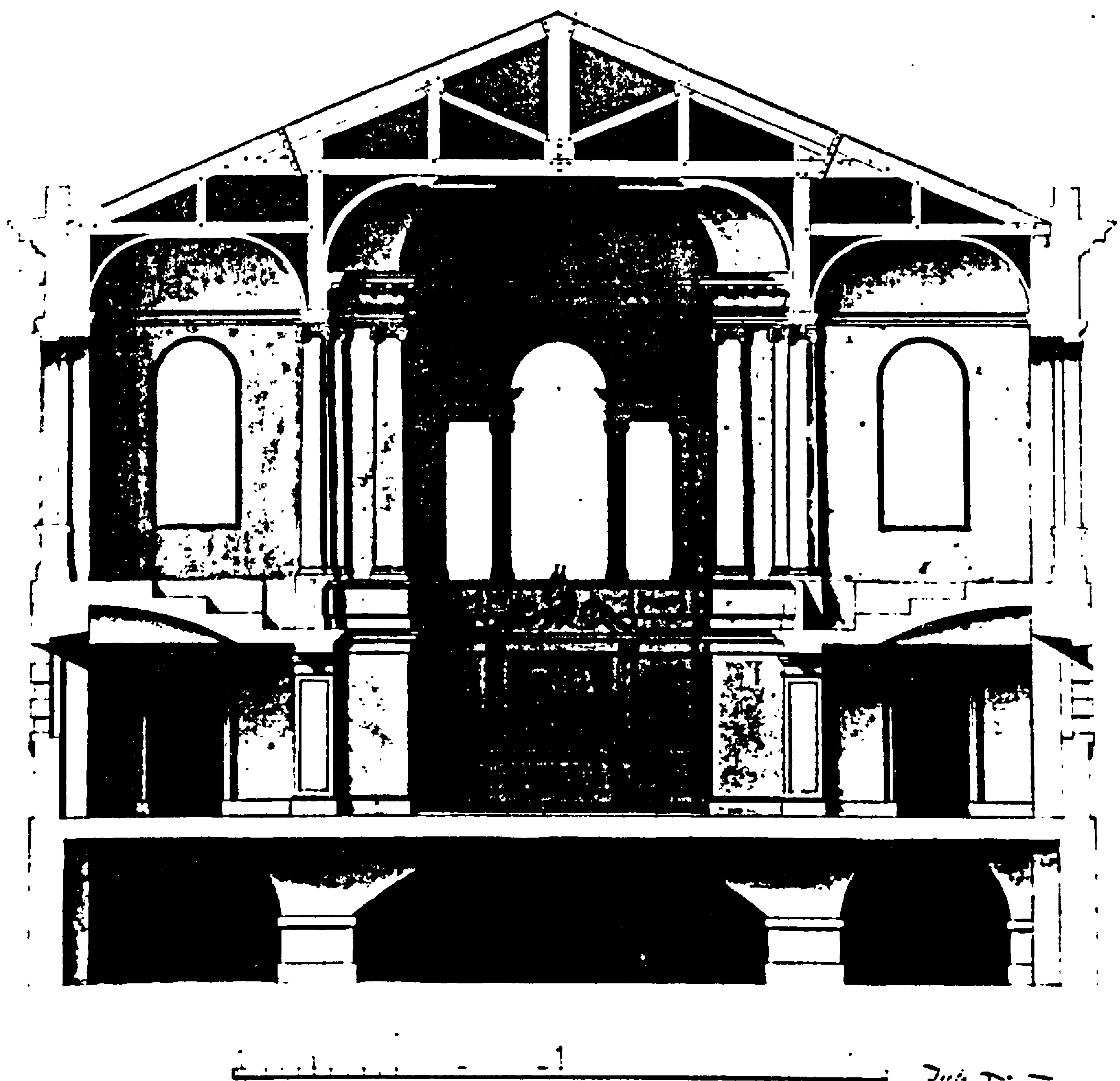


Fig. 5.7

Project drawing by Flitcroft for St. Giles in the Fields (RIBA drgs. collection). An accompanying sheet gives scantlings of timbers. However this is not as the structure was built.

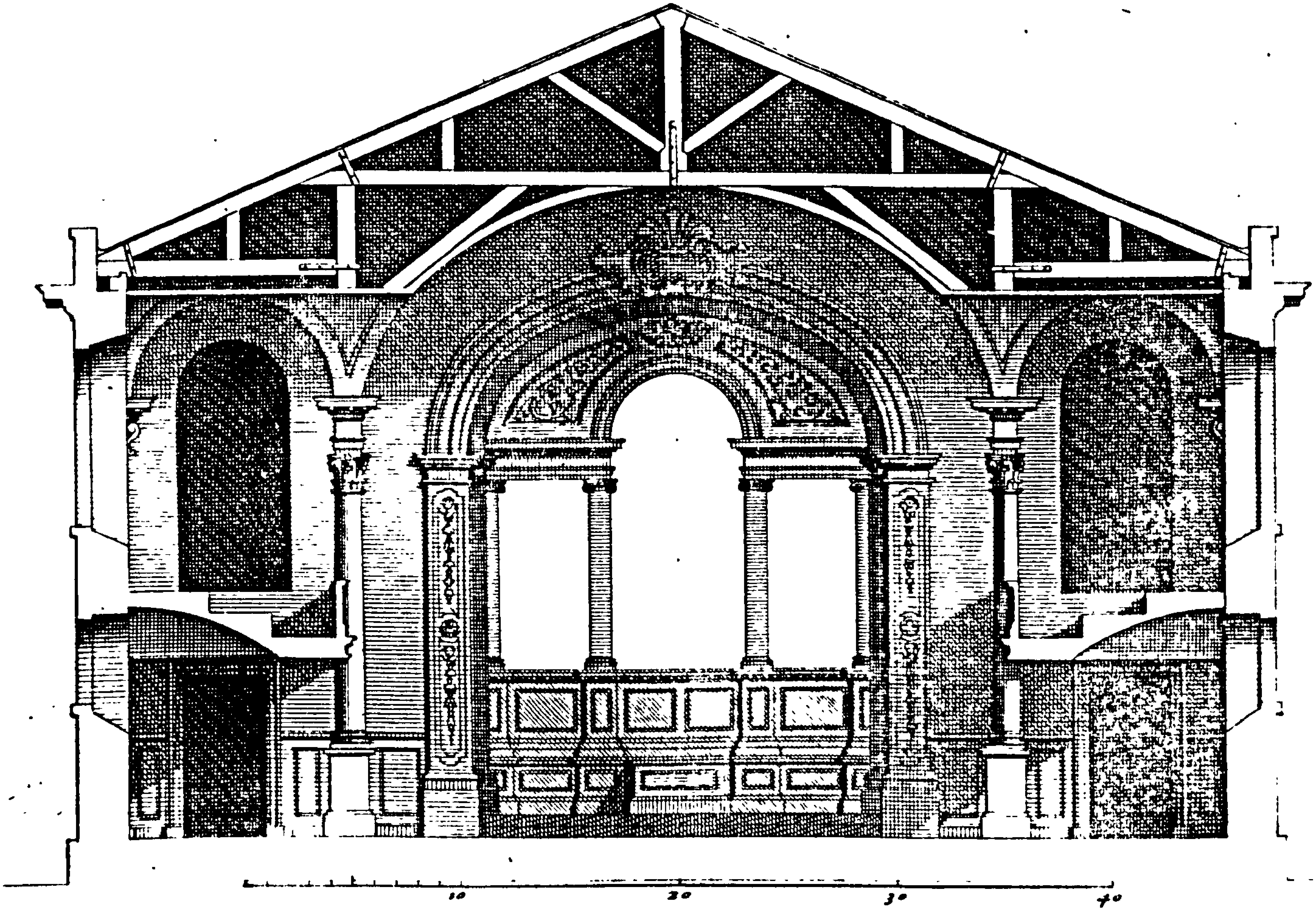


Fig. 5.8

James Gibbs Book of Architecture
St. Peter's Vere St. - also
called Oxford Chapel or
Marylebone Chapel.

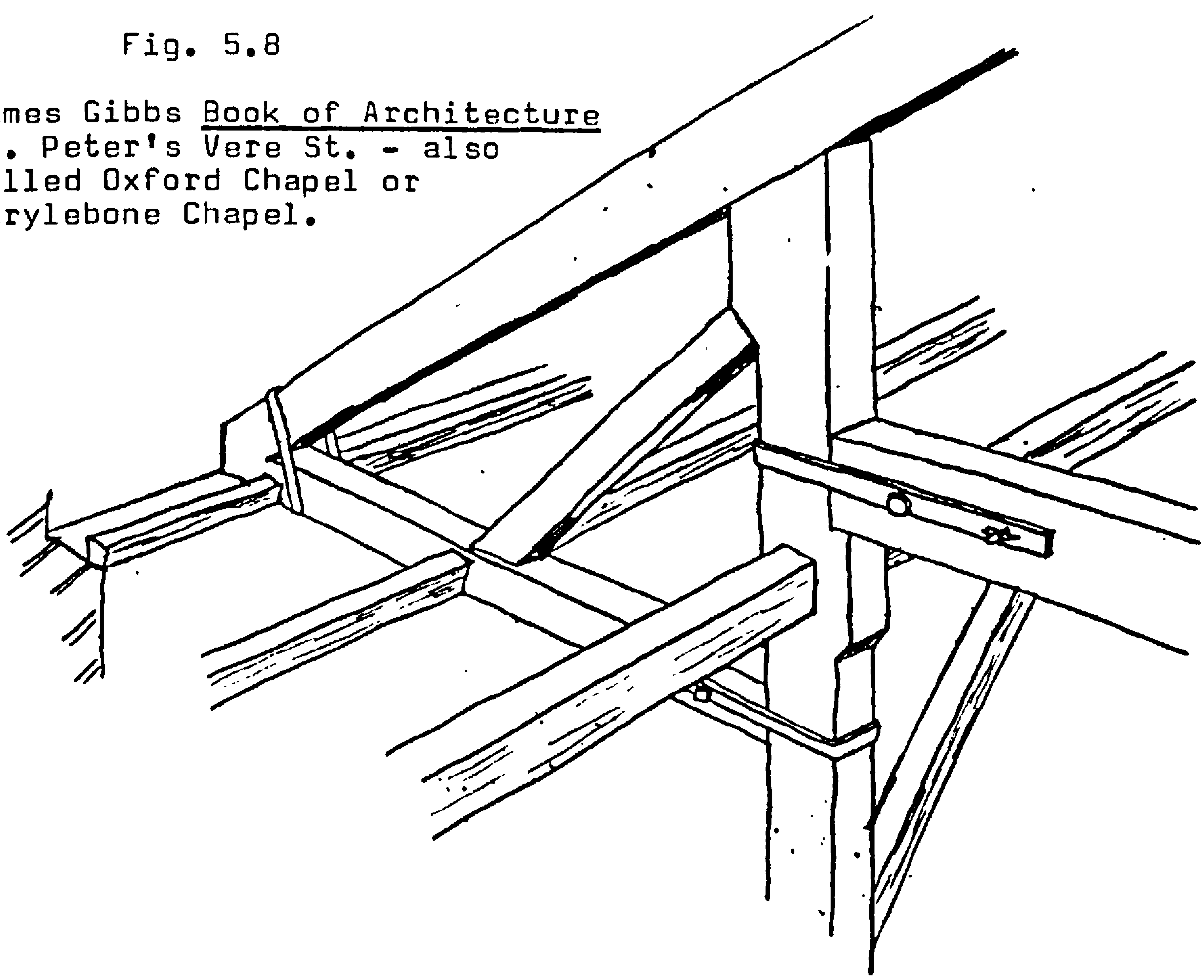


Fig. 5.9

Detail of the roof structure as built

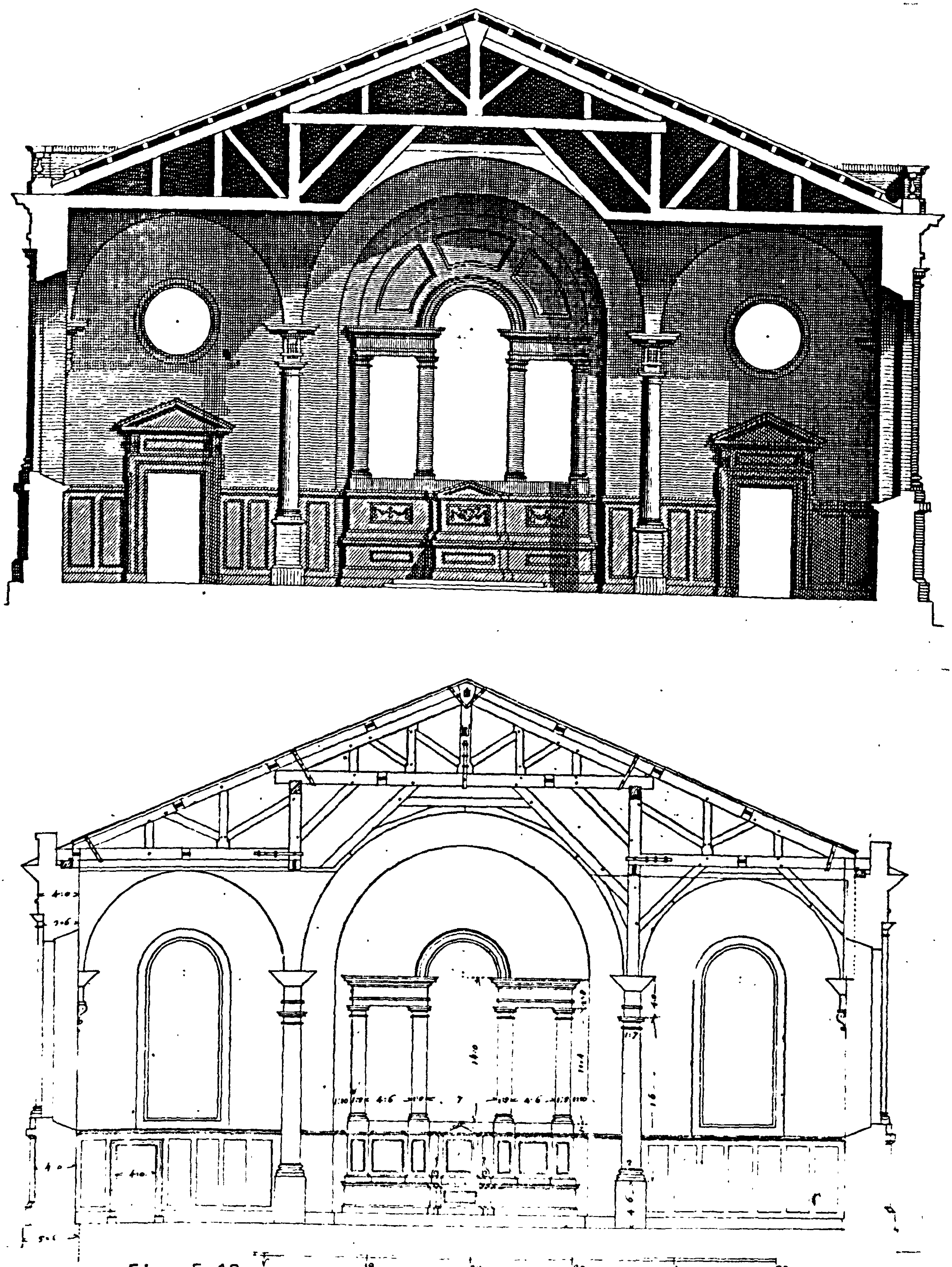


Fig. 5.10

All Saints, Derby
a) from Gibbs Book of Architecture
b) 'Working Drawing' from Ashmolean Museum Gibbs Collection.

'a' shows the intermediate trussing over the crown of the aisle vaults. The main trusses are built as shown in 'a' although the roof uses close spaced purlins as shown in 'b',

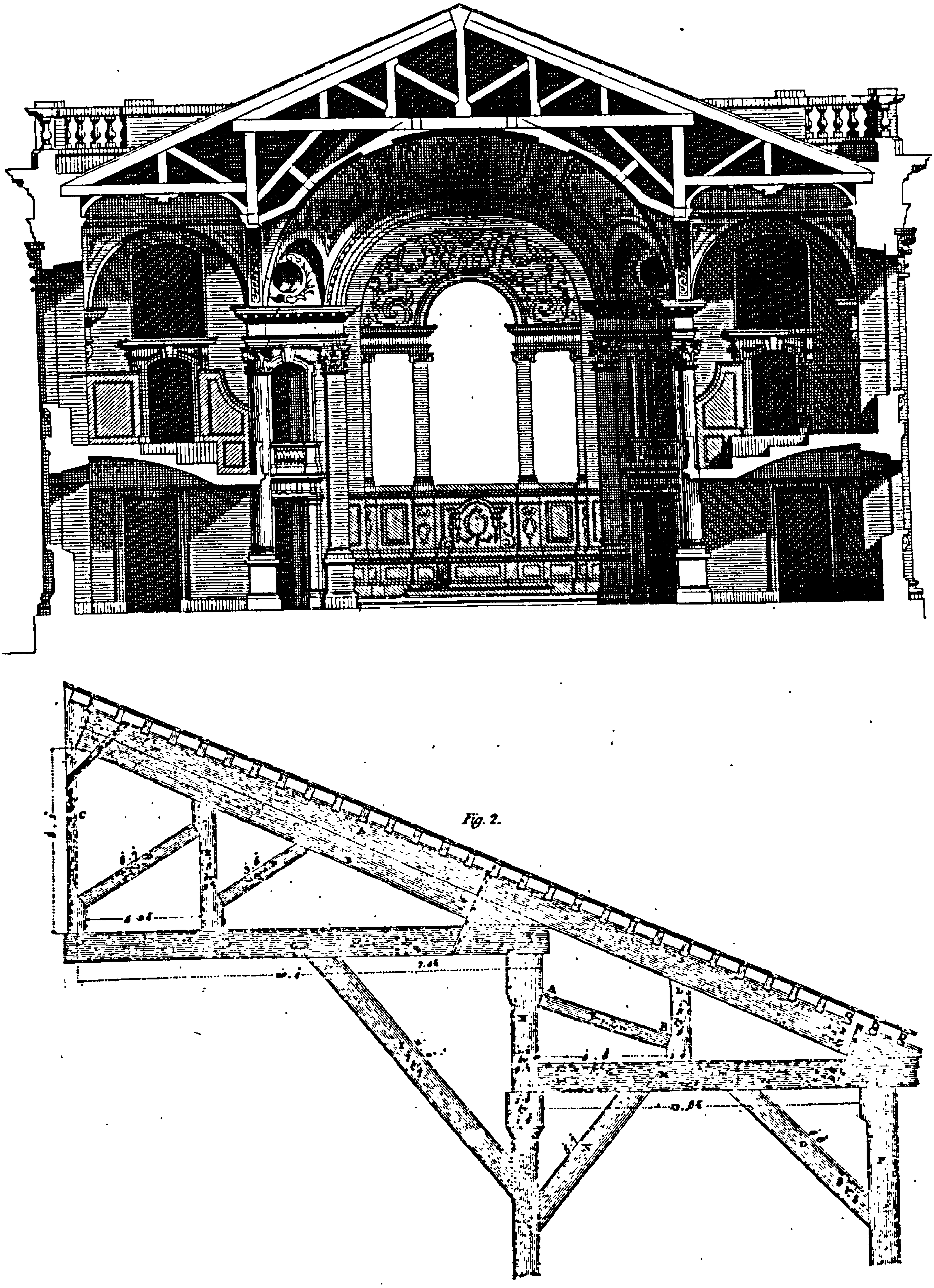
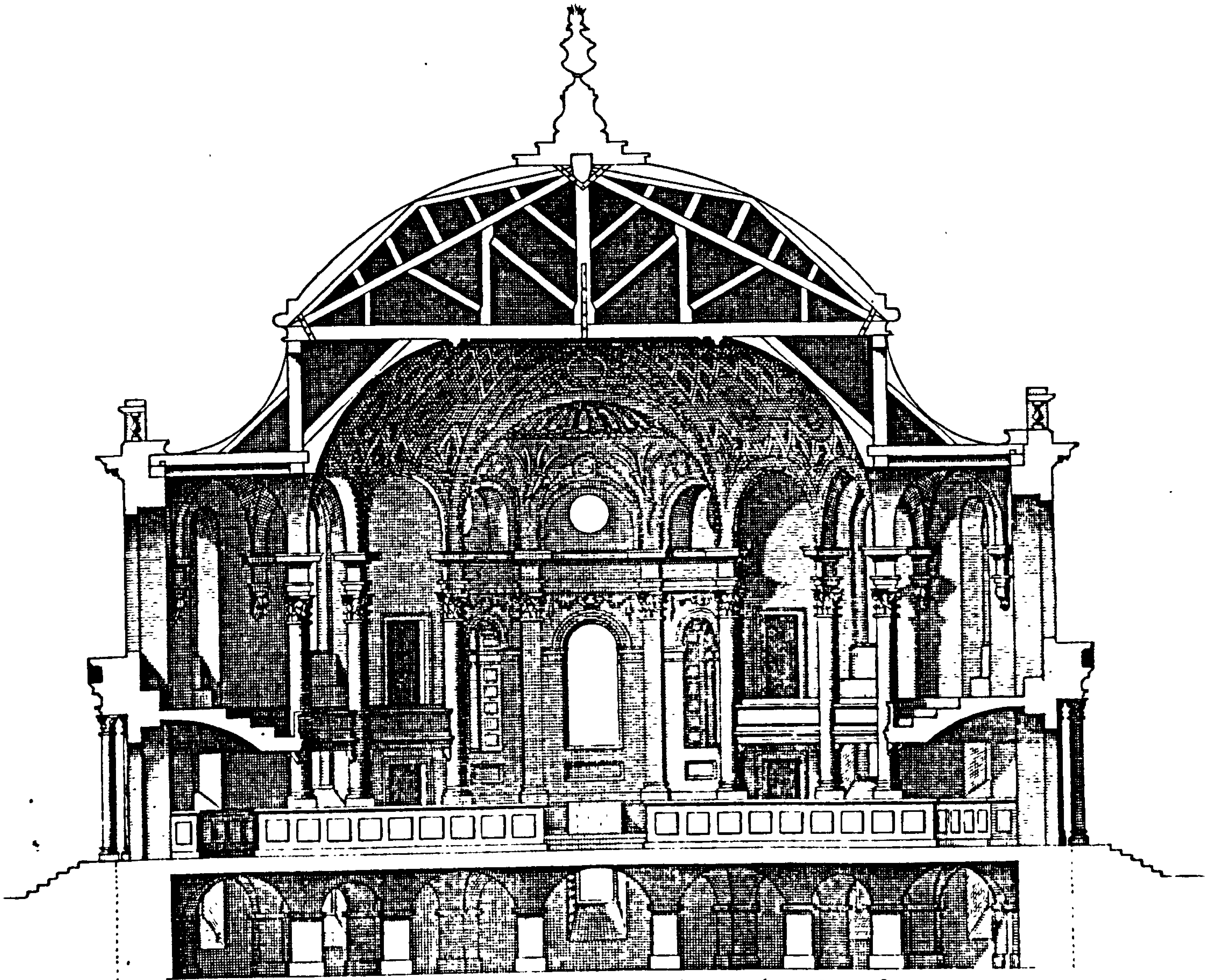


Fig. 5.11

St. Martin in the Fields

a) as drawn by Gibbs in his <u>Book of Architecture</u>
b) as recorded by Nicholson - note the absence of puncheons and differences in aisle framing.



Section from South to North

Fig. 5.12

Project for St. Martin in the Fields
Gibbs' Book of Architecture.

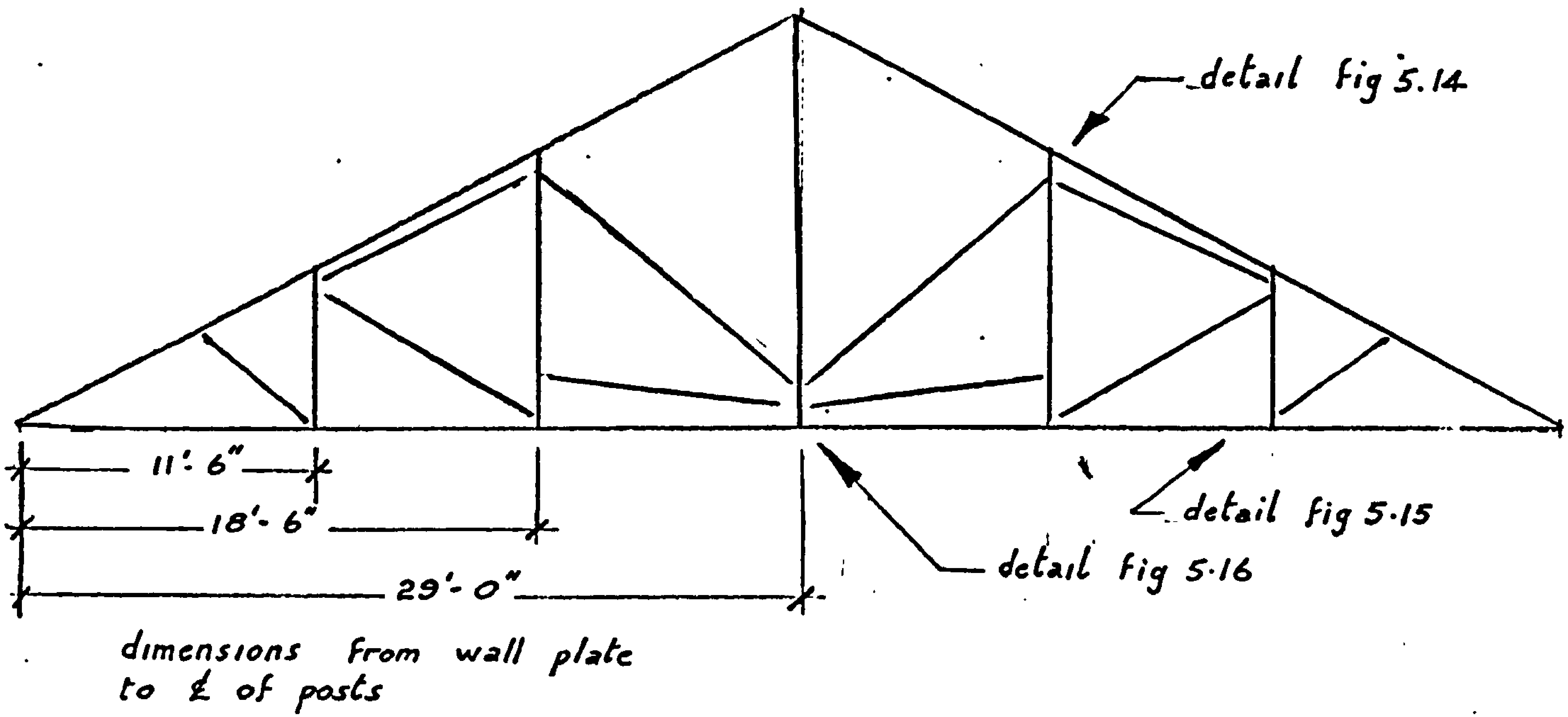
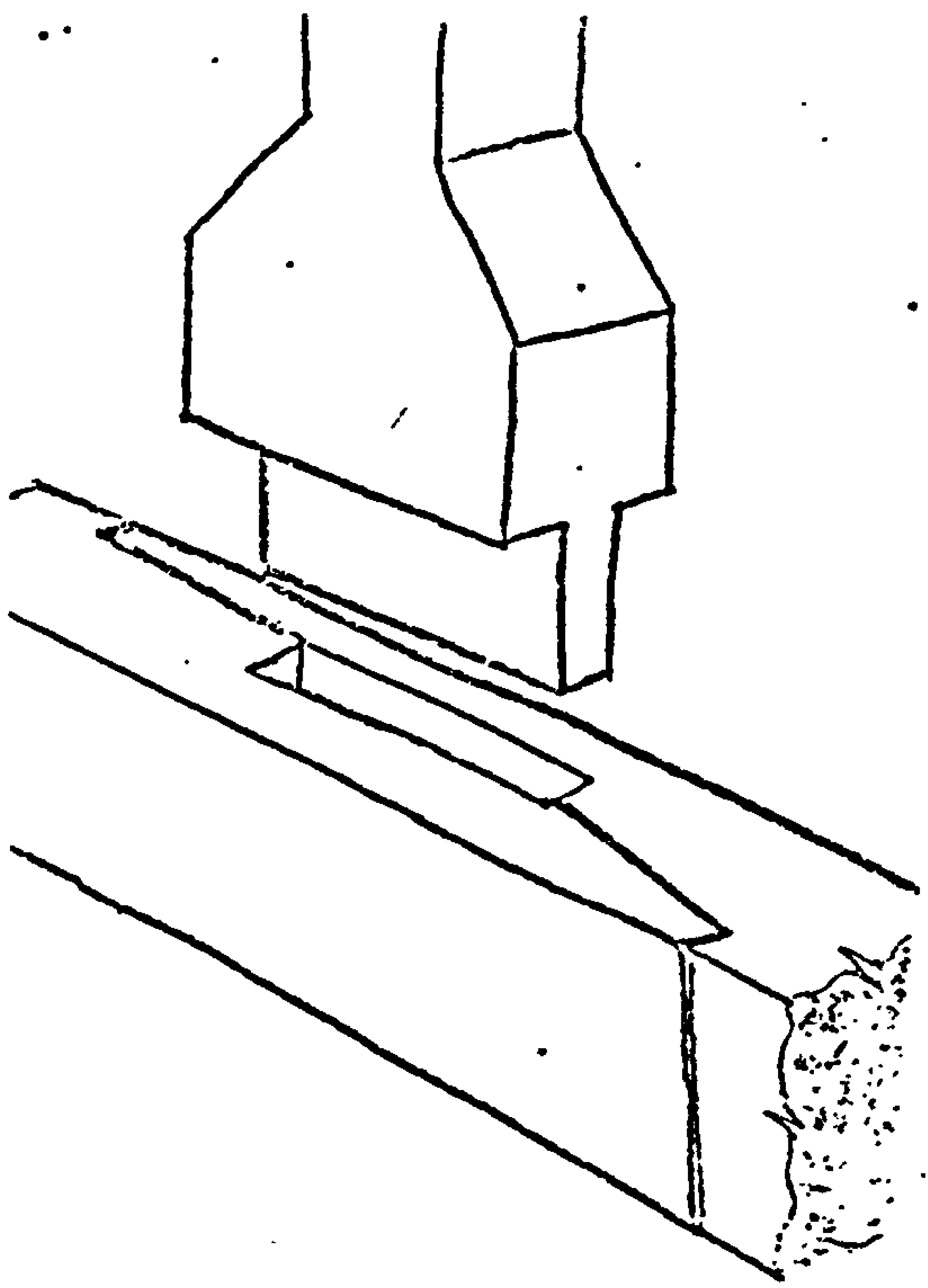


Fig. 5.13

St. Martins-in-the-Fields - Gibbs
Diagram of portico roof truss

Fig. 5.16

Detail of Fig. 5.13
Exploded view at foot of king post
showing scarf joint in tie beam
(partly conjectural)



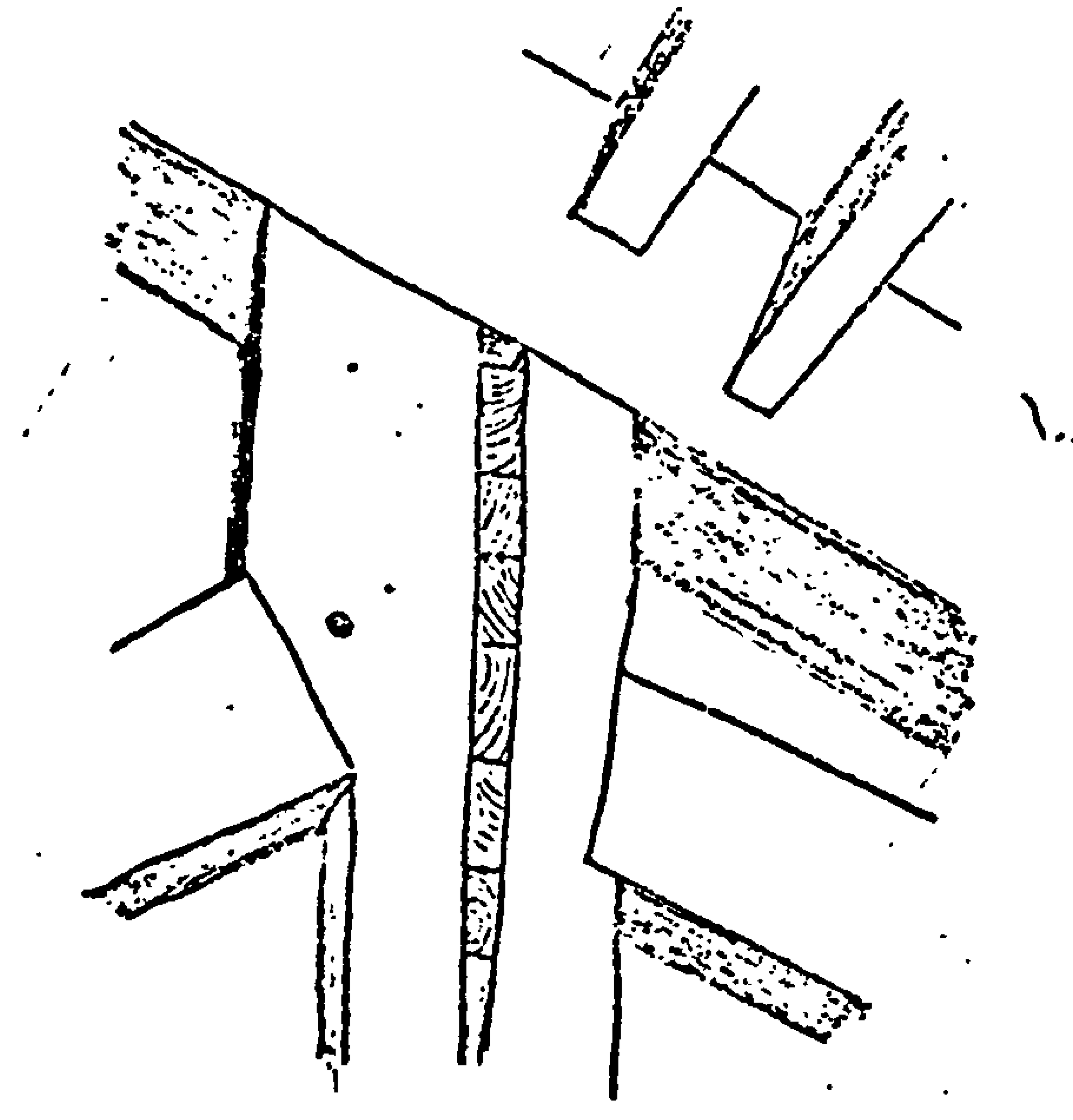
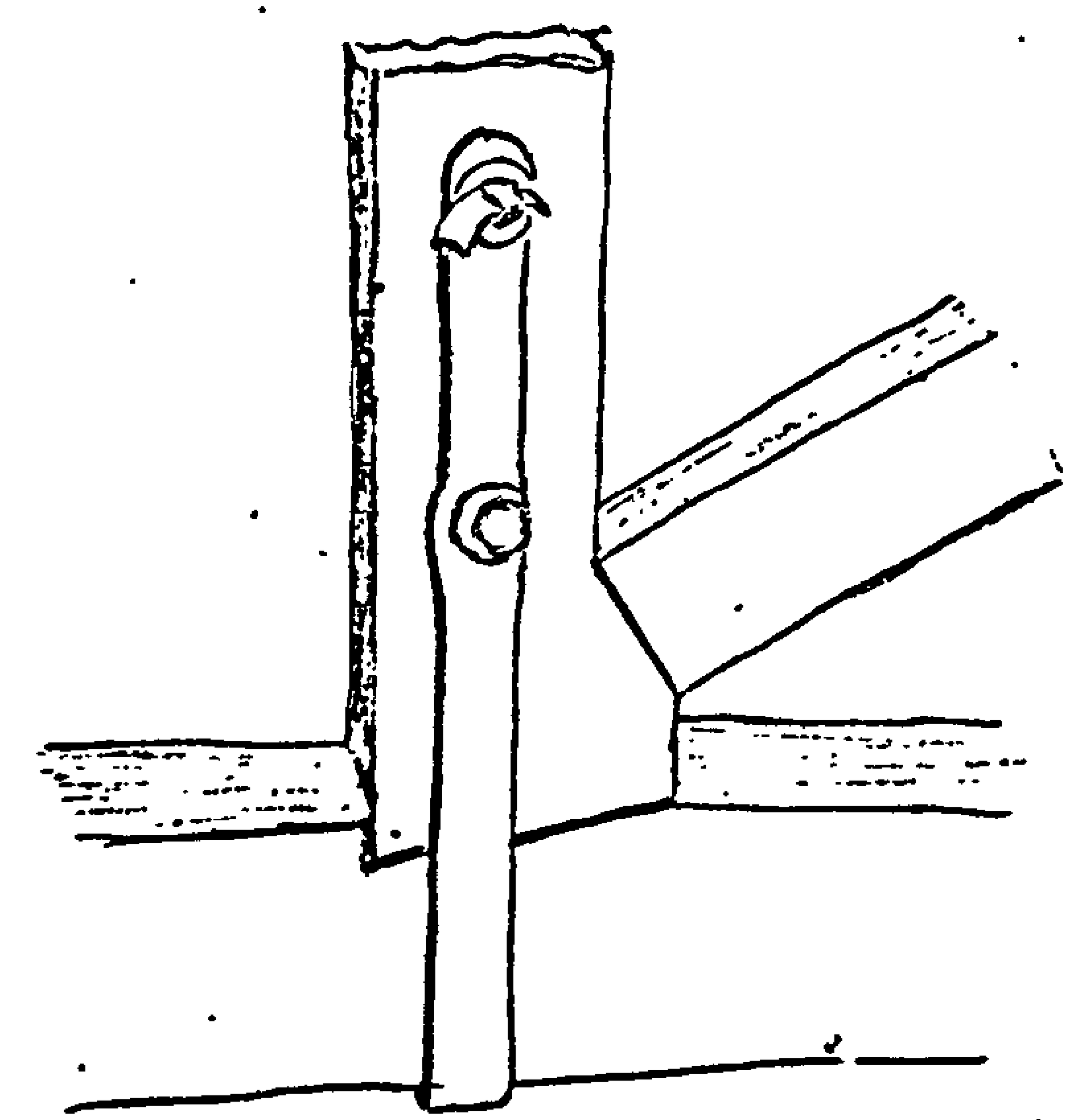


Fig. 5.14

Detail of Fig. 5.13
Wedges in head of secondary post

Fig. 5.15

Detail of Fig. 5.13
Foot of secondary post



ENGLISH TEXT BOOKS

One possible medium for the spread of knowledge of the new form of king post truss as well as the other developments of carpentry was the text books of the period. The effect of these is difficult to assess against other methods of transmitting knowledge. The spread of ideas through the direct contact of craftsmen can only be recognised when we have both examples of their work and some biographical information to connect them. Similarly the influence of text books may only be assessed with any accuracy given some information on their distribution. An alternative approach however is to see the text books as a mirror of development rather than as an influence upon it. The text book writers may either have been leaders in the field, the first to invent the new forms which were then copied by the carpenters, or they may themselves have simply recorded what was considered to be good practice. To see which I will begin with a comparative study of the texts and some assessment of the authors.

The books of the period vary considerably, in the audience that they were written for, in the background of their authors and in the material that they cover. To provide a background against which to assess the books dealing with structural carpentry a broader coverage of the texts of the period is necessary. The books to be discussed here therefore include more general architectural works and the early texts on carpentry published from the end of the seventeenth century.

In their book on Caroline houses, Hill and Cornforth (1) provide a list of architectural texts that would have been available to the builders of that period. Nicholson in his Architectural Dictionary (2) reviewed the text books on carpentry available largely during the eighteenth century. These two collections of texts reflect two quite different traditions of writing. (It would be tempting, but not strictly accurate, to refer to these as seventeenth and eighteenth century traditions). The two lists show a sharp contrast both in the type of book, the material that they contained, and in the audiences to which they were addressed.

In Hill and Cornforth's list most of the works are either foreign texts or translations of them. Works by English authors are few and generally less well illustrated than the others. Just as the Continent was the source of the architectural fashions so it was also the source of the best illustrated books, and the purpose of these was as much to transmit styles of architecture as the principles of construction. They were books for gentleman: expensive productions dealing with the principles of design, the siting of buildings, their aspect and planning, the proportions of their rooms, their elevations and the details of their ornament. These were the things that a gentleman builder wished to know. All that he needed to know about construction was the proportioning of walls and openings to give adequate strength, the best choice of roof pitch to throw off the water without overburdening the walls, the choice of stone to ensure durability and good appearance; and of course how to supervise the work done under his direction.

Such mundane details as the sizes of floor joists or the framing of timbers for the roof he could safely leave to his carpenters who would have been trained in such matters. In painting or sculpture the requirements of the builder might go beyond the capacity of native artists or craftsmen. In such cases foreign artists would have to be imported as well as foreign ideas.

By the eighteenth century however the picture had changed. The demand for 'classical' architecture had spread to an emerging middle class. The architect was also emerging as a recognisable professional, and texts were required to instruct the craftsmen who would build the Palladian mansions and Classical churches that were demanded. Thus the works that Nicholson reviewed were books directed towards the craftsman rather than towards the patron. They instructed him in the orders of architecture, the geometry of construction, the setting out of work and the provision of adequate structural strength in floors and roofs. The latter problem received less attention. Adequate strength was always a problem and, although the scale of buildings was increasing, the emphasis of the books was to provide designs for the craftsman to copy so that the buildings should conform to the canons of taste.

A third group of texts covers the ground between these two; aimed neither at the gentleman builder nor at the craftsman but at the 'purchaser'. Less easily categorised than the other two groups, the works here dealt more with an understanding of building than did the works on architectural form but were less concerned with the craft skills than the manuals on carpentry. While this is not completely satisfactory as a general description it is difficult to be more precise because the category also included books on what we might today call surveying or estate management. These books were not at all concerned with architectural form but did deal with the supervision of building as well as with the management of property.

In assessing all these books and putting them into some perspective one needs to consider the professions and the declared intentions of their authors as much as the content of the works.

Books for gentlemen builders

During the late sixteenth and the seventeenth century, architecture was a 'proper' subject for a gentleman to study and a number of books were written during this period both by and for gentlemen. More were written than were eventually published. Such books were clearly desirable. Airs and Girouard (3) have separately described the state of architecture and the process of building at the time. The former cites Bishop Goodman's comment that "no kingdom in the world spent so much on building as we did in this time" (4). With the extent of country house building, a concern for new architectural styles and an absence of professional architects, it was clearly necessary for the gentleman builder to acquaint himself with the practical art of architecture. Although there were a few professional architects practising after the Restoration, many builders still needed to act as their own architects and the need for books for these gentlemen builders continued to the end of the century.

Only a few copies survive of Shute's First and chief grounds of architecture (5). Wotton's Elements of architecture was well regarded in its day and its significance has been discussed by Frederick Hard (6). Both books drew upon Vitruvius as well as more recent sources. Gerbier's work (7), however, which offers far more practical advice on building, drew much more upon his own observation and experience than upon other written sources. The same is true of the unpublished works of Pratt and North (8). Although these last two could have had no influence on the architects or craftsmen of their day, they provide some insight into the competence of the builders of the period. Not all were skilled in the details of construction and very few would have concerned themselves with the details of carpentry.

Wotton seems to have understood the principle of the roof truss but unfortunately does not make it clear to his readers. Like Shute before him he based his work on Italian sources, but while Shute restricted himself to engravings of the five orders, Wotton made a critical study of his sources and concerned himself more with the practical aspects of building. He selected his material from a number of sources and commented on them (9). On structural principles he cites Bernardino Baldi's commentary on Aristotles Mechanics (10) which covers both the principles of the arch and the roof truss. His reference to the latter however is tantalisingly brief. He says merely that the roof has been dealt with by others:-

> "..., but by none more learnedly than Bernardino Baldi Abbot of Guastala ... who doth fundamentally, and Mathematically demonstrate the firmest knittings of the upper timbers, which make the roofe."

