## OCCASION

This publication has been made available to the public on the occasion of the 50th anniversary of the United Nations Industrial Development Organisation.

## DISCLAIMER

This document has been produced without formal United Nations editing. The designations employed and the presentation of the material in this document do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations Industrial Development Organization (UNIDO) concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries, or its economic system or degree of development. Designations such as "developed", "industrialized" and "developing" are intended for statistical convenience and do not necessarily express a judgment about the stage reached by a particular country or area in the development process. Mention of firm names or commercial products does not constitute an endorsement by UNIDO.

## FAIR USE POLICY

Any part of this publication may be quoted and referenced for educational and research purposes without additional permission from UNIDO. However, those who make use of quoting and referencing this publication are requested to follow the Fair Use Policy of giving due credit to UNIDO.

## CONTACT

Please contact publications@unido.org for further information concerning UNIDO publications.

For more information about UNIDO, please visit us at www.unido.org

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna International Centre, P.O. Box 300, 1400 Vienna, Austria
Tel: (+43-1) 26026-0 · www.unido.org · unido@unido.org

19844

**United Nations Industrial Development Organization**

Distr.
LIMITED

ID/WG.525/10(SPEC.)
21 September 1992

ORIGINAL: ENGLISH

---

**Seminar on the Use of Wood in Construction in the Latin American and Caribbean Region**

Quito, Ecuador, 4-8 November 1991
**Item 12(a) of the programme**

[illegible]

# TIMBER ROOF DESIGN AND CONSTRUCTION - EVOLUTION, CURRENT PRACTICE AND TRENDS*

Prepared by

C. Mettem**

---

* This document has not been edited.

** Engineering Coordinator, Research and Consultancy Group, TRADA Technology Ltd. High Wycombe, United Kingdom.

## TABLE OF CONTENTS

# CHAPTER 1

## Introduction

In popular terms, the word 'roof' means simply the part covering the top of a building, as seen from the outside. The carpenter or the timber engineer knows differently however.

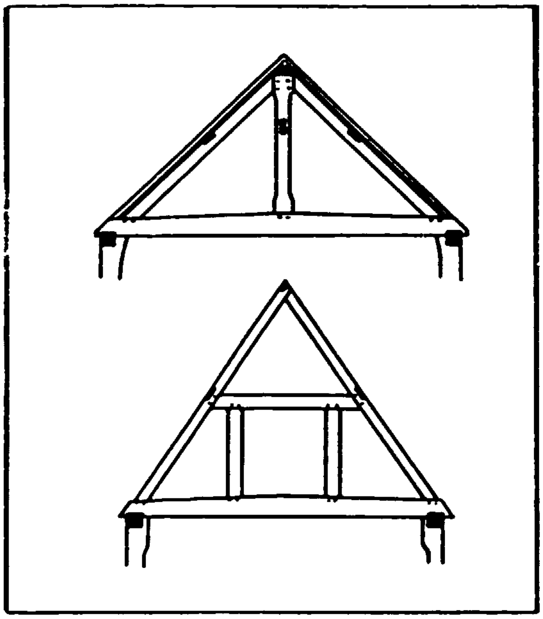

Figure 1.1

King and Queenpost Trusses

Whilst laymen and non-technical authors may mention a roof of tile or slate, thatch or palm, the person who knows what goes on beneath these coverings will discuss the roof in terms of a coupled roof, rafters and purlins, collars and ties, King and Queen posts, Fig 1.1, trusses and trussed rafters, Finks, Howes and monopitches, Fig 1.2, and so on. It is almost as though the mysteries of the medieval carpenters' guilds have been passed right on to modern times, to create a cognoscenti who speak a different language.

The function of the roof is obvious - it is needed to keep out the rain, and to provide shelter from the sun and the other extremes of climate. Everyone is assumed to be familiar with it.