He then excuses himself from dealing with this further, going on to quote Palladio on roofs, who after discussing the effect of the roof slope on the disposal of water, declares that the roof should neither be too light nor too heavy. This is hardly an informative structural principle, although he does point out that the roof is "a band to all the work". It is a pity that Wotton chose not to enlarge upon his quotation of Baldi because it was to be over a century and a half before an English text was to provide a satisfactory explanation of roof truss behaviour.

Gerbier's two books on building are concerned with the process of construction, its supervision and the prices of materials. They are more like the guides to purchasers and the books by surveyors which were to appear in the following century than the contemporary books dealing with the principles of architectural design. He makes suggestions for the scantlings of some of the timbers to be used in building, gives advice on the construction of floors but says nothing about the structure of the roof. All this information was to guide the clerk of works in ensuring that the workmen produced sound work.

The bias of the book is clear in his phrasing. "... The clerk of works must have a care to see the carpenters to..." and "the clerk of works must be careful not to suffer the carpenters to ..." This is not a book directed to the carpenters themselves. (Presumably they were expected to have been taught their business as apprentices). Instead it provided instruction for the management and supervision of the work. However it should be noted that the gentleman builder would not necessarily do this himself but instead, employ a clerk of works for the purpose.

Gerbier was a professional architect rather than a gentleman builder and his books were published to advertise himself in this capacity (11). In contrast Sir Roger North tells us in his autobiography that he studied drawing and architecture as a young man simply for his own interest (12). However, so diligent were his studies that he became a proficient architect and built a number of works. His knowledge extended to the problems of construction which must have been more of a problem for most of the amateur architects of the time.

Roger North dwelt on this problem in his unpublished treatise on building (13). His recounting of cases where poor design or poor supervision led to faulty building leads one to suspect that, at a time when many great houses were being built, it must have been a problem to find competent or trustworthy clerks of works. Roger North may well have intended publishing his treatise, for the work offers advice on the design and construction of houses and is written in a style that suggests more than simply personal notes. Unfortunately, however, he does not deal with the structure of buildings and there is thus no way of telling how well he understood problems of structural carpentry.

Of the gentlemen builders Sir Roger Pratt became a practising architect and served as one of the commissioners for the rebuilding of London after the fire. Among his unpublished notes there is quite clear advice on constructing a roof truss (14):-

> "The beams it's true must be Trabes Euerganeae, whereof you will see examples in Vitruvius, Serlio etc and into these must the principal rafters be very strongly footed, bolted and keyed, to prevent the kicking of them up etc. and so to truss up a king piece with its toggles at the top, and most strong dovetail at the bottom to truss up the beam under it."

Here was the first clear statement in English that showed an understanding of the behaviour of a king post truss. It shows the concerns of at least the knowledgeable carpenters of the time; the proper footing of the principal rafters, the formation of a joggle at the head of the king post and the trussing up of the tie beam so that the king post should assist it.

It is worth considering Isaac Ware's Complete body of architecture (15) at this stage because although it was written over a century later than Wotton's book it has a greater affinity in its scope and intended audience to this much earlier work than it does to many of its own contemporary texts. Much larger and more comprehensive than Wotton's book, it is also illustrated, but the illustrations remain subordinate to the text. It is not simply a collection of architectural details and examples. It is a book on the principles of architectural design, intended for the designer rather than for the craftsman. Although it contains references to the practical aspects of construction, Ware's knowledge of practical matters seems to be weaker than Gerbier's, presumably because by this time a builder could draw more easily on an experienced body of craft skills.

While structural details are shown the wide coverage of the book does not permit more than a few poor drawings. However Ware would have done better to have omitted these, for they only serve to show his ignorance. He mentions trussed girders but neither the text nor the illustrations are clear enough to be useful. Although he gives the scantlings of timbers, his illustrations of roof trusses suggest both a lack of understanding of the principles involved and an ignorance of the common practices of the time. He shows the details of construction of a king post truss but draws the king post without joggles (fig. 6.1). Of the design of roofs he says:-

> "There is no article in the whole compas of the architect's employment that is more important or more worthy of a distinct consideration, than the roof; and there is this satisfaction for the man of genius in that profession, that there is no part in which is greater room for improvement." (16)

It would seem that by the mid eighteenth century the craftsmen had acquired a greater technical knowledge and competence than some of the architects of the day because by this time books had been produced that showed correctly detailed trusses.

Curiously Ware did show correctly detailed king post trusses in his drawing for a timber bridge (see chapter 7).

Chambers produced his book, which was in many ways superior to Ware's, soon afterwards (17). In this there was no drawing of carpentry details. By the mid eighteenth century instructions on these practical issues had become the province of specialist books written for the craftsman.

The fire of London was a significant event because the acts for the rebuilding of the city (18) set down the minimum standard for building and specified the scantlings of structural timbers. Tables of scantlings were to become common in carpentry texts, the earlier ones quoting the sizes given in the acts while recommendations were to change during the eighteenth century.

Books on building

The first book to appear with drawings showing the framing of timbers was Richard's Palladio in 1668 (19) although this did not provide tables for sizing the members. This book which was a translation of Le Muet's Palladio includes an appendix dealing with the framing of hipped roofs, showing the method of setting out the timbers devised "by that ingenious architect Mr William Pope of London" (20). This method seems to have become standard for it was to be reproduced in many subsequent text books. It shows the method for determining the lengths of the hip rafters including cases where the plan of the building is not a rectangle. The need for instructions in this technique presumably reflects the growing use of the hipped roof in buildings of the new architectural taste.

Drawings show the layout of a simple floor with joists and summer and the framing of a timber framed building including the roof structure (fig. 6.2). The drawings of roof structures show the correct framing of the king post and mortices in the principal rafters to receive the purlins. A feature of these members is the use of knees at their feet. This is not commonly found in practice (21). Clearly Richards was well aware of the correct design of a king post truss but not enough is known about him to be able to identify his source for this information. It was to be some time before books were to appear which were specifically intended for tradesmen. The early books after the first still reflected the needs of the purchasers and builder rather than those of the craftsmen. Describing themselves as architects and surveyors or carpenters and surveyors the authors of these books addressed themselves to city and country purchasers and builders, and might include the prices of work as well as comments on construction and structural requirements. Primat, later revised by Laybourn (22), began his work with advice on valuations and rents. The second part of the book however was for the builder, quoting the Building Acts, giving scantlings for timbers and even providing drawings showing the layout of timbers in floors for a range of buildings. These books coped with the medley of information by dividing the work into sections and have the appearance of a number of books bound together.

Some authors chose to set their books out like a dictionary or encyclopaedia. John Harris's Lexicon Techtonicum (23) is a general work of this type not dealing specifically with building but including a few building terms. However, it is of little interest here. The most complete work using this format was the Builders' Dictionary (24). There were few illustrations in this book but the text is very thorough. Not only are building terms defined but it contains instructions for framing floors, girders and roofs. The most interesting feature of the work, however, is that it was the first work to provide a sound theoretical analysis of the relative strength of beams. It drew upon work that had been done earlier in France and citing this source correctly stated the strength of a beam to be proportional to its width and the square of its depth. However, although this analysis was made clear by a number of worked examples, it seems to have been almost totally ignored by subsequent publications (25) until the end of the century.

A similar format was used by Campbell in his London Tradesman (26). This book divided building, as the title suggests, into the work of different trades and acted as a guide to the purchaser or builder. It is useful here in that the author described the kind of work that was normally carried out by the different trades, thus showing the variety of tasks that the carpenter had to be capable of handling.

The best known work of this type is Neve's City and country purchaser (27) which was essentially a dictionary of building terms. Although less thorough and less comprehensive than the Builders' dictionary and having no illustrations, this work went into a third edition in 1736.

Carpenters' texts

The earliest text books for carpenters were concerned with measurement rather than with construction. Their intention was to provide the craftsman with an aid to the computation of areas and volumes. This might be done by the use of a specially marked carpenters' rule as described by Digges or More (28). The latter described a number of errors commonly made by carpenters in measuring timber and attempted to correct them. However the techniques which he suggested could have made little if any improvement. He described the use of arithmetic in measurement, by which he meant multiplication, but the calculation techniques otherwise sought to avoid the use of such advanced manipulation of figures. Similarly the specially marked rules were designed to allow the areas of boards to be easily reckoned. The alternative was to provide a table of results. Bedwell (29) published a pamphlet containing such a table and

Darling (30) a comprehensive book of such tables: from simple multiplication tables to tables of areas. Darling assumed the use of only an ordinary 2ft rule but the specially marked rules seem to have been more popular with the authors of these books. (I cannot say how popular they were with the carpenters of the time.) The best known of these is probably Gunter's sector (31), a rule with complex scales allowing a wide variety of calculations to be performed.

Just as a slide rule might be marked in a variety of different patterns so the scales incorporated into this new form of carpenters' rule was a matter of choice. In two different books Leybourn (32) described differently marked rules. The scales included logarithmic and trigonometrical scales and the books gave instructions for calculating the volumes of complex shapes. One has the impression that these scales probably provided more entertainment for their inventors in their devising than they did assistance to carpenters in their use.

Leybourn's scales were the last that I know of to have been invented to assist the carpenter to measure timber but tables to assist him in his calculations continued to be produced throughout the eighteenth century. William Salmon's Builders guide and gentlemen and traders assistant; or a universal magazine of tables (33) is exactly what it says in the subtitle, essentially a ready reckoner. The most important book of this kind was by Hoppus, a work which was to continue to be published into the twentieth century (34).

Although Richards and Leybourn had included some detail of timber framing in their works it was not until the seventeen thirties that books were to be produced that addressed themselves to the carpenter and tackled specifically the problems that he would meet in everyday construction. There was then a flood of works on building construction compared with the trickle of the previous century. These two decades saw books by Halfpenny, an architect and carpenter, by Francis Price, surveyor of the works at Salisbury Cathedral, by Batty Langley, originally a landscape gardener, by William Salmon who styled himself a carpenter, and by Hoppus (35). These were all men who were themselves engaged in the practical aspects of building and who wrote books intended to instruct their fellow craftsmen. They were, however, not primarily concerned in these books with the traditional arts of building construction but more with showing how to set out the classical details now demanded. The new style of architecture needed craftsmen who could set out the details of the five orders, who could form entablatures and mouldings correctly, build centerings for elliptical arches and groined vaults, set out niches and form twisted handrails for grand staircases. In their titles they might be directed toward the builder generally, as in "The art of sound building ..." or specifically to the carpenter as in "The carpenters companion ..." but their contents had much in common.

The apparent intentions behind these works seems to be best summarised by Halfpenny who says (36):-

> "the reasons that first induced me to publish this work was the daily errors that I saw workmen commit in framing their works for buildings on account of their want of knowledge of the proportions contained in this book, being the only thing that I know that is wanting to make the art of building compleat."

It is important to recognise the kind of work undertaken by the carpenter at the time. As well as providing the structure of floors and roof he was responsible for preparatory work needed by other tradesmen; scaffolding and arch centering for masons and the basic framing for the work of the plasterers. Much of the skill and knowledge which the carpenter required to enable him to carry out this preparatory work involved the practical application of geometry. Although ready reckoners for the measurement of timber continued to be published, by now the standard of mathematical ability among carpenters must have improved if they were to cope with these geometrical problems. Indeed Campbell in The London tradesman (37) suggests that carpenters were well educated. What the carpenters required were instructions for the setting out of the complex geometrical shapes which were required by the architecture of the day and the books thus concentrated on problems of geometry.

Although many of these practical texts on carpentry have already been reviewed by Peter Nicholson (38) he dealt with the whole range of carpentry problems. He was concerned to assess the correctness of each author's work, to show the development of different methods of setting out carpenters' work and to establish the contributions made by the various authors - not least himself. The concern here is rather to concentrate on the way in which each author has dealt with the construction of roof structures and to assess the reliability of their drawings as indicators of the practice of the day.

Two books appeared in 1733 that showed roof construction in some detail. Both specified sizes for structural members and have illustrations of roof trusses. Not only were they similar in content but they adopted the same method of presentation; being essentially a collection of plates with a short descriptive text for each. However in spite of these similarities the books are quite different in the quality of their contents and present a useful contrast.

Little is known of James Smith who wrote The carpenterscompanion, being a treatise on carpenters work ... especially roofs (39). His only other work was A specimen of ancient carpentry (40); a collection of illustrations of roof structures, mainly hammerbeams. Although for this later book he must have examined the roofs that he illustrated, one suspects that The carpenters companion was based largely upon his own invention. The trusses that he illustrated are curious, and many simply impractical; although among the designs provided are some of the standard trusses of the day. He correctly showed a number of king post based trusses but all his queen post designs are incorrect in having the straining beam supported by the queen posts, as in the medieval forms of roof truss (fig. 6.3). It is possible that he saw some of the queen post trusses of his day but did not examine them in detail and thus drew from an imperfect recollection.

His drawings for the structuring of attic rooms bear some similarity to those that were being built at the time. The unnecessary inclusion of metal strapping in these drawings might be because Smith had copied what he could see of the structures and had invented what he could not. It would be unreasonable, however, to regard all his designs as possibly imperfect copies of actual trusses. Such a view might lead us to attempt to reconstruct the actual trusses from which the drawings were derived but this would be fruitless. One of his raised tie beam roofs for example (fig. 6.3b) simply could not be built and to be able to draw such a truss shows such an ignorance of practical carpentry that the book cannot be seriously regarded as an indicator of the normal carpentry practice of the time.

This view is reinforced by a consideration of his designs for trussed girders which will be discussed in a later chapter. It is sufficient to note here that they are more fanciful than practical.

Price provided the better of these two contemporary works; a book highly regarded in its own day, it contained a testimonial by Nicholas Hawksmoor, James Gibbs and John James (41). By 1735 the book was in its third edition. Perhaps one should expect a more competent product from the surveyor to Salisbury Cathedral (42). Even the critical Peter Nicholson says of his book that "there was hardly anything wrong" (43). Even so, while he began by illustrating correctly a number of sound roof structures, Price also went on to include a collection of unlikely looking arrangements for no apparent reason. As he said himself "How necessary these roofs may be thought I cannot say" (44). While these were not all well designed he provided a roof with a wide overhanging eaves that in some ways anticipated the structure of St Paul's, Covent Garden. If this and some of the other trusses were his own invention then he demonstrates more skill than most authors of the period.

The illustrations reproduced here (figs. 6.4 & 6.5) show both the practical (his plate G) and the fanciful designs (his plate H). His plates G and I show sensible king post and queen post arrangements. His mistake seems to have been to attempt to combine these two basic forms. However, while we may imagine these structures to be unnecessarily complex this does not mean that they were not used. A version of his truss type F was built in restoration work carried out at Canterbury Cathedral (45) and the similarity is such that we must assume the design was adapted from that in this illustration. Apart from this clear influence on a completed structure, versions of these drawings can also be found in later carpentry books by other authors.

The practice of providing a variety of roof trusses was to be continued by subsequent writers. Oakley, in a little book titled so as to suggest universal appeal (46), drew a number of bizarre structures that show no appreciation of structural principles. One must assume that these unique designs were his own invention. Salmon (47) also had a variety of designs but much of his work seems to have been derived from others and many of his trusses are recognisable as those illustrated by Price. Hoppus (48) shows no advance on anything previously produced and again some of his trusses seem to have been taken from Price.

One cannot separate completely those books dealing with structure from those concerned with geometry and decorative details or even from the building pattern books. There were authors who produced books on more than one aspect of design and construction occasionally combining them in a single work. Halfpenny was the first to deal with the practical problems of geometry. His Art of sound building (49) begins with elementary lessons in plane geometry. The topics gradually become more advanced, eventually dealing with the three dimensional problem of setting out groin vaults. Since the book is essentially concerned with setting out he covers masons' as well as carpenters' work.

He is well known for a number of books of plans, largely of farm houses (50). It was not until 1757 that, in conjunction with Morris and Lightoler (51), he produced a book which illustrated designs for roof structures, and these were not of a kind normally found in contemporary buildings. Halfpenny favoured design of roofs relying upon numerous small timbers rather than the heavy trusses which were common by then. A drawing of his survives (52) for a building showing the use of this type of roof but no built examples have been found.

Batty Langley was the most prolific writer on building in the eighteenth century but not the most helpful in providing an indication of the general practice of the day. He showed a variety of roof trusses in several of his works but a comparison of these various collections shows that they are all different. While sometimes they might contain drawings of trusses actually built, as in his Treasury of designs (53), many are presented with no description and no explanation so that their origin and intended purpose are not clear. Those in his Treasury of designs, some eighteen assorted roof trusses, are included among fourteen plates of carpentry details added to the end of the book almost as an afterthought (fig. 6.6). (The rest of the book comprises a collection of decorative details). His Builders jewel (54) also ends with over twenty different roof designs. The drawings often suggest that his principal intention was to show how to determine the lengths of the rafters. The most common reference to roofs in the eighteenth century text books was the determination of the lengths of rafters, particularly the hip rafter.

However well known Langley may be as a writer, these illustrations cannot be relied upon. Like Smith, his other carpentry details (and indeed other aspects of his work) call into question his competence in dealing with practical aspects of building. His carpentry details are clearly not taken from practice. The variety of splices that he gives contain some that would be hopelessly impractical, his own design for a trussed girder is patently ridiculous, his comments on brickmaking are absurd (55) and his views on the strength of timber are made without any reference to experimental tests. Small wonder that Nicholson, in his review of Langley's work was particularly harsh (56).

Among all these drawings of different trusses are some individual designs that were taken from actual buildings. Price shows roofs that he reported to have been "executed in noted buildings". Unfortunately they are not identified and although they have some resemblance to roofs that can still be found, without positive identification their identity must remain in doubt and so the accuracy of his observations cannot be checked. Batty Langley identified some of his illustrations and so we can see that (as discussed earlier) they were not always accurate in all respects. Indeed there are occasionally quite significant differences between the actual structure and Batty Langley's version of it. The outlines of the structures may have been preserved but the accuracy of important details cannot be relied upon. A comparison of his two versions of the roof of St Paul's, Covent Garden suggests that this may be due simply to inaccurate drawing of the plates, but whatever the reason it makes the drawings unreliable as a record of the structures that they purport to show. Hoppus includes a drawing of a structure that resembles the Sheldonian roof. Although it is not identified in the text, nor is it the same in all respects as the original, the similarity is striking. This illustration was published before Parentalia (57) (which gives full details of the roof) so the drawing is not a copy. Hoppus must have either visited the roof himself or taken the trouble to discuss its structure with someone else who knew it. The unusual form of this roof allows it to be identified and one is thus tempted to wonder how many other structures (however poorly drawn) have been reproduced in these books but which now remain unrecognised.

Some of the roof truss designs in the books are of commonly used forms while others may be of forms which could be used in unusual circumstances. A raised tie beam for example might have been required fairly often although this would hardly be the form naturally chosen if it were not necessary. Unfortunately the inaccuracies in the drawings make it difficult to distinguish between truss forms that might have been used from those that are mere inventions of the author. But given that some roofs were simply invented by the writers of the books, one needs to ask why this should have been thought necessary. There were a variety of problems to be solved and the variety of drawings to some extent reflects this. Roofs of different pitches, roofs over raised ceilings or containing attic rooms, roofs with flat tops or internal gutters were all built and have been illustrated in the books. It was possible that authors were attempting to anticipate other problems which might arise. Perhaps this is what Price is referring to when he suggests that without his additional designs the others might not have variety enough.

If one were only discussing Price, clearly a knowledgeable writer and a practical tradesman, one might accept such a charitable explanation. However other authors show in their drawings either simple ignorance or a desire for novelty and invention for its own sake.

In the absence of any generally understood principles (for none had yet been published in English) nor any forum for debating issues, it is not surprising that individual views should vary so much. The tables for scantlings for both floor and roof members, which most of the books included, show this variety of opinion. Furthermore authors could indulge their inventiveness with impunity. It would be expected however that a carpenter, whose reputation and business success stood or fell with the structures that he built, would be conservative. Thus it is small wonder that the same variety of trusses was not found in practice. A structure proven in a building would be used again. There would be no incentive to flirt with others.

Collections of architecture

In addition to the books for carpenters that had drawings of roof structures, a number of books were published where roof structures were included as part of drawings of complete buildings. The collections of architects work which were published during the eighteenth century did not set out to illustrate the structures of the buildings but sections taken through a roof might well have the trusses drawn in. The accuracy of these drawings is in some cases questionable. Those of Campbell have already been considered (and found wanting) and Ware's drawings of Houghton Hall are ambiguous (58). Even the drawings in Gibbs' Book of architecture may vary from the actual construction (59) although, as he himself points out in his Bibliotheca Radcliffiana, design and executed product may often be different and this may account for the discrepancies (60).

Vitruvius Britanicus (61) and both Kent's and Ware's Designs of Inigo Jones (62) contain drawings of buildings with king post roof trusses. The most noteable book however is Gibbs'. A large number of his buildings are drawn with roof trusses shown in the sections. He uses the king post form consistently, although in both the drawings and the executed trusses shows a preference for square cut joggles at the foot of the king post rather than the splayed joggle which was more common. In his drawing for the church at Derby he also shows clearly the use of close spaced purlins rather than common rafters. Most striking of his drawings is the projected design for a domed church for St Martin in the Fields (discussed earlier).

Paine's Plans (63) showed roof trusses in most of his sections but these were not king post trusses. Instead he favoured a derivative of the queen post truss that appears to have been his own design since it is not illustrated anywhere else. It was not particularly successful in practice and the complexity of its construction would not have recommended the design to an ordinary carpenter.

Construction details were shown for the more modest houses illustrated in William and James Pain's British Palladio (64). This shows the layout of floor structures in some detail and is important in showing the use of, and the details for, trussed girders.

Whatever their accuracy the influence of these books is difficult to assess. They were not written for carpenters but it is nevertheless possible that carpenters may have seen them and been influenced by seeing the use of king post trusses in these buildings.

Apart from the books illustrating complete buildings, the authors that have been considered so far have shown the roof trusses isolated from any other construction. They discussed the choice of roof pitch to suit the different coverings that might be used and gave tables of scantlings for the members of the truss and the purlins and rafters to be carried. However the purlins themselves were not shown in the drawings nor were the wall plates which support the roof trusses. (The exceptions of course were where the roof truss was included as part of a drawing of a complete building). William Pain was the first author to show a complete assembly with the trusses sitting on the wall plates and carrying purlins. Pain was critical of the texts available in his day and in the preface to his Workman's general assistant he says (65):-

> "The deficiencies and confused plans of those books now used by workmen, is but another inducement to collect together in view the most easy and certain rules to carry out the building art. These are the result of experience and by the author long used in conducting business, who now offers the public a general practical treatise wherein great care has been plainly and faith-

fully to answer the purpose of the manual artificer."

Nothing is known of Pain's career as an architect but he published a large number of books. Of these Colvin (66) says that "they were as successful in popularising the 'Adam style' as the earlier books of William Halfpenny had been in disseminating Palladian and rococo motifs...". Structural carpentry details appeared in his Workman's general assistant(67), his first book, and in his Practical house carpenter which was to be revised by Brooks as late as 1860 (68).

His books were essentially collections of plates with only sufficient text to provide explanations. Details of doors, windows, stair-railing etc were given. He gave tables of scantlings for structural timbers, details of trussed girders and framing arrangements for roof trusses. In these roofs he restricted himself to a few sensible trusses rather than presenting the bewildering variety that earlier writers had shown. He has drawings of king and queen post trusses and a mansard truss for accommodating attic rooms. He also included some varieties for different spans but they were all sound forms and correctly detailed (fig. 6.7).

Here at last was an author who seemed to be aware of what he was doing. He produced a number of titles and his works ran into several editions. Compared with earlier writers his work shows a distinct improvement in the grasp of the subject. However he includes no discussion of structural principles and his books were to be completely overshadowed by the much more comprehensive and more prolific writings of Peter Nicholson.

Although Peter Nicholson practised as an architect, chiefly in Glasgow (69), he is much better known as a writer of books on a variety of subjects other than building (70). Moreover his books on architecture were frequently reprinted, sometimes plagiarized, and many editions were published after his death. There were a number of American editions and indeed his work appears to be at least as well known in the United States today as it is here (71).

It would be out of place here to attempt to do full justice to his work and I shall therefore concentrate on his contribution to carpentry and in particular structural carpentry.

The first thing to note is that Nicholson was a theoretician. His contribution to structural understanding will be discussed in greater detail in a subsequent chapter but it is important to note here that he was not content simply to accept earlier ideas. On the contrary, he was highly critical of much of the earlier work (72). Many of the techniques of applied geometry that he provided in his books were devised by himself. At the time his contributions were recognised both here and in France (73).

While capable of improving the standards of applied geometry Nicholson had also a thorough grasp of the practical problems of construction. His books cover a broad spectrum of building crafts and deal with each in some detail. Moreover they are far better illustrated than any of the previous books for tradesmen. Nicholson himself made the engravings for his first book but many of the illustrations in later works were done by his son.

The illustrations showed the overall layout of the basic roof trusses and the carpentry details, the joints and metalwork, more clearly than any of the previous authors. Nicholson did not invent varieties of truss to handle different conditions but he did follow the earlier practice of including drawings of exceptional trusses that had been constructed in the past. In these, as in other aspects of his work, the standard of these 'measured drawings' was a vast improvement on what had been produced before. The accuracy and detail of these shows that they must have been carefully surveyed for inclusion in his books.

Apart from being a more reliable guide to carpentry practice than any of the previous works Nicholson made two important advances. He was the first author to give a description of the mode of action of a king post truss (74):-

> "Let the two rafters CD, and cd, be firmly fixed to the tie beam Dd, and the upper ends Cc be firmly fixed to the king post E, the joggles being at right angles with the rafters - It is evident that if a weight acts upon the point E, the vertex of the truss, it will not descend; for suppose the rafters to revolve at points D,d, to descend, the points C,c, must come nearer to each other; but this cannot be so long as the top of the king post is incompressible..."

The analysis continues in the same way to consider potential movements at each of the joints in the truss and thus to illustrate the nature of the forces in each of its members.

His other contribution was to abandon, indeed to deprecate, the use of tables of scantlings and instead to show how to calculate the relative strengths of beams and compressive members. He showed how earlier tables were in fact quite unsound in the sizes they gave and instead of relying upon traditional practice he referred the reader to the experimental work carried out on the continent. This was a complete change of direction and one that was to be taken up by writers that followed him (75).

Nicholson seems to have been the right man at the right time. The building and structural needs of the eighteenth century were comparatively simple and it had been possible for the majority of designers to 'muddle along' using little more than well established techniques. There had been little differentiation between architecture and engineering. Only a few men specialised in the latter and bridge design, for example, was still the province of the architect. However the problems were to change in the nineteenth century. The development of roads, canals and ultimately the railways made bridge building a part of the now specialised engineering profession. The introduction of new materials in construction placed greater demands upon the skill and knowledge of the designer so that the simple techniques were no longer sufficient. Designers had to acquire a knowledge of mechanics and strength of materials. Nicholson was the first to introduce these into his text books. Although his books were written in the eighteenth century tradition of instructing the artisan, they provide the rational approach to design that was then needed for the engineers of the nineteenth century.

Footnotes - Chapter 6

1. Hill and Cornforth (1966)

2. Nicholson (1812), pp.162-204.

3. Airs (1975) and Girouard (1966)

4. Airs (1975), p.1

5. Schute (1563), facsimile edition (London, 1912)

6. Wotton (1624)

7. Gerbier (1662 and 1663).

8. An edited version of Pratt's notes is provided by Gunther (1928). North's notes on building are in BM. Add 32540, ff.1-80.

9. Wotton's sources are listed in Chapter 2, fnt.25.

10. Baldi (1621)

11. Colvin (1978), p.336

12. Jessop (1887)

13. Not only does North here show his knowledge of construction by a thorough treatment of building problems, but his knowledge of mathematics is demonstrated in notes on mechanics - BM. Add. 32540, ff.81-140 - and his skill as a draughtsman by his surviving drawings - BM. Add. 23005.

14. Gunther (1928), p.212.

15. Ware (1756).

16. Ibid. p.121.

17. Chambers (1759).

18. 19 Car. II.

19. Richards, Godfrey (1668) This is the second edition of the work. I have been unable to trace a first edition.

20. See Chapter 3, fnt.12.

21. Little is known about Pope; see Colvin (1978), p.651.

22. Primat (1667), subsequently revised by Leybourne (1668) under a different title.

23. Harris (1704).

24. Builders' Dictionary, London (1734). In 1774 the Builders' Magazine was published. This was of larger format and illustrated, while the former was not, but the text was clearly based upon the Dictionary. The author for neither is known.

25. Emerson (1758) stated the same law but it was not referred to in a book on carpentry until Nicholson suggested its use - see below.

26. Campbell R. (1747).

27. Neve (1703). There were editions of Neve's work in 1726 and 1736, the former reprinted in facsimile in 1969.

28. Digges (1592) and More (1602).

29. Bedwell (1631 a & b.

30. Darling (1658). This was revised by Leybourne (1676).

31. Gunter (1685)

32. Leybourne (1669)

33. Salmon (1759).

34. For a catalogue of the first hundred years of Practical Measuring see Wilson (1955). However Wilson's catalogue does not include copies in the Bodleian Library, Oxford, which are the 1st edition, London 1736; 2nd edition, London 1738 and an edition published in 1809 in York.

35. Hoppus produced his own book (see note 49 below) but also revised the work of Salmon (see note 48). Little of his work seems to have been original and he was probably a surveyor rather than an architect.

36. Halfpenny (1725). He also produced Practical Architecture in 1724, which gave dimensions of various architectural details at different sizes, and The Builders' Pocket Companion in 1728 under the pseudonym Hoare. These are guides to the geometry of building. He is also known for books of plans (see note 51 below.

37. Campbell R. (1747), under 'Carpenter'

38. Nicholson (1812), under 'Carpentry'

39. Smith, James (1733)

40. Smith, James (1787)

41. Price (1733). There were subsequent editions of 1735, 1753 and a 5th edition of 1765. The second and subsequent editions were published under the title The British Carpenter with additional plates for each edition.

42. His post as Surveyor to Salisbury Cathedral led to his other published work - Price (1753)

43. Nicholson (1812), p.178. In his general review of the books on carpentry from which this quotation is taken, Nicholson also said - p.202 - "Of the several works quoted, Price's alone can justly claim the title of a treatise on carpentry".

44. Price (1733), p.14

45. Hewett (1974), p.123

46. Oakley (1766)

47. Salmon (1755)

48. Hoppus (1737). There was a third edition in 1748.

49. Halfpenny (1725)

50. The first of these - Halfpenny (1751) - presumably met with some success because it was followed by larger books of plans - Halfpenny (1752a & b).

51. Halfpenny, Halfpenny Morris and Lightoler (1757).

52. RIBA Drawings Collection. The drawing is dated 1739.

53. Langley (1736)

54. Langley (1741)

55. In an appendix to his Sure Guide to Builders, London 1729, Langley discusses the "Several Acts of Parliament now in force". In this he opined - pp. 175-6 - that clay was composed of a mixture of sand and "oily juices".

56. Nicholson (1812), pp188-195 & 202.

57. Wren (1750).

58. Ware (1735)

59. Gibbs (1728). The drawing of St Peters, Vere St., differs from the actual construction.

60. Gibbs (1747), preface

61. Campbell, Collen (1715)

62. Kent (1727) and Ware (1757)

63. Paine (1783)

64. Pain and Pain (1786)

65. Pain (1759)

66. Colvin (1978), p.606. A list of his works is provided

67. Pain (1762)

68. Pain (1794) The revised edition was published by John Weale in 1860. The plates were redrawn and there were some additions to the illustrations, notably the introduction of a more recent form of trussed girder.

69. Dictionary of National Biography

70. He wrote a book on dialing. He also made a valuable contribution to bridge construction with his work on railway masonry. For a list of his works see the Dictionary of National Biography.

71. A poem celebrating the books of Peter Nicholson was published in the Journal of the Society of Architectural Historians 3.

72. See the Architectural Dictionary article on Carpentry referred to above.

73. Dictionary of National Biography

74. Nicholson (1797), pp.65-6

75. eg. Tredgold (1820)

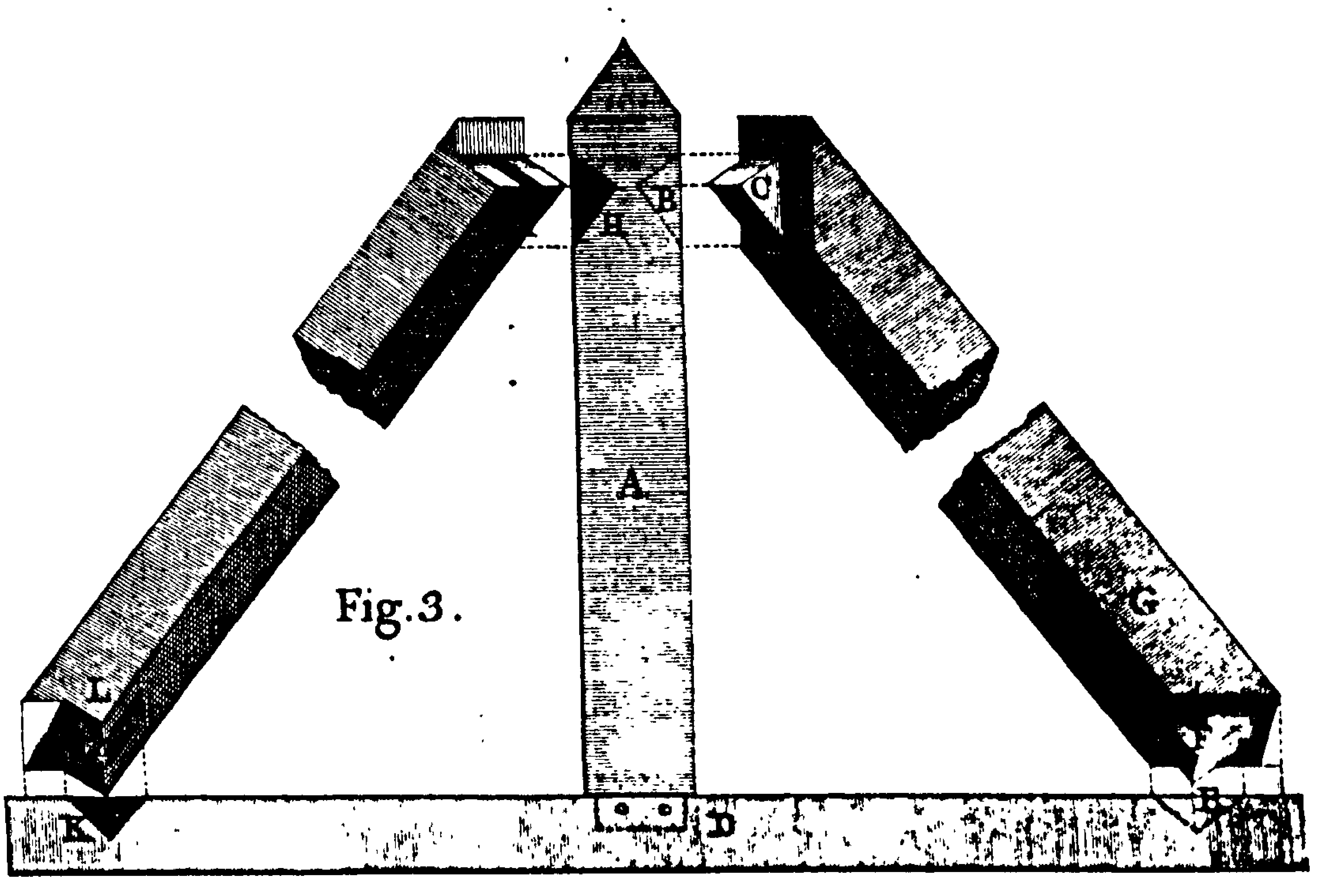


Fig. 6.1

King post roof truss according to Issac Ware - Complete body of architecture

Fig. 1.

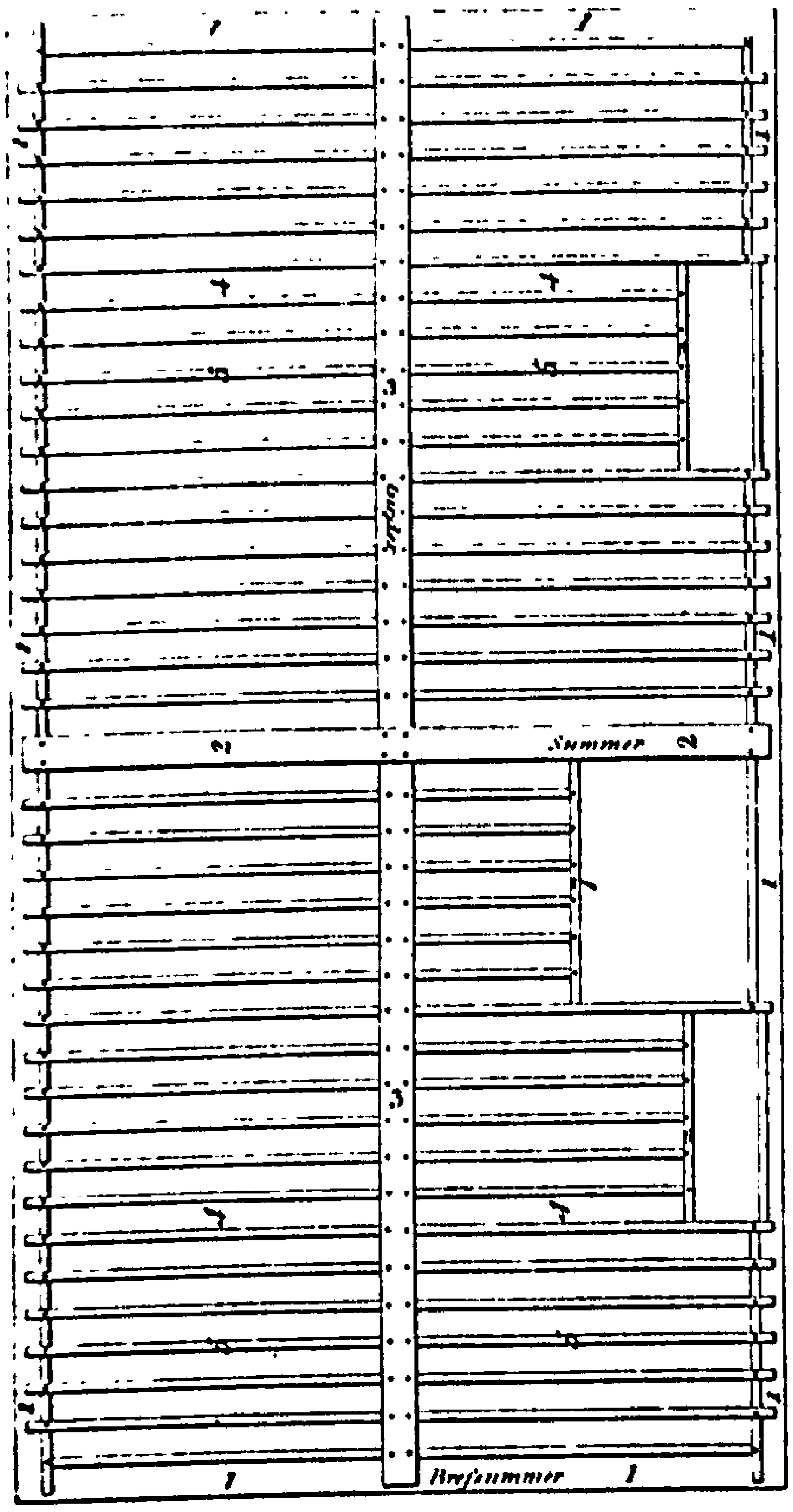


Fig. 2.

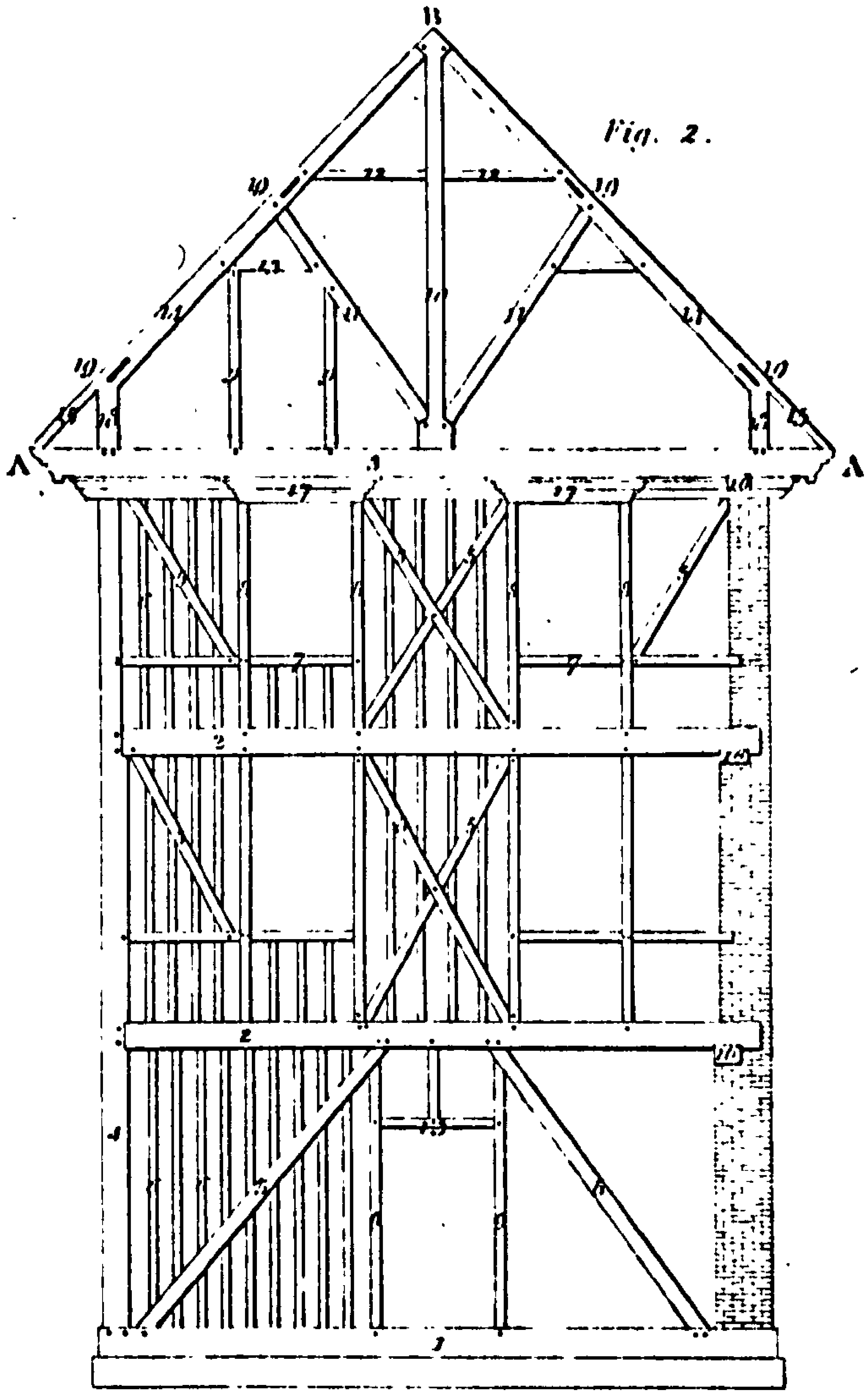


Fig. 3.

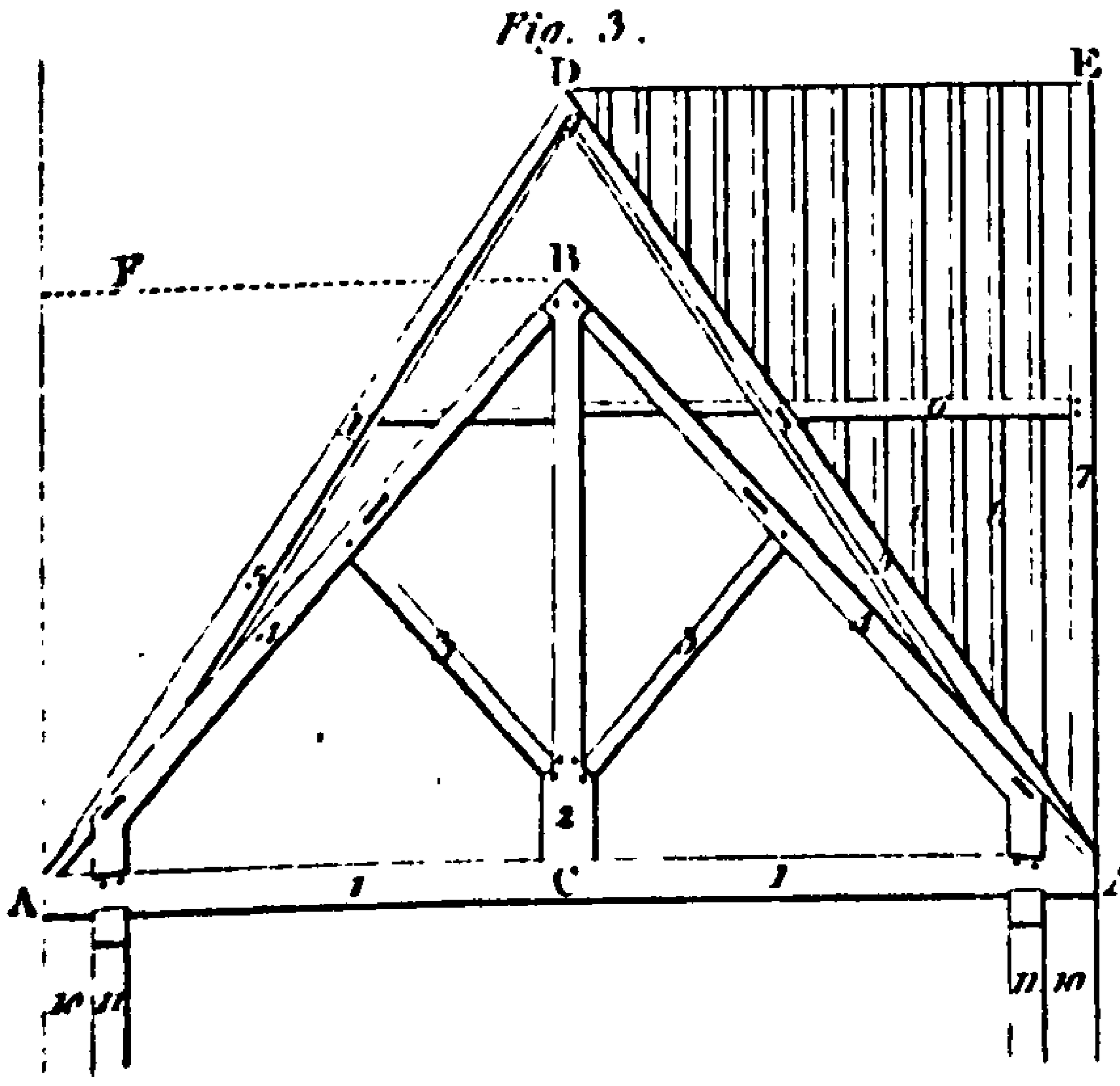
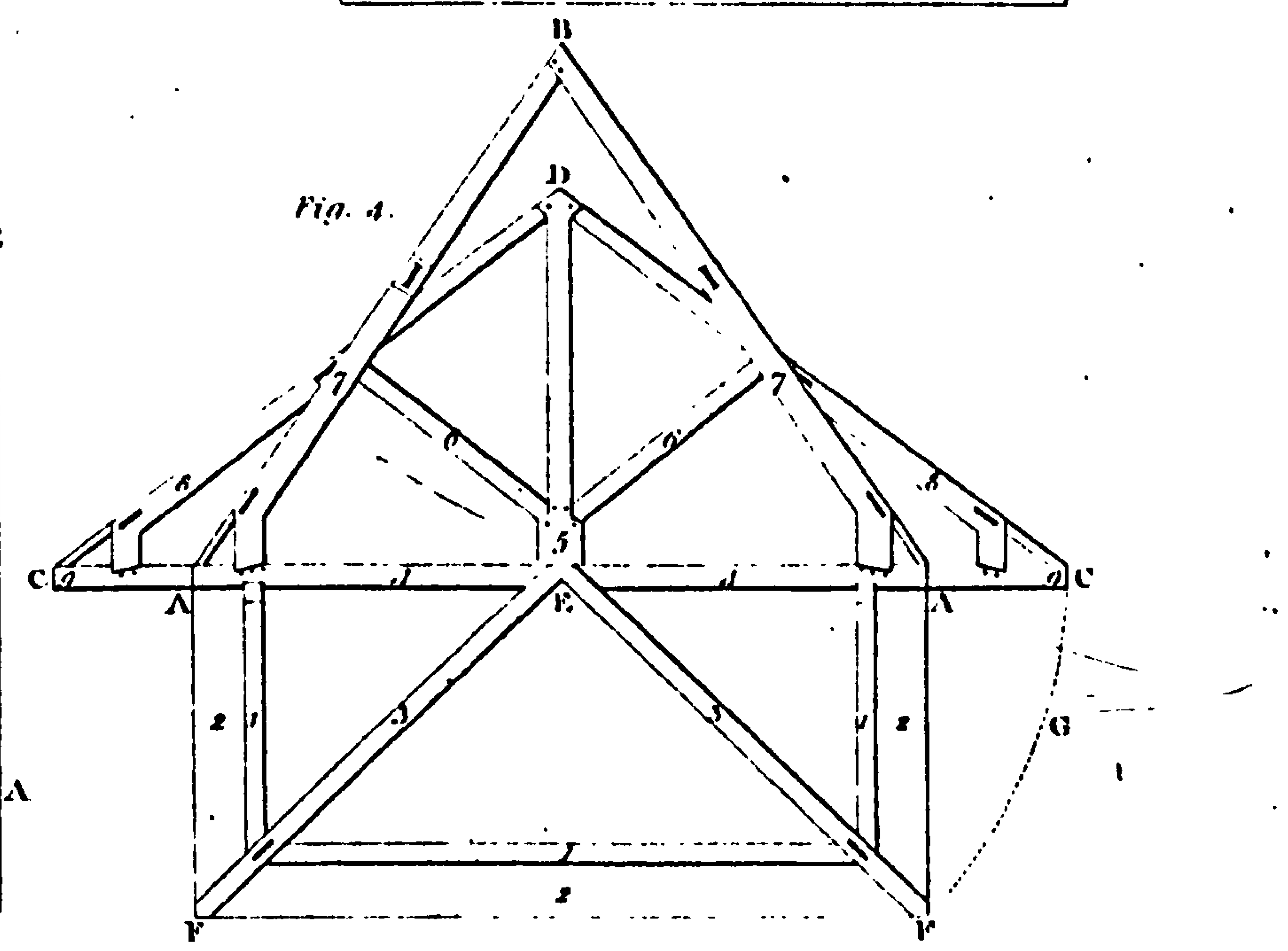


Fig. 4.



by P. Nicholson. London, Published by P. Nicholson & J. Barfield, Wardour Street, 1812. Engraved by J. Taylor.

Fig. 6.2

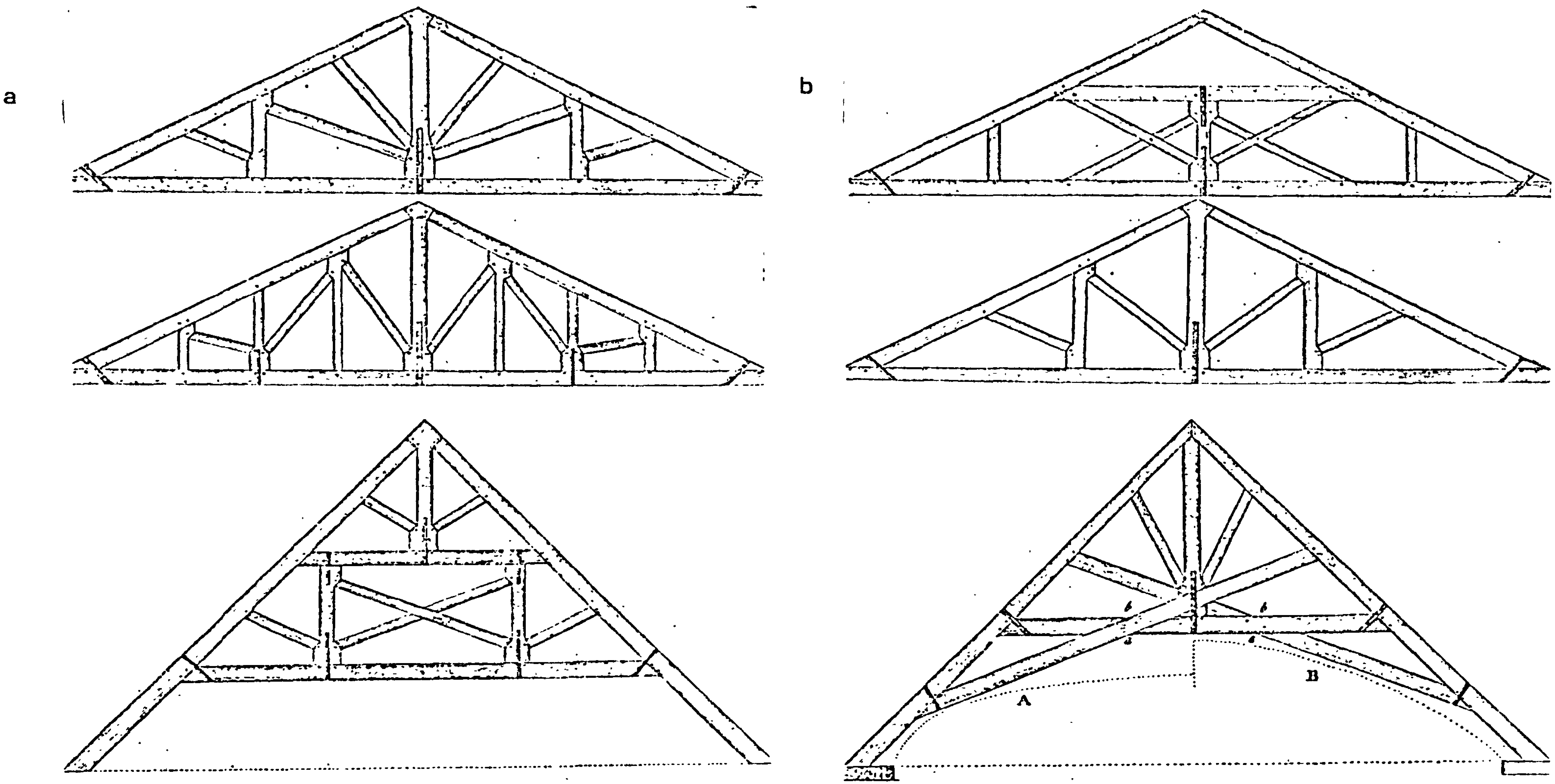


Fig. 6.3

Illustrations from James Smith's <u>Carpenters companion</u>, plates 12, 13, 18 & 22.

Fig. 6.4

Plates G, H & I from Francis Price's Treatise on carpentry.

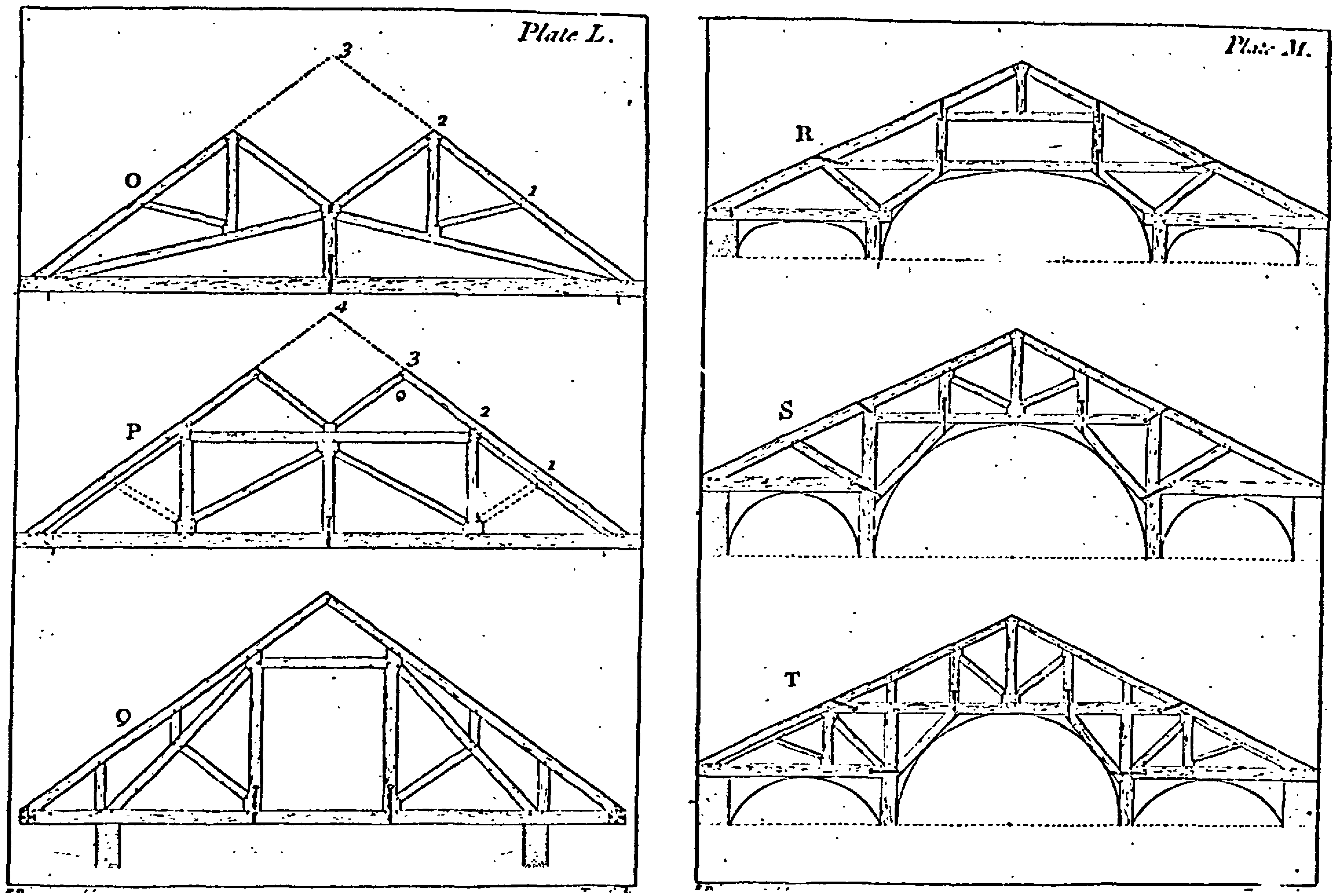


Fig. 6.5

Plates L & M from Francis Price's
<u>Treatise on carpentry</u>.

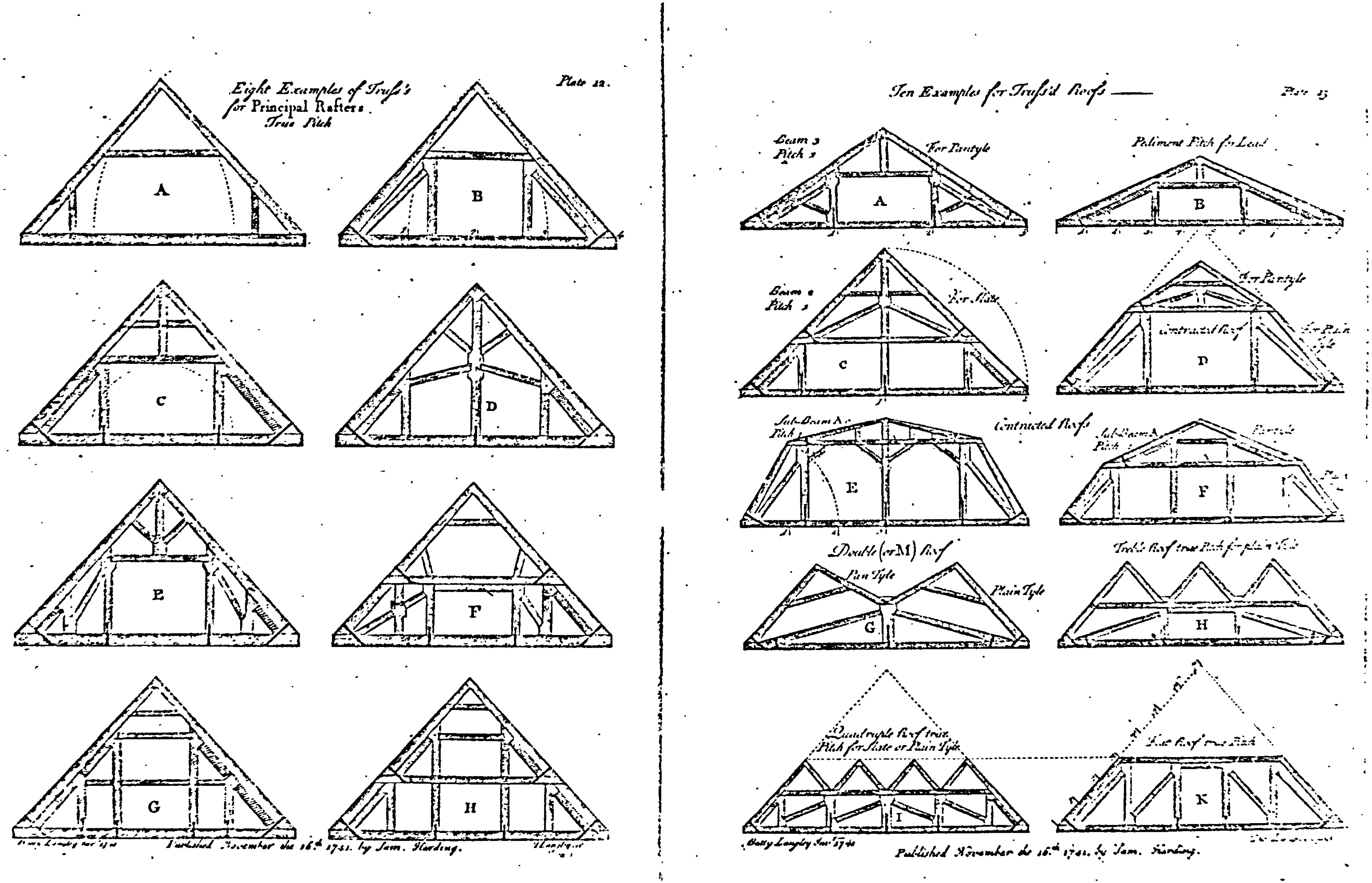


Fig. 6.6

Plates 12 & 13 from Batty Langley's
<u>Treasury of Designs.</u>

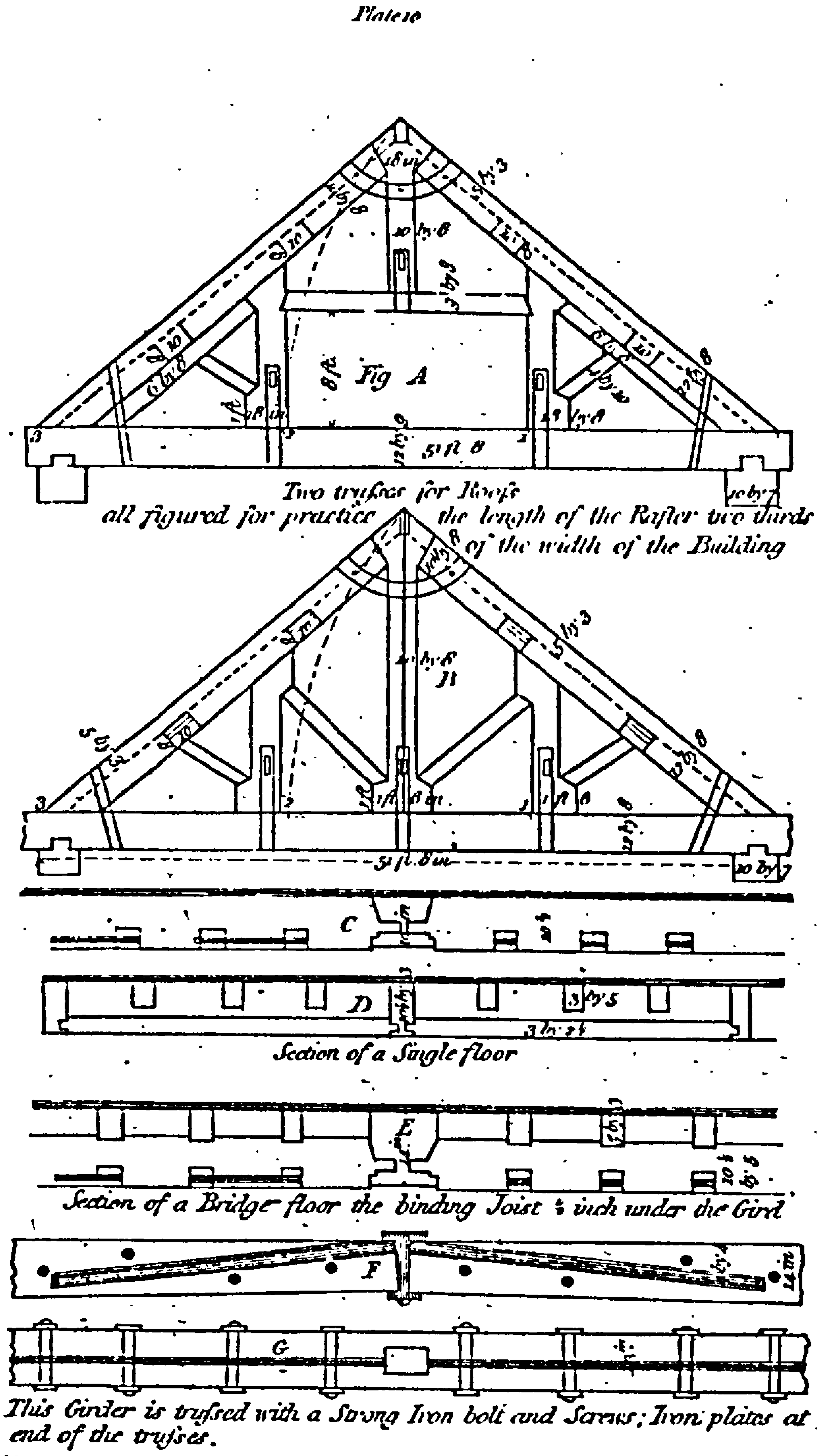
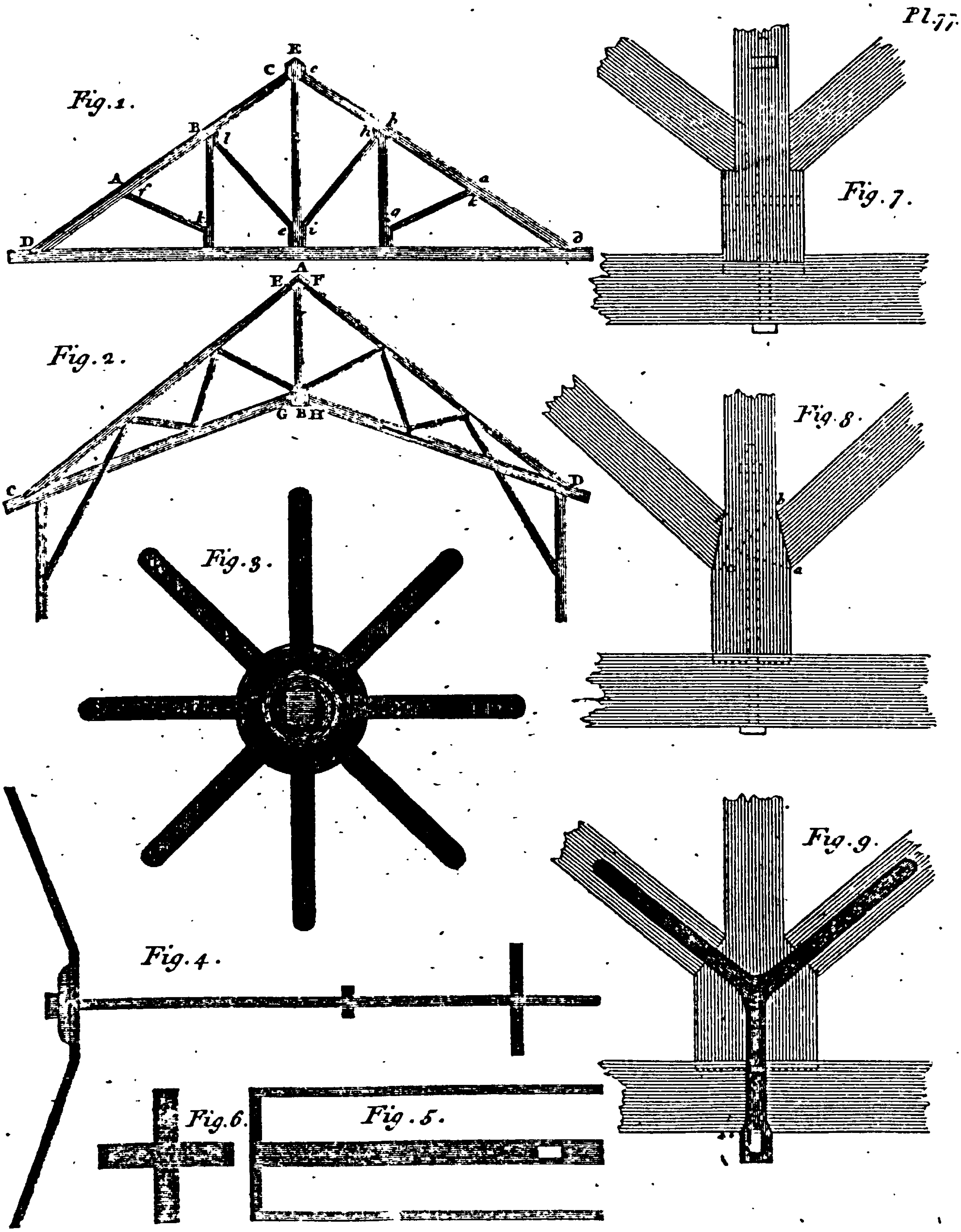


Fig. 6.7

From William Pain's <u>Practical House Carpenter</u>



London Published July [illegible] by I & J. Taylor 56 High Holborn.

Fig. 6.8

Illustration to accompany Nicholson's explanations of the king post truss. Note that Nicholson was concerned here with the details of the truss not the sizing of members.

OTHER 18TH CENTURY TRUSSES

In early Italian texts, the most prominent and clearly-drawn trusses are those of Palladio's trussed timber bridges. So far little mention has been made of these, partly because they received scant attention in the English eighteenth century texts but also because they present rather different design problems from those of roof trusses. To complete the picture, some assessment must be made of the significance of this type of truss and of other truss forms that were also being used. The truss, then, was not simply a device for supporting a roof. It could, as Palladio showed, be used to construct a timber bridge. Trusses might be used to form the centering for the construction of a stone bridge and, in a building, the use of a truss to carry a ceiling as well as a roof is only a short step from using a truss to carry just a ceiling or even a floor. A truss may also be used to form a partition, freeing the architect from the need to have walls on upper floors carried directly by walls below. It was even possible to form a kind of truss within the depth of a floor by using a 'trussed girder' instead of a solid timber beam, thus increasing the spans that were possible in floors.

Unfortunately few of these structures are available for examination. Timber bridges, however well built, will eventually perish and be replaced, usually with stone structures. The timber centerings used for these were, by their nature, temporary and we have to rely exclusively upon contemporary drawings for our knowledge of their form. Although the trusses used in buildings are more likely to have survived, discovering their construction may be difficult because they are hidden within floor or wall structures. It is true that such trusses were commonly illustrated in the carpenters' text books of the period but, as has been seen in connection with roof trusses, these are of doubtful reliability.

Bridge trusses and centers

Building a timber bridge and building the temporary centerings for a stone bridge are similar problems in that similar gaps have to be spanned by both structures. There are differences, however, because whilst the centering must be shaped to correspond to the shape of the arch, a permanent bridge structure must provide an acceptably level roadway. The permanent bridge must be durable although the temporary centering may have to carry greater loads.

Parsons in his book on Renaissance engineering (1) shows the centerings for the nave arches of St Peter's,Rome, for Santa Trinita Bridge and Scamozzi's design for the falsework of the Rialto Bridge. These all have forms which resemble king post structures. The St Peter's structure is essentially an arrangement of struts and there are no joggles on the heads of the king posts. In the other two falsework structures these posts do have joggles to receive other members but they are still not tension members. The Santa Trinita Bridge centre does have struts from the foot of the central post but these struts appear to be there to stiffen the long inclined timbers rather than to carry any load. Thus while king post forms were being used there was no truss action being developed in these structures.

Palladio's bridge designs, on the other hand, do rely upon truss action. Three of his five 'trussed' bridges use a combination of king post trusses. Of the other two, one is essentially an arch formed of braced timber panels and the other, while looking like a truss in elevation, is rather different in plan (fig. 7.1). Instead of the Pratt Truss that we might recognise today, the bridge is seen in plan to depend upon the lower members being cantilevered out from the supports. In the eighteenth century little attempt was made to copy these bridge forms in English texts. Price gives some examples of bridge trusses which are derived from Palladio but he is the only eighteenth century author to do so.

The Thames bridges, in and near London, were sufficiently important to attract considerable attention both of designers and of the public generally. There was great competition over their designs which was not simply confined to the presentation of alternative proposals. The contenders seemed to have no inhibitions about publishing pamphlets which would not only extol the virtues of their own designs but also criticize their rivals' schemes. Such ungentlemanly conduct has left us with some interesting insights into the design methods of the time (2). These eighteenth century bridge designs present a fascinating story that cannot be dwelt on here (3), but the debate over the Blackfriars Bridge designs is the best known of these controversies because it extended into the journals of the time (4). Naturally major engineering works like this attracted public interest and, if everyone was not competent to understand the technical issues of the debate, all could appreciate the impressive scale of the projects and the dramatic nature of the construction. Therefore we have a fair record of bridge works in prints, drawings and paintings (5).

King post or queen post trusses do not need to be used for bridge designs because the functional constraints are quite different from those in building structures. It is the deck of a bridge that needs to be flat rather than its soffit. As Palladio showed, it is possible to form the truss as part of the parapet of the bridge and to suspend the deck from it. This was eventually done in some cases: for example by Nicholson in his Clyde Bridge at Glasgow (1805) (6). Generally,however, there would be ample room below the deck of a bridge for it to be strutted from the piers and this seems to have been a common arrangement. James King's design for Westminster Bridge (1737) used simple struts radiating (fig. 7.2) from the piers. In the event though, a design by Labelye for a stone bridge was adopted (7).

William Etheridge who worked as a carpenter under Labelye during the building of Westminster Bridge used a similar arrangement of radiating struts, although on a much larger scale, in his Walton Bridge (1748-50) (fig. 7.3). His design for the so called mathematical bridge at Queen's College, Cambridge, which was built by James Essex (1750), is a small scale essay in the use of similarly radiating timbers which form, at least visually, an open work arch of timber.

Much the same radiating strut arrangements were used for bridge centerings. Batty Langley's falsework designs for Westminster Bridge were rather primitive (8) but Labelye used an arch like centre in constructing the bridge. Possibly the best known falsework design of the eighteenth century is Mylne's for Blackfriars Bridge (1760-9), made famous through Piranesi's engraving, but a similar form was to be used much later by Rennie in building Waterloo Bridge (1811-17) (9).

Examples of the use of trusses in bridge design can, however, be found. Curiously Isaac Ware, in spite of his apparent ignorance of roof design, shows a timber bridge relying upon king post trusses (10). The king post, and particularly its metal strapping is, however, quite superfluous in this design (fig. 7.4) and only lends support to a poor opinion of his carpentry knowledge. George Dance Jr made a drawing for the centering for an arch of London Bridge which he repaired in collaboration with Sir Robert Taylor (1756-66). The drawing shows the centering formed of three stages of king post trusses, a clumsy arrangement compared with later bridge centerings. It also seems a rather retrograde design for the time. It was criticised in a letter to the London Magazine (11) because of the excessive amount of timber used and an alternative design was proposed (fig. 7.5) on the grounds that there had been recent improvements in the methods of framing timbers.

<u>The trussed partition</u>

The trussed partition appeared during the eighteenth century as a development from earlier and simpler timber partitions. The advantage of this structure was that it freed the architect from the need to have walls on upper floors directly supported by walls of the floors below. This of course was of considerable advantage in planning houses, especially since rooms on bedroom floors or in attics, where servants' accommodation was provided, needed generally to be much smaller than those on the principal floors below. Instead of using a brick or stone wall, the arrangement was simply to have a partition of timber trussed in such a way that it was capable of spanning between the walls on either side carrying its own weight.

Smith and Price both illustrate the use of timber partitions. That shown by Smith is not trussed (12). The only advantage that he claims for its use is that a timber partition is thinner than one of brick, thus occupying less space and costing less. The illustration that he provides shows a partition between a two storey room and two rooms of normal height on ground and first floors. It is thus arranged to carry the joists of the first floor room on one side. Having no trussing in it, it simply rests on the ground. Price in his book, however, shows more than one kind of trussed partition (fig. 7.6) and it is quite clear that these were intended to span between, and be supported by, the walls on either side rather than to be carried by floors below. He shows both king and queen post types, the latter apparently being used in partitions before they were being used commonly in roofs.

Batty Langley also shows trussed partitions but, as with his roof trusses, he gives different designs in each of his books. His <u>Builders' Complete Assistant</u> (13) has a range of trussed partitions spanning from 10 to

50ft. Again both king and queen post derivatives are shown, and his queen post design for the 50ft spanning truss includes a doorway. His Builders Jewel (14) gives designs for three trusses spanning from 40 to 60ft (fig.7.7). In one of these he uses an arrangement of timbers with horizontal members forming a continuous strut halfway between the two floor levels. In this instance the member is discontinuous, being interrupted by the studs, but this and similar designs by Price anticipate an arrangement that was to become common later, when partitions were often divided by a continuous horizontal member into two trusses one above the other. The importance of this development was that it facilitated the inclusion of doorways into trusses because the division could be made by a member running across the head of the doorway. The lower truss would then be framed using a queen post type of truss, while either king or queen post devices could be used for the upper section.

It is probable that trussed partitions were used to carry floors from an early date even though Smith did not recognise the possibility. Pratt (15), in the seventeenth century, wrote somewhat enigmatically:-

> "All trusses coming from other floors ought to lie so much more backward, than they come forward, otherwise they will much lose their strength in supporting, not having that counterpoise which is requisite in them.
>
> Sometimes the same timbers may be so layed as to become trusses to two several floors. As near as may be they are to take up these timbers to which they are trusses, in the weakest part of them which is nearest the middle."

The first sentence suggests cantilevering but without a drawing Pratt does not make this clear. The indication is that, whether as partitions or not, trusses may be used to support a floor. At Clandon Park, Guildford, a queen post truss was used to support the ceiling over the hall; and a queen post truss was also used to support a floor of Vanburgh's Foundry at Woolwich Arsenal (16). Neither of these is a partition.

Price and Langley both show how metal straps are to be used at the feet of the posts that carry the lower chord of the truss. We may assume therefore that they believed there were tensile forces in these members. Unfortunately, however, the illustrations of this type of structure in these early text books were not as clearly drawn as the roof trusses and it is difficult to see in detail how they were built. The problem is to know whether or not each was regarded as capable of carrying a floor loading as well as its own self weight. Nineteenth century text books show that by then this was the intention (17) but without more evidence from actual buildings it is not clear when this practice was introduced. Given the doubtful reliability of some early carpentry illustrations, the exposure of actual trusses (possibly during restoration work) is required before their development can be reliably described.

The only example of a trussed partition that I have been able to examine so far is at Moor Park where the top few feet of a substantial truss,which forms one of the walls of the stairwell, is visible in the roof space. This probably dates from the early eighteenth century remodelling of the house. The jointing of this truss is unremarkable, being, as one might expect, essentially similar to the jointing of roof trusses with posts having joggled heads to receive the struts. However, not enough can be seen of the structures to determine what it is carrying. In some houses the presence of such partitions may be inferred from the position and size of floors on upper rooms and from the position and size of floors on upper rooms and from the section of the house (18). One might therefore expect that if the direction of floor spans could be determined, the function of the partitions would then be known. However, it is also possible for floors to have been carried by trussed girders whose position and presence are even more difficult to detect.

The trussed girder

The trussed girder was a device for increasing the strength of a simple timber beam. By providing some arching action within the beam itself, and at the same time introducing some pre-cambering, the strength of the beam could be increased and its deflection under load reduced without any increase in the depth of the floor which it supported. At least that is what architects and carpenters must have imagined at the time. Like the trussed partition, this improved the architect's freedom in planning his rooms.

Practicable designs were commonly illustrated in nineteenth century text books where a variety of types was shown. By the nineteenth century a girder might be 'trussed in its own wood', trussed with iron, or simply trussed with flitches of hard-wood. This last method was commonly used during the eighteenth century. It involved two or three pieces of hard timber let into a beam in such a way that they formed an arch shape within the beam. The method for doing this is adequately described by Smith (19):-

> "The manner of trussing a girder is first to saw the girder down the middle the deepest way; then take two pieces of dry oak, about four and a half inches wide and four inches thick; let half the piece be let into one side of the girder and half into the other, as you see in plate the fourth. fig. 1 mark'd a a, which are the two trusses; fig 2 is another way which is by cutting the girder thro' and driving a wedge against the ends of the trusses, as the wedge d, when these are thus prepared,

bolt them together with iron bolts and keys, or much rather a screw at the end of the bolt."

For greater clarity this is also illustrated in fig. 7.11. Price (20) also showed the use of three pieces of timber to truss a girder of which he says:-

"... is yet a stronger method, because it divides the bearing into three equal parts".

It might seem from Smith's description that the result was a beam which appeared externally to have been cut down the middle and bolted together again. However, in practice the flitches were not completely let into each half of the beam, so that when these two halves were brought together they did not completely meet. The timber flitches can then be clearly seen from the top of the girder and so this structural device is fairly simple to identify. If a girder were found that did appear to have been cut down the middle and bolted together again it would not necessarily mean that it had been trussed because as Smith points out:-

"Some carpenters cut their girders down the middle, and bolt them together without trussing only changing the ends different from what they grew, whereby the grain of the wood is crossed and it becomes much stronger than if it had continued without sawing down the middle, and thus putting it together".

Price in his British Carpenter is more explicit about the origin of this arrangement, correctly crediting Alberti with the idea (21).

The origin of the trussed girder remains obscure. The earliest illustration of a structural device resembling a trussed girder was provided by

Jousse (22). In his Theatre de Charpenterie he shows girders trussed with both two and three pieces of timber but his trussing is external to the girders, being placed above them. The trussing pieces in his structures strut against small blocks of timber, much like diminutive king and queen posts. In some building applications this form of structure would have been acceptable. A truss in a floor, however, has to be shallow and present a flat top.

The trussed girder was not mentioned in an English text book until the works of Price and Smith,quoted above, both of which were published in 1733. However, it is clear that the form was already in common use. Accounts for work done at Whitehall Palace (23) show that a trussed girder was used there as early as the 1680s. There are a number of references to trusses, but for that over the Queen's bedchamber the size is given as 24ft x 2ft x 2ft. The size of this timber is too large for the truss to have been for a roof: beams of about 12ins square were the norm for spans of this order. It may therefore be concluded that this was a trussed girder. John Grove was carpenter for the work at the Palace and his own account book (24) also has a number of references to trusses giving prices for their framing in both oak and fir.

Neither Grove's price book nor the building accounts provide sufficient information to reconstruct the precise form of the trusses used. Therefore there must be some question about their design because early trussed girders in buildings by both Wren and Hawksmoor take quite different forms from those shown in the early text books.

When restoration work was carried out on the library at Trinity College, Cambridge, in 1921, a form of trussed girder was found in the floor structure to carry the heavy bookcases above. The structure was described at the time by Fletcher (25) and his drawings are reproduced here (fig. 7.8). These show that the trussing is on either side of the beam or girder, rather than having been let into its centre. It is thought, however, that this is an early modification to the structure made shortly after its completion, when it was discovered that the untrussed timbers were insufficient to carry the weight of the bookcases above (26). Whether or not this is so, similar trussed girders have been found in floor structures at Blenheim Palace. For one of these I have to rely on a survey drawing made some years ago (fig. 7.9), and the precise location of this construction is no longer known (27). Similar trussed girders are, however, still visible in another part of the building. The Blenheim trusses differ from those at Trinity in being composed of a number of timbers bolted together, rather than having one large member cut away to let in the trussing pieces.

This method of trussing has not been found elsewhere and its use may have been confined to Wren and Hawksmoor.

The advantage that it would have had over other types is that there would have been no need to cut the beam down the centre, surely a laborious job. On the other hand it must have been more difficult to ensure a tight fit between the various parts of the truss as there was no provision for driving in wedges to tighten the pieces of timber against each other.

While the transverse girders at Trinity College are externally trussed the longitudinal girders have a form of internal trussing. Each girder comprises a pair of horizontal timbers, between which there is a simple arch of two inclined pieces resting on a lower support at the head of the column. Although this arrangement involves the trussing timbers coming from below the soffit of the girder (an arrangement that is clearly less convenient than having a flat soffit, creating as it does a large ceiling void) it can easily be seen as a possible forerunner of the trussed girders described by Price and Smith. If the arch was made shallower and then enclosed within the structure of the girder, a flat soffit would have been achieved and the supports for the girders could have been simplified. It is thus possible that the type used at Trinity was the form from which the standard trussed girder was to develop.

Perhaps an early example of this standard form was used at Iver Grove, Buckinghamshire. This house, built in 1722 and attributed to Vanburgh, was restored by the Ministry of Works in the 1950s. Progress photographs (28) taken during the restoration include those of a floor girder with a longitudinal cut and bolting that suggests that it may have been trussed. In the absence of records to the contrary I assume that this girder dates from the first building of the house. Unfortunately the carpenter is unknown and insufficient records exist to be certain about the origin of this structure.

Easily datable trussed girders, however, survive in the roof at Osterley House. This roof comprises several parallel pitches, of small span, formed with simple coupled rafters. The feet of these rafters are carried on pole plates which in turn are carried by trussed girders spanning between outer and inner load bearing walls. The structure can be accurately dated because a carpenter's bill of 1736 survives for alterations to the house (29). This bill is itemised in sufficient detail to enable identification of several pieces of work then carried out. Among the items are several relating to the roof and to these trusses. Comparison of the trusses built at Osterley with the drawings in the text books shows that the former are of relatively simple design. It is this simple design that must have been most commonly used rather than the elaborations described by some of the authors of the books, because, where other trussed girders have been seen, they all have a similar simple arrangement.

If the technology of the trussed girder was well established by the time these early text books were produced, then it seems as if their authors were concerned to develop it even further. There were already a number of alternative designs in use and yet both Price and Smith offer their own variations; nor were they the only authors to do so. Some of the arrangements that they show seem sensible, but others are clearly not. The problem is to determine which may or may not have been used in practice. Some bizarre designs can be clearly rejected as quite impracticable. For others, prototypes might have been tried even though their designs may not seem to us to be very convincing.