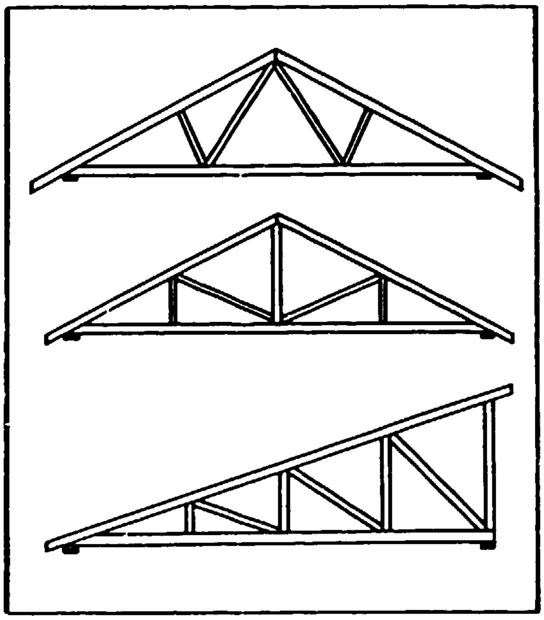

Figure 1.2

Fink, Howe and Monopitch Trussed Rafters

However, drawing to scale or marking out, cutting and jointing even fairly simple carpentry framing or trusses is a skill that few people can command in this modern age of DIY, space technoiogy and sophisticated communications.

Mistakenly, there is a danger that the timber roof can be regarded as something 'not modern' and not 'high-tech'. Despite this aura of mystery, it is possible to familiarize oneself with the technicalities of timber roofs.

People who do understand them fall broadly into two categories. There are the craftsmen, skilled carpenters who have served apprenticeships, and who fortunately still exist in modern society, albeit in short supply, and there are the so called 'professionals'.

These are structural engineers, architects and surveyors, who rely upon textbook learning, codes and standards, and who can gain further experience whilst carrying out their work on the design and specification of timber roofs.

Professionals who are involved in the structural aspects of buildings should certainly aim to acquire a good understanding of timber roofs, since as will be shown in this overview paper, structural timberwork has not only been the principal means of roof construction for centuries, but also it is likely to retain a leading future role in this respect.

Good modern publications are available on the subject of timber engineering, and from these much can be learnt that is relevant to roof structures. Certain useful codes of practice and standards are also available, and these will be cited in this paper.

On the whole though, it is not easy to encounter comprehensive information on all types of timber roof. Part of the aim of this paper is to bring together several of the aspects involved, and to provide leads to the reader who wishes to pursue each of them.

A number of books can be recommended which deal with the history of timber framed buildings, including their roof construction. However there is far less information which is readily accessible on roofs of the eighteenth and nineteenth centuries, a period in which many developments of importance to engineers were taking place.

Likewise, the introduction of modern engineering calculation methods to the early twentieth century 'cut roof', or construction on site using individual members, is only available in specialist establishments or in libraries. Information on the development of industrialized, prefabricated truss components, which were the forerunners of trussed rafters, is also not too easily found in readily available books.

There are numerous ways of constructing pitched roofs over domestic buildings and

**Figure 1.3**

**A 72.0 metre span glulam roof truss**

**Flower Market, San Remo, Italy**

other similar sized structures. This paper provides a review of the techniques which are available to timber engineers and structural designers for providing satisfactory and stable overall roof assemblies. It is essential to think in these terms, rather than considering merely two-dimensional frames or elements.

Great changes and improvements in the design of roofs have taken place since the introduction of trussed rafters, some thirty-five years ago.

A little before the introductory phase of prefabricated timber roof components, there had been a considerable popularization of glued laminated timber, or 'glulam', as it is known. At first, it seemed as though the trussed rafter might displace glulam for small and medium span roof construction. Recently however there has been a revival in the use of glulam for such purposes.

This has been led by excellent quality installed timberwork and accompanying programmes of technical dissemination and publicity, which have taken place on the continent of Europe, notably in Germany, Switzerland, France and Italy, Fig 1.3.

Large structures for public use for a variety of purposes, as well as big industrial structures, have gradually demonstrated the 'seriousness' and modernity of timber as a twentieth century material.

The glulam revolution is now being experienced in Britain, too. Whilst trussed rafter roof construction pushes into many non-domestic and longer-span multi-storey fields, Fig 1.4, such as commercial and industrial premises, shopping centres, sports complexes and the like, glulam is providing an alternative and complementary structural material, Fig. 1.5.