Of the simple designs for trussing, where two or three flitches of hard timber were let into the girder, two arrangements were possible. The chase, cut to take the flitches, could be continuous allowing them to meet, or separate chases could be cut leaving a gap between the flitches. Elaborations on this simple theme had additional pieces of timber included between the flitches and at the ends for them to butt against. All these arrangements however are 'passive', relying upon the trussing timbers to take up their loads only when external loads came onto the girder. Other methods used a wedge or wedges to tighten the flitches and possibly to pre-camber the girder. In the simplest of these designs a wedge was used at the centre of the beam and between two flitches to drive them apart and back against their end stops. If the basic design of the girder incorporated a dovetail piece at the centre, between the two flitches, this could be improved by forming it in two pieces so that a wedge could be driven in between. Timber wedges could be used in each of these designs but wedge shaped iron bolts were preferred. (fig. 7.10).

The text book authors took these active designs as the starting point for their less practical arrangements. Price describes an extremely complex combination of flitches and wedges (30), viz:

"in g. h, i is shown the manner of trussing girders that are to bear above twenty four feet.

First cut two pieces of timber, which together make the scantling proposed, with some good, dry, and strait grain'd English Oak, of four inches by three, or six inches by four, as the nature of the thing shall require. Let half into one piece as in g, at l, m, n, as tight end ways as it is possible to drive them in; then cut a vacancy in the other half, as h, which shall drive also on that of h, as tight end ways as that of l, and m, as is possible; lastly bolt them together, as is shown above and they are fit for use."

An example of this structural arrangement has not so far been found and, until it is, its practicability must remain in doubt. Price provided the soundest text book of his day and the designs that he showed seem for the most part to be sensible. There is therefore some possibility that his design might have been tried out, but it does seem rather elaborate. Smith on the other hand gives a design for a trussed girder that can surely never have been used by any carpenter in practice (at least not with any satisfactory results) (31):-

"In plate the fifth (fig. 7.11) you see those two trusses that I spoke of, marked 3, 4, of my own invention with one inverted arch I propose that made of iron mark'd A, which is let into the trusses. The upper one I take to be of greater strength tho' the trusses are inverted; for the pressure being upon the arch, whose buttment is good, I think a great weight can in no way occasion the bending of the girder."

Smith does admit to the device being of his own invention but he was not alone in presenting such fanciful designs; and even greater claims were made for them. Oakley (32) gives the following recipe:-

> "... first provide yourself with an English oak plank about three inches thick, out of which to cut your trusses, then suppose B to be the upper side of the girder, in which first to begin to fix your dovetail piece marked a, which must have a good bearing at fig. 1. then proceed to let in the truss marked o, so as to have a good bearing at 2, and at the same time fix the bracing truss marked n, fix the next dovetail piece so as to have a good bearing at 3, and so in like manner, till all the trusses and dovetails are fixed, then by driving the wedge, which must not be too taper, you will tighten the whole work, and if properly executed will cause the girder to spring an inch or more. I have seen this applied to practice."

The italics are Oakley's. However in spite of his emphasis the application of such a method to practice is beyond my imagination. It seems curious that Oakley should feel the need to emphasise the practicality of the device. Did he perhaps appreciate how unlikely it must have seemed? In his review of the eighteenth century texts, Nicholson is quite damning about Smith's design, and might well have been of Oakley's as well had he bothered to include it in his review. He says of Smith's design (33):-

> "Nothing could be more unmeaning than these examples. The observation ... is void of principle and contrary to mechanical strength."

The purpose of trussing a girder, by whatever means, was to limit its deflection; but the effectiveness of any method must have depended upon the manner of assembly and the degree of skill with which this was carried out. Salmon gives a recommendation on the way that the truss should be put together. Quoting a 'judicious builder' (34) (although he does not say whom), he recommends that:-

> "Girders are best trussed when they are first sawn out, for their drying and skrinking, it tightens the trusses in them yet the more."

As suggested by Oakley, where trusses used wedges, the intention may also have been to apply some precamber. William Pain recommended that (35):-

> "The girder ... be cut one inch camber in 20ft etc notwithstanding they are to be trussed."

Pain shows clearly the way that the trussed girder, and also the trussed partition, might be used in framing a house. In his book of plans (36) he shows the layout of floor timbers and even draws out the trussed girders in elevation to show how they should be framed. The continued use of the trussed girder throughout the 18th century saw it being introduced as an element of the larger roof trusses. In a theatre the roof structure over the stage would have been used to carry scenery and the lower chord of the truss would have been subjected to considerable bending loads. Henry Holland overcame this problem in his roof for Covent Garden Theatre by using a trussed girder in the lower chord between the queen posts of his roof truss (37).

In the nineteenth century there were further developments in the trussed girder but it was then also demonstrated experimentally that a trussing in fact added nothing to the strength of a beam (38). Today we can see clearly that the removal of one piece of timber from a beam, and its replacement by a similar piece of timber, even if at a different angle, would do no good. The only effect would be to precamber the beam by the tightening of wedges against the flitches and it is possible that the reduction of the deflection was seen as evidence of increased strength. Iron structures which were also called trussed girders were devised during the nineteenth century; but these relied upon different structural principles and fall outside my interests here.

I have dwelt on this form of structure rather more than on the bridge trusses and trussed partitions because the former have at least some family resemblance to the roof truss. The only resemblance one can see between the trussed girder and the roof truss is in the arch action developed by the flitches in the former and the principal rafters in the latter; but it is by no means certain that this analogous behaviour was appreciated when the trussed girder was being used. Nor would I necessarily assume that there was any connection between the 'invention' of this form of construction and the 'discovery' of the roof truss.

The first known use of trussed girders in this country was by Wren and, given the earlier illustrations by Jousse, one might assume Wren brought the idea from France, but it is also possible that the device had earlier origins in this country. If so, then the forms that we find being used by Wren and by Hawksmoor are simply adaptations of an existing device.

In his history of the London Carpenters' Company, Jupp (39) cites one of their rules of 1654. This states that:-

"When any chimney shall be set upon a truss of timber that it shall be set two foote six inches from the upside of the truss to the upside of the floor."

The regulation appears to be a fire precaution. It is quoted by the O.E.D. as the earliest use of the word 'truss' in building and although the definition in the O.E.D. refers to a trussed framework it is possible that this regulation refers to a trussed girder, being used as the support for the base of a chimney.

At present there is simply not enough evidence to come to any conclusions. More examples of this type of structure need to be discovered before any reasonable suggestions about its origin can be made. By the time our earliest known examples were built the form appears to have been well established.

Footnotes - Chapter 7

1. Parsons (1976)

2. Westminster Bridge attracted many designs with pamphlets published by Hawksmoor, Batty Langley and John James. In these, there are different ways of calculating the effect of the obstruction by the bridge piers to the flow of the river.

3. For an account of eighteenth century bridge engineering see Ruddock (1979).

4. A summary of this can be seen in the Dictionary of National Biography under the entry for Mylne.

5. The best known must be Piranesi's engraving made from a drawing sent to him by Mylne. BM. Kings Maps xxii, 38d.

6. An illustration of this appears in Nicholson (1812).

7. BM. Kings Maps xxii, 37.

8. Langley (1750), plate lxii.

9. The centres for these two are compared by Tredgold (1820), plate xv, although many other illustrations of them were produced.

10. Ware (1756).

11. The Dance drawing is in BM. Kings Maps xxii, 36, 1, i. His use of the design is confirmed by a letter to the London Magazine, 1759 pp.672-3.

12. Smith, James (1733), plts. 6-8 and Price (1733), plt.N.

13. Langley (1738)

14. Langley (1741), plt. 83.

15. Gunther (1928), p.248.

16. The structures are shown in photographs of the interiors at the National Monuments Record

17. See for example Newlands (1857).

18. The presence of such partitions may also be inferred from eighteenth century books of plans

19. Smith, James (1733), p.16.

20. Price (1733), p.6

21. Ibid.

22. Jousse (1627), p.150.

23. Reproduced in the Wren Society VII, p.88 are the extracts from the works account. Grove's bill relating to this, dated January, 1685, appears on p.100.

24. BM. Add. 30092. The book has references to carpenters' work in the Royal Palaces between 1686 and 1715. There is an item, f.3, describing a truss of the same size as that referred to above but there is nothing to show whether or not it is the same one.

25. Fletcher (1923), pp.388-91.

26. I am grateful to Mr Peter Locke of Donald Insall and Associates for this information

27. Drawings were kindly supplied by Mr Chris Rayson, the present architect to Blenheim Palace. They were drawn by his late father.

28. Ministry of Works (now D of E) photographic collection

29. Victoria and Albert Museum

30. Price (1733), p.6

31. Smith, James (1733), p.16

32. Oakley (1766), plt. 39

33. Nicholson (1812), in an article on Carpentry pp.177-9

34. Salmon (1755)

35. Pain (1759)

36. Pain (1786)

37. An illustration of this may be found in Nicholson (1826), plt. 123.

38. Barlow (1817), reports the results of experiments that he carried out on this form of construction.

39. Jupp (1887), p.36. but quoted by the Oxford English Dictionary under 'Truss'.

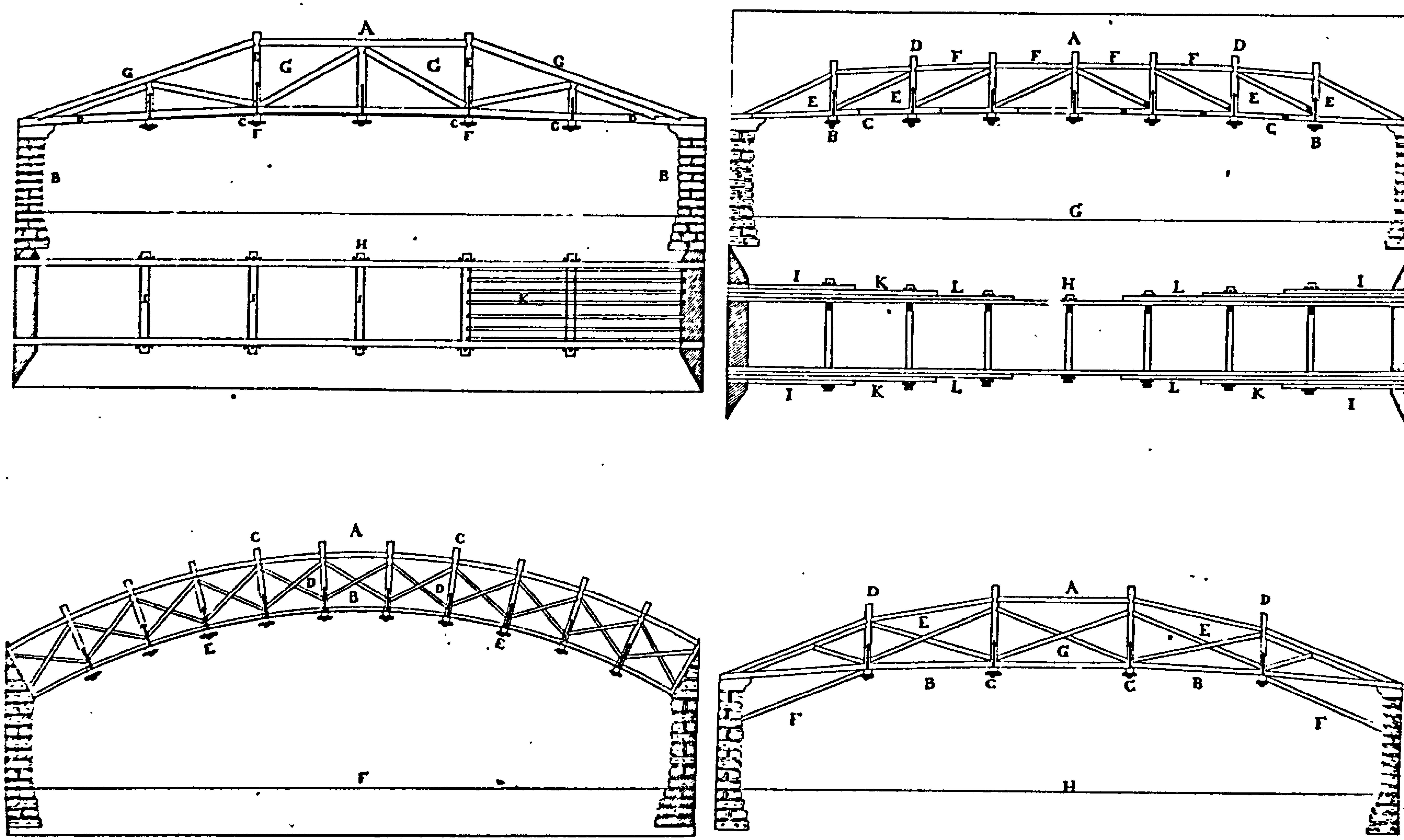


Fig. 7.1

Bridge designs from Palladio
Third book of architecture

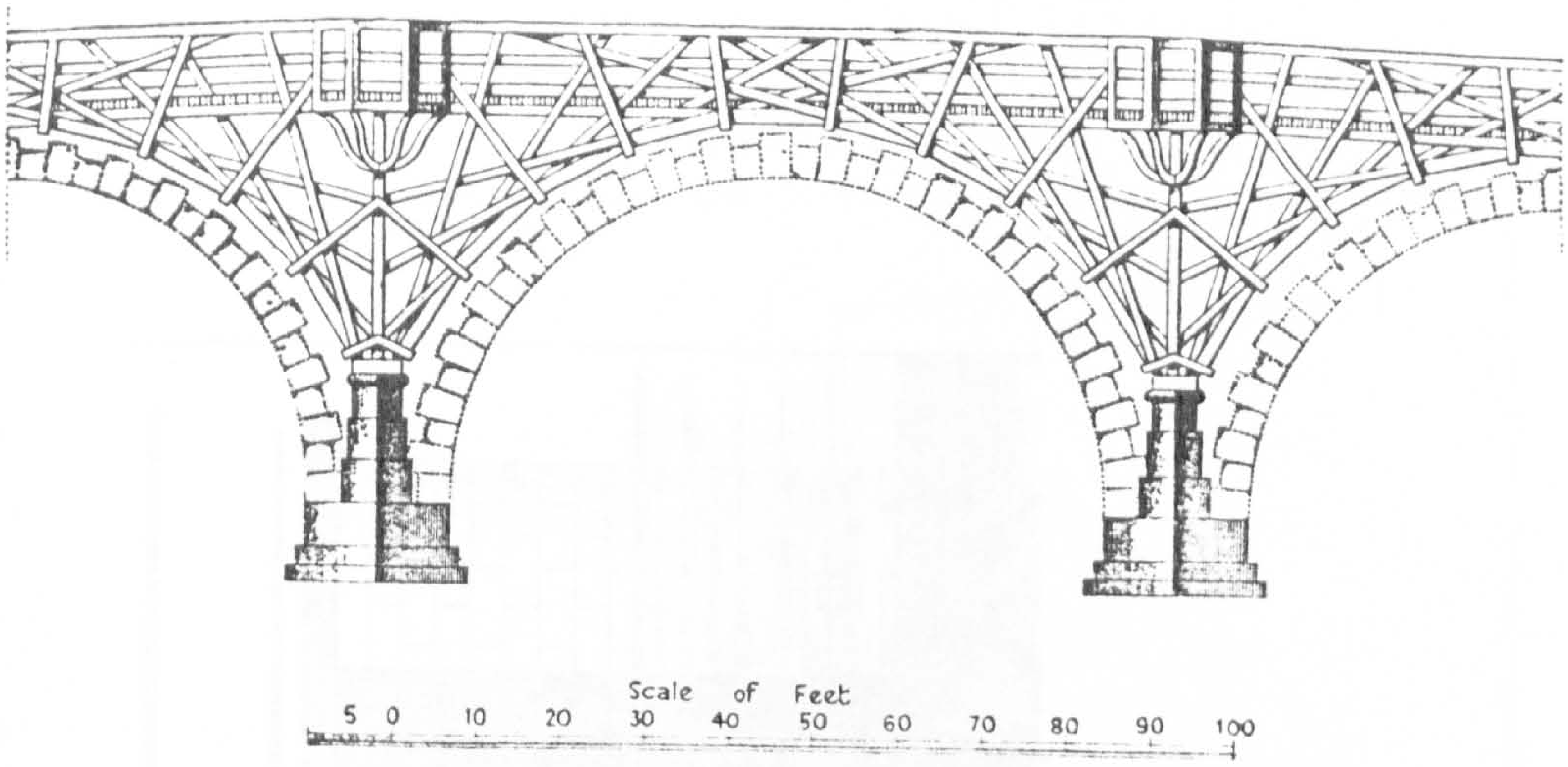


Fig. 7.2

James Kings design for a timber bridge at Westminster with the profile of Labelye's stone bridge superimposed. This illustration is reproduced from the Oxford History of Technology Original drawings are in King's Maps.

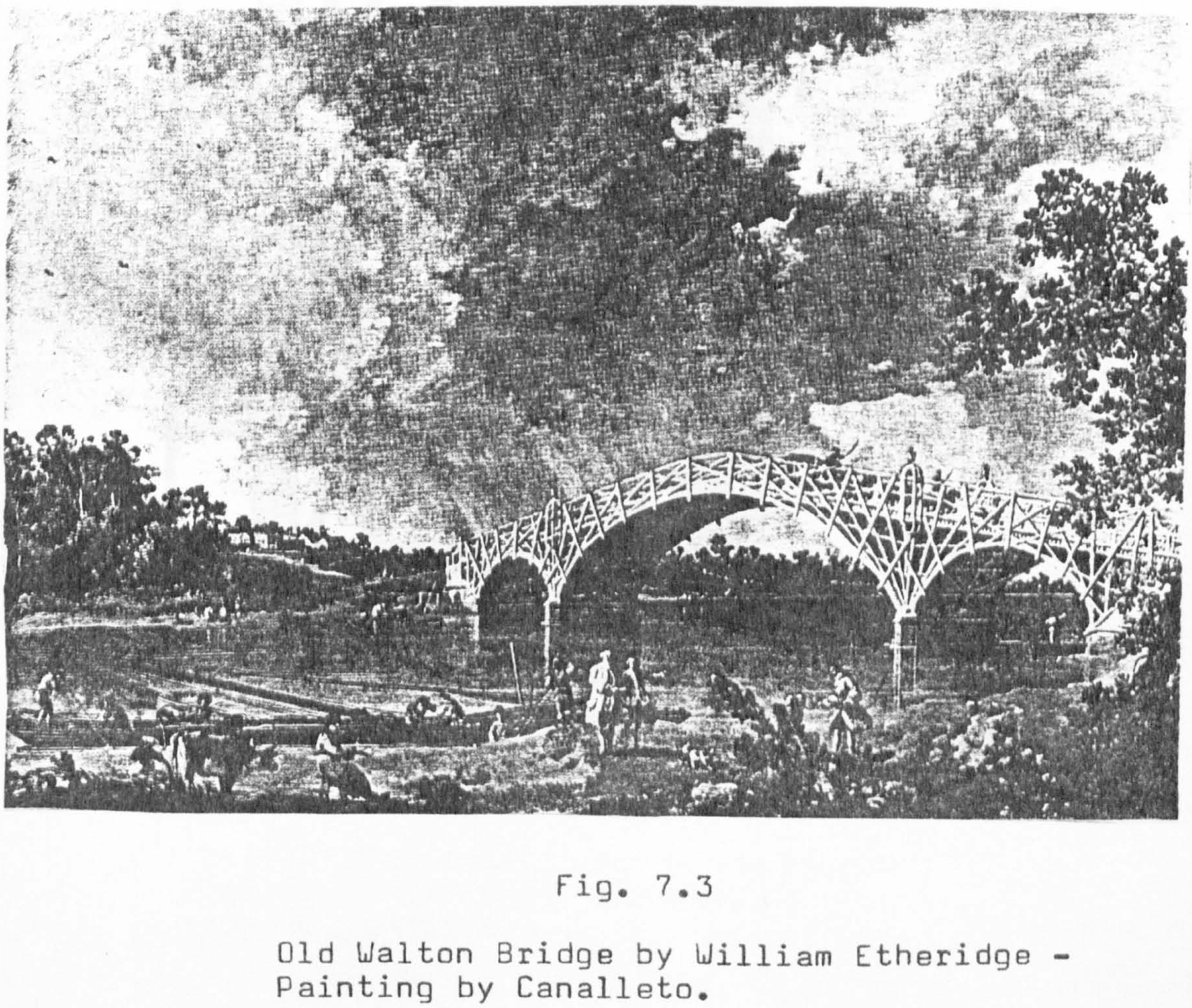


Fig. 7.3

Old Walton Bridge by William Etheridge - Painting by Canalleto.

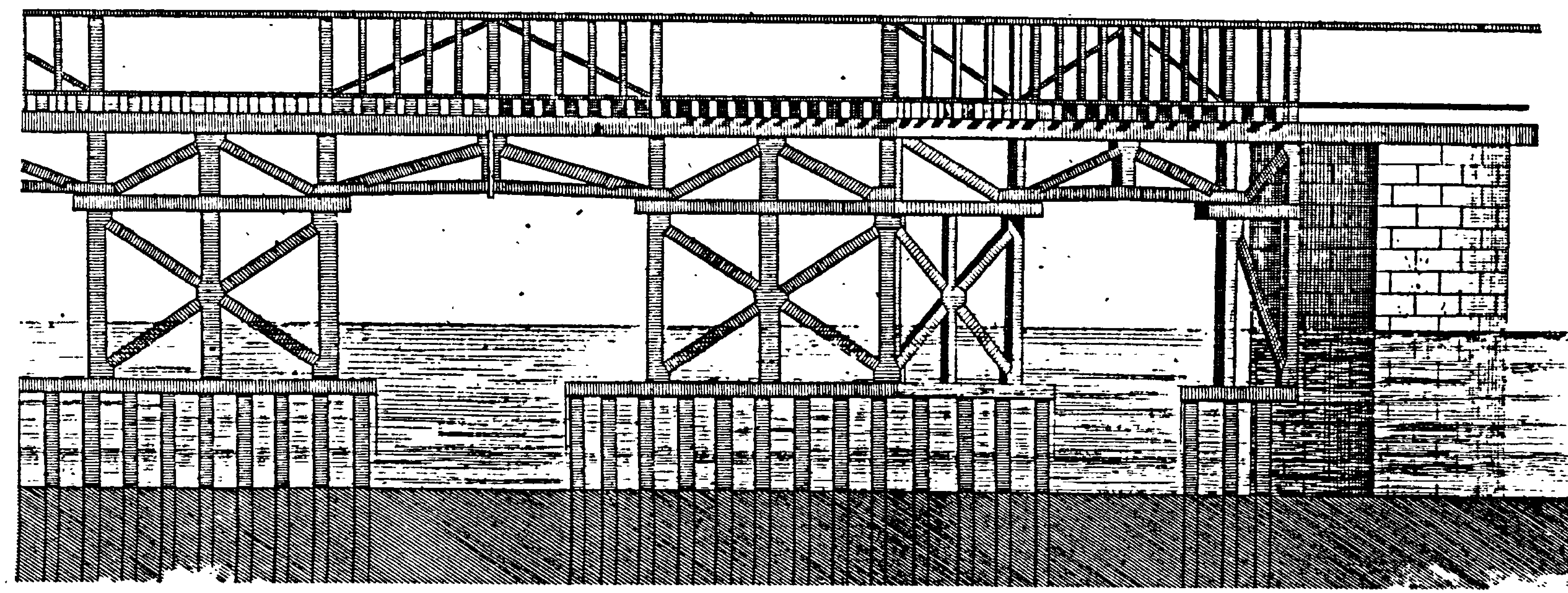


Fig. 7.4

Ware design for a timber bridge.

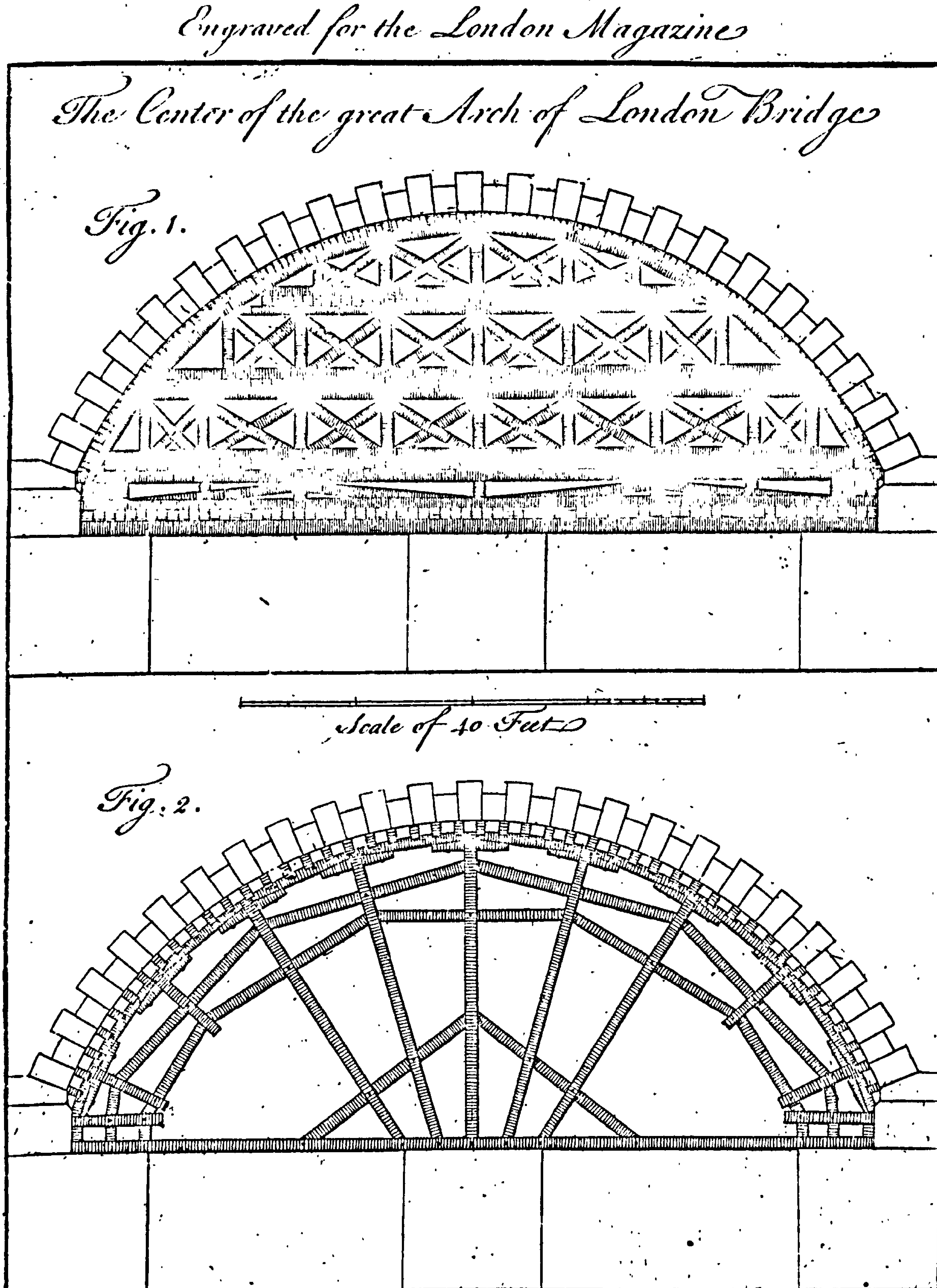


Fig. 7.5

Alternative centerings. Arrangement used by Dance (top). Anonymous proposal (bottom).

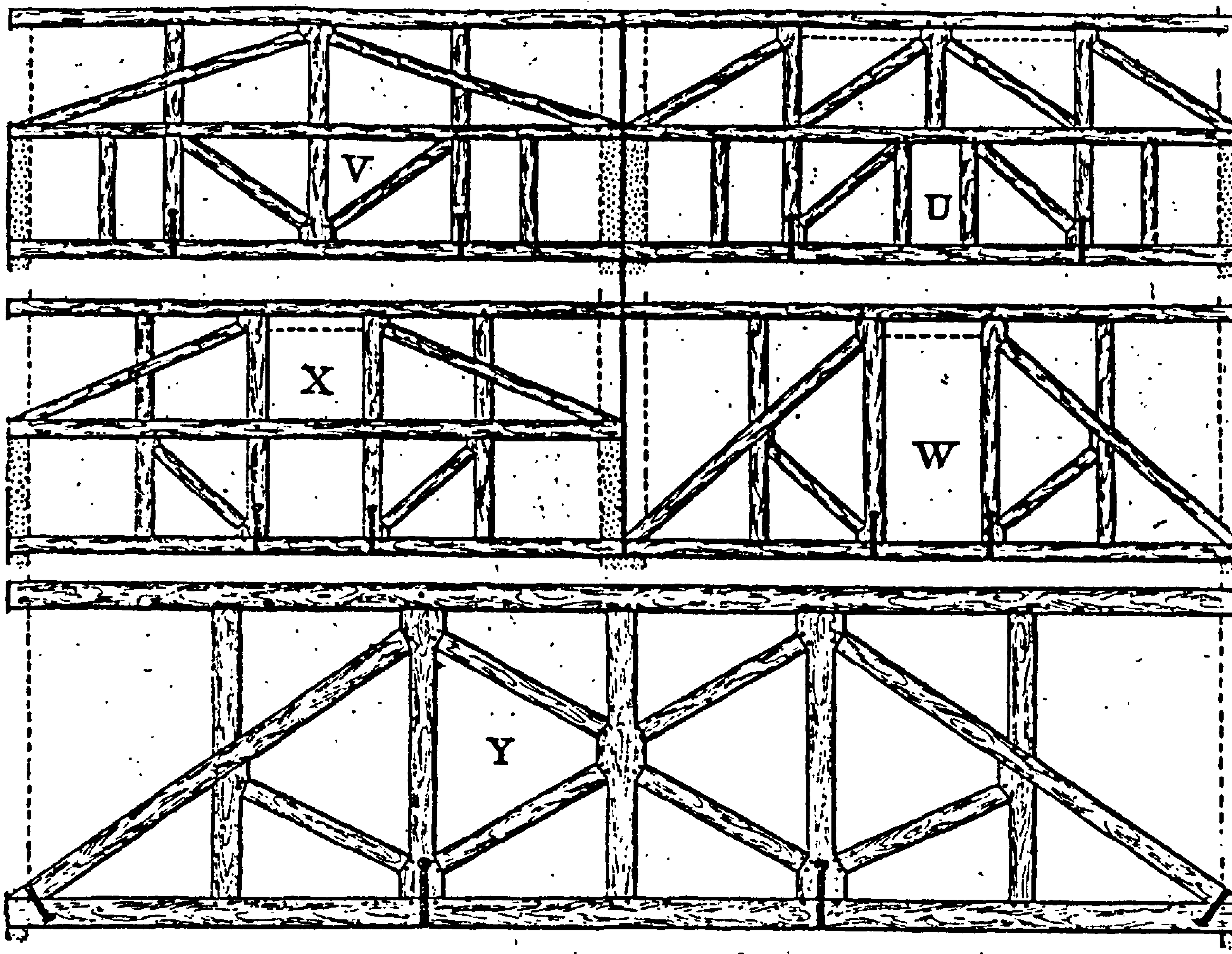


Fig. 7.6

Trussed partitions from Price, F. British Carpenter, 1765, Plate N.

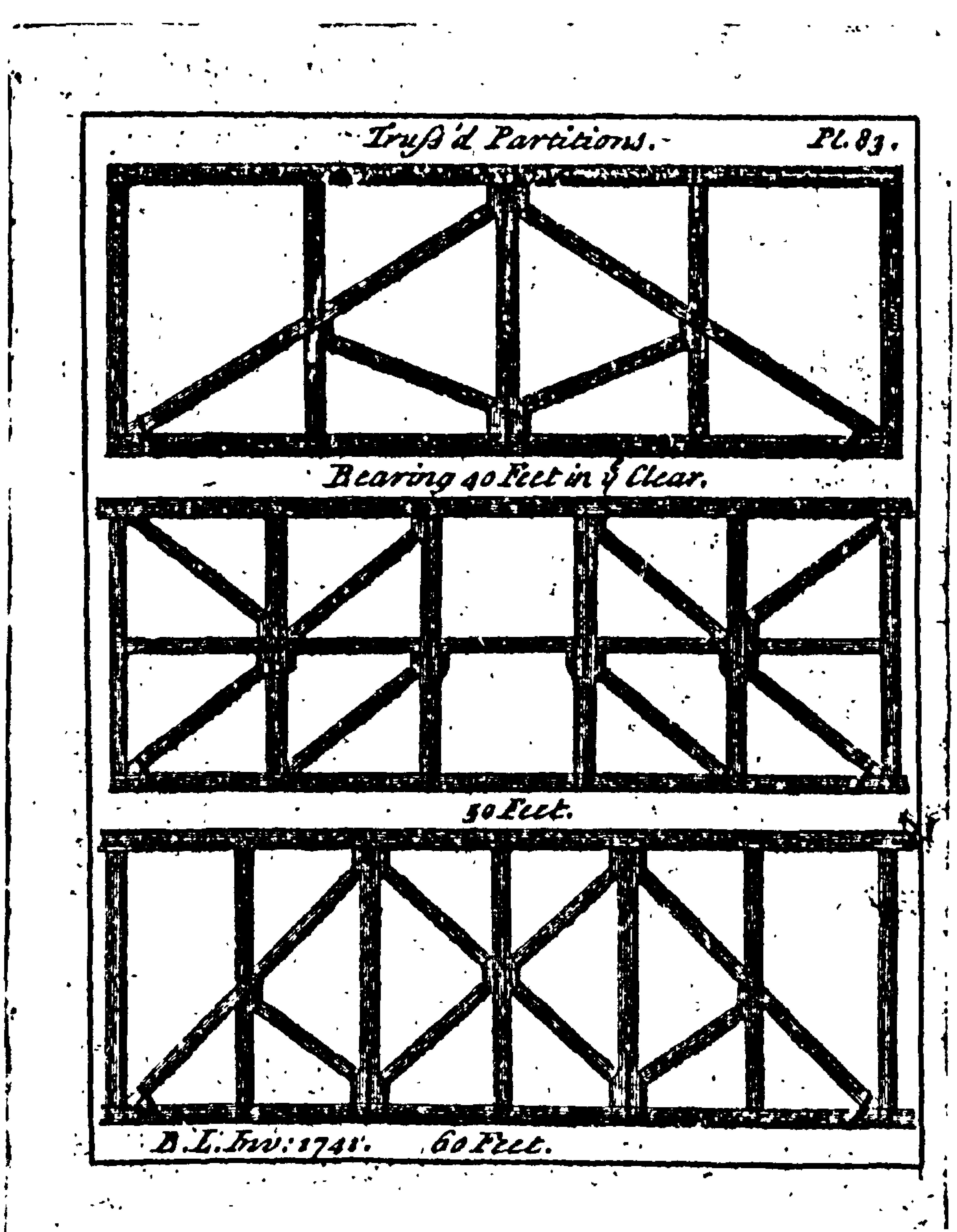


Fig. 7.7

Trussed partitions from Langley, B. Builders Jewel 1741, Plate 83.

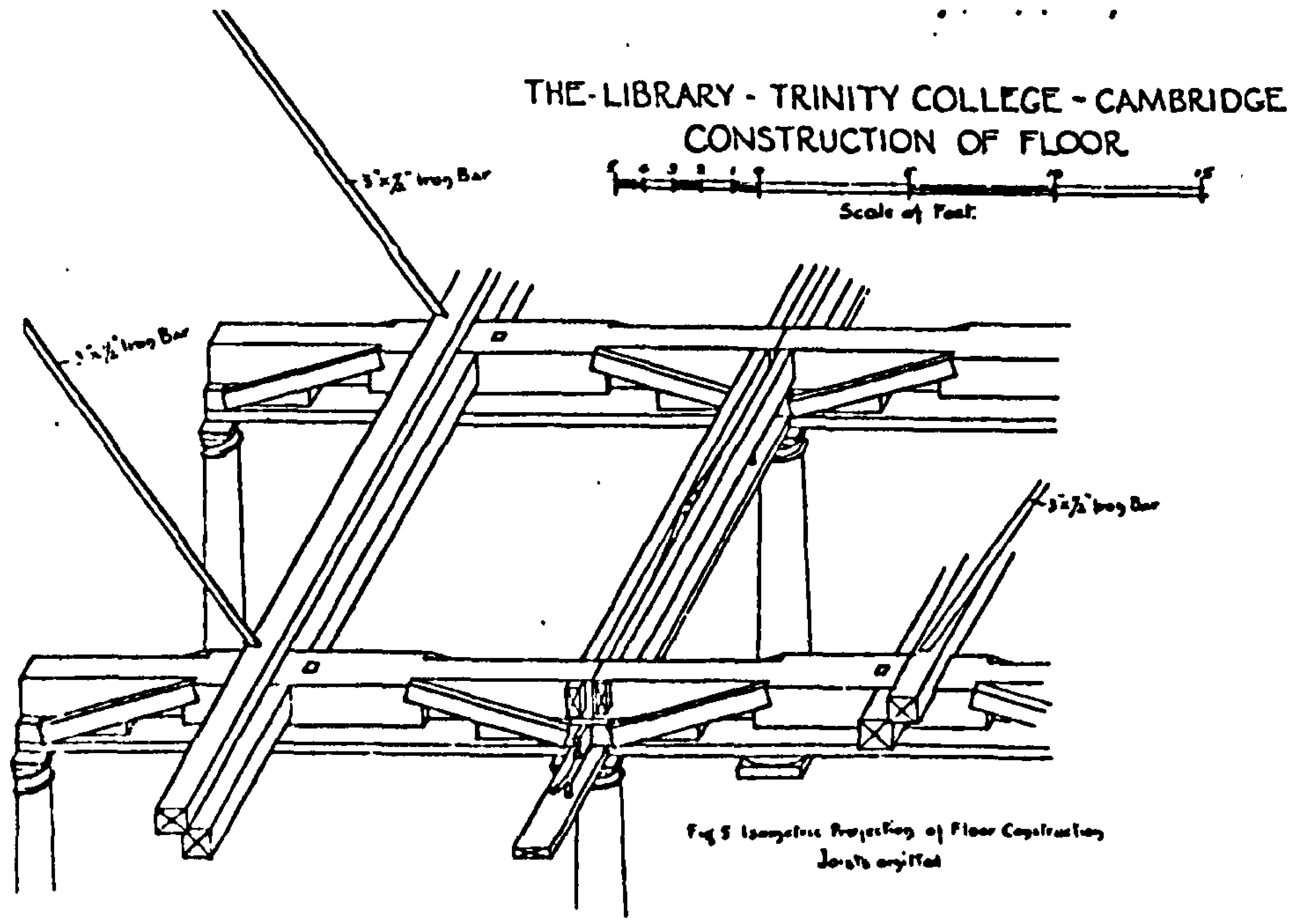


Fig. 7.8

Floor construction of Trinity College Library, Cambridge. Drawing by Fletcher, H.M. RIBA Journal.

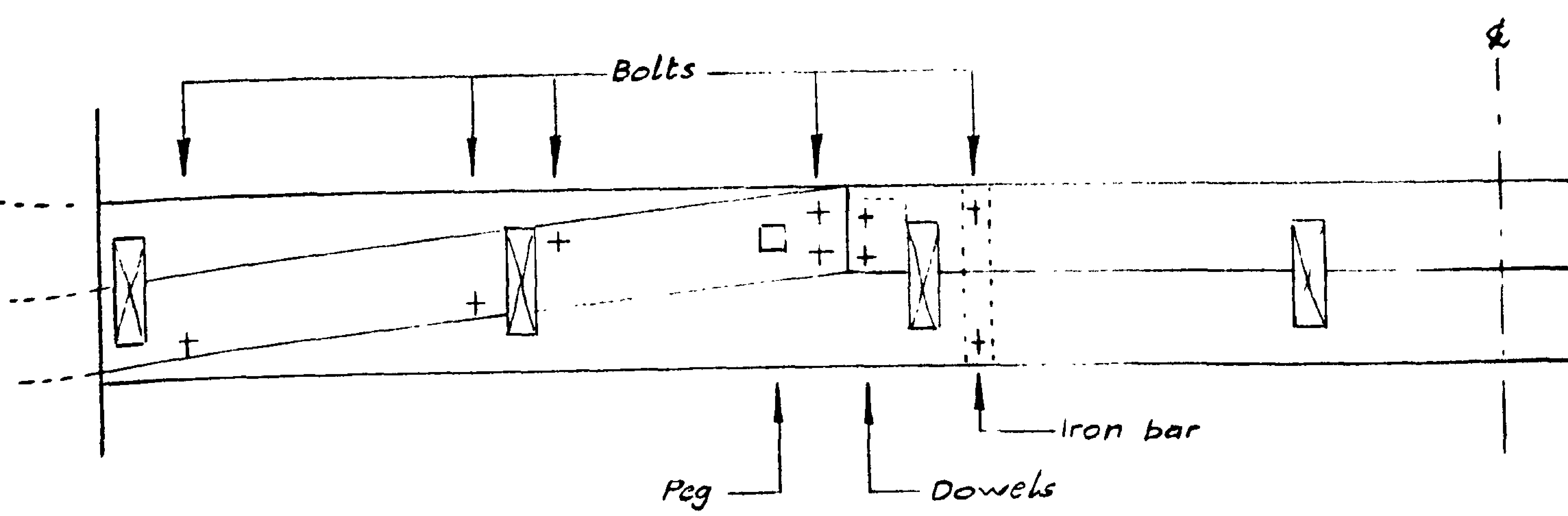


Fig. 7.9

Drawing of a truss at Blenheim Palace - from an original by Rayson - architect to Blenheim.

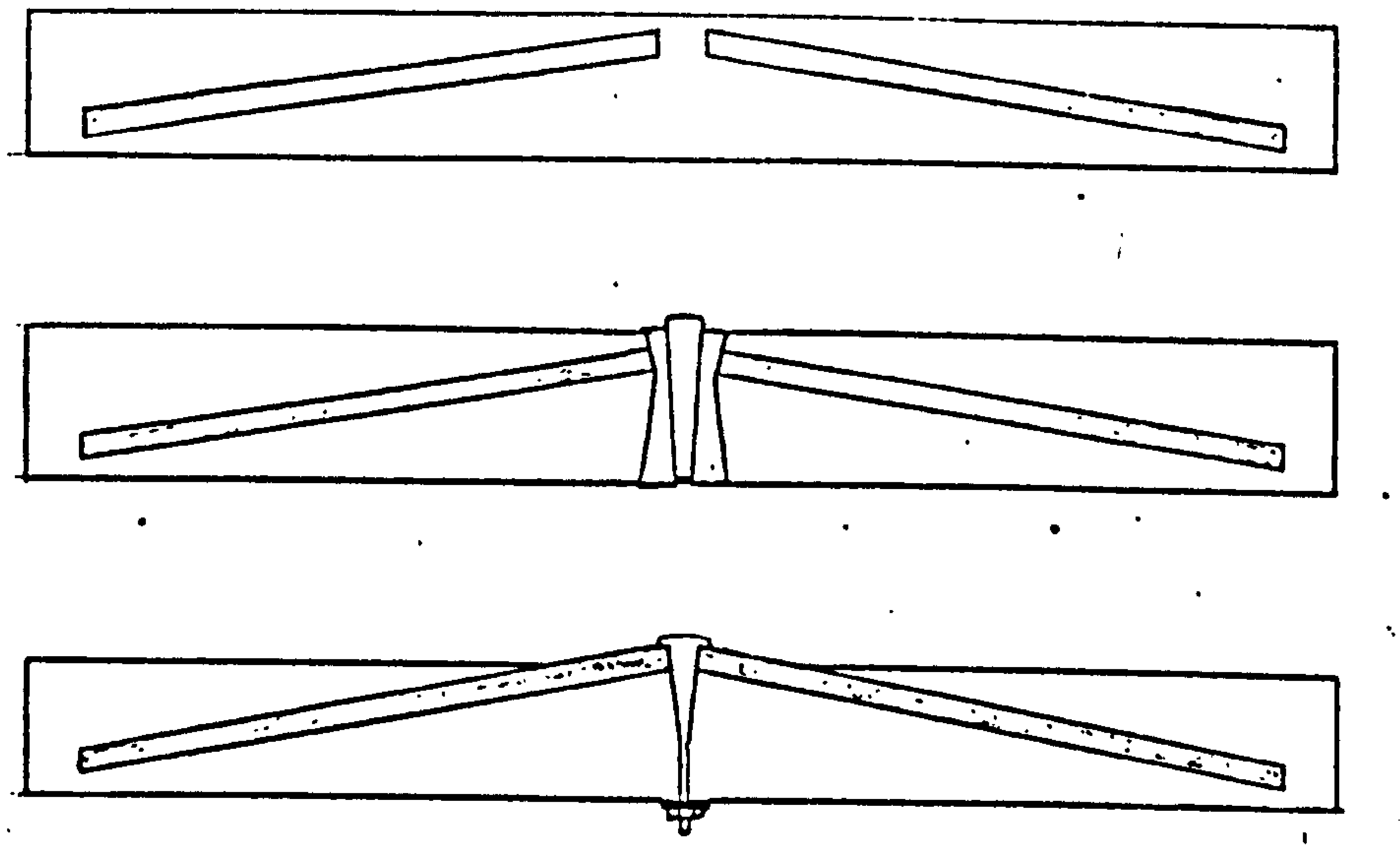


Fig. 7.10

Arrangements used in trussing girders.

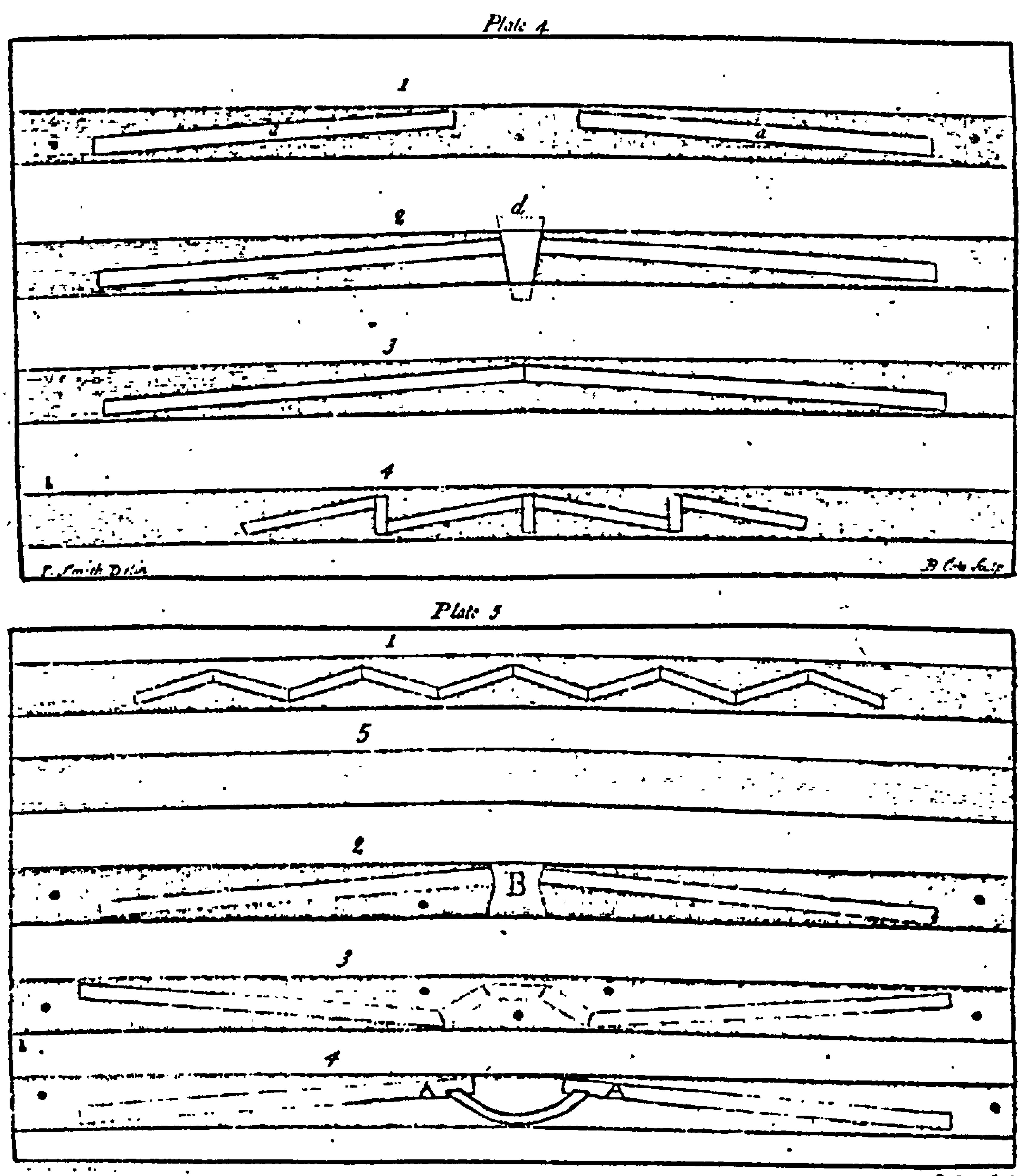


Fig. 7.11

James Smith designs for trussed girders.

THE QUEEN POST TRUSS

The development of the queen post truss does not present such a clear picture as that of the king post. While the form was known and used in Italy during the seventeenth century, alongside the king post truss (1), it does not seem to have been introduced into this country at the same time as the latter. Even Gibbs, assumed to have obtained his structural ideas from Italy, never used the queen post truss. It may be that its development in Italy was later or slower than that of the king post and was not sufficiently widespread to have attracted the attention of English architects. However, this can only be speculation and the relative development of the two types of truss in Italy is beyond the scope of this study. Besides, a relatively slow adoption of the form in this country can easily be accounted for by the initial development of the king post truss. If this was adequate for most tasks there would have been little incentive to experiment with a relatively untried form. Even for long spans, where today we can see the obvious advantage of the queen post, the temptation would have been to continue to use the known form and adapt it to cope with the greater spans.

The nearest approach to the queen post truss in use at the beginning of the eighteenth century was the form that had been developed and used by Wren to form the flat topped roofs described earlier; but he never extended the use of this type of truss to carry ridged roofs. There were some attempts to develop the use of the truss to carry ridged roofs during the early part of the eighteenth century, and these seem to have been developed from the Wren trusses rather than taken from Italian precedents. Hooke's type of queen post truss seems to have been his own design but in the light of currently available evidence, this seems to have had few imitators. However the queen post form was used in trussed partitions throughout the first half of the eighteenth century; and so the stage was set for its adoption into roof structures which appeared to take place round the middle of the century.

To examine the development of this type of truss we have to be clear about the definition of the form. In the king post truss the tie beam is trussed up by the king post, which in turn is carried by a simple arch of two pieces of timber: the principal rafters. In a queen post truss the tie beam is supported at two points by the queen posts which in turn are carried by an arch of three pieces of timber. In most cases the principal rafter does not form part of this arch which instead comprises a pair of secondary rafters set below the principals (2) and a collar or straining beam. A combination of king and queen post trusses is possible, and indeed common, where a short king post stands on top of the straining beam (fig. 1.8). In some cases this king post might be carried down past the collar to the tie beam.

While all this has been said before it is necessary to emphasise it here because of the similarity between the latter type of king-and-queen post truss and the king post truss with secondary posts. Texts can be found that refer to secondary posts as queen posts. However, the important difference is that the former are strutted from the king post while the true queen post is carried by a separate arch of timber.

Given this definition the first structure in England that may be called a queen post roof was Wren's Sheldonian Theatre (fig. 3.12). The trusses in this structure use both king and queen posts, all three being supported from the same arch composed of four timbers. It is true that the queen posts are braced by struts from the base of the king post but it is unlikely that these were seen as providing major supporting forces. The braces are long and slender and raked at too great an angle to have had much effect. No joggles were provided for them to strut against and it seems possible that they were simply designed for temporary support during construction.

Following this early structure, there is no record of Wren having used queen post trusses until the 1680s, when it is known from Clayton's drawings that four London churches were put up with queen post roofs; when Chelsea Hospital was built and when roofs at Greenwich Hospital (fig. 8.1) and Hampton Court were constructed. All these roofs have flat tops rather than the form adopted for the Sheldonian. Therefore a central post was not needed and the arrangement of timbers could be made simpler. It was earlier assumed that the roof structure of the Sheldonian was Wren's own design rather than being derived from any foreign sources and these later queen post trusses can be seen as a development from this. They are simpler and today they probably appear as the more natural form of structure. At the time however the reverse was possibly true. Rather than seeing the Sheldonian roof as a queen post truss with an additional post it would possibly be more in keeping with the way that the structures developed to see it as a king post truss with two posts added to reduce the slope of the roof and to provide additional attic space. Seen this way the flat top queen post truss is a structural improvement on this since it achieves much the same effect while at the same time reducing the number of joints necessary in the timber arch.

It seems curious, however, that it should have been so long before this development took place and that then, moreover, there should have been a number of such structures. Quite possibly there was no real need for this type of structure until the wide span roofs of the hospitals had to be built. Although the roofs at Greenwich might have been framed with king post trusses, at Chelsea the attics could not have been built to provide usable space without adopting the queen post structure. Having designed such a roof for Chelsea and Greenwich, providing a form simpler and easier to construct than had been the case at Oxford, sufficient experience would have been gained to have encouraged further use of this type of structure. Such reasoning would account for an early drawing for the roof of St Benet, Thames which uses a king post truss while queen posts were used in the roof which was eventually built.

Such reasoning will not however account for the difference in detailing between the surviving trusses. The trusses at Chelsea and the roof of St Benet, Thames, rely upon carpentry for the restraint of the head of the queen posts while at Greenwich and Kew the posts are suspended from the timber arch by metal straps. As discussed earlier, the Greenwich roof was the responsibility of Hawksmoor and it may be that this alternative detail was his rather than Wren's. Hawksmoor's roof for Greenwich Church uses a similar detail but this cannot be used to confirm the arrangement as his design.

The simplest development of the flat topped queen post truss to form a ridged roof is by the addition of a king post and rafters above the straining beam. That this was possible might have been inferred from drawings in Palladio but there is no known instance of Wren having made any such developments. If he had developed the queen post truss from the king post in the way suggested above, in order to solve specific building problems, then we should not be surprised by this failure to develop the form further. Having modified the king post truss to produce a structure for a flat topped roof, it does not seem likely that he would then have modified this structure to reproduce the original outward form. Development of the queen post in this way would have to wait for those who were not party to the original development;

and the first example of a queen post structure used in this way is provided by Hawksmoor's St Alphege, Greenwich. Sadly this roof was lost during the war but there are eighteenth century drawings of the structure.

The exact arrangement of timbers used by Hawksmoor in forming the trusses of this roof is shown differently in two eighteenth century drawings, although they agree on the basic design (3). In both drawings a king post is carried by a long pair of principal rafters (fig. 8.2). Below this there are queen posts, carried by secondary rafters, and a straining beam thus forming a second timber arch independent of the first. Within this basic layout there is a pair of additional posts between king post and queen posts together with inclined strutting. Although the straining beam is interrupted by the posts which support the tie beam there can be no doubt that the basic principles of the queen post truss were being applied in this design. It is in the arrangement of the struts and the detailing of the carpentry that the drawings of the structure differ.

In giving his version, Batty Langley even suggests a modification to improve the strength of the truss. Rather than have the struts at the base of the king post to support the adjacent pair of posts (fig. 8.2a) he suggests that they should be reversed. This change would have made the structure very much like a modern Pratt truss. The other drawing made by William Newton, and part of the survey drawing referred to earlier, does show such a modern looking, truss-like, arrangement but achieved by reversing the next paid of struts (fig. 8.2b). These struts were essentially secondary structural members and, whichever way they were arranged, the similarity between the forms that result and more modern truss forms is only a coincidence. Either arrangement might have been used at the time. In Batty Langley's version the inner pair of posts must be seen as being strutted from the feet of both the king and queen posts; an arrangement having some similarity with Inigo Jones structure for St Paul's, Covent Garden, and shown immediately below in Langley's figure. In Newton's version the layout of the strutting follows that used in king post roofs with secondary posts, and so was equally possible in terms of contemporary techniques.

Batty Langley's drawing cannot be relied upon. The drawing of St Paul's, Covent Garden, drawn next to it in his plate, has already been shown to be inaccurate. Moreover we should note that, of the different arrangements shown for the detail at the head of the queen post, Newton's is confirmed by a photograph (4) taken of the church shortly after the disastrous fire during the war. The fire destroyed the roof but remnants of the roof trusses, where they had fallen into the nave, are visible. Enough is visible to confirm the layout of the main timbers and the use of metal straps to secure the heads of the queen posts to the principal rafters. Batty Langley's drawing omits these straps but the photograph strongly suggests that much the same detail was used at St. Alphege as in the roof structure of the hall of Greenwich Hospital. This would not be surprising as Hawksmoor (5) appears to have been working on both at the same time. We must thus accept Newton's drawing as showing the metal strapping and detail at the head of the queen post correctly. The strut at the head of the queen post cannot however be seen in the photograph and Batty Langley's version of strutting arrangements may be correct even though it is difficult to understand why Newton should have made a mistake about this (6).

Hawksmoor seems to have been the only architect to have used this development of the queen post during the early eighteenth century. Other architects built church roofs with similar wide spans but, in spite of the advantages of the queen post truss, they relied upon variations on the king post form. John Price, in his roof for St George's, Southwark, (1734-5) used a king post and secondary post layout as the basis for the roof although he felt the need to provide additional posts and struts in this wide span structure (fig. 8.3). The roof is hipped and he used a queen post truss to carry the hip rafters so was not unaware of this structural form. James Horne also used a king post and secondary post layout at Holy Trinity, Guildford (1749-63). In each of these churches the slope of the roof is sufficiently steep to require some additional strutting of the principal rafter between the heads of the secondary posts and the apex. Price used a pair of inclined struts set high on the king post while Horne used a collar beam strutting across between the two principals. For both churches a queen post truss might have provided a simpler solution.

Horne came close to using a queen post structure in his Southwark church. The building (Christ Church) has since been demolished but his drawing for the roof structure survives (fig. 8.4). The design has posts that appear to be a combination of secondary posts and queen posts. They are shown strutted from the foot of the king post, as secondary posts, and so have to be set fairly close to the centre of the tie beam. As a result puncheons were included to assist the principals. While not providing the advantages of a queen post layout there is strutting between the heads of these posts, divided by the king post and inclined upward slightly. Completing the timber arch is a pair of secondary principals. The origin of this hybrid is uncertain. It is possible that Horne knew of the structure of St Alphege and this may have been an attempt to produce a simplified version of the design, although he does not seem to have realised the advantages of the queen post layout.

The earliest trusses that have been found that take the form of a king post and principals set on top of a flat topped queen post truss are those forming part of the roof at Houghton Hall, Norfolk. The roof shape of this building is unusual because behind the parapet of the principal elevation it has a flat top while further back the roof rises to form a ridge. Presumably the intention was to keep the roof low at the front so that it should not be visible from the ground in front of the house. Changing to a ridged roof behind, however, made a more economical design since slate could then be used istead of lead. The two forms enclose a single attic space. The flat roof at the front is naturally framed with queen post trusses. In the space behind and under the ridged roof the same basic truss form has been used. To form the ridge the heads of the queen posts have been carried up a little above the straining beam in order to form an abutment for the feet of a pair of upper principals that terminate in a king post (fig. 8.5). The king post stands on top of the straining beam. There is no upper principal rafter as in the roof of Greenwich Church but this is hardly surprising considering both the size of the timbers which have been used (they are larger than would have been normal at the time even for this span) and the way that the structure seems to have been derived.

It seems safe to assume that the structural design was Ripley's (who supervised the construction) rather than Campbell's (who provided the designs for the house). The upper extension follows naturally from the queen post structure and might well have been prompted by a knowledge of Palladio, as suggested earlier. Ripley was a carpenter by trade and might well have seen the queen post trusses at Greenwich Hospital in his capacity as surveyor there. There is some difficulty over dates, however, if these trusses are to be seen as the source for Ripley's design because his appointment at Greenwich overlaps with the period during which Houghton was built and there can be no certainty that he knew of this roof structure before then.

Of the architects working in the first half of the eighteenth century one might have expected Gibbs to have used the queen post truss. It has been noted earlier that he would have acquired a knowledge of structures through his training in Italy where he might have learned of a queen post truss as well as the king post. That he had done so is shown by one of his drawings now in the Gibbs collection at the Ashmolean Museum (fig. 8.6). This section of a house shows the roof truss formed in the 'Italian manner' with the queen posts and the king post stopped short of the beams. This is the only surviving Gibbs drawing known which shows such a structure and there are no known examples of his use of the queen post truss in any of his buildings.

Text books

The text books show a number of ridged roofs relying upon queen post trusses, an arrangement which has not been found in any of the roofs so far surveyed. This may be due to the smallness of the sample and its selection from among the larger buildings of the period. However, the illustrations give the impression that some of the structures shown may not have been used at all by practising carpenters. The possibility that authors invented much of what they show has been raised before, particularly in relation to trussed girders. Roof trusses, if anything, provide more scope for the inventive mind. The sight of one queen post truss might be sufficient for an author to create a whole family of similar structures. However, it is not so much the variety of roofs proposed that leads to the suspicion that they were invented by the authors. It is the inconsistency of the details used which suggests that the principles of this type of truss may not always have been fully understood.

Price (7) shows a number of structures with the queen posts unstrutted by secondary rafters (fig. 6.4). In one of these he shows the secondary rafters dotted in as if their use was optional (his plate I) although the head of the queen posts are drawn with joggles to receive them. Batty Langley (8) shows several of his queen post trusses with secondary rafters included but shaded differently from the other timbers (fig. 6.6). Although there is no text to explain this, the presumption is that these timbers were also seen as optional. One may suppose that the authors assumed that the joints between the posts and principal rafters were sufficient to transmit the forces. If this were so then why should secondary rafters be used at all? Was it that they had seen examples both of cases where secondary rafters had been used and where they had not? No examples of the latter arrangement have been found except for the queen post trusses at Ragley and assumed to have been designed by Hooke.

Given the errors in the text books that have already been noted, it is not surprising to find queen post trusses incorrectly drawn by Smith. Batty Langley's tendency to include less than practical designs has also been seen (9). The drawings certainly indicate that some form of queen post truss was in use but the drawings by Price are more likely to be reliable and, as they also show the form without secondary rafters, it seems probable that this arrangement did receive some use. How much and whether it derived from Hooke's early experiments with the form are questions that will have to wait for more examples to be found.

The early text books showed a variety of M shaped or multiple pitched roofs, designed to reduce the height necessary for a wide span. In this type of roof the tiles or slates were carried on coupled rafters. These in turn were carried on longitudinal plates supported on the trusses, and it did not particularly matter what shape of truss was used. Price and

Batty Langley provide drawings of both king and queen post trusses used to form roofs of this kind (figs. 6.7 & 6.8). Batty Langley seems to have been more ambitious than other authors in the number of multiple pitches he suggested might be carried.

Again Price is the more likely to be reliable. His plate L (fig.6.7) shows both king and queen post trusses carrying M shaped roofs carefully drawn. The latter is interesting in that the struts which prop the straining beam against the load from the plate also carry a central post which is there to truss up the tie beam. The queen posts, having no metal straps, do not seem to have been seen as fulfilling this role.

There was considerable copying. Salmon and Hoppus (10) reproduced many of Price's illustrations. Therefore while there are indications in the text books that such forms were in existence it is difficult to say how widely they were used. Did other authors copy earlier drawings simply for convenience; or were they showing structural devices which they had not seen for themselves? Without more evidence I prefer to be uncharitable and assume the latter. One may only assume that they knew of these structures when there is evidence for their widespread use.

Multiple pitches of this kind were certainly used in the early eighteenth century. The roof design for Burley-on-the-Hill was of this form, there is a drawing in the Clerk Collection by Townsend for a roof of this type and one was used at Osterley House based on trussed girders. At Chilton House, Buckinghamshire, the pitches were supported on poorly designed king post trusses but at nearby Claydon House substantial queen post trusses were used.

The other truss shown by Price, in his plate L, is a ridged roof with wide overhanging eaves. This was the problem that Inigo Jones had to solve in roofing St Paul's, Covent Garden, and the problem that was later to confront Hardwick when he restored the church after the fire of 1795. In his drawing Price nicely anticipated Hardwick's solution. The structures are not exactly the same because Hardwick kept his main inclined members parallel, used wider spaced queen posts, and had a king post above the straining beam. However, it is possible that he may have been influenced by Price's drawing.

James Essex

Rather than being used to frame simple ridged roofs it was in handling special problems that the queen post truss was used. Both Hawksmoor and Gibbs used it to frame domes (11). It was apparently used frequently in the framing of trussed partitions to support the hip rafters in long span roofs and to carry multiple pitched roofs.

It should not be thought surprising that while the queen post was used for this type of problem it did not find its way into simple ridged roofs. The latter, by its very shape, suggests the use of a king post truss, while other roof forms do not. If anything the queen post truss appears better suited to forming the basis of an M shaped roof than the king post. Consider Price's drawing. Not only do the secondary rafters follow the outer slope of the roof, but more than one pair of purlins can be supported more easily.

The Price roof with the overhanging eaves is a case where a ridged roof poses special problems which can be solved more easily with a queen post truss. Other examples where the queen post provided a better solution than the king post can be seen in the cathedral restoration work of James Essex.

Essex showed some originality in his structural designs. He built the mathematical bridge at Queen's College, Cambridge, to the design of Etheridge (1749-50) but his ingenious roof for Clare College Chapel (1764-9) is equally complex. The structure had to be squeezed between a low pitched roof (so as not to protrude above the parapet) and the high barrel vaulted ceiling. The resulting structure has some resemblance to a combination of scissor braced and collar braced principals carried above the walls on short columns. His other roofs at Cambridge did not require such originality and mostly used simple king post trusses. It is worth noting however that these have timbers of much smaller scantling than was common at the time.

His largest structural carpentry project was for the Chapter House roof at Lincoln. The outer form of the roof was not beautiful, resembling an octagonal version of the bent pyramid of Dahshur. I do not know why such an odd shape should have been used but it was certainly not because of his inability to produce a structure for something more elegant. His drawings (12) for this roof show that he explored a number of alternatives, most of them based on queen post trusses. Both plans and sections survive and the drawings show that he worked out the structure in some detail. The structure he built, (now under additional timbers to restore the original roof shape) used queen post trusses (13). Queen post trusses were also used in his cathedral nave roofs.

Replacing the roofs of Gothic cathedrals presented a special problem because of the steep pitch. A king post roof without any additional strutting from the post would provide inadequate support for the principal rafters. Variations on the king post form were tried. At Lichfield, for example, where the designer of the replacement structure is unknown, an early drawing (fig. 8.7) shows a secondary pair of principal rafters bearing on the (curved) tie beam in order to carry struts with a pair of struts also carried high on the king post. In the event an arrangement using secondary principals was adopted (14).

Essex, however, adopted queen post trusses for his restoration work on the roof of Ely cathedral. This is a more satisfactory basis for the roof because the queen posts, together with additional strutting if necessary, provide better support for both principal rafters and tie beams. It has been suggested that (15) queen post trusses over the North-West trancept at Lincoln are by Essex and that trusses over the South-East trancept at Canterbury are also his (fig. 8.8). Neither of these can be definitely attributed to him but it is likely that they are his work (16). (This last truss has been referred to earlier and was clearly taken from Price.) There is considerable variation in their designs which might seem surprising but there is also considerable variation in the designs of the king post roofs which he built at Cambridge.

Queen post trusses were later to be used by Wyatt at Salisbury and Smirke at York (17) although by then the queen post truss was a major contender to the king post for all roofs.

Late eighteenth century roofs

The queen post truss only appears to have become popular for framing simple ridged roofs during the second half of the eighteenth century and there is some evidence that this popularity grew, not from a development of earlier structural forms in this country, but from a knowledge of queen post trusses in Italy. English architects were visiting, and indeed spending long periods studying in, Italy and their drawings show an interest in this form of roof. During the same period Dumont published a volume of drawings (18) that included a number of illustrations of Italian queen post roofs.

George Dance Jr. seems to have been the first English architect to adopt this 'Italian' form of roof. He travelled to Italy to study architecture, and towards the end of his stay won the competition for the design of a public gallery at Parma (1763). His drawings (19) for this scheme include sections which show the use of queen post trusses (fig. 8.9). These are designed very much in the Italian manner with the queen posts and the short king post stopped short of the tie beam and the straining beam.

On his return to England, Dance made little use of the queen post truss. There are surviving drawings (20) showing its use at Coleorton Hall (1804-8) and for the alterations to Francis Baring's house in Mayfair (1803) but by then it was in common use by other architects. Other drawings by Dance show king post trusses. Even All Hallow's, London Wall, (1765-7) built shortly after his return from Italy has king post trusses. This use of the king post is not surprising however. He would surely have been influenced by his father and thus have been likely to rely upon the established structural forms rather than have experimented with something new.

Thomas Hardwick travelled in Italy to study architecture from 1776-9 and while there made a drawing of the Pantheon, Rome. He must have had some interest in structure because, instead of drawing a simple elevation, he produced a section of the portico roof in order to show the roof timbers (fig. 8.10). These have the same general layout of timbers as in Dance's Parma design except that the posts stand on the beams.

Henry Holland did not himself travel to Italy but instead commissioned Charles Tatham to collect drawings for him there in 1794 (21). These drawings show a number of roofs in some detail. Holland had already used the queen post truss and must have both known of these roofs and instructed

Tatham to obtain details of these particular examples.

Holland showed an early interest in queen post trusses, using them in the roof of the stable block at Berrington Hall (1778-81). These trusses are detailed in a rather unusual way because the secondary rafters are not continuous but are cut short below the inclined struts. This suggests either a lack of familiarity with the form on Holland's part or simply his willingness to experiment; more likely the latter.

For his later theatre designs (22) he would presumably have studied Dumont's work on this subject (23) which not only shows numerous plans of auditoria but also includes drawings of roof structures. It may thus have been the drawings of Italian queen post roofs in this book that gave Holland the idea of obtaining his own drawings of these structures. Those that Tatham collected for him include the roofs of the Basilica of St Paul, Rome, the Theatre Argentina, Rome, and a theatre in Bologna besides a number of small roofs (fig. 8.11). By the time these drawings were collected, however, Holland was already a master of structure, as we can see from his Drury Lane Theatre roof (24) and the designs in his sketch book for the roof of the Riding School at Woburn (fig. 8.12).

While there were architects who could use the queen post truss competently, there was at least one who could not. Wherever James Paine acquired his knowledge of structures he seems also to have acquired a particular liking for the queen post type of roof, using it in preference to the king post in all his drawings. These appear both in his book of country houses (25) and in his unpublished drawings (26). He did travel briefly to Italy in 1755, apparently not thinking much of the experience (27), but we cannot be certain that he saw queen post roofs while there. It seems a pity, however, that his enthusiasm for the form did not encourage him to study it more closely. Although he does draw some trusses correctly (28) most are a curious arrangement of his own design (fig. 8.13).

Although it appears an unlikely arrangement, this type of truss was actually built. Without more surveys he cannot be sure how frequently he used the form but the roof of his Temple of Diana at Weston Park was built as shown in the illustration (29). As one might expect, the arrangement was not altogether successful. In the trusses at Weston Park there is no strapping at the base of the queen posts and the tie beams have sagged, allowing the joints here to open up. The secondary pair of posts appears to be acting as struts.

By the late eighteenth century the queen post roof was becoming sufficiently well known to be used in a number of buildings, although not always correctly. Warrington Town Hall (30), built in 1773, had roof trusses which were framed as a combination of king and queen post forms - an arrangement reminiscent of Horne's design for Christ Church, Southwark, or Hawksmoor's, St Alphege. This suggests an imperfect understanding of the queen post, or perhaps a lack of confidence in it, although, in the absence of known contemporary structures from the same area, it is difficult to put this structure in any clear pattern of development.

Eventually William Pain (31) produced a clear drawing of a queen post roof truss in one of his books on carpentry (fig. 6.7). By the end of the century queen post trusses appear to have been widely used, wherever longer spans were required, in preference to king post trusses with secondary posts. Soane used them in his reconstruction work at Aynho, they were used (as mentioned above) in cathedral re-roofing and illustrations of roofs in the works of Peter Nicholson give some indication of their popularity (32).

Tracing the development of the queen post truss presents much greater difficulties than that of the king post. For early eighteenth century buildings it is possible to make a reasonable guess at either the architects who might have used trussed roofs or the kinds of buildings in which they might be found. This cannot be done so easily in looking for queen post trusses. By the time they appeared the king post was firmly established and it is thus difficult to predict either the architects who might have favoured the new form or the kinds of buildings for which its use might have been advantageous. As shown, both Essex and Dance knew of the form but used it sparingly. Thus tracing the diffusion of this innovation into the structural vocabulary of eighteenth century architects can only be done by examining a large number of roofs on a more or less random basis. With an apparent gradual acceptance of this structure, the proportion of roofs in which it is likely to be found is small compared with the number of king post roofs and so the number to be examined in this way would have to be very large in order to net a usable number of queen post trusses. Such an extensive survey is quite beyond the scope of this study.

The clear drawings of queen post trusses by Price indicate that the form was in use by the 1730s. (That Smith drew queen post trusses, albeit inaccurately, shows that Price did not simply invent the form). However it is probable that a number of his drawings are of trusses of his own design; whether built or not is not certain. In either case the presence of a number of buildable trusses in a highly recommended book provided models which architects or carpenters could have copied.

They would have had some knowledge of its basic outline from the traditional form of queen post roof. This similarity may well account for the design of the queen post truss by Hooke. He was clearly aware that a king post was in tension and must have recognised that traditional queen posts were in compression. His diary records meetings with carpenters and his close attention to constructional details. It would not have been difficult for him, with his practical and inventive turn of mind, to have devised a way of putting queen posts into tension. With the extensive use of traditional queen post roofs one might have expected to see some adoption of this idea.

The picture that we have here is certainly not very clear but this is perhaps not unexpected. If few architects or craftsmen used the queen post structure initially, they may have been those who had learned of it abroad, those who recognised its advantage in special circumstances or perhaps those who were simply interested in structural innovation. As the use of the form gathered momentum during the eighteenth century, one would expect its advantages to become gradually more widely recognised. It may be that its success in the nineteenth century was because a greater understanding of structural mechanics allowed more rational designs, with the queen post then seen as a natural competitor to the king post. During the eighteenth century there were no formal design procedures available for the analysis and hence the rational design of structures. Furthermore, the level of structural understanding among architects and the degree of interest which they showed in structural matters, varied considerably. A new technique would have to make its way against a sea of comparative ignorance. It would only be when a greater level of structural understanding was more widely available that any sensible choice could be made between alternative techniques and structural design could be improved more rapidly. It is thus necessary to examine, as far as the evidence will allow, the degree of structural understanding during the period.

Footnotes - Chapter 8

1. This is clear from the illustrations of Palladio and Serlio in which the queen post truss predominates.

2. The term 'secondary rafter' can be found in some nineteenth century books while others offer no name for this member.

3. Langley (1740)

4. Richards, J M (1942) p.33

5. "Mr James desired to have the use of two bays of the Mews on the West side being each 32ft long, and the area outside the Mews on the South, for one year for his use in framing the Roofe for Greenwich Church." From the minutes of the Greenwich Building Committee, April 9th 1713. Wren Society VI p.67.

6. It may seem curious that inaccuracies occur in this way, but one should bear in mind the difficulties of surveying a roof. One is working in cramped conditions and in the dark. One's interest may be drawn to certain details which one wishes to record accurately and not notice ambiguities in other areas until one is back at the drawing board. These may then have to be resolved from memory or with the use of photographs. Even today with good lighting there can be omissions or mistakes. The problem was clearly more severe in the eighteenth century.

7. Price (1733)

8. Langley (1740)

9. Some of Batty Langley's more sensible designs were clearly copied from Price.

10. Salmon (1755) plate O. Hoppus (1737) p.84, pt. lxxv.

11. This arrangement is shown in a drawing by Hawksmoor for the Greenwich Hospital domes - RIBA Drawings Collection D9/6. Gibbs used the device for the Radcliffe Camera - Gibbs (1747).

12. BM. Add. 6772, f.254-65

13. Hewett (1974) p.138

14. The drawing is in the Lichfield Record Office. The restoration of the roof was carried out in the eighteenth century and was not part of the seventeenth century restoration as suggested by Hewett.

15. Hewett (1974) pp. 131 & 139.

16. Connections between Essex and the cathedrals can be traced in his surviving correspondence at the BM. but I have found no definite proof that he designed their roof structures.

17. Hewett (1974) pp.148 & 164.

18. Dumont (1766)

19. Soane Museum - Dance cabinet 4:11:2.

20. Soane Museum - Dance cabinet 3:5:8

21. Colvin (1978) p.808. The drawings are now in the RIBA. Drawings Collection.

22. Drury Lane, 1791-4; Covent Garden, 1792; Aberdeen 1795.

23. Dumont (1775).

24. Illustrated in the Survey of London and by Nicholson (1852) pt. xxxi.

25. Paine (1767)

26. Victoria and Albert Museum

27. In the preface to his Plans.. he advises against foreign travel.

28. Those for the chapel at Chatsworth are shown as normal queen posts

29. The illustration here is from his Plans... The roof space under the dome is inaccessible so the actual form of this structure cannot be determined.

30. Peter Locke - Personal correspondence. Photographs of the roof structure were taken during demolition and kindly supplied by Ardin & Brookes

31. Pain (1786).

32. Various books by Peter Nicholson contain drawings of roof trusses as built.

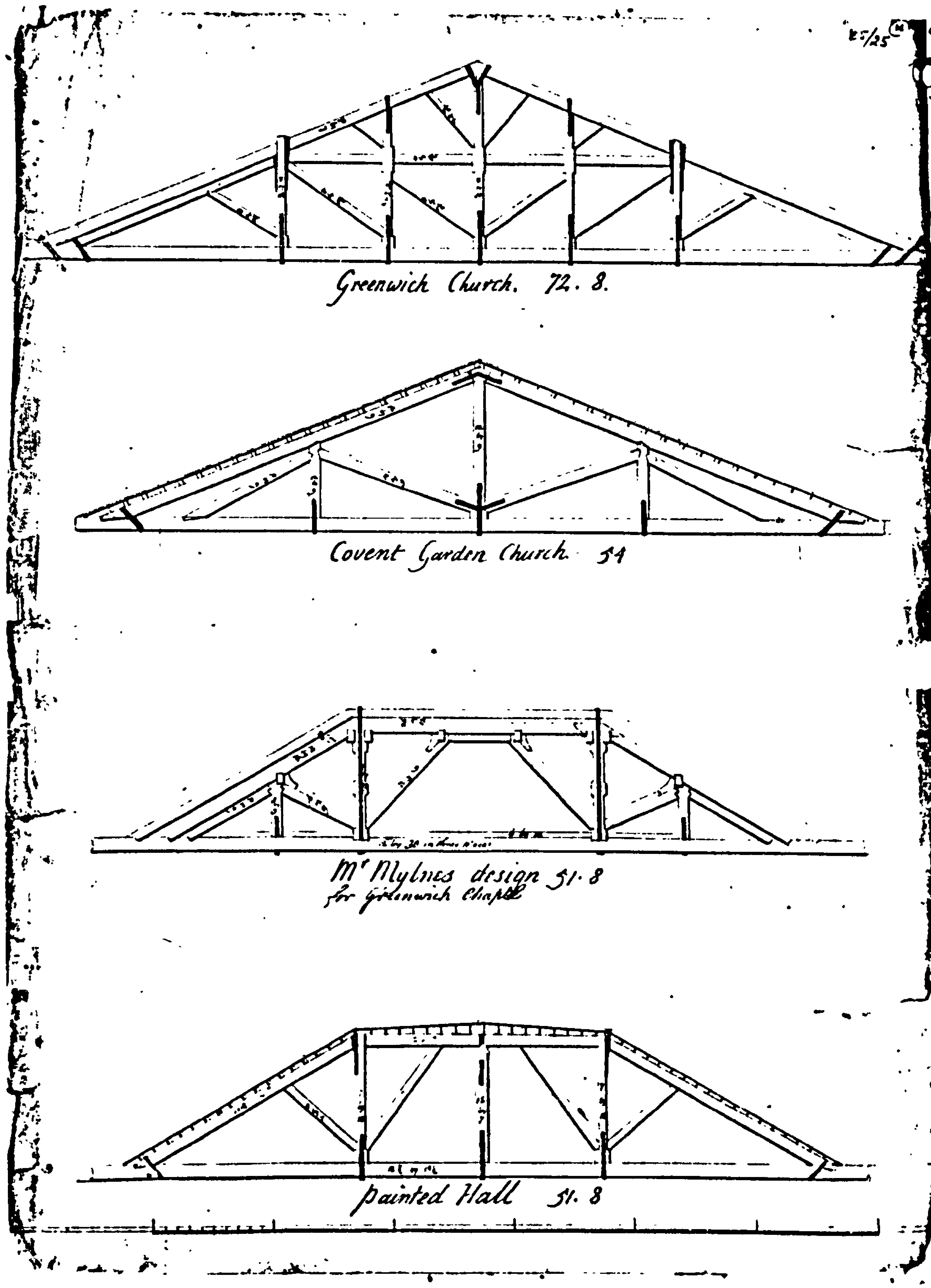
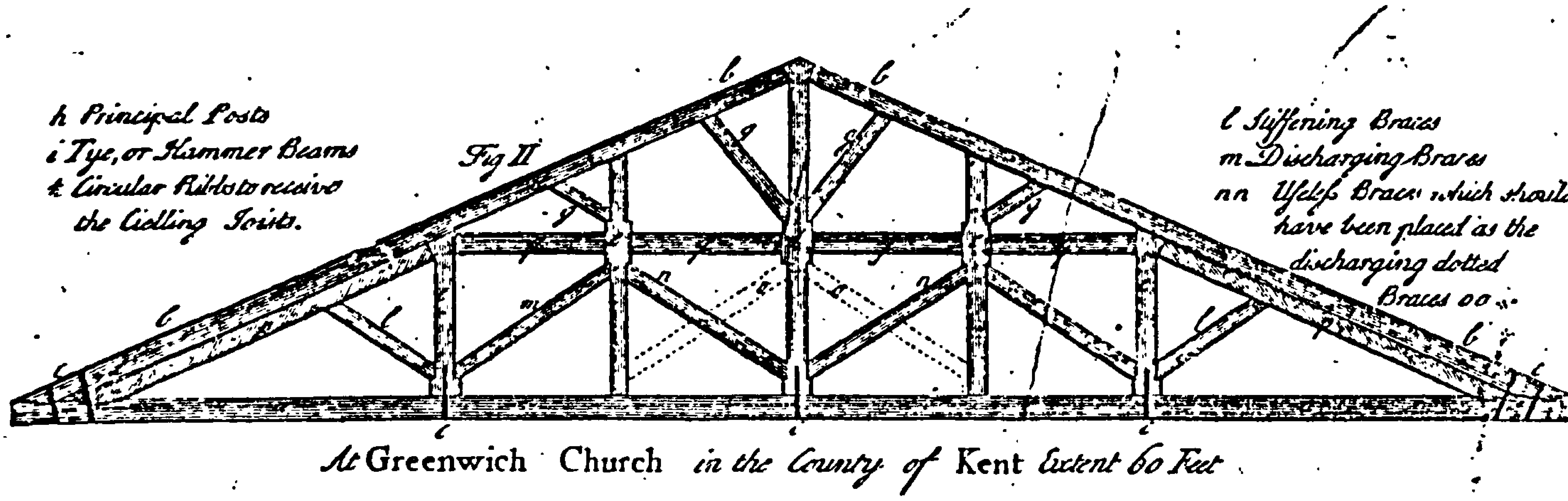


Fig. 8.1

Drawing by William Newton (RIBA Drawings Collection). This appears to be a study in preparation for his Greenwich Chapel design.



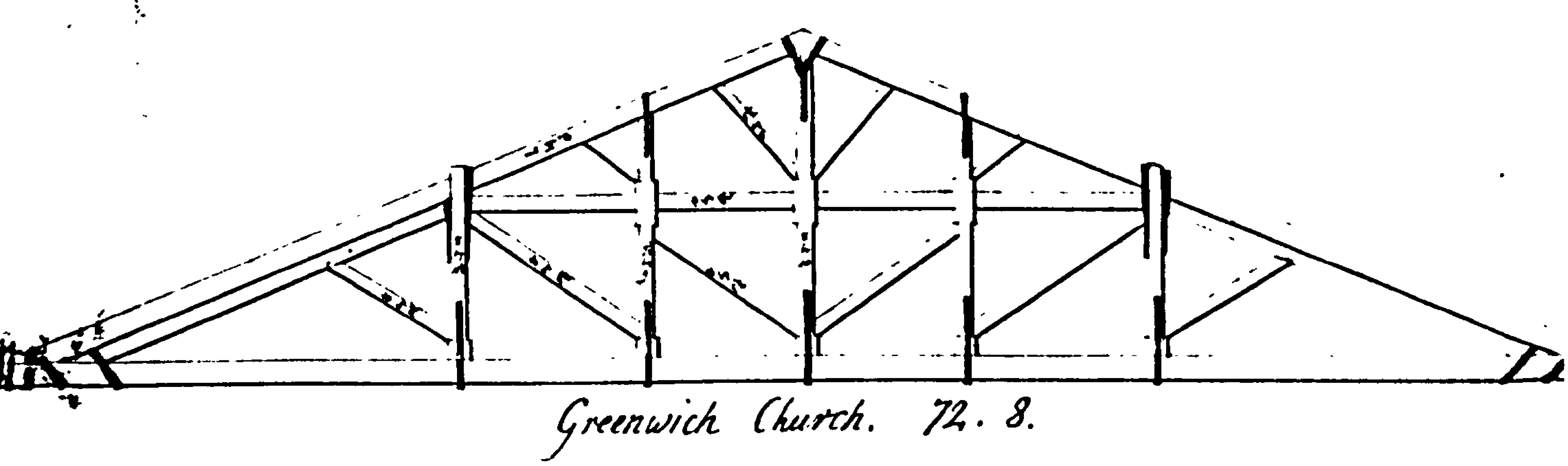


Fig. 8.2

Alternative versions of the roof structure.
a) Batty Langley - Treasury of Designs,
b) William Newton - detail of Fig. 8.1.