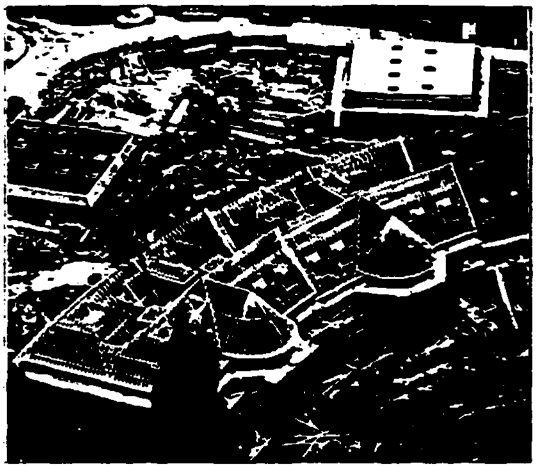

**Figure 1.4**

**Trussed rafter roof in non-domestic application**

**Beaconsfield**

The power and flexibility given to structural design by the spectacular growth of inexpensive microcomputer systems has undoubtedly contributed to the rapid expansion of timber engineering. Computerized design, estimation and manufacture of timber roofs has enabled this adaptable, environmentally friendly, and infinitely renewable material to remain to the fore in modern times.

It is still the case that nothing can compete with timber for the structure of the roof. It wins in terms of economy, lightness and its almost endless adaptability in shape. It is this timber roof structure, and many of the aspects and factors associated with it, that will be examined in this overview paper.

**Figure 1.5**

**Glulam is providing an alternative method in Britain**

**Littledown Recreation Centre**

## CHAPTER 2

## The historical development of roof carpentry

A dictionary definition of carpentry is 'heavy woodwork which is fitted together, as for ship or house building'. This is a useful definition, since it distinguishes carpentry from cabinet making and joinery.

The terms 'heavy woodwork' and 'fitting together', are of course relative. The thickness of the rafters of a modern trussed rafter construction is not great, compared with the same elements in a medieval cathedral roof. Nevertheless the principle remains.

Likewise 'fitting together' in terms of modern timber engineering, is less complex than in the mortises and tenons, dovetails and pegs of former times. All the same, the jointing method remains at the crux of both carpentry and timber engineering techniques.

Indeed it has been said that the history of developments in structural carpentry can be ascribed largely to the history of jointing methods and the ways used to overcome the perpetual problem of obtaining sufficiently large and long timbers.

A difficulty in setting out to summarize historical development, is that at whatever point in time one decides to begin, it is possible for someone else to point out an earlier precedent. In the case of carpentry, if one makes a selection on the grounds of the 'fitting together' definition, then this might eliminate mention of early round timber construction, jointed with pegs and lashings. Does one also leave out log-built and stave construction?

In many cases these were by no means crude structures, and quite sophisticated 'fitting together' techniques were involved, both for the elements and for the jointing of the corners and junctions.

### Early history:

Hitherto, it was said that the basic principles of timber framing were probably first known in Western Europe in the Bronze Age. New discoveries in peat levels in Southern England have now shown that Neolithic settlers in the British Isles brought with them skilled carpentry techniques.

These immigrants arrived from more easterly parts of Europe some 6000 years ago. Their carpentry and engineering skills enabled them to build correctly surveyed elevated timber walkways through the Somerset marshes, which have been preserved in the acid waters, and which have recently been radio carbon dated.

We can speculate that such peoples built good quality houses using timber too, in view of the extensive forest cover available over the land at the time.

Further afield than Britain, no lesser an authority than the Bible gives us a great deal of information about the building of the Temple in Jerusalem, which was begun 'in the four hundred and eightieth year after the children of Israel were come out of the land of Egypt, in the fourth year of Solomon's reign'.

Since it is also documented, in Egyptian as well as Hebrew writings, that the Israelites under Moses left Egypt during the reign of Rameses II, in 1250 BC, then the date of the building of the Temple is closely fixed. The First Book of Kings gives a great deal of technical information about the construction. The walls, of course, were of stone. However the roof consisted of beams and boards of cedar.

Evidently, the Temple builders understood the wisdom of not enveloping the timber beams within the stonework for fear of decay, since we read that 'without, in the wall of the house he made narrowed rests round about, that the beams should not be fastened in the walls of the house'.

Furthermore, 'made he for the door of the temple, posts of olive tree ....and the two doors were of fir tree: the two leaves of the one door were folding'. 'He built the walls of the house within with boards of cedar, both the floor of the house, and the walls of the ceiling'.