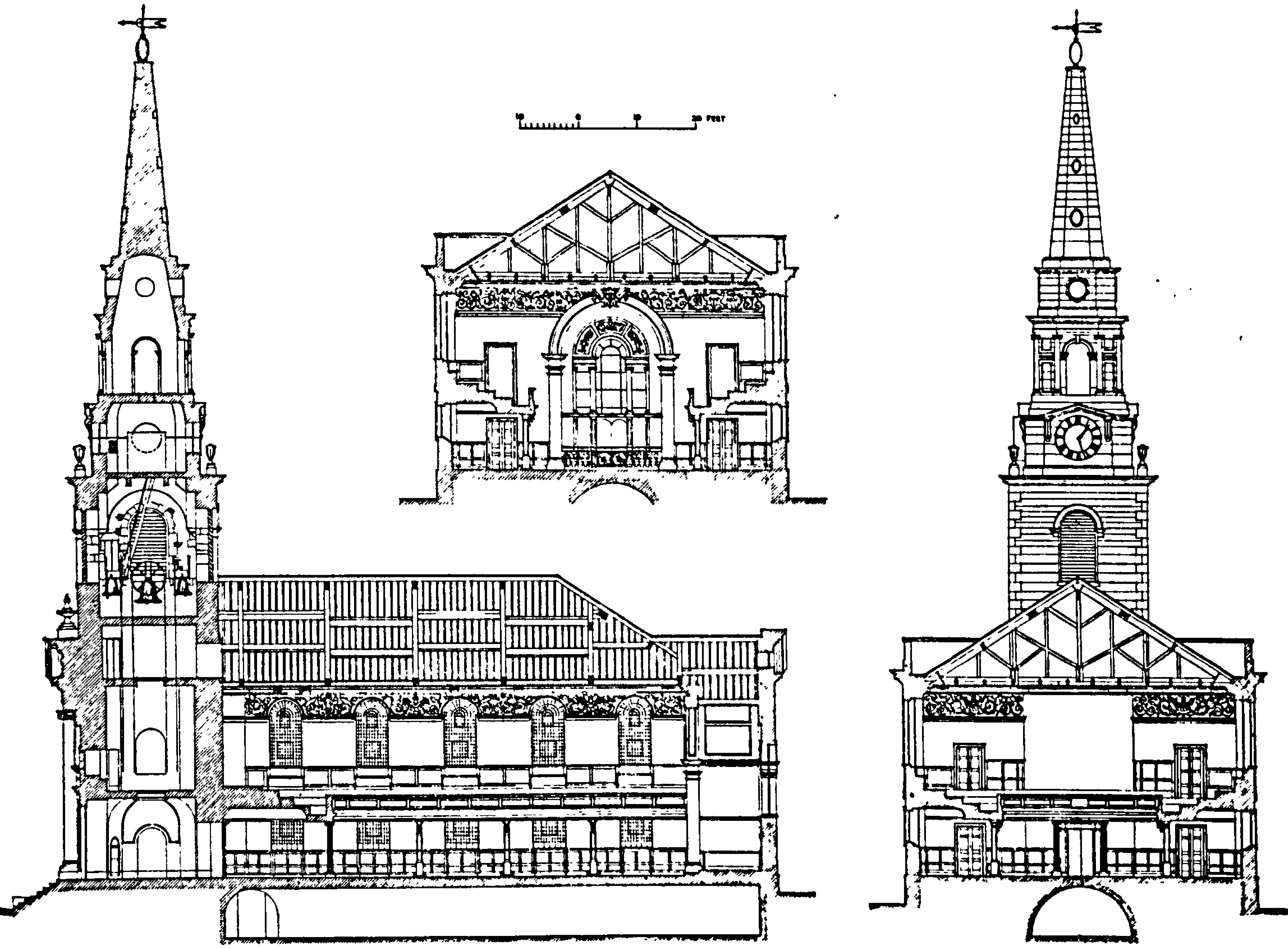


Fig. 8.3

St. George the Martyr, Southwark. John Price, 1734 (From <u>Survey of London XXV</u>).

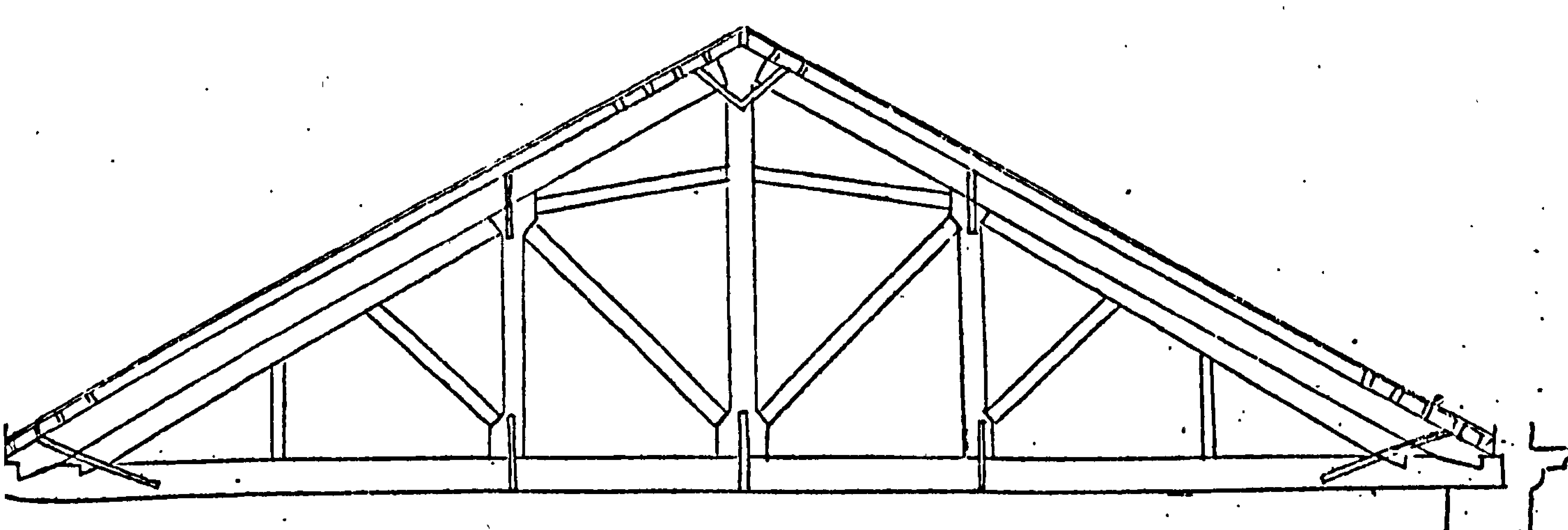


Fig. 8.4

Roof truss design by James Horn for Christ Church, Southwark. This appears as an unusual combination of king post and queen post designs (Kings Maps).

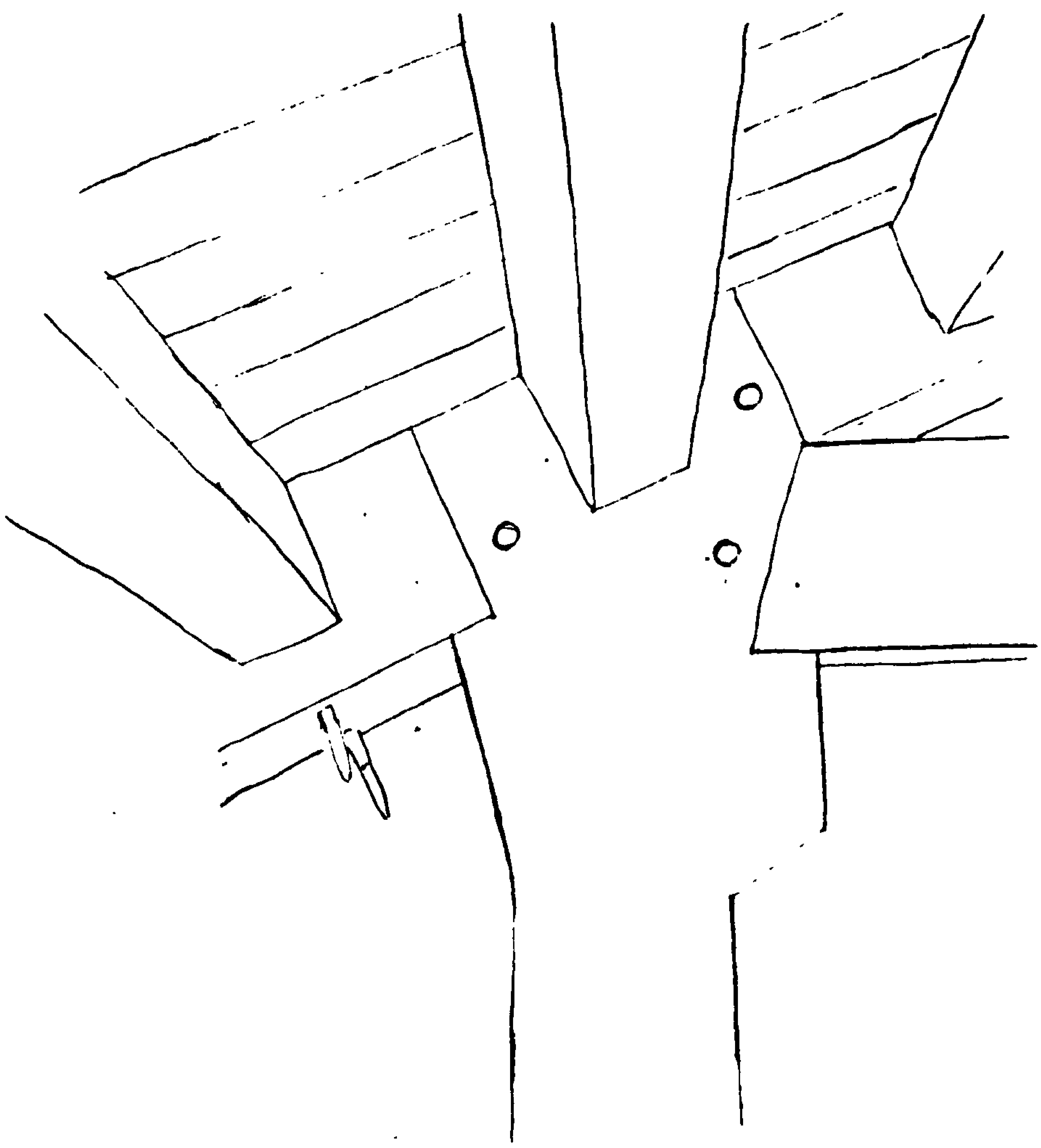


Fig. 8.5

Houghton Hall, Norfolk - detail at head of queen post showing extension to support the upper principal rafters.

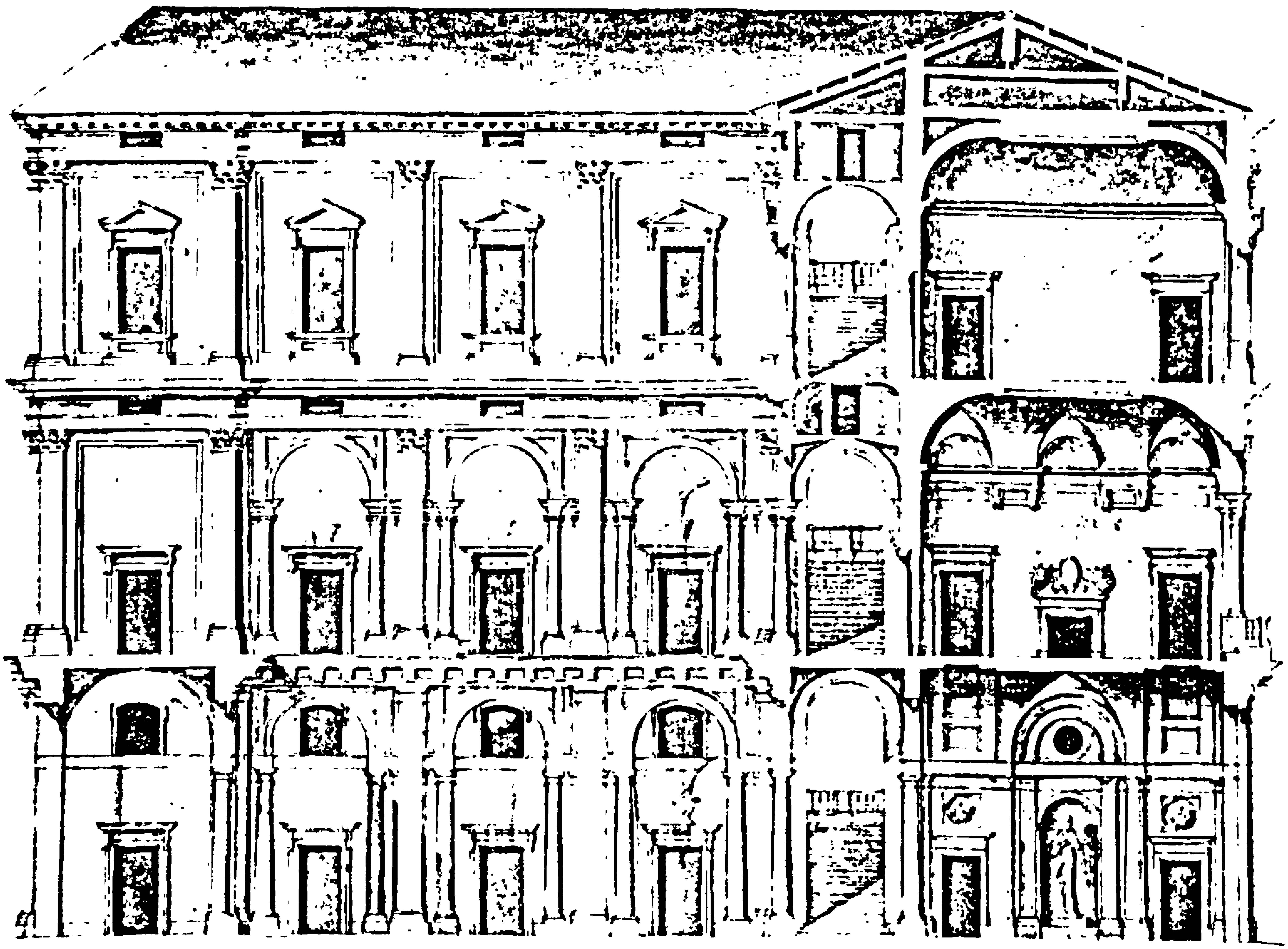


Fig. 8.6

Gibbs drawing showing the use of a queen post truss with 'Italian' detailing. (Ashindean Gibbs Collection).

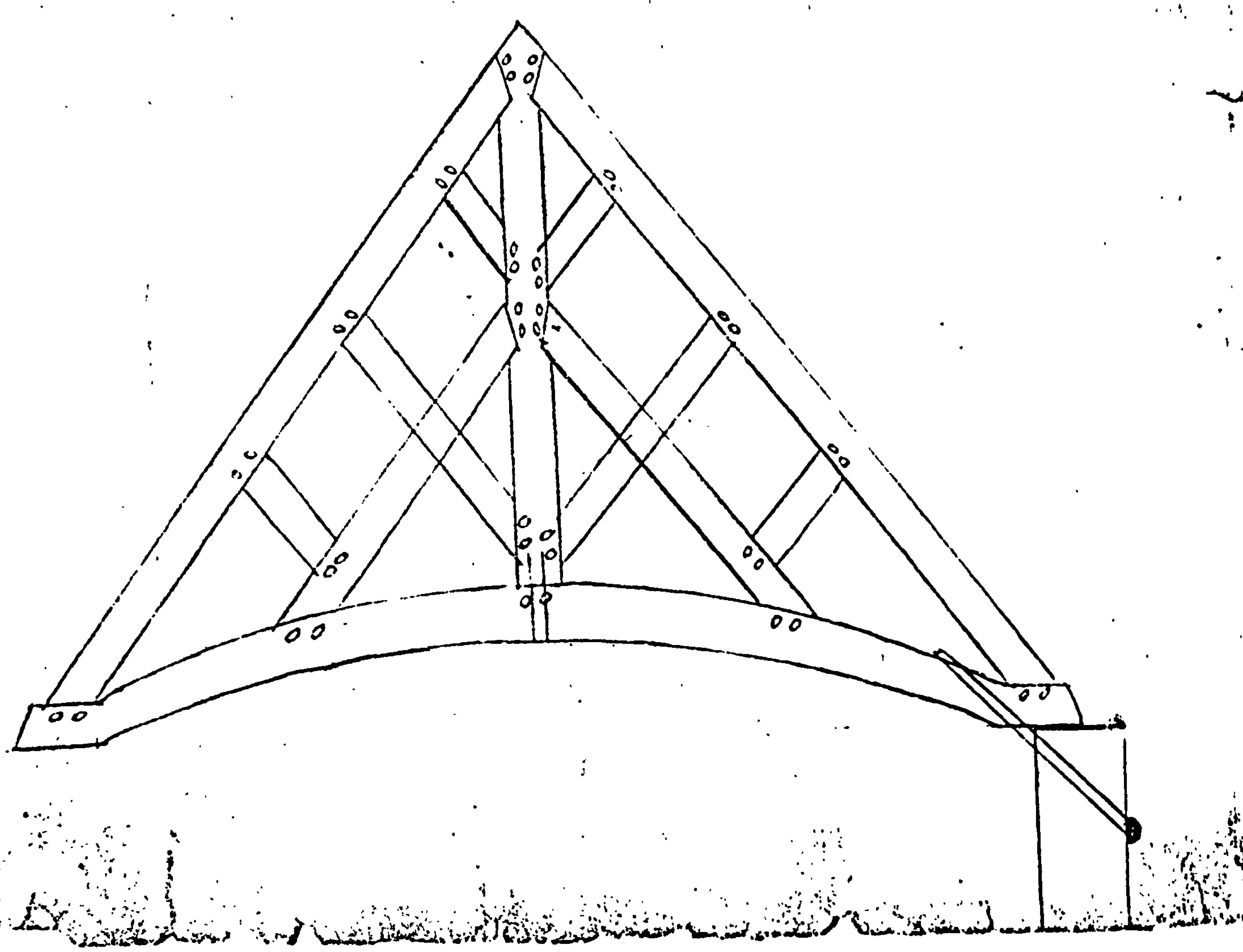


Fig. 8.7

Early eighteenth century drawing for a proposed re-roofing of Lichfield Cathedral - Lichfield Record Office.

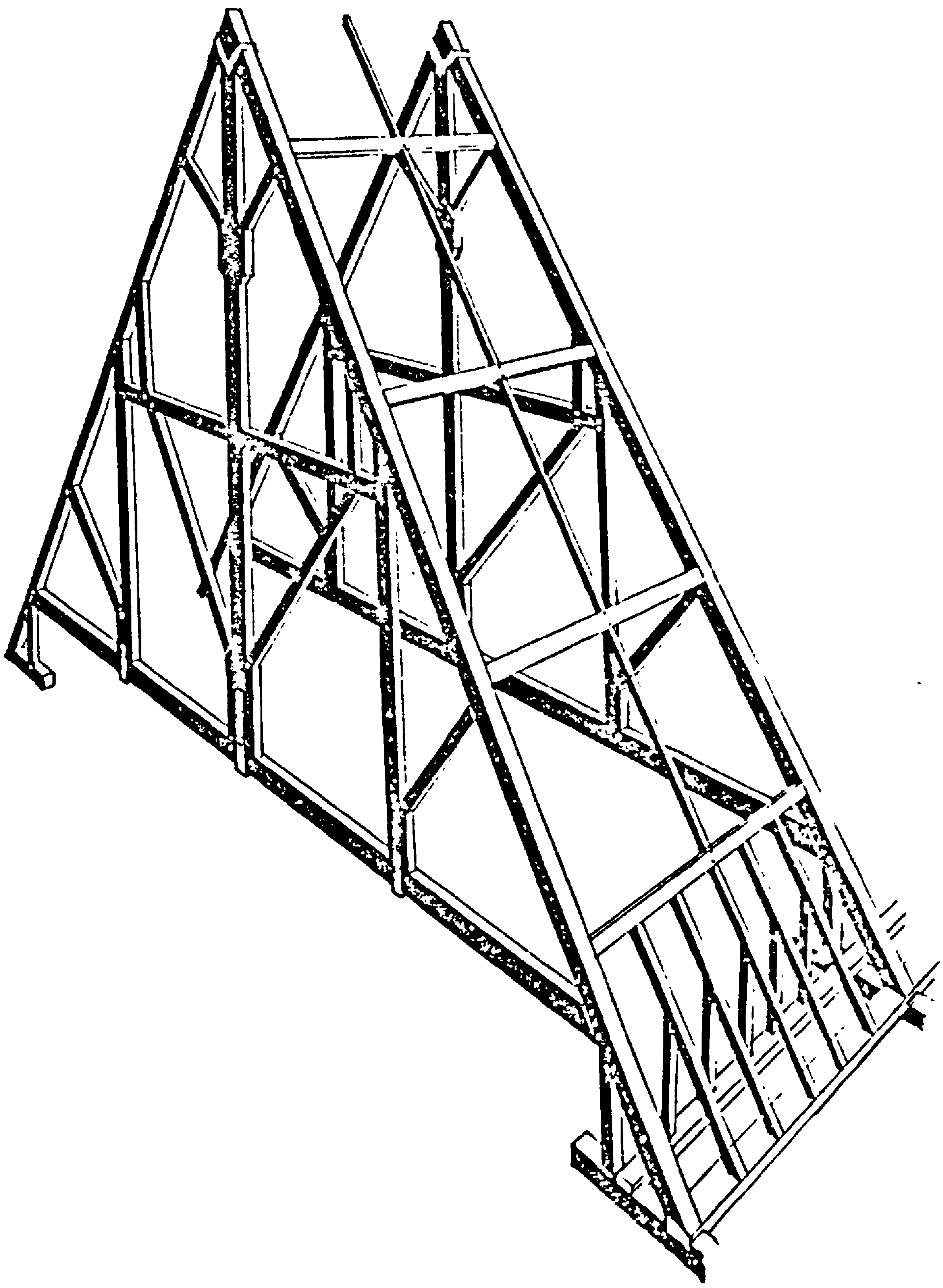


Fig. 8.8.

Canterbury Cathedral S.E. trancept roof.
From Hewett, English Cathedral Carpentry.

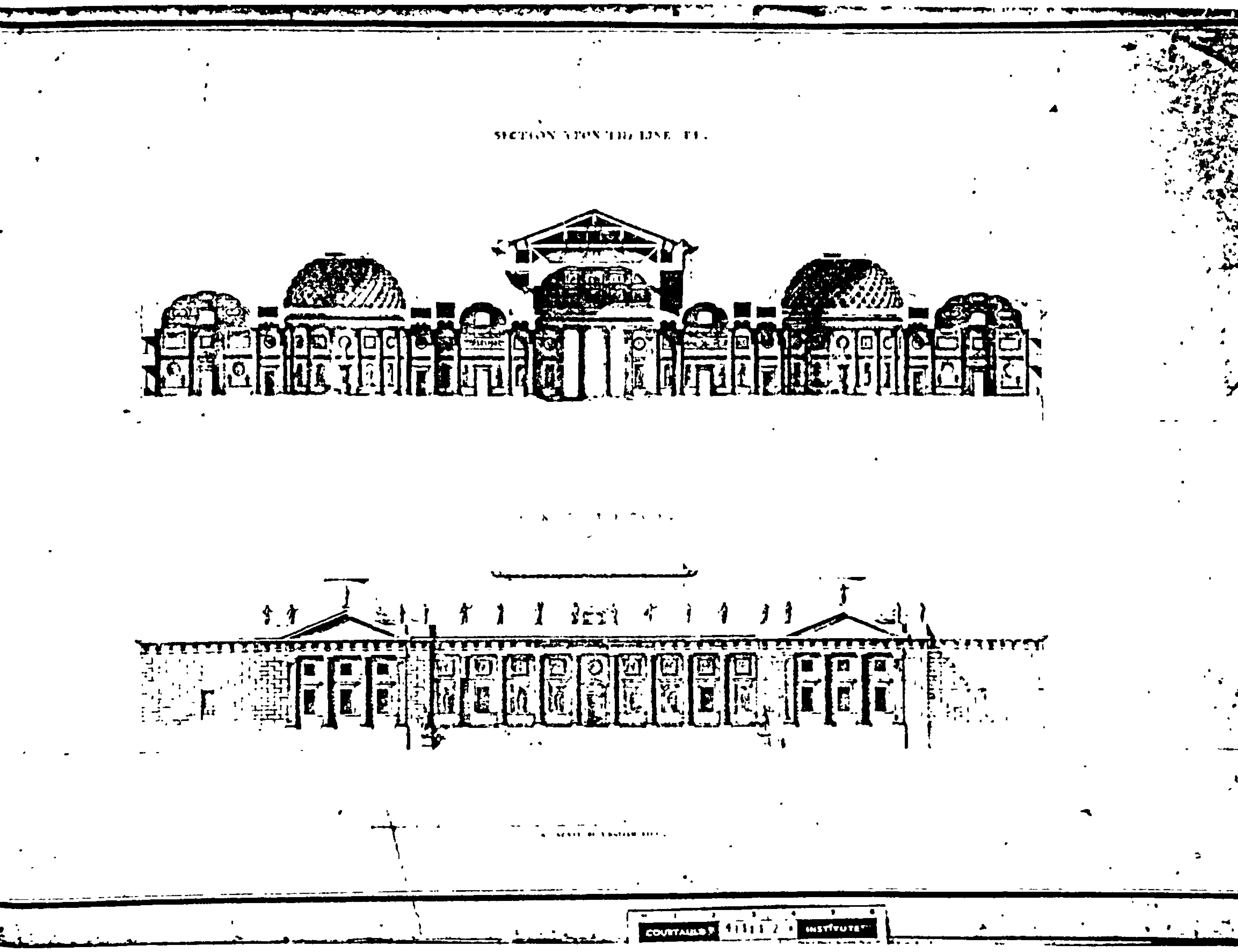


Fig. 8.9

George Dance Jr. Parma Design showing use of queen post trusses. (Soane Museum).

Fig. 8.10

Drawing of the Pantheon, Rome
showing structure of portico
roof by Thos. Hardwick.
(RIBA drawings collection)

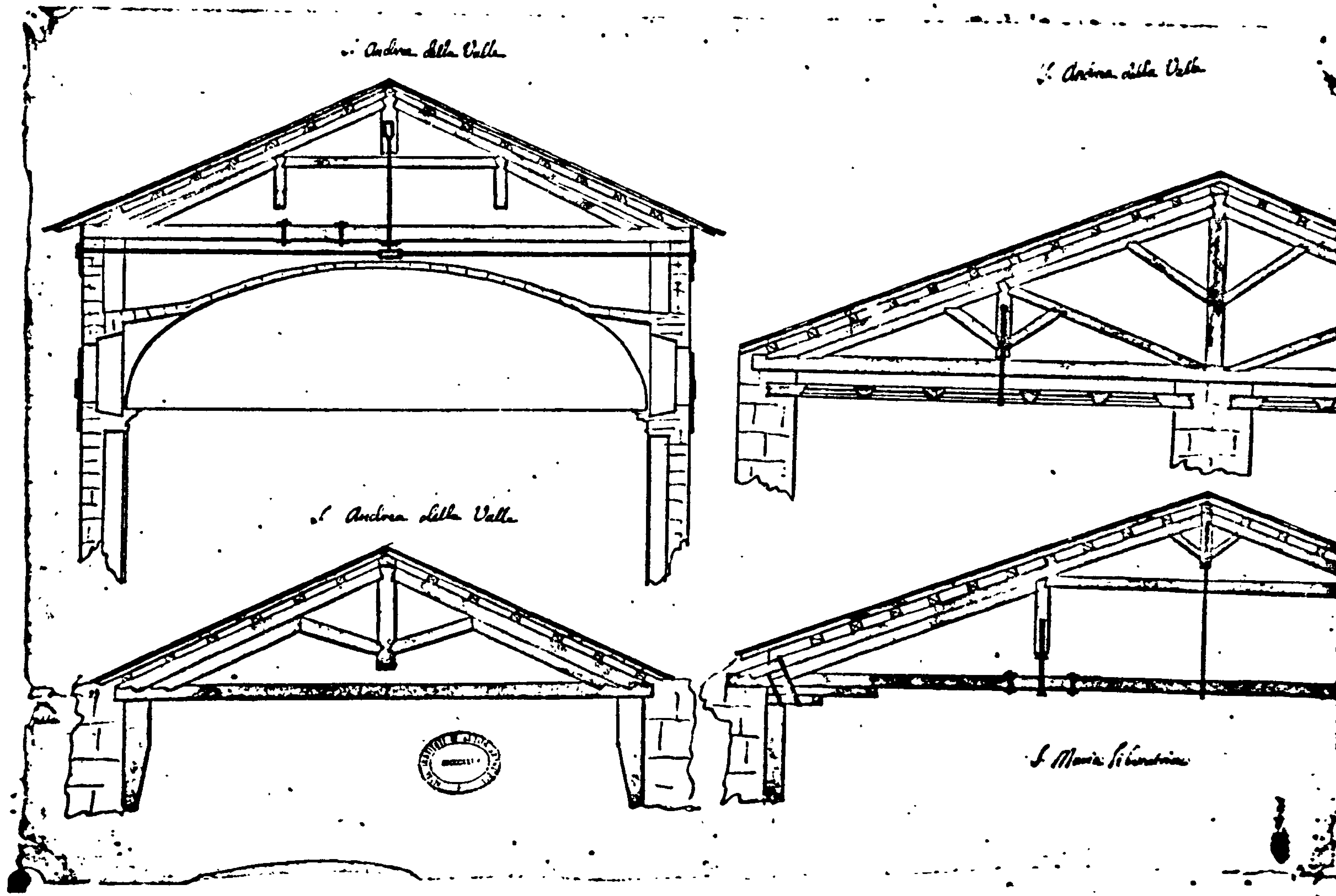


Fig. 8.11

Drawings of Italian roof trusses collected by Henry Holland (RIBA drawing collection).

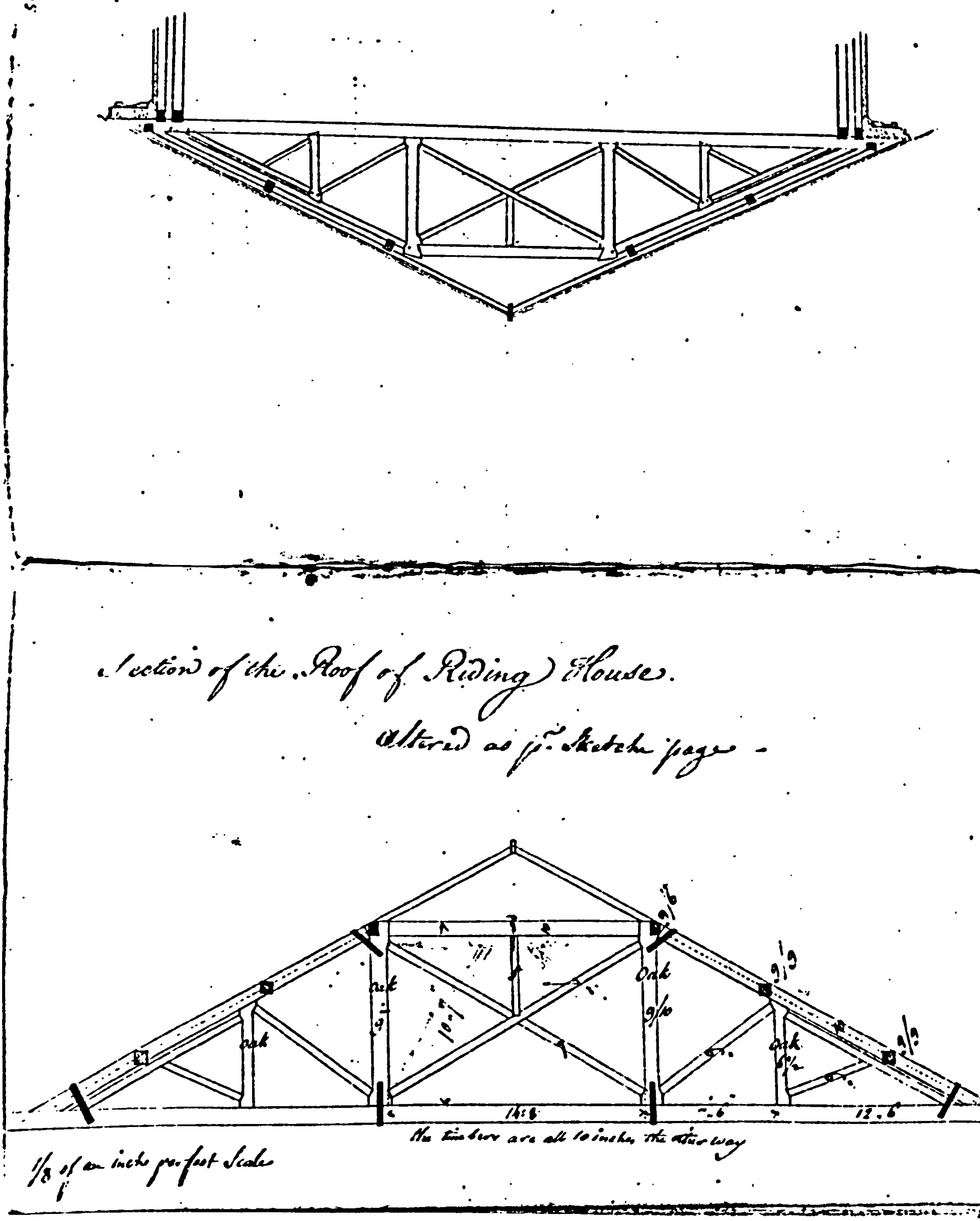
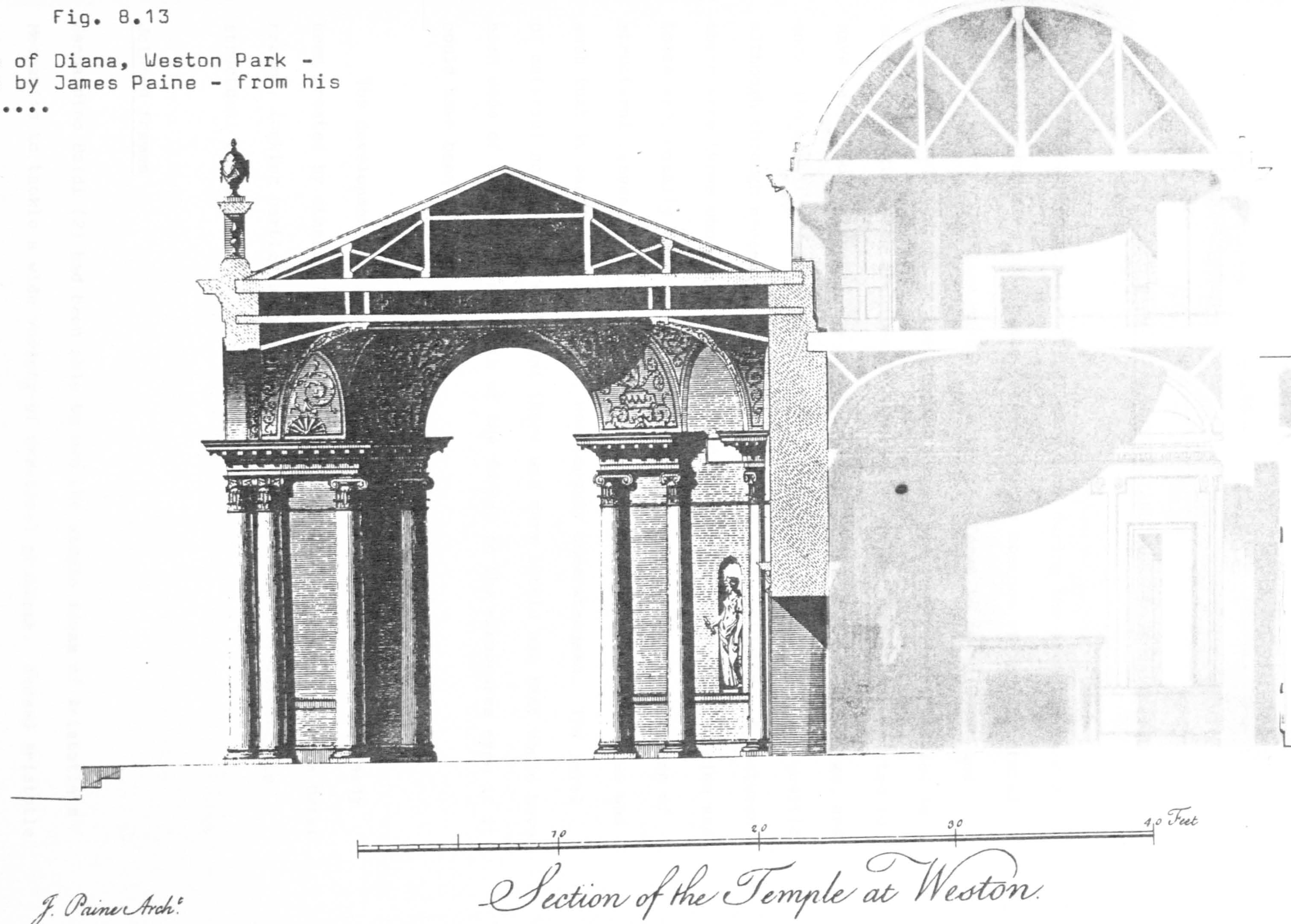


Fig. 8.12

Pages from a sketch book of Henry Holland.
(RIBA drawings collection).

Fig. 8.13

Temple of Diana, Weston Park - design by James Paine - from his Plans.....



STRUCTURAL UNDERSTANDING

The development of structural carpentry during the seventeenth and eighteenth centuries took place largely in the absence of any structural theories which would have enabled the various forms to be analysed and the forces and stressed in the members determined. The period studied is one which begins with architect/scientists who might have been expected to have had a sound grasp of the structural principles of their buildings, and ends with architect/engineers who found themselves in much the same position although through necessity rather than intellectual curiosity. In between there were those who clearly had a sound grasp of structural principles and those who, equally clearly, did not. However a detailed understanding of structural issues was hardly important. The basic design of the truss was such that it was fairly adaptable, was largely understressed. The level of material science was such that there was very little use that could have been made of any better analysis of the forces in the structures even if it could have been carried out.

The development of structural theory during this period has already been treated by others (1) and it is only necessary here to present a brief resume, looking particularly at those aspects which relate directly to structural carpentry.

Jointed frames

Bernardino Baldi (2) had been able to use the simple ideas of Aristotle's Mechanics to tackle a wide variety of practical problems. Indeed Aristotle had provided the basis for the work centuries before and Baldi merely extended the number of examples. The theoretical basis of the book is essentially the use of Archimedes' work on the lever; the principle that forces of different magnitude may be balanced by lever arms of different length, or conversely that small forces may be made to exert larger forces by the use of a suitably long lever. Added to this was the recognition that movement could be decomposed into two components at right angles to each other. Given these two simple ideas one had the components to construct the theory of the parallelogram of forces.

Leonardo de Vinci seems to have been aware of the parallelogram of forces (3) and the use of force polygons was to be developed by Stevin and de la Hire (14) by the end of the seventeenth century. This work was not to be extended into usable techniques however until the work of Rankine, Ritter and Bow in the nineteenth century (5). Until then it seems to have remained largely an intellectual exercise rather than developed for any practical purpose. Emerson in 1758 (6) provided exercises for the determination of the forces supporting an inclined beam; hardly one would imagine a pressing need for engineers at the time. His book deals with the mechanical principles of various machines, and with the behaviour of arches (7) but says nothing about the forces in frameworks. Young dealt with carpentry and the construction of roof trusses in his lectures to the Royal Society (8) but did not cover the calculations of forces in the members. His treatment of this subject is curious because the lectures could hardly have been intended for the average carpenter. Nicholson in his Dictionary (9) included the determination of forces in simple structural arrangements under the subject heading 'Mechanics'. This used the principle of the parallelogram of forces but he still did not apply it to the analysis of roof trusses. The first work on structural carpentry in which it was used in this way was that by Thomas Tredgold in 1820 (10).

Although there was no use made of this theory in formal calculations Mainstone points out that both Leonardo and Wren were aware of the inclined thrusts in their structures and sketched these on their drawings (11). One of the concerns of architects at the time, indeed the main structural concern, was the nature of thrusts in arches because this was important for the determination of the size of the restraining buttresses. This problem was tackled by Wren, Hooke and de la Hire (12). Of the three it was Wren who began with the practical problem of how to determine the size of a buttress and ironically the one who produced the least satisfactory result. He used the simple principle of balancing the mass of the arch with the mass of the buttress assuming that the fulcrum had to lie within the base of the latter; a simple Archimedian approach. He made no attempt to consider the internal forces in the arch itself and hence the integrity of the structure as an assembly of small components. Hooke and de la Hire on the other hand began with this problem. No one however was particularly concerned with the outward thrust of principal rafters nor the forces in a king post. They were resisted without difficulty by the structures being built. The implication seems to be that arch theory was developed because it was wanted but that forces in other structures were unimportant and attracted no attention. Bridge building was a problem, roof building was not.

Bending of beams

The other aspect of carpentry that was the concern of structural theorists was the strength of beams whose investigation began with the work of Galileo (13). Contributions to work in this area include Bernoulli's theoretical treatment of the deflection of beams (14) (which made the important assumption that plane sections remain plane after bending) and Hooke's Law (15). Experiments were carried out on the bending of beams by Belidor and Musshenbroek

(16) during the eighteenth century but again these ideas were not to bear fruit until the nineteenth century when Fairbairn and Hodgkinson made serious attempts to establish usable theories of beam strengths.

The nineteenth century problem was to find a method for calculating the strength of cast iron beams but as early as 1734 the rule for determining the strength of rectangular timber beams had been published. In the article on beams in the Builders Dictionary of that year (17) there is the correct statement that the strength of a beam is proportional to the width multiplied by the square of depth. This article draws on the work of Parent whose contribution to the French Academy in 1708 is cited in the article.

Emerson also dealt with the strength of beams and although this book was less likely to have attracted the attention of the majority of builders his statement of the rule was much clearer:-

> "The lateral strength of any piece of timber, in any place, whose section is a rectangle; is directly as the breadth and the square of the depth." (18)

He went on to make general comments about the strength of beams in practice, considering the strength of different timbers and suggested that a parabolic shape was ideal for a beam. By the time these works were published however the use of tables of scantlings for sizing members was well established. They continued to be used by writers throughout the eighteenth century and in spite of the obvious inconsistencies between them no attempt was made to put the sizing of timbers onto a rational basis until the work of Peter Nicholson at the end of the century. Again one assumes the traditional approach was satisfactory and no theory was needed.

Theoretical approaches

The early developments in structural theory were seldom carried out with any practical intention. The motivation seems to have been largely intellectual curiosity rather than a perceived need. The intention was to improve understanding of the forces occurring in nature rather than to improve the standards of design. Baldi's 'practical' problems are only described as such because they were taken from everyday situations. They are only 'problems' in the philosophical sense. The forces required to pull out a nail hardly required analysis because a perfectly satisfactory tool already existed.

It is doubtful if the development of Serlio's geometrical flat floor proposed by Wallis was a practical proposition in spite of the theoretical analysis that he provided to go with it (19). Examples of this type of floor were built, although not in such an elaborate form as proposed by Wallis, but it did not become commonly used and Nicholson was critical of it as a practical structure (20). Although the theoretical treatment of the structure was available it is most unlikely that it was ever applied. What would one have done with the results of the analysis had one obtained them?

Given the level of understanding of structural mechanics at the time it seems quite possible that a theory could have been developed by the end of the seventeenth century to describe the forces in a timber truss, especially after the introduction of the king post form into this country through Baldi's Mechanics. A common sequence of events in structural design is that a form is first invented and then, in order to develop it further attempts are made to provide some quantitative analysis (21). In this case however the description of the structure and a theoretical analysis of the forces in it, albeit only qualitatively, was presented in one package. It seems not unreasonable to assume that either Wren or Hooke could have provided a quantitative analysis of this problem. Presumably though there was no need for one. Just as with the analysis of the flat floor by Wallis, little could have been done with the results. The science of materials was not sufficiently well developed to have made any use of the results in sizing the timbers even if the forces in the members had been determined. To have developed a theory of trusses would have been a purely academic exercise.

Why though should such an effort have been devoted to the geometrical flat floor by Wallis and such an interest shown in it while there was no particular interest shown in the forces in a roof truss or indeed in any other practical problem? In the description of the Sheldonian roof given in the Natural History of Oxfordshire (22) it was the multiplicity of timbers used in the tie beam rather than the rest of the construction that excited interest. The same was true of the floor design. What appears to have excited writers at the time was the ingenious nature of these forms rather than their practical value.

Girouard (23) points out how the Elizabethans had been fascinated by the 'ingenious device' in the planning of buildings as much as in other things. So it seems to have been at the end of the seventeenth century. In what we might regard today as strictly practical or scientific matters it was the curious and unusual that received attention rather than the everyday issues. The record of subjects discussed by the Royal Society is full of descriptions of the curious and the bizarre rather than of attempts to explain the commonplace which today we would regard as the proper task of science. It was only a few of the members who helped to give birth to the sciences that we know today (24).

Although there were approaches to the problems of structural analysis by the beginning of the eighteenth century Mainstone regards the beginning of the development of structural analysis in building to be 1742 when an analysis of the forces in the dome of St Peter's, Rome, was attempted (25). This was needed because movement in the structure had resulted in severe cracking and its security was in doubt. The later developments of bending theory and the analysis of trusses did not occur until they were needed by the engineering requirements of the nineteenth century, in particular the development of the railway and the need by engineers to be able to analyse bridge structures. The general pattern thus seems to be that techniques of structural analysis are not developed without first the invention of the forms to analyse. But invention of the form does not automatically lead to the search for a means to describe it structurally. That only comes about when its refinement or its use in more difficult circumstances makes such an analysis essential.

And yet, given the undoubted contributions to mechanics made by Hooke and Newton, why should practical applications not have developed in this country? Why should it have been from France that the ideas on the strengths of beams were eventually and belatedly imported? Why should de la Hire and Coulomb have made greater contributions to the understanding of arches than workers in this country?

The simple pragmatic reason offered above, ie. that theoretical developments only occurred in response to need, may be part of the answer but it is not sufficient by itself. One may then wish to invoke differences of national character and temperament as an answer and while these may seem a little vague and insubstantial they did manifest themselves in a concrete way. The

French were much quicker to develop schools of engineering than the English. The influence of this upon the technical education in the two countries is still being felt today. But it was also recognised during the eighteenth century when France had an established system for technical education.

As early as 1749 John Gwynn (26) was complaining that the standard of design in England lagged behind that of France. To be sure the applications were chiefly military but Gwynn recognised that the English tended to respond only to immediate need and advocated the establishment of an academy:-

> "King Charles II... founded such a school in Christ's Hospital which has produced many proficients. King William established a mathematical lecture to breed up Engineers and Officers, which was discontinued however after the peace of Ryswick. The fault of the English has usually been to neglect the means of teaching military qualifications when the use of them has not been immediately necessary."

Informal understanding

If there were no formal techniques for the design of trusses during this period, their development must have depended upon an intuitive understanding of the nature of the forces acting. To attempt to assess the nature of such intuitive understanding and its possible effect on the development of structures is to tread upon dangerous ground. It is difficult enough to try to assess the nature of structural understanding of someone today (as any examiner in structures must be aware). Attempting the same task with designers long dead is that much more difficult because one cannot even question them on their ideas. Moreover in forming our view of the world we draw upon the whole of our knowledge of natural science and the nature of this knowledge changes with time. One cannot affect an artificial ignorance in order to attempt to see the world in the same way that our predecessors did because one cannot know the relative importance they placed upon the concepts which they used to form this view.

This kind of difficulty is illustrated by Moxon's treatment of the framing of floor joists (27). Medieval carpenters had built floors with the joists 'laid flat'. Seventeenth century floors had their joists laid on edge as is now done. While this is done today in order to give the greatest stiffness for the quantity of material used it seems as if the reasons at the time were quite different.

> "The joysts ... are framed so as to lie with one of their narrowest sides upwards ... The reason is because the stuff of the bressummers and girders are less weakened by cutting the mortices in them in this position ... for as the tennants for those mortices are cut between the top and bottom sides and the flat of the tennants are no broader than the narrowest side of the joists so the mortices they are to fit into need ... not be above an inch thick.
>
> "... great care must be taken that the bressumers and girders be not weakened more than needs lest the whole floor dance. The tennants (28) are cut through the two narrowest sides rather than the two broadest sides because the stuff of the girders retains more strength when least of the grain of the stuff is cut."

Moxon recommends the correct practice for joists but not for girders. The ends he wishes to achieve are understandable but not the means he uses. Apart from some confusion between strength and stiffness he does not know what affects the properties of a beam. One may sympathise with his wish not to remove too much material and thus agree with the reasoning of the first paragraph but our present appreciation of structural behaviour makes the reasoning of the second paragraph less easy to follow. At least we have Moxon's reasoning; but what would the construction suggest without it? Are there any simple structural concepts which we may assume to be natural? It would not matter whether they lead to correct conclusions about the behaviour of structures as long as they correspond to untutored intuition.

Mainstone (29) tackles this problem distinguishing three complementary types of structural intuition; geometrical or spatial intuition, physical or muscular intuition and intuition based on deformations under load.

His first category - spatial understanding - he says is "recognising the possibility of preventing the fall (of an object) by placing an obstacle in its way". In earlier roof structures the tie beam had been the obstacle in the way of the struts falling, but in the trusses considered here the king and queen posts were seen as obstacles to prevent the deflection of the tie beam. Only this can account for the use of the metal straps. The joggles were equally obstacles to the downward movement of the posts as is shown by Pratt's instructions on the framing of a king post truss (30) and by Nicholson's analysis of the forces in a truss (31).

Understanding a roof truss, a framework of jointed timbers, would have involved largely the understanding of the forces at the joints. The joints were, after all where the carpenters skill and knowledge were concentrated. He would have had to recognise whether a member was pushing or pulling the other members that it interacted with at each end; Mainstone's second category of structural understanding.

Once the first trusses had been built and were in use, then observation of their behaviour might have improved the designers' understanding of the structure. This is Mainstone's third category of intuitive understanding based upon the observation of structural movements. The necessity for repairs to structures that had failed, like those needed to the Banqueting Hall roof, might be supposed to have provided useful lessons in this way. However their effect was probably limited. At a time when there was no formal means of discussing such events the lessons would only be available to a few. Much more significant would be the effects observable in large numbers of trusses allowing an accumulation in large numbers of trusses allowing an accumulation of experience such as the dropping of a truss because of shrinkage of the king post: a problem mentioned by Salmon (32).

Although one may accept that such forms of understanding existed and readily find structural features to which they might have been applied, one cannot be sure that they were present in any individual case. After all it would have been perfectly easy for a carpenter to copy a satisfactory roof structure that he had seen built without necessarily understanding himself how it worked. If the form were faithfully copied one would not know whether or not the carpenter was aware of the forces acting in the truss.

Moreover, structural understanding is not something that one either has or does not have. Just as colour blindness does not mean a total inability to see colours so the forces in a structure may be partially understood. At a simple level one may for example understand the overall behaviour of an arch without fully grasping the nature of the forces acting at the face of each voussoir. Such a level of understanding is given by the simple model of an arch as the mirror image of a hanging chain (33).

The understanding of trusses may well have been the reverse of this in some cases. That is, the forces acting at the joints may well have been understood without a clear grasp of the overall behaviour of the whole frame. Such a level of understanding might account for some of the more curious examples of structural invention - those by James Smith (34) for example.

What evidence then should one accept of either understanding or lack of understanding of structural principles in roof trusses? The only indication that there might be of structural knowledge or the lack of it is where there was some variation from the standard form; where the carpenter either produced a recognisable improvement or made a structural mistake. In using such indicators however one must recognise that one makes the implicit assumption that the variation was deliberate.

Understanding the truss

The design of a roof truss was as much a problem of construction as of determining the forces in the members. The basic principles of the king post were few and a fairly simple intuitive understanding of its behaviour would lead to adequate if elementary rules of design. The carpenters' problem was then to make the truss with adequate joints capable of transmitting the forces.

The characteristics of the king post truss are:-

(i) The strap at the bottom of the king post to enable it to truss up the beam.

(ii) The joggles at the head of the king post to enable the principal rafters to support it.

(iii) An adequate joint at the feet of the principals so that they might be restrained by the tie beam.

(iv) Where struts and secondary posts are used the use of joggles for the struts to bear against.

A strap at the foot of the king post was in general use throughout the eighteenth century and was used by those architects and carpenters in the seventeenth who were using the king post form. Its function in trussing up the tie beam was clearly recognised by Pratt (35). However its use is also shown in some of the trusses invented by Smith in places where it would serve no useful purpose (36) so that its presence is no guarantee of structural comprehension. Rather the absence of a strap in the drawing by Isaac Ware (fig. 6.1) confirms his lack of understanding of the truss as does the absence of joggles at the head of the post.

The most serious jointing problem in a king post truss was not the jointing of the members of the truss at all but the joint for the purlins. Removal of timber to form the mortice clearly weakened the principals. The effect of this will be minimised if the truss is framed so that the struts are as close as possible to the purlins so reducing the amount of bending in the principals. Of course the problem can be avoided altogether if there is no purlin to be jointed into the principals and it may have been the realisation of this that led to the use of close spaced purlins of light scantling rather than of common rafters and heavy purlins.

Jointing of the truss members was by mortice and tenon joint. Joggles in king posts and secondary posts to receive the ends of the struts might be either simple splays or be cut with square shoulders (fig. 1.10b). Gibbs is notable for his common use of the square cut joggle but there can have been little difference in strength and the use of this detail can hardly be regarded as a serious weakness of detailing.

Once joggles were introduced for the king post they were used generally on all posts where members were jointed in. Although it was expensive in timber it was a way of forming a secure buttment for the struts without unduly weakening the post with mortices.

One striking detail that requires some explanation is the use of metal strapping at the head of the king post. This appears first in the work of Hawksmoor and increasing use seems to have been made of metal straps at the head of the post until by the beginning of the nineteenth century they were used almost universally. The early nineteenth century text books showed a wide variety of alternative strap types although Hawksmoor used Y shaped straps running over the top of the principals.

There seems no obvious reason why such strapping should have been used unless it was felt that the joggles might not be sufficient in themselves to trap the king post. The joggle used by Inigo Jones in his Stoke Bruerne roof is very broad but later joggles tended to be narrower, either to save timber or possibly to make the truss easier to assemble.

The geometry does not automatically ensure that the post is trapped by the ends of the principals which might slide upward relative to the head of the post. The truss thus relies upon friction in the joint to be secure. If the metal strapping was added in recognition of this tendency it indicates considerable thought about the nature of the forces in the truss on the part of either Wren or Hawksmoor. Hawksmoor's form of strapping is clearly well suited to the restraint of the principals.

Other methods of strapping do not seem quite as efficient although they were probably easier to fix. In order to slip upward the principals also would have to move apart and thus it would also be satisfactory to tie the two principals together rather than strapping them directly to the king post.

This is only speculation. What is curious about the use of metal strapping is that it does not seem to be recommended particularly by the eighteenth century writers who leave it out of their drawings. One suspects it may have been included in nineteenth century works simply because its use had become customary by then (37). Nicholson's analysis of the king post truss (38) was intended to show where the proper places were to use metal strapping and suggests that the intention behind these straps was to overcome the problem of sagging of the trusses through shrinkage of the timbers.

The thrusting out of the principal rafters seems to have been recognised by the builders of earlier 'traditional' roof frames (39) and so the addition of metal straps at the feet of the principals in these new trusses probably does not indicate any new awareness of these forces. It more likely reflected a practical difficulty posed by the use of shallower roof slopes. As the angle between principal rafter and tie beam was reduced it would have become difficult to form a mortice and tenon joint with the tenon restrained by a peg. At the same time the tendency of the tenon to slide out of the mortice would be increased if the joints were not well made. Thus the metal strap or bolt to hold the principal down to the tie was a prudent safety measure. Taking the outward thrust directly on the metal strap is an interesting development of this.

As with other features of the truss Pratt shows a clear recognition of this problem. (see quotation page 126).

Structural ignorance

Some of the design drawings from Wren's office with struts bearing onto the tie beam suggest that the draughtsmen may not have fully appreciated the function of the king post. However joggles to carry the struts were used in all the built examples. Similarly joggles were commonly used on secondary posts.

Attempts to invent new forms of truss or to modify existing ones provide a more substantial indication of structural understanding. The trusses shown in the text books have already been discussed in some detail and, as has been seen, the indications are that the level of structural understanding of some of their authors was often weak. Some were clearly completely ignorant of structural principles and there is also the possibility that they were equally ignorant of other practical aspects of building (40).

Halfpenny is interesting because, unlike other authors, as well as offering an unusual design of roof, he also used the form in the design of a building (41) although one must doubt whether any roofs of this type were ever built. The roof type which Halfpenny called an 'intersecting roof' was drawn in his last publication (42). The plates inscribed 'Wm. Halfpenny Invt.' show a variety of roof shapes, including a type of hammerbeam roof, each framed with a multiplicity of small timbers. According to the text the purlins supported by these are to be only 4 inches x 4½ inches and the members of the trusses are all smaller than this. It is not clear why this design should have been offered when the king and queen post trusses were already established and when timbers large enough to build these were available.

Paine's trusses in the Temple of Diana at Weston Park (fig. 8.13) have no metal strapping at the feet of either pair of posts and over the life of the building the tie beam has sagged. One can understand how the design of a poor structure like this might be repeated. The combined stiffness of the principal rafters and the tie beam combined with arch action of some of the members would result initially in only small deflections. The sag in the tie beam under the ceiling load probably developed over a period of time through a combination of shrinkage and creep. In any case it would have been hidden by the ceiling and so the architect would not have been exposed to evidence of a weakness in design.

Among the Adam drawings are a number of sections of buildings which include roof trusses. The majority of these are, as one would expect, king post types although they are seldom drawn with the care that one finds in the drawings of other contemporary architects. Perhaps one would regard this as an indication of a lack of interest in structural details. A drawing of Osterley House includes an unusual layout of roof timbers (fig. 9.1). The 'truss' appears to be a combination of king post and queen post types. One must assume that the internal partition is non-structural and it is difficult to see then how the structure could have worked. There seems to be no way that the forces in the principals can be taken back to the wall plate without relying upon bending in the tie beam. The structure appears as a combination of mere visual forms. The designer in this case exposes his ignorance when he tries to extend the form of the truss to cope with a new situation and has only a passing understanding of the original form to rely upon.

As earlier in the century, ignorance of structural principles was no bar to the successful practice of architecture because one could still rely upon the skill of one's carpenters or clerks of works to provide the structural design. Chambers, not necessarily ignorant of structural matters, wrote to his builder at Milton Abbey House with only the briefest instructions for building the roof. For the roof of the porter's lodge he considers that the builders should know how to build "such a trifle" without direction (43). Elsewhere in the house he directs that for small spans a simple king post roof should be used while trusses with secondary posts are to be used for long spans (44). He provides only the simplest of sketches with no constructional details and it seems to be up to the builder to decide what shall be a long and what shall be a short span.

It would seem that there were a number of architects with little or no knowledge of the practical aspects of building. If one believes the more practical minded architects, who had received their training on actual building work, the only training that their less practical rivals had received was in foreign travel. John Gwynn complained that:-

> "... nothing more is required to model a youth of moderate parts into a complete architect than to put him apprentice to a bricklayer, mason or carpenter, under whose tuition he will gain the great art of scoring straight lines ... His servitude being ended ... he may be sent to Rome, and after he has spent the usual time traversing that city, he may cause it to be inserted in the London papers, that Mr Trowel, the celebrated architect ... has had prodigious honours conferred upon him ... His next business is to decorate his house with borrowed plumage, and then get some friend to beat the drum, and stun the public with ecomiums upon this prodigy of art."

In quoting this Jenkins (45) assumed that Gwynn had Mylne in mind when he wrote this piece of invective, quoted only in part here. Thus Gwynn may not have been a disinterested commentator. However he was not the only writer to express such sentiments and the method of architectural 'training' that he describes seems to have persisted until at least the end of the eighteenth century.

Peter Nicholson echoes these sentiments in his Architectural Dictionary (46) when he is critical of:-

> "fanciful designs, which too often from a want of principle, prove absurd in the execution, and then bring him (the architect) into disgrace; it is for this reason that he is so frequently supplanted by the clerk of works employed under him."

It is not clear whether or not Nicholson had anyone in particular in mind when he wrote this, but he too attributes this state of affairs to excessive foreign travel. Nicholson was a quarrelsome character who would not have been prepared to suffer fools gladly and his view cannot therefore be regarded as completely unbiased. However this view of architectural practice is supported by Peter Pindar who says of James Wyatt (47):-

> "I know the foolish kingdom all runs riot,
> Calling aloud for Wyatt Wyatt Wyatt,
> Who in their good opinion hourly gains,
> But where lies Wyatt's merit? Where his praise?
> Abroad this roving man spent half his days,
> Contemplating of Rome the great remains."

Structural Competence

Although there were architects who practised with little technical competence, there were others who showed considerable concern for the problems of building. There were architects who prepared working drawings for their buildings, giving details of the structural arrangements and there were architects who by the end of the eighteenth century were able to develop the truss forms and use them over greater spans than before and to carry much heavier loads even without the guidance of formal analytical techniques.

We have seen variations that indicate ignorance but what variations were used which might indicate a higher level of understanding of the truss?

If secondary posts were not used, then, at their upper end the struts were commonly cut flush with the lower face of the principal rafter. A refinement was to notch the principal slightly to receive the end of the strut (48). This may show an appreciation of the forces involved but such a refinement was hardly necessary since the mortice and tenon joint was sufficient to prevent any movement.

The gradual sagging of roof trusses under load is mentioned by a number of text books and it was recognised that this could be caused by the shrinkage of the king post. This allowed inward movement of the struts and the principals and hence the whole truss to drop. For this reason oak continued to be recommended and used for the king posts even though the tie beams were being built of fir.

Gibbs' use of wedges to tighten the joints in the portico roof truss at St Martin in the Fields has already been remarked upon. Both the use of this detail and the general framing plan of this truss shows that Gibbs was aware of the greater than normal forces on this particular truss. I know of no similar examples even in Gibbs' other buildings.

Perhaps the clearest indication that the action of the truss was understood was the use of jointed tie beams. For long span trusses this was often necessary and a willingness to form the tie in two pieces shows that the carpenters were not expecting it to act as a beam. The joint most commonly used was the splayed and tabled scarf tightened with a key; a joint capable of transmitting the tensile force in the tie (fig. 9.2). However the appreciation of the presence of a tensile force was not necessarily new. The books on building - even Palladio - commonly refer to the beam's function in tying the walls together.

The form of truss used by Inigo Jones at Covent Garden was not adopted by any of his immediate successors. There was a brief appearance of the form in the drawing by Flitcroft for St Giles' in the Fields but not then built. However it was used much later by Nash in his designs for Shanbally Castle (49). The roof by Nash is of quite modest span (30ft) and there seems to be no apparent reason for the adoption of this arrangement where a simple king post truss would have served. The scantlings are no less than one would expect for this span and it almost looks as if Nash were merely experimenting with this type of truss. Thomas Johnson also used a similar form for the roof of St Nicholas, Warwick (50). Johnson had presented himself with a serious problem designing a pyramidal roof based upon two long spanning trusses. Thus some novel design was to be expected.

It seems unlikely that these two trusses were copied from Inigo Jones design, particularly in view of the poor performance of the Covent Garden roof (51). Either these were independent inventions of architects prepared to experiment with new forms or, more likely, they were based upon a knowledge of similar Italian trusses. Trusses of this form were included in the collection of drawings that Holland had collected for him in Italy (fig. 9.3).

George Saunders seems to have adapted this kind of arrangement to improve the spanning capabilities of a queen post truss in his Birmingham Theatre roof (fig. 9.4). (Saunders was later to provide the structure to replace Wren's Sheldonian Theatre roof). Much the same structural arrangement was used by Holland in his Riding House roof (discussed earlier).

There appear to be two developments in parallel here. Architects were practising who were increasingly capable of producing new designs in structures rather than being dependent upon the simple established forms. This, in itself, speaks of an improved understanding of structural principles on the part of these architects. They were also taking greater charge of the details of building, producing what are recognisable today as working drawings, rather than leaving matters of building detail in the hands of the craftsmen. Much more important though was a move away from intuitive design and the sizing of structural members by little more than rule of thumb, towards a much more scientific approach. This change in approach to structural design is marked by the appearance of the text books of Peter Nicholson whose work has already been described.

Technical education in England during the eighteenth century was concerned with the education of craftsmen rather than of professionals. Belidor in France wrote his Science des Ingenieurs as early as 1729 (52) but English engineering texts did not appear until the nineteenth century. Most of the technical books were directed toward carpenters and the only books for professionals were the architects pattern books. Hamilton noted (53) that both Rennie and Telford had learnt French and German in order to read continental sources. The Ecole des Ponts et Chaussées was founded in 1747 while in England we find mainly references to schools for tradesmen during the eighteenth century.

Nicholson's contributions to the 'science' of carpentry were devoted mainly to improvements in the application of geometry and he did no original work himself on the development of structural principles. His inclinations were toward mathematics rather than experimental science being content to cite the results of others rather than carry out his own experiments. His contribution to structural understanding was not through original work but rather by bringing to the subject an attitude of mind that questioned established practice and replaced tradition with reason.

By doing this Nicholson established a high standard of technical literature for the writers of the nineteenth century to follow. The practice of providing rational rules for design and for citing experimental results as a basis for design which Nicholson began was to be followed by these later writers. Tredgold publishing early in the nineteenth century (54) was to follow much the same pattern. By the end of the eighteenth century building structures were already of such a scale that simple roof truss designs were not adequate and more complex arrangements were being produced. Whilst a few 'experimental' structures might be built with limited structural understanding the general expansion of structural problems at this time with the development of industry and the development of railways during the nineteenth century demanded the improved standards of structural understanding that Nicholson had begun to teach through his books.

Footnotes - Chapter 9

1. See for example Hamilton (1952), Straub (1952) or Mainstone (1975).

2. Baldi (1621)

3. See Hart (1925)

4. Stevin (1608) and De la Hire (1695). A translation of the former has been published by McCormack (1919).

5. Rankine (1858), Ritter (1888) and Bow (1851)

6. Emerson (1758), p.87

7. Ibid. pp.110-6

8. Young (1807), pp.168-71

9. Nicholson (1812)

10. Tredgold (1820), plt.1

11. This has been pointed out by Mainstone (1975), p289

12. Hooke's manuscript discussing the problem of arches is in the Guildhall Record Office
Mainstone (1975), p.284 provides a critique of Wren's method of dealing with arch thrusts.
De la Hire (1695) was the generally accepted account of arch behaviour.

13. Galileo (1638). A modern translation is provided by Crew and de Salvio (1914).

14. Bernoulli (1705).

15. Hooke (1678).

16. Belidor (1729) and Musschenbroek (1729). It was the work of these two which was to be referred to at the end of the eighteenth century by Nicholson in his various carpentry texts.

17. Builders' Dictionary (1736)

18. Emerson (1758), p.93

19. Wallis (1671), pp.589-604

20. Nicholson (1812) vol. 1, p191

21. Such a simplification cannot be made without some amplification. There are clearly cases where the development of a structural form has been dependent upon the development of structural understanding. Perhaps the clearest example of this was the design and construction of the Britannia and Conway Tubular Bridges, recently discussed by Rosenburg & Vincenti (1978). However, the majority of structural forms are developed and used before any theoretical description is available. Even where there is theoretical support, the theory will only be an approximation; adequate until the development of the form takes it outside the limits of the simplifying assumptions and possibly a collapse indicates the need for a more refined theory.

22. Plot (1677)

23. Girouard (1966), p.35-42

24. The catalogue of observations reported includes many that are simply unbelievable. They suggest a positive desire to astound, or to be astounded. Even today one may recognise in many people an avoidance of rational explanation and an attraction for the mysterious.

25. Mainstone (1975), p290

26. Gwynn (1749)

27. Moxon (1679), p139

28. Presumably he means 'mortices'.

29. Mainstone (1975), p295

30. Gunther (1928), p212

31. Nicholson (1797), p65

32. Salmon (1755), p77

33. Mainstone (1975) used this model which was that devised by De la Hire. A curious model, also frequently used, is that which envisages the arch as a set of balls balanced upon each other to form a catenary. This is quite false because it suggests that there is a perfect arch shape, ignoring both the variety of arch shapes possible and the changes in thrust line caused by live loads.

34. Smith, James (1733)

35. Gunther (1928)

36. Smith, James (1733). Inspection of this joint was often difficult and often impossible so that no systematic record of different joint types could be made.

37. Metal strapping was by no means universally used. It is possible that it may have become more common with the increasing use of fir rather than oak for the king posts. However, the sample of roofs examined in this study was not large enough to test such an assumption.

38. Nicholson (1797)

39. There are sufficient comments in early books to show that this was recognised.

40. Batty Langley's comments on the manufacture of bricks and his absurd belief about the composition of clay has been noted earlier.

41. RIBA Drawings Collection. Waterford Cathedral drawings.

42. Halfpenny, Halfpenny, Morris and Lightoler (1757), pp.51-2, plts. 82 & 83

43. Chambers' letter book - BM. Add. 41133, f.45

44. Ibid. f.53

45. Jenkins (1961), p.100

46. Nicholson (1812) under the heading 'Constructive Carpentry'.

47. Quoted by Dale (1936)

48. eg. used by Flitcroft in his roof at Chiswick House - Ministry of Works (D of E) Photographic Collection

49. RIBA Drawings Collection. Shanbally Castle, 8. f.3v

50. There is a model of this building at Warwick County Museum.

51. This had required repair early in the eighteenth century. See Survey of London.

52. Belidor (1729) was to be reprinted in a number of editions until as late as 1830.

53. Hamilton (1952)

54. Tredgold (1820)

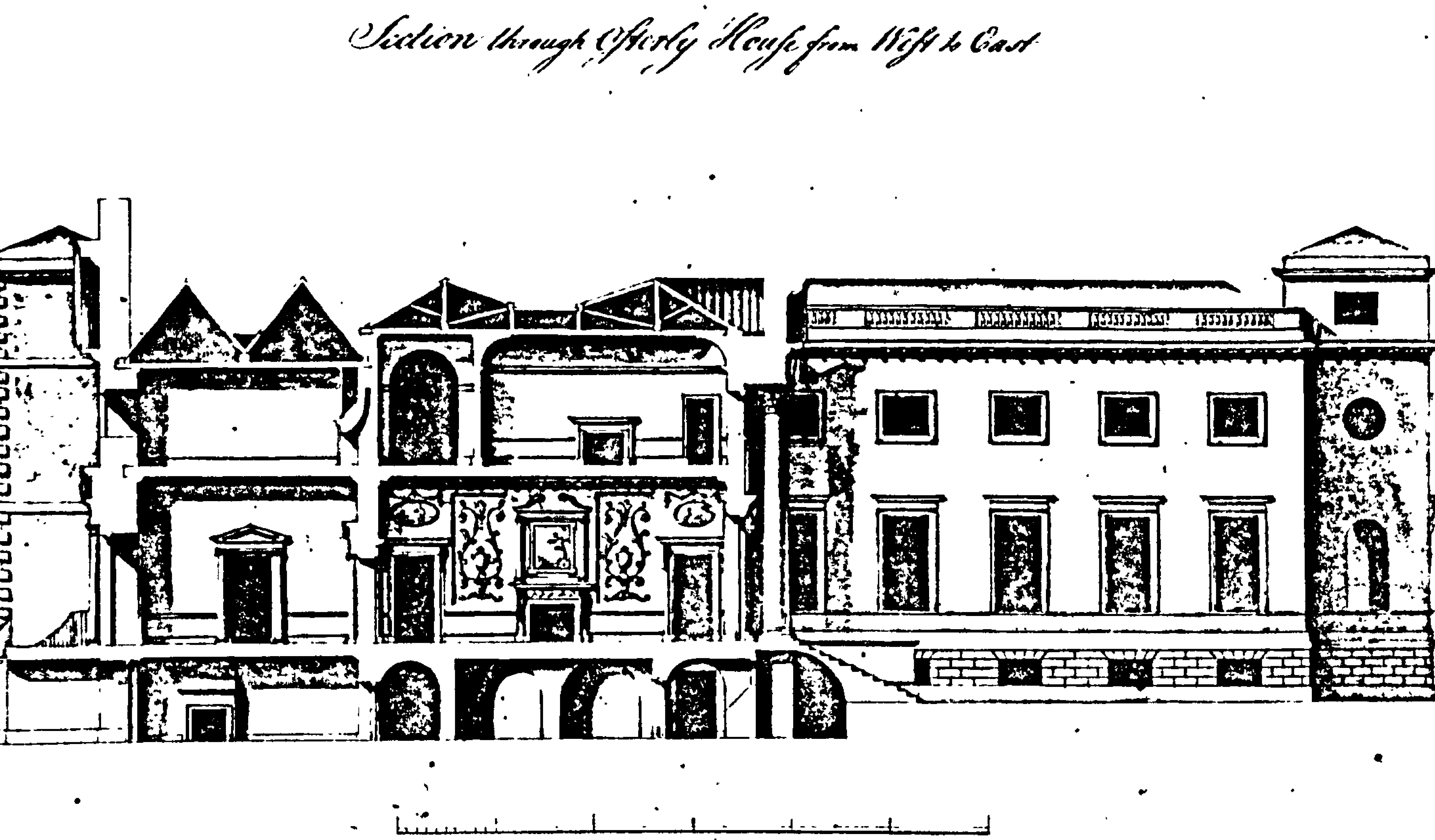


Fig. 9.1

Adam drawing for alterations at Osterley. (V. & A.) The roof truss was not built.

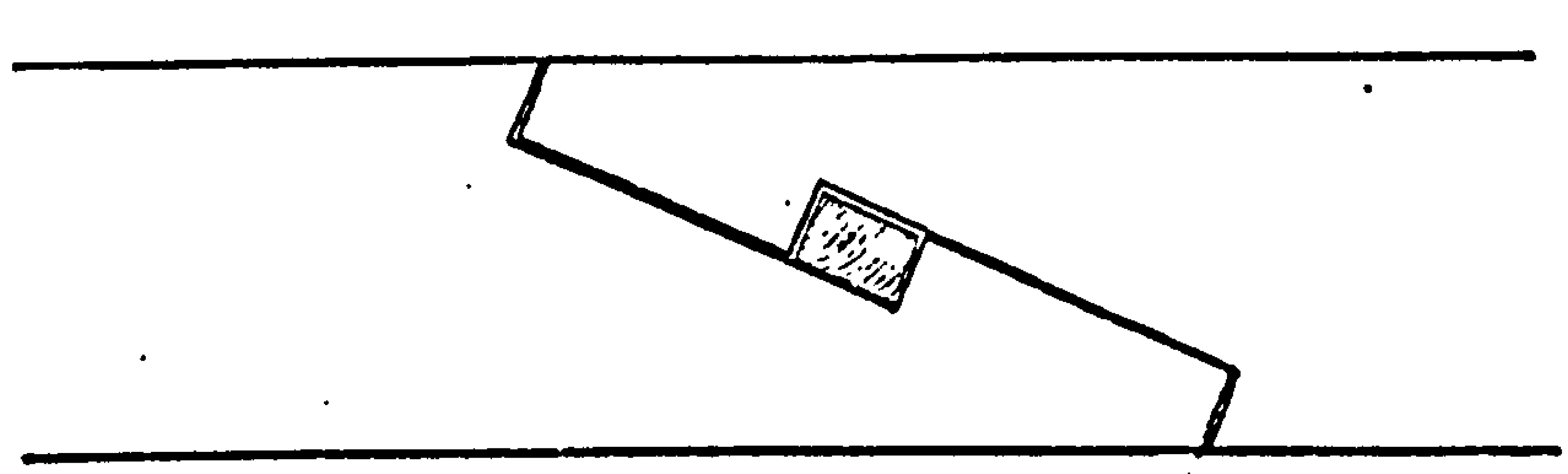


Fig. 9.2

Scarf joint typically used in tie beams.

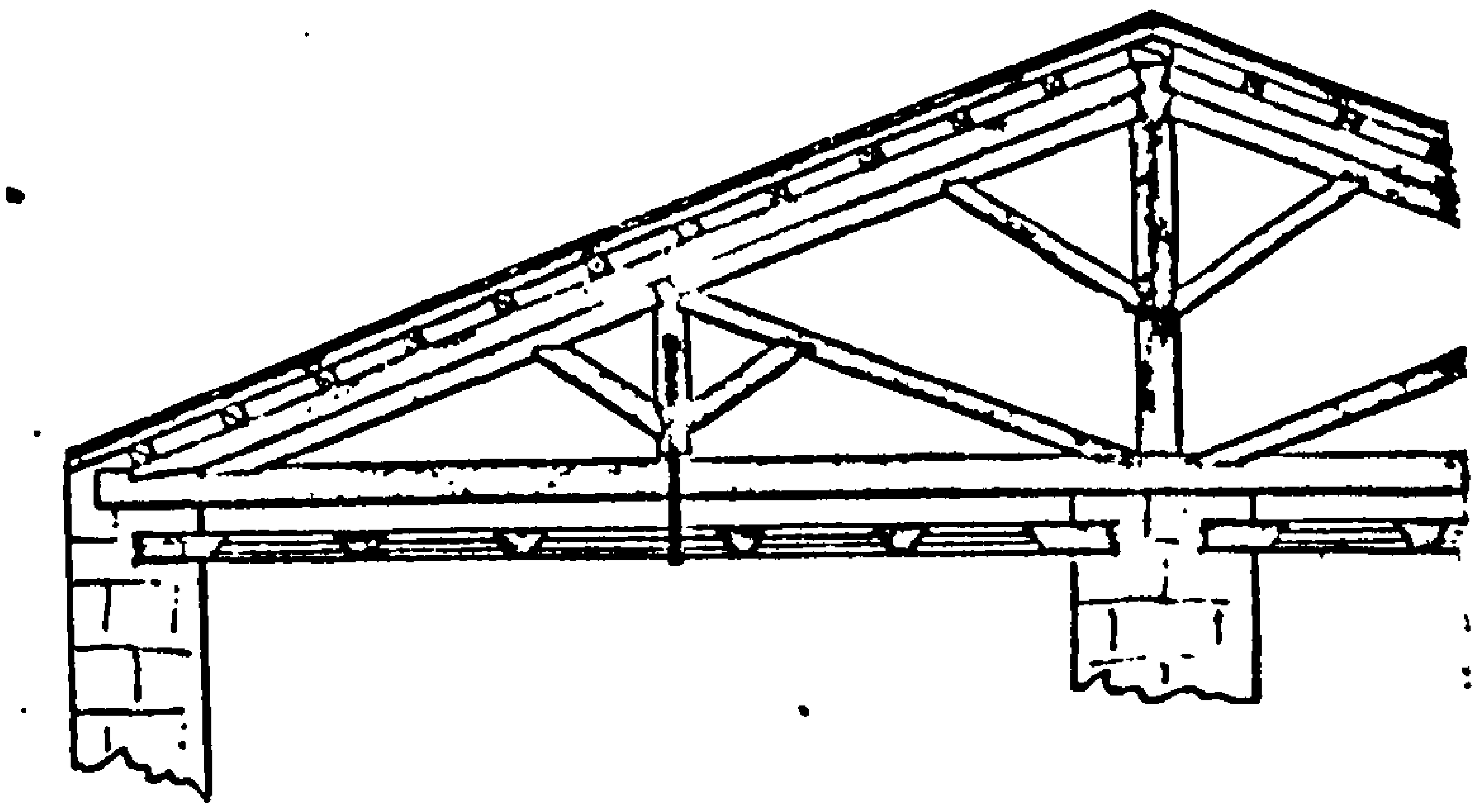
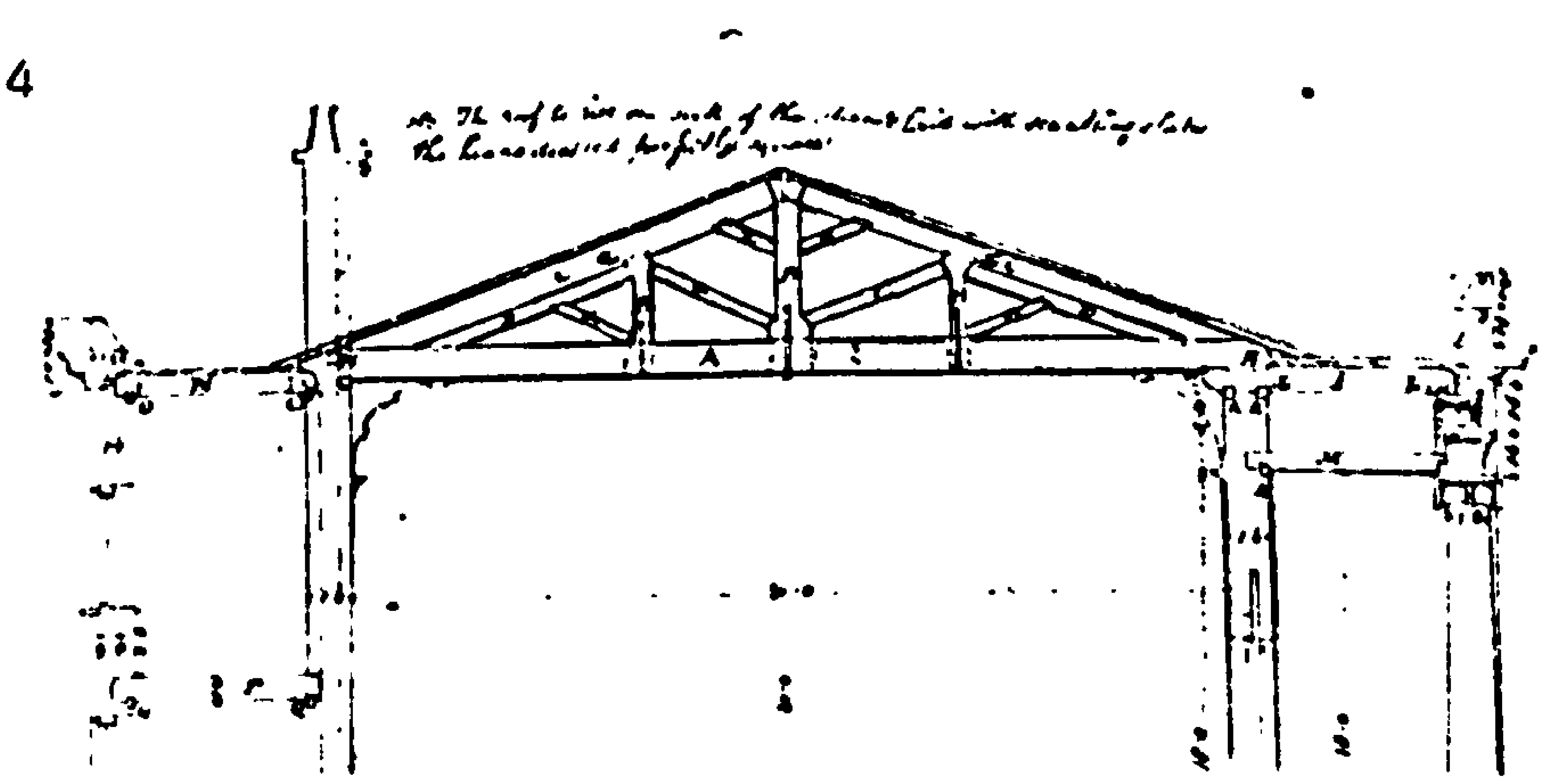


Fig. 9.3

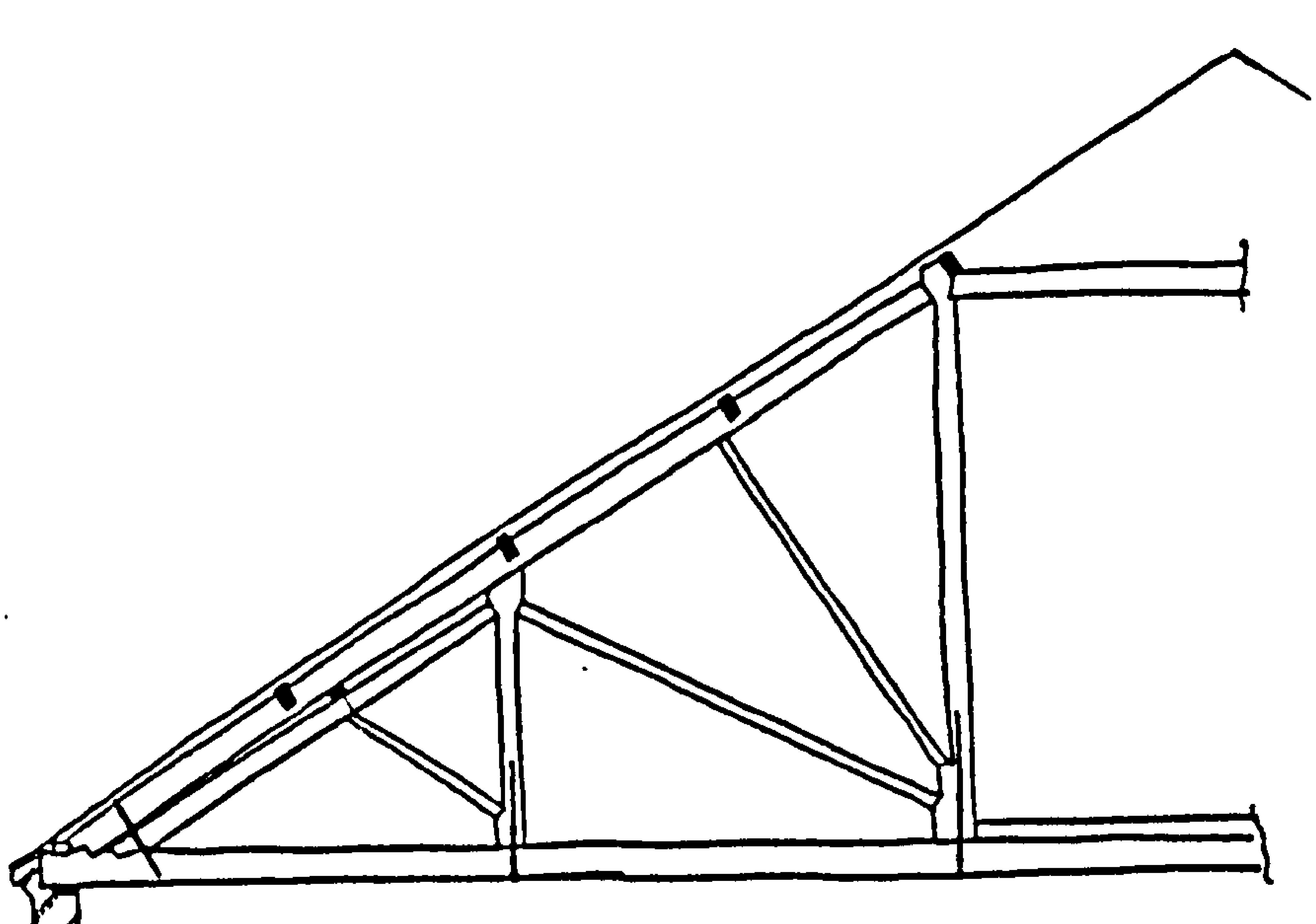
One of a number of drawings collected
for Holland of Italian roof structures

Adaptations of this arrangement
in King and queen post forms.

Fig. 9.4



Nash drawing with section showing roof truss.
This particular form seems to have enjoyed a
revival toward the end of the 18th century.
This is part of a large set of 'working
drawings'. (RIBA drawings collection).



Birmingham Theatre by Saunders -

CONCLUSIONS

The modern forms of king post and queen post trusses are distinguished from their medieval name-sakes by their quite different construction and structural behaviour. Because of the superficial similarity between the two forms of king post truss, it might be assumed that one had developed from the other. However, the evidence presented in this thesis suggests otherwise. The medieval form of king post truss was not in common use throughout the country, but was largely confined to the north of England. In the south of the country, roofs commonly used collar braced and queen post roofs. It was in this region, traditionally using queen post roofs, that the modern form of king post truss first appeared, where it was used during the seventeenth century for longer spanning roofs.

Whilst this new form of truss was being developed during the eighteenth century and its use was spreading to other parts of the country, the traditional forms of roof continued to be used for more modest buildings. Therefore, the initial geographical separation between the two forms of king post truss and the persistence of the older type of structure alongside the new both argues for a quite different origin of the new truss form and suggests that knowledge of its use might have been confined to a relatively small group of architects or craftsmen.