The Phoenicians, the greatest seafarers of the ancient world, who visited the British Isles, and perhaps sailed even further into the North Atlantic, acted as King Solomon's timber merchants. It was they who provided logs from the great cedars of Lebanon for this construction.

**Anglo Saxon period:**

In Britain, and in south west continental Europe, no such pre-Christian documentation exists. Even during the earlier Anglo Saxon and Franconian reigns, timber construction generally has to be deduced from archaeological evidence such as post holes.

It is known however that amongst the prodigious efforts of Charlemagne (771 to 814) were included a large timber bridge over the Rhine at Mainz, and palaces and fortresses which incorporated skilled timber construction.

Offa, the King of Mercia, became King of all England during Charlemagne's reign. Offa was one of the few rulers who was treated as an equal by Charlemagne. Since he constructed a great earthen defence to the west of his kingdom which can still be seen, and since medieval timber frame construction is still very much in evidence in Mercia, it seems likely that pre-conquest structural timberwork in Britain was by no means elementary.

The Norman invasion and settlement of Britain had such a profound influence upon the society and economy of the country, that it led to wholesale reconstruction. This masked a great deal of the earlier Anglo Saxon construction, which on the whole has survived mainly in the form of masonry and comparatively rare timber joinery details, seldom in carpentry.

An Anglo Saxon church built of timber, Fig 2.1, stands today as a solitary witness in Greensted-Juxta-Ongar, Essex, where the walls of the nave, formed from split oak staves, have been scientifically dated to the year 835.

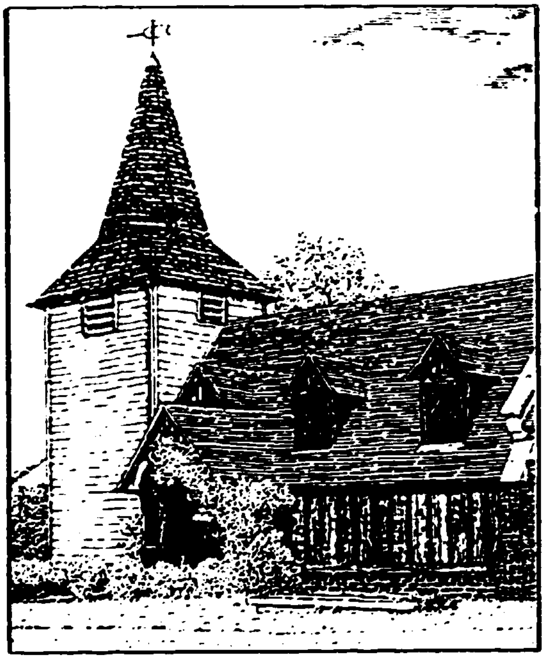

Figure 2.1

Greensted-Juxta-Ongar church, Essex

The connexion between carpentry and ship building, as well as roof construction, has already been mentioned. There are also, of course, ancient Christian links between fishing, wooden shipbuilding, and construction methods for places of worship.

To this day, parts of the church, such as the 'nave', are named after parts of the ship. It seems likely therefore that early British building carpentry followed nautical guidelines, both in form and in details such as the joints.

The majority of Saxon timber buildings were of the type classed broadly as 'box frame' and hence these were the forerunners of about a thousand years of uninterrupted timber frame tradition in Britain.