The earliest of the new type of king post structures that have been found are the work of Inigo Jones and Christopher Wren. Other examples built during the seventeenth century have mostly been the work of their associates. Where such a definite attribution has not been possible, there has been evidence to suggest a likely connection with these designers.

Therefore, the king post truss appears to have been first introduced and used amongst the small number of professional architects of the period.

Inigo Jones and Webb carried out work for the royal household and members of the court before the Civil War, while Wren and Hawksmoor did considerable work of royal patronage after the Restoration. Therefore it might be a natural assumption that they all acquired their knowledge of the roof truss from the carpenters of the Office of Works. Instead, evidence has been presented to show that Inigo Jones and Wren used a knowledge of Italian roofs as a source for their own designs, passing this on to their associates. However, the way in which the two acquired this knowledge was quite different.

Inigo Jones is the more likely of the two to have acquired his knowledge of structural design from his carpenters. However, he is known, from a sketch which he made in Italy, to have seen king post structures while there. This is sufficient to account for his knowledge of the truss. Wren, whose first buildings were not royal commissions and who had not then travelled abroad, would not have had access to either of Inigo Jones' possible sources. Instead, his knowledge and understanding of the king post truss can be attributed to his possession of a copy of Baldi's Mechanics. This book is referred to in Wotton's Elements of Architecture and there is also good evidence to show that Wren's father used the same work to design and build a roof according to the truss principles that it describes.

The different methods by which the two architects acquired their knowledge of the truss can be used to account for the differences between the designs that they produced. If Inigo Jones simply copied a structural form that he had not necessarily fully understood, he would not have been able to develop it with any surety. This may explain the rather poor designs for the roofs of the Banqueting House and St Pauls, Covent Garden. Although they represented a considerable advance on traditional roof structures, they had defects that we do not find in Wren's roof structures. Wren, from a firm grasp of the structural principles of the simple king post truss, was immediately able to develop the form, producing variations upon the theme with secondary posts and braces in order to cope with longer spans. He was able, early in his architectural career, to design the relatively complicated trusses for the Sheldonian Theatre and subsequently to develop a variety of queen post trusses for roofs with flat tops.

The importance of Wren's constribution to the development of the king post roof truss lies as much in the circumstances of its use as in his understanding of its principles. The quantity and scale of his work at the end of the seventeenth century, particularly the building of the Royal Hospitals and the rebuilding after the Fire of London, encouraged the spread of knowledge of the new roof types through his assistants and carpenters who were involved in their design and construction. In this way there was a rapid expansion of the group of men with knowledge and experience of these structures.

Knowledge of the roof truss might then be disseminated to other architects and carpenters. There is evidence to show that this occurred in a number of ways. Knowledge might be passed in either direction between the architect and carpenter of a building. It might be passed between carpenters working together or between architects. As well as dissemination through direct contact, knowledge might be acquired by simply copying or adapting the form of existing structures. It can be shown that all of these occurred but it is not possible to determine the relative importance of the various methods by which knowledge was spread. At the same time a spread of knowledge of the truss does not necessarily mean a spread of understanding of its structural behaviour.

During the eighteenth century other architects brought a knowledge of continental roof structures to England. To what extent these contributed to the already growing knowledge of the trussed roof is difficult to say. On the basis of present evidence, the most important contribution was made by James Gibbs. One may assume that he acquired his knowledge of the trussed roof during his training in Italy. In England his designs had an originality that demonstrates a high level of structural understanding. Drawings in his Book of Architecture include roof trusses that indicate an interest in this aspect of design. Moreover, the publication of this book may have contributed to the dissemination of knowledge of the king post truss.

Carpenters' manuals with illustrations of roof structures must be regarded as another potential means for the dissemination of structural knowledge but their actual value is questionable. Many of the books produced for carpenters during the eighteenth century were chiefly concerned with mensuration and geometry, often treating structures as a secondary issue. Those that contained drawings of roof trusses, or other examples of structural carpentry, often show a poor understanding of the principles of sound construction. In some cases this might simply reflect a lack of interest by the authors. However, it has been argued that some, far from intending to provide an accurate picture of the practice of the day, were concerned with displaying their own inventiveness.

Invention was unnecessary because quite simply adaptation of the basic king post or queen post structure were sufficient for both the longer spans and the variety of roof shapes that were being built. The search for variety simply led to errors. The illustrations in the books suggest that the carpenters of the time had a better knowledge of structural design than authors and raise questions about the general level of structural understanding.

Only Francis Price, William Pain and, at the end of the century, Peter Nicholson, showed a sound knowledge of the principles of structural carpentry. Even Price, the earliest of the three, was not above a display of inventiveness and there are inconsistencies between the contents of Pain's different books. However these three authors give a generally reliable picture of good carpentry practice. The many editions of each suggest that there was a demand for their works and therefore we may reasonably assume that they made an important contribution to the dissemination of structural knowledge.

'Structural knowledge' here means simply a knowledge of structural forms and a few elementary rules of design based upon tables of scantlings. Nicholson was eventually to publish the first account in English of the mode of action of the king post truss. He also adopted a more scientific approach to the design of structures that was to become necessary in the nineteenth century. However, until the appearance of his books, eighteenth century authors, with one exception (the Builders' Dictionary), made no attempt to present any structural principles upon which design might be based.

During the eighteenth century the level of structural understanding clearly varied considerably. Just as the carpenters' books provide some indication of this, the surviving drawings of architects show a variation in ability to design satisfactory structures. While there were some architects able to produce 'working drawings' for their structures, and even original designs when the need arose, others relied upon the knowledge of their carpenters for design as well as construction.

There is insufficient evidence at present to be able to gauge the general level of structural knowledge during this period and still less the level of structural understanding. It has been suggested that the carpenters tended to be conservative in their approach to structural design. This would account for the persistence of traditional roof forms throughout the eighteenth century. It would also account for the relative slowness with which the queen post truss was adopted by carpenters who already knew of the king post truss. Knowledge of the king post truss gradually spread during the eighteenth century until it became the new vernacular form. Meanwhile, the drawings and completed structures of a few architects show that they had a sufficient interest in structural design and sufficient structural understanding to design and use queen post trusses. As longer spans were required the advantage of the queen post over the king post ensured the greater acceptance of the former.

This study has been concerned with establishing the origins of the king post and queen post trusses that supplanted earlier traditional roof structures. It has explored the dissemination of these new structures during the eighteenth century until they became generally adopted by the beginning of the nineteenth. Because of the nature of the evidence used, in the form of surviving structures and contemporary drawings, a relatively clear picture of this development has emerged while the degree of structural understanding that accompanied it is not clear. It has been shown that these forms were sufficiently simple and robust to be widely adopted without a detailed knowledge of their behaviour. At the same time there were designers who were capable of further development of these forms when necessary. What remains in doubt is the method that they used. How did they ensure that their designs would be satisfactory in the absence of any means of structural analysis? Was it from some 'theoretical' appreciation of their behaviour or simply the experience of previous structures? There is some evidence for both but a detailed exploration of this question must remain the subject for future research.

Appendix 1

THE DEFINITION OF A TRUSS

The use of the word 'truss' may cause confusion because it is used to refer to two quite different types of structure. The Oxford English Dictionary (OED) provides the following definition:-

> "A framework of timbers or iron or both, so constructed as to form a firm support for a superincumbent weight, as that of a roof or bridge."

This definition applies to both kinds of roof truss which are found in side purlin roofs; the traditional roof truss, relying upon members in bending and compression only, and the more modern structure (whose development has been the subject of this study) where the posts act in tension to support the tie beam. This is unfortunate because there is no trussing action in the former type of structure which perhaps should be called simply a roof 'frame'.

The word 'truss' is also a verb which means (OED) "to make fast something with or as with a cord, band or the like; to bind, tie, fasten" and it seems as if the early use of the word in carpentry derived from this meaning. The first use of the word appears in the sketch made by Dean Wren for his roof at East Knoyle where he refers to the fastenings as 'trusses'. The purpose of these is clearly to act as ties.

A derivation of the term, as used in describing structures, from the action of the ties seems likely. John Harris in his Lexicon Techtonicum (1) has the definition from naval architecture; the truss

> "serving either to bind fast the yards to the mast ... or to hole (sic) down the yards in a storm".

This meaning is still in use.

Pratt used the term in his essay when he describes the framing of a roof (2):-

> "... and so to truss up a king piece with its joggles at the top, and most strong dovetail at the bottom to truss up the beam under it."

In a manuscript addition to a copy of Neve's City and country purchaser a definition of 'truss' is given which is quite specific about the tying action (3):-

> "A Trusse is a combination or junction of timbers brought together by the art of the carpenter to hang or truss up short or weak pieces of timber without any prop or support underneath."

The word was used by Price in association with roofs but the term 'roof truss' had not appeared by then (4):-

> "How necessary those sections of roofs may be thought, I cannot say ... yet the trusses in each may be acceptable ..."

Hoppus who appears to have copied his illustrations from Price (5) uses the term slightly differently. He advertises in his work "a variety of truss roofs of the newest invention". It seems that the work 'truss' here is a contraction of 'trussed'. Batty Langley (6) provided "Sections of truss'd roofs with remarks". Later William Pain was to include in one of his books '7) "Two trusses for roofs". This was on the same plate as a trussed girder in which the flitches were referred to as trusses.

During the eighteenth century the adjective was used more commonly, as in 'trussed beam', 'trussed partition' or 'trussed girder'. Batty Langley uses the term 'truss'd beam' in describing his design for Westminster Bridge. His beam (and beams in other bridges) were trussed in the same way that the tie beam of a roof was trussed by the king or queen posts. Langley and others also refer to trussed partitions (8) but these were never called simply 'trusses'. This seems to have been reserved for the components of a trussed girder. (This structure was described in chapter 7) and it has been argued that the use of the word 'truss' appearing in building accounts refers to trussed girders. It was used in this way by Grove in his price book (9).

The earliest use of the word truss cited by the OED is from the Carpenters Company notes of 1654:-

> "When any chimney shall be set upon a truss of timber that it be sett two foote 6 inches from the upside of the truss to the upside of the floor."

This presumably is a fire precaution but it also seems likely, given the context within which the word is found and the other examples of its use, that this regulation is referring to a trussed girder. If so then this usage does not fit the definition of truss given by the OED.

More examples are needed to trace the adoption of the usage which we have today but it was certainly developed by the nineteenth century. The OED gives:-

> "These bridges are built on piers far apart and formed of a truss of continuous trellis work."

Gwilt's Encyclopaedia of Architectures (10) gives the derivation as from the French 'trousse' and says:-

> "A combination of timber framing so arranged that if suspended at two given points ... no timber would press transversely upon another except by strains exerting equal and opposite forces."

I take this to mean that there would be no members in bending. If so this definition is at odds with the use of the word to refer to traditional roof trusses which depend upon bending in the tie beam.

What has happened it seems is that the term 'truss' to describe a structural framework came into use during a period when such frameworks comprised members only in tension and compression. Architectural historians have since applied the term - having no other - to earlier roof structures which developed no trussing action. The widespread use of this misnomer means that we are now probably stuck with it although 'frame' would be an adequate and less confusing term for these earlier structures.

Footnotes - Appendix 1

1. Harris (1704).

2. Gunther (1928), p.212

3. In the Yale Center for British Art, New Haven, there is a copy of the 1726 edition of Neve (1703) which has been interleaved with blank pages. On these are manuscript additions to the definitions. The fly-leaf of the book has the name Carolus Hornby.

4. Price (1733)

5. Hoppus (1737)

6. Langley (1740)

7. Pain (1794)

8. See Chapter 7

9. BM. Add. 30092

10. Gwilt (1842)

Appendix 2

TRANSLATION FROM BERNARDINO BALDI

From Baldi, B. In mechanica Aristotelis problematica exercitationes... (Mainz) 1621 p.102-103.

"Sed tectorum contignationes imbecillaq; transuersaria Mechanici corroborare solent, additis nempe arrectaria trabe atque cauteriis.

"Esto enim transuersaria trabs AB parietibus utrinque fulta IK, arrectarius CD. Cauterii utrinque AB. BD, ita transuersariae trabi in AB, & arrectario in D inserti, ut ne quaquam inde elabivaleant. Tum ferrea fascia EF mediam transuersariam trabem AB, a parte inferiori ipsi arrectario connectens. Debetautem arrectarii pes ubi C, aliquantulum a transuersaria trabe distare, ne deorsum ex pondere vergente paululum arrectario ipsam transuersariam premat. His igitur ita constitutis pondus quidem transuersariae trabis, quod suapte natura premit in medio ubi C, ferrea fascia arrectariae trabi affixa distinetur, Arrectariam cauterii sustinent, has vero transuersariae capita AB, quibus induntur. Tota igitur eiuscemodi operis vis in eo consistit, ut probe cauterii transuersariae & arrectarii trabi inserantur fixis enim cauteriorum pedibus in AB, non descendet a partibus seu capitibus D, iis vero stantibus stabit & arrectarium, quo inde suspendo transuersaria trabs ei ex ferrea fascia alligata ne quaquam pendebit. Stabit ergo compages tota & suapte vi robustissime connexa totius tecti pondus sustinebit.

"Quoniam autem usu venire solet, cauterios nimia longitudine debiles, aliquando tum proprio tum extrareo cedentes ponderi deorsum vergentes pandare, Architecti capreolis hinc inde suppositis, ceu fulcris, huic medentur infurmitati.

"Sint enim cauterii debiles hinc inde AB, AC, media trabs arrectaria, quam Monachus dicimus AD. Cauteriorum mediae partes E, F, in punctis igitur EF ut pote maxime ab extremis distantibus debiles arrectariolis EH, FI, eorum capitibus E, F, duos cauteriolos sibi ipsis ad pedem arrectarii in D, resistentes apponunt quibus ita constitutis nec E, nec F ad partes H,I, descendere valent."

Engineers (Mechanici) are accustomed to strengthen the junctions of roofs with weak transverse-beams by the support of uprights and rafters (cauterii).

Consider the case of a transverse beam AB, (fig.1) supported at either end by walls I, K, and with an upright CD. The rafters AD, BD on both sides are set into the transverse beam at A and B and into the upright at D in such a way that they cannot slip. There is an iron strap EF, which joins the mid-point of the transverse beam AB to the lower end of the upright. However, it is essential that the foot of the upright at C should be slightly distant from the transverse beam lest with the upright deflecting downward slightly from its own weight, it should put pressure on the transverse beam itself. Thus, if the structure is built in this way, the weight of the transverse beam, which by itself would naturally deflect in the middle, that is at C, will be relieved by the iron strap attached to the upright. The upright will in turn be supported by the rafters, and they in their turn will be restrained by the ends of the transverse AB into which they are joined. Hence the whole essence of this system depends upon the correct joining of the rafters to the transverse and upright beams so that with their bases on AB the rafters do not move at the sides or at the head from D. If the rafters are fixed in this way the upright will also stand firm when hung at that point and the transverse beam joined to it by the iron strap will not deflect at all. Thus the whole structure will be stable and being very strongly jointed will, by its innate forces be able to sustain the weight of the whole roof.

However, since one finds from experience that rafters are very weak in relation to their length, yielding both because of their own and imposed weights and tending to bend downwards, Architects remedy this weakness by shoring them at these points with short pieces of timber or posts (fulcra).

In such a case consider the weak rafters AB, AC, (fig. 2) and in the middle an upright AD, which we call the king post (Monachus). The midpoints of the rafters E and F (are shown) since it is at these points E, F that weak rafters are particularly under stress, being the points at the greatest distance from each end. And so when they are shored up at each side with the short uprights EH, and FE, with their heads at E and F, they are placed in resistance by two smaller rafters running to the foot of the upright at D. Under this arrangement, neither E nor F can bear downwards towards H or I.

(Translation by Mrs S Pepper and Miss C Makie)

Notable in this clear description of the mode of action of the king post truss is the apparent Italian origin of the term 'king post' in the Latin 'Monachus'* and the insistence on the gap between the bottom of the post and the tie beam, adopted in Italian examples but not followed by architects in England.

* C T Onions (Ed), Oxford Dictionary of English Etymology (London 1969), gives 'monachus' as the late Latin for 'monk'. The translation here provides the English name for the post and implicitly assumes a misprint in Baldi's text. The alternative is to assume that the Italians name was 'monk post'. My instinct is to assume that the appellation 'king' is more likely for the principal member of a structure, at least until more evidence is available.

Appendix 3

THE GEOMETRICAL FLAT FLOOR

This type of construction was, for all its ingenuity, not a very practical device and was, as far as we know, little used. It is thus a relatively unimportant form of structure but as it attracted so much attention during the seventeenth century it is worth setting down here what little is known of it.

The geometrical flat floor is an arrangement of timbers where no member spans directly between the supports. Instead each member is carried by a wall at one end and at its other end by another beam, which is in turn supported in a similar way. The simplest practical arrangement has four members as shown in fig. A3.1., although it is clearly possible with three members. This device was first described and illustrated by Serlio (1) although he used more than four timbers (fig. A3.2). He claimed to have invented this type of structure and offered it as a means of structuring a floor, either when timbers could not be obtained of sufficient length to span in the normal way or for use if the carpenter made a mistake and cut a beam too short. This second reason seems rather fanciful since it involves a greater total quantity of timber. I suspect Serlio was simply seeking to justify a form that he liked for its own sake and I assume that he had derived the arrangement he illustrated from the simple basic layout.

As with other floors our knowledge depends upon chance discovery and the best known uses of the geometrical flat floor is in ceilings. However a likely contender for its earliest use in this country must be Smythson's floor for the prospect room at Wollaton. The structure of this was reported a few years ago (2) and it seems as if it was discovered in an inspection of the condition of the structure. The rectangular floor plan would seem to make it a poor candidate for structuring in this way and the layout of timbers used is rather awkward. Girouard (3) suggests that this structure was used because it would have been difficult to obtain timbers to span across the room. This seems unlikely. Smythson would have had to find timbers of that length for the tie beams of the roof above. More likely he was simply interested in the device and wanted to experiment with it.

Drawings by Robert Stickles (4) among Sir Thomas Tresham's papers, and dated 1596, show an elaborate two storey lantern apparently designed to be stood upon a geometrical flat floor framing (fig. A3.3) The framing fills in a basic square plan while the largely glazed lantern above is octagonal. It is not clear whether the framing was intended to be exposed as a decorative feature but an alternative reason for its use might have been to enable the timbers to frame round a central hole in the lower floor of the lantern. This is suggested by one of the sketches but the same result could have been achieved with more conventional construction.

Another use of the device for framing a floor was found in the structure of Kelmscott Manor during restoration work (5). In this building the span of the floor was surely not too great to frame up in a simpler way, and again it appears as if the structure might have been used as an experiment by the carpenter. Some initial trials in floor structures seem likely because the use of the geometrical flat floor to provide decorative ceilings use fairly complex arrangements.

Two decorative ceilings were used in Somerset House and illustrated in Richard's Palladio (fig. A3.4). He advertises these on the title page as:-

> "... designs of floors of variety of small pieces of wood, lately made in the Palace of the Queen Mother at Somerset House; a curiosity never practiced in England before." (6)

In the general text he says that these "... being a novelty in England, I thought good to present the design thereof, although not in my author". (7)

It is tempting to attribute the design of these ceilings to Inigo Jones. We know that shortly after his return from Italy he was in the Queen's employment and that work on Somerset House was then in hand (8). No doubt he would be anxious to try out any devices he knew about. However other designers are possible contenders. De Caux for example was working for the Queen on Somerset House during 1611-12 (9).

Although Richards claim these as the first of their kind in England they are fairly sophisticated derivatives of the basic Serlio layout and I find it difficult to imagine their design without some earlier trials of simpler structures. The same may be said of the other and perhaps better known examples of a decorative ceiling which survived into this century.

The ceiling in the Schools Tower, Oxford was a much simpler design than those in Somerset House. It is more difficult to date and has no obvious candidates as designer. The date 1618 has been suggested (10) but I do not know on what evidence. The ceiling remained intact until restoration work was carried out on the building in 1952. It was then proposed to replace the timbers on the underside of the new concrete floor that was to be built. Funds to complete the work were not available and the timbers were put in store. On my recent enquiries it was discovered that they had been lost and the only record now known to remain is the drawing made before their removal (11). This shows the layout and cross section of the members but unfortunately not the details of jointing.

It was presumably the ceiling in the Schools Tower that interested John Wallis in this type of structure. Wallis both made a model of his complex design and an analysis of the forces in it (12). The story is presented by Grew (13) in his catalogue of the items in the possession of the Royal Society. The Society had:-

> "A model of a geometric flat floor. Given by (Bishop Wilkins). Contrived and delineate by Dr J Wallis, Professor of Geometry at Oxford, who was pleased to give me the following account.
>
> I did first, saith the doctor, contrive and delineate it in the year 1644 at Queens College in Cambridge. When afterwards I was made Professor of Geometry at Oxford, about the year 1650. I caused it to be framed of small pieces of wood, representing so many pieces of timber; prepared by Mr Rainsford, a joyner in Oxford, and put together by myself.

"This I shewed soon after to divers in Oxford and particular to Dr Wilkins and Warden of Wadham College in Oxford, who was so pleased with it that he caused another to be made for himself according to that pattern, which he kept by him for many years and afterwards presented to the Royal Society.

"After the King's restoration, I caused another to be made and in the year 1660 presented it to his Majesty ...

"On the model first mentioned, I read two public lectures ... the one in the year 1652 as to the construction of it; the other in the year 1653 as to the computation of what weight every joint of it sustains."

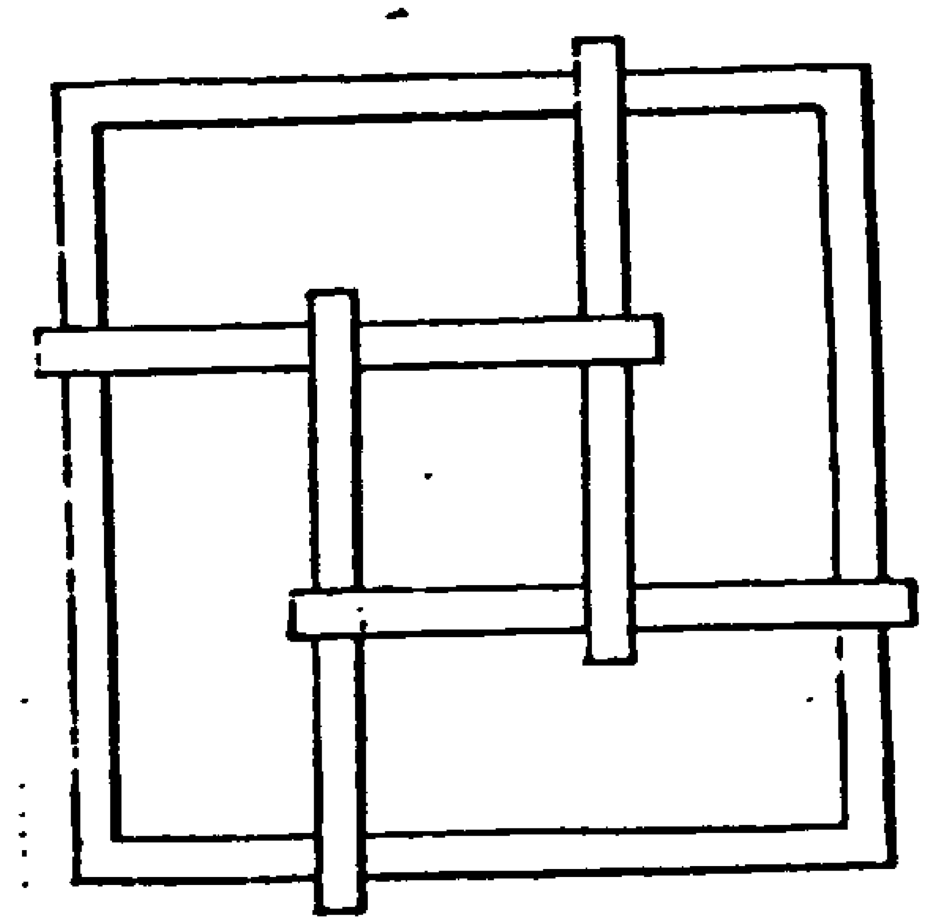
The account goes on to discuss the loadings and then says:-

"I do not know that yet it hath been reduced to practice in more than four pieces in this form. Such is one of the floors in the tower of the publique schools at Oxford ..."

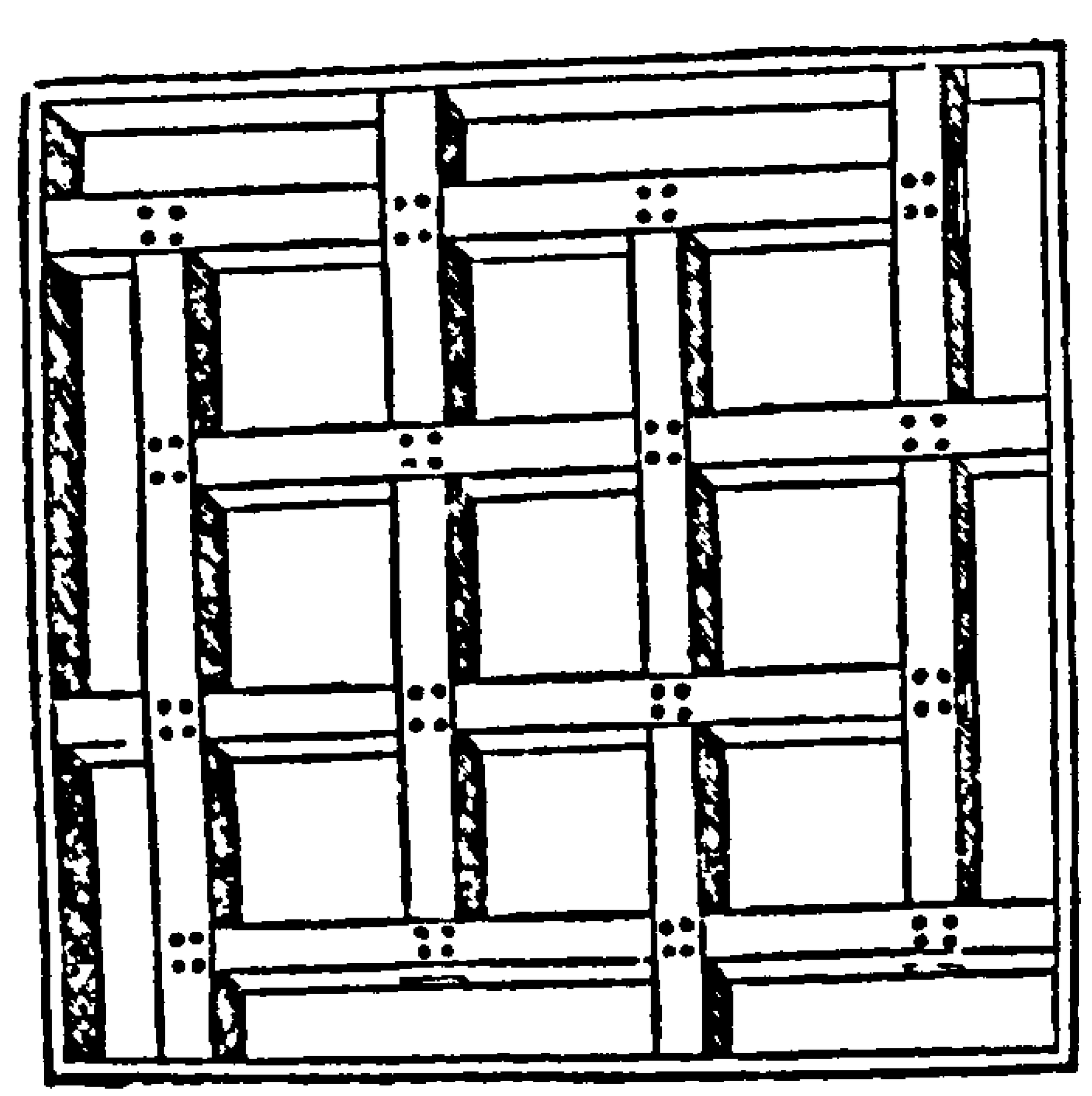
It seems unlikely that any practical use was ever made of Wallis's ideas in spite of the fact that his name is often associated with this form of construction. It was almost certainly too elaborate to have worked successfully. It was mentioned by Batty Langley (14) but Nicholson (15) says that:-

"notwithstanding the ingenuity of this method of construction, it has long been out of use, probably, from the general introduction of foreign timbers, which furnishes any lengths requisits for the purpose of building."

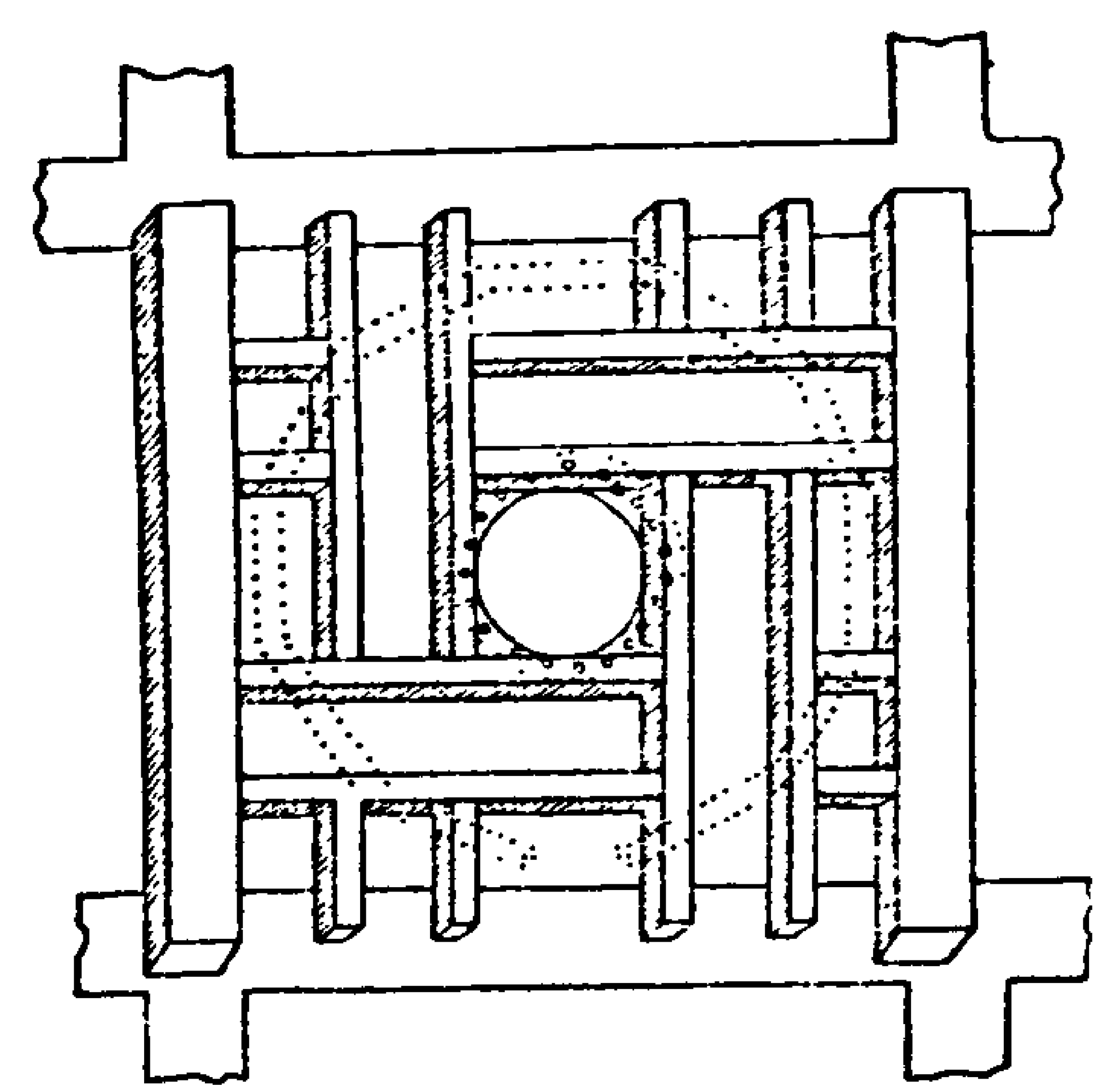
The only major example of this king of construction that is known to survive is in the floors of Independence Hall, Philadelphia. This has been described by Nelson (16). It probably owes its success to the simplicity of its framing (fig. A.36). It seems likely that this will prove to be the longest spanning floor of this kind but it equally seems likely that more structures of this type will come to light.



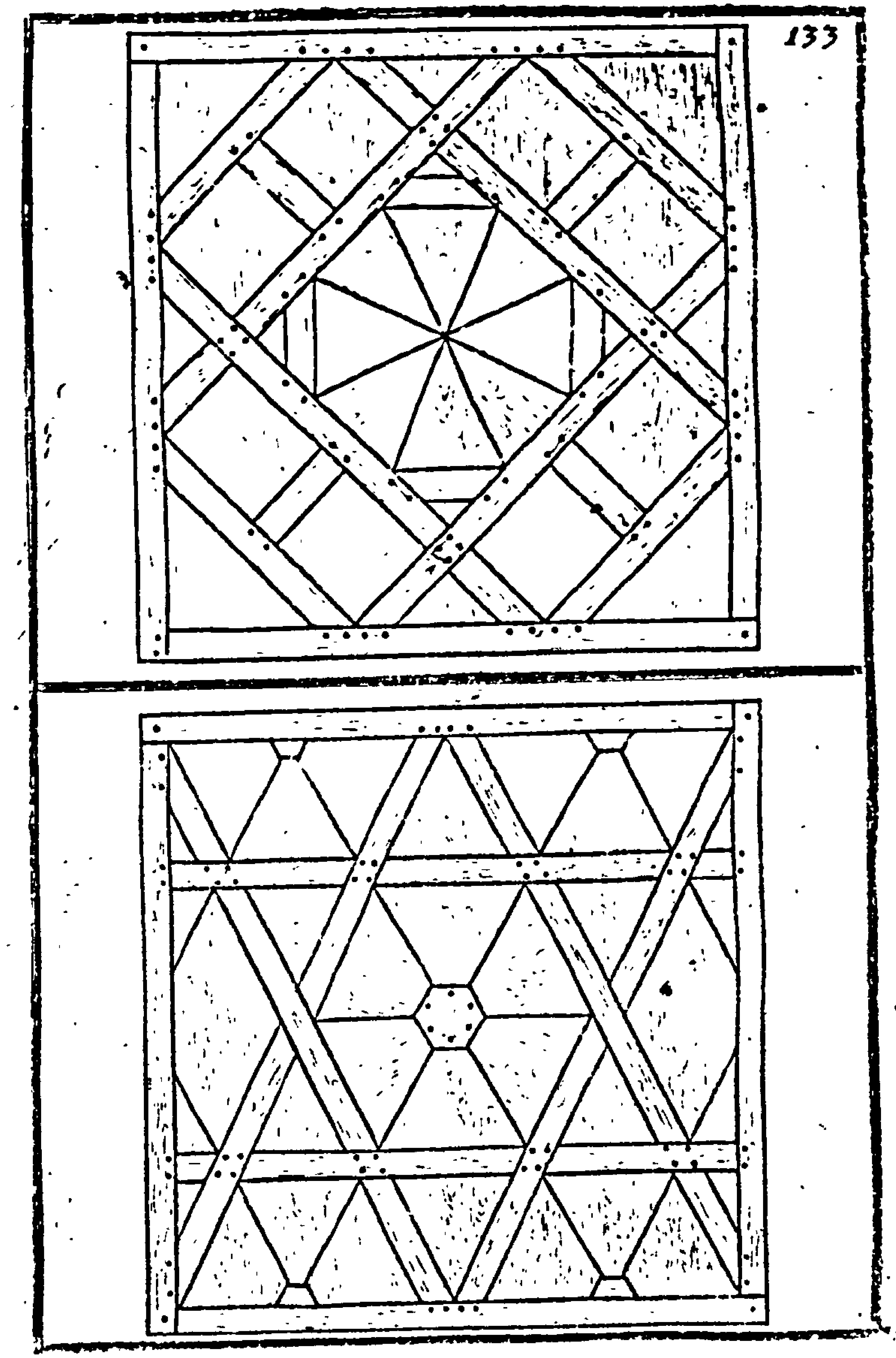
A 3·1



A 3.2



A 3·3



A 3·4

Footnotes - Appendix 3

1. Serlio (1566)

2. Desch (1958)

3. Girouard (1966), p.82

4. BM. Add. 39831, ff.3-4

5. Insall (undated)

6. Richards, Godfrey (1668), title page

7. Ibid. By his author he means Palladio

8. Colvin et al (1975), p.120

9. Ibid.

10. Letter in Oxford University Archives UA/C/2/11

11. Oxford University Archives UA/p/1/1

12. Wallis (1670)

13. Grew (1681), p.361

14. Langley (1750)

15. Nicholson (1812)

16. Nelson (1976)

Appendix 4

FLOOR FRAMING

Perhaps for constructional reasons medieval carpenters laid their floor joists 'flat' rather than 'on edge', but the text books which appeared towards the end of the seventeenth century showed floors framed as today.

Now beams are built deep and narrow rather than broad and shallow, because it is recognised that this uses the material most efficiently, but this was not why it was done originally. Moxon in his Mechanick exercises (1) gives quite a different reason.

> "The joists" he says, "are framed so as to lie with one of their narrowest side uppermost ... The reason is because the stuff of bressumers and girders are less weakened by cutting the mortices in them in this position."

He then goes on to use the same basic argument for arranging the beams into which the joists are framed with their broad side uppermost.

> "... great care must be taken that the bressumers and girders be not weakened more than needs, lest the whole floor dance.
>
> "The tennants are cut through the two narrowest sides rather than between the two broadest sides because the stuff of the girders retains more strength when least of the grain of the stuff is cut".

Moxon's reasonings here are too simple to produce the right answer although one can sympathise with his intentions. He was writing shortly after the fire of London and the Acts for the rebuilding of the city specified the scantlings to be used for structural timbers (2). Moxon reproduced a table of these sizes and says that they were "well consulted by able workmen before they were reduced into an act" (3). The act and this table gave the sizes for floor joists, summers and girders, purlins, principal rafters, common rafters and beams.

Presumably, if able workmen were consulted, the sizes represented those commonly used at the time. This starting point is important because, in setting down the table, Moxon began a practice that was to be followed by most subsequent authors of books on carpentry. Leybourne (4) and Ricards (5) were the principal seventeenth century writers, and they both reproduced the scantlings recommended by the Acts. Later authors, however, introduced their own tables which differed in several respects from those given in the Acts. These differences were partly needed to take account of developments in carpentry which had occurred. The range of spans covered by these later tables tended to be larger which perhaps suggests a general increase in the scale of problems being tackled. Imported fir became more commonly used in construction in place of oak and tables thus had to be extended to cover both timbers. In floors, the use of bridgings and bindings (6) for higher quality work, instead of simple common joists, meant that tables had to be further extended to deal with these members.

As well as increasing the range of the tables, authors made their own recommendations on sizes which differed, not only from those specified in the acts, but also from each other. It is not clear, therefore, to what extent any of these tables may have represented common practices of the time. Few carpenters would have had to provide tie beams of up to 90ft span and yet Batty Langley (7) provided a table as far as this. This alone must cast doubt upon its reliability. The general reliability of these tables of scantlings is called into question by comparing the recommendations given by the different authors. Taking a range of books over nearly a century, between Francis Price of 1733 (8) and Thomas Tredgold in 1820 (9), not only is there no general agreement but there is no obvious trend in the sizes suggested. There are even considerable differences in some cases between contemporary texts. A complete analysis of these tables is, therefore, not a particularly rewarding task, and it is sufficient to indicate some of the more glaring inconsistencies.

The only obvious trend during the period occurred in the sizes recommended for the floor joists. Later authors tended to specify larger sizes and if this represented actual practice it may have reflected an increase in the loads generally occurring or a desire to make floors stiffer. Larger sizes of timbers were suggested by some authors for more important buildings and they then gave two sets of figures for each span. (10).

A comparison of scantlings given for fir and oak members is surprising because initially those given for oak were larger (11). Today one would expect smaller sizes to be possible with the stronger and stiffer material. However, it is possible that larger oak members were used because of the greater density of the material. An oak floor would be much heavier than one of fir and the self weight would have been a major part of the load carried. Taking a layout suggested by Batty Langley with girders at 12ft spacing, spanning 20ft and carrying a good quality floor of bridging and binding joists, the self weight in oak (including boarding) approaches 18lbs/ft^2 (12). Super imposed loads would seldom have reached these figures, especially in domestic buildings. Eventually William Pain produced tables which reversed this pattern and had the fir members larger (13).

This general trend in the sizes of floor joists is not reflected in the sizes of girders where later sizes given tended to be smaller than those at first required. Unlike joists, girders remained broader than they were deep although this was presumably for the reason given by Moxon, ie. the need for enough timber in which to cut mortices. However, this was not a universal rule and Smith (later copied by Salmon) had girders slightly narrower than their depth.

An analysis of these sizes based upon present day structural principles hardly seems appropriate because it would be difficult to select criteria on which any test for structural consistency might be based. A uniform live load upon which we would base calculations today would not be appropriate because at the time the self weight of the floor would have been more significant If the self weight is used as a basis then, because of the variation in sizes, a number of specific layouts would have to be examined. Since there would have been no way of recognising the stress levels in the members at the time carpenters would have been concerned more with the deflection of the structure. However this need not necessarily have been the deflection under dead load. The live load deflection, recognised by the liveliness of the floor, would more likely have been of greater interest.

These tables appear to have had no theoretical basis and even when authors attempted to apply some rational thought to problems the results showed an ignorance of science. Nicholson (14) was to ridicule Batty Langley's argument that oak being denser than fir must consequently be stronger. It is possible that the wide variations in sizes simply reflected a wide variation in those being used by carpenters. William Pain offering a table of sizes said (15):-

> "I do not insist that the scantlings of timber ought to be exactly as by the table, for they must be varied in some respects, as the workmen shall be needful".

And the scantlings he then gave varied from those in one of his earlier books (16). A similar variation is seen in the works of Salmon (17) so that it is difficult to imagine any guiding principle when there are such differences within the work of a single author.

Nicholson was to point out the errors and inconsistencies in many of these tables and sizes in his Dictionary article on 'Carpentry' (18). A firm basis for determining the relative strengths of beams had been stated much earlier in the Builders Dictionary (19) and by Emerson (20) in 1734 and 1758 respectively. The former was also reprinted in 1774 (21) but Nicholson's first book referred to Galileo's work on the relative strength of beams (22). Nicholson deprecated the use of tables of scantlings, which he never used himself. Instead he provided summaries of the experimental work that had been carried out to determine the strength of beams and gave worked examples showing how to find the relative strengths for different sizes and spans.

Footnotes - Appendix 4

1. Moxon (1677)

2. Baldi (1621)

3. The commissioners for drafting the acts were Wren, Hooke and Pratt but we have no knowledge of how they proceeded apart from using their own experience and the statement by Moxon that they consulted 'able workmen'.

4. Leybourne (1668)

5. Richards, Godfrey (1668)

6. A good quality floor used binding joists spanning between the girders with bridgings of much smaller scantling laid over these

7. Langley (1738)

8. Price (1733)

9. Tredgold (1820

10. For example Salmon (1752) p.76

11. Ibid.

12. The calculation is based upon figures given in Langley (1741)

13. Pain (1794). But note below the inconsistencies in his tables

14. Nicholson (1812), under 'Carpentry'

15. Pain (1794)

16. Pain (1759)

17. Compare Salmon (1752) with his Country Builder's Estimator (London 1746) p.18

18. Nicholson (1812)

19. Builder's Dictionary (1734), under 'Beam'

20. Emerson (1774)

21. Builder's Magazine (1774)

22. Nicholson (1797) p.69

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