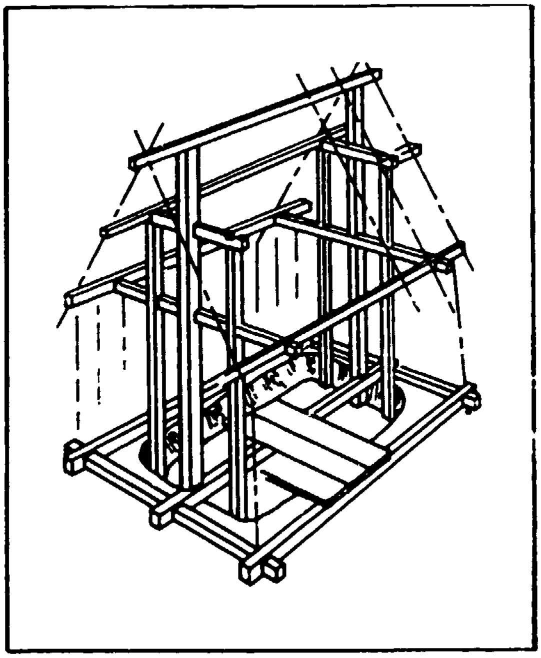

**Figure 2.2**

**Reconstruction of a Saxon timber frame building**

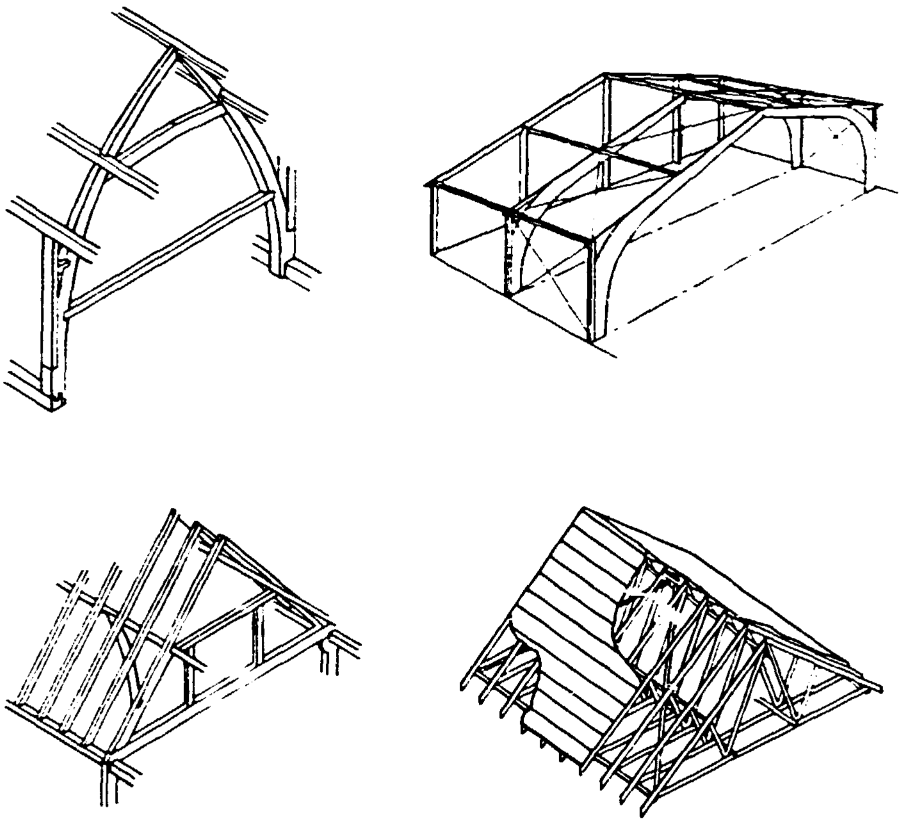

Figure 2.3

**Cruck frame and glulam portal; box frame roof and trussed rafter roof**

Although early Saxon construction was based on posts inserted in the ground in prepared pits, later Saxon buildings developed the use of a sole plate, giving greater durability. Saxon carpentry joints differed from those seen in later medieval times, Fig 2.2.

It seems clear therefore that during the so-called 'dark ages', timber framing had developed a degree of sophistication well before the Norman Conquest of Britain.

**Cruck frame construction:**

Another type of early timber frame construction which was certainly in existence before the end of the first millennium was the cruck frame. Cruck frame construction probably does not have its origins in continental Europe, since it is found more in the north west parts of England, rather than in East Anglia.

**Figure 2.4**

**Fifteenth Century cruck framed cottage, Harwell, Oxfordshire**

Later, when considering modern timber construction, it will be possible to recall the box frame and the cruck frame. These two concepts can be considered to have been passed down to timber frame and to trusses or trussed rafter construction on the one hand, and to glulam portals, arches and domes on the other, Fig 2.3.

This is not of course to claim that there is a strict technical or historical pedigree, but rather to note that there have always been two distinct framing concepts, which we still recognise.

The timber building tradition which had been started by the Saxons in western Europe, developed through Norman times, using various forms of timber framing.

Quite a large number of cruck frame buildings still survive, for example in the village of Harwell, in Oxfordshire, there are ten cruck frame dwellings, all surviving from the fifteenth century, their timbers having been dated by radio carbon methods, Fig 2.4.

The species used were the native hardwoods, mainly oak, but also elm and poplar. These trees were used in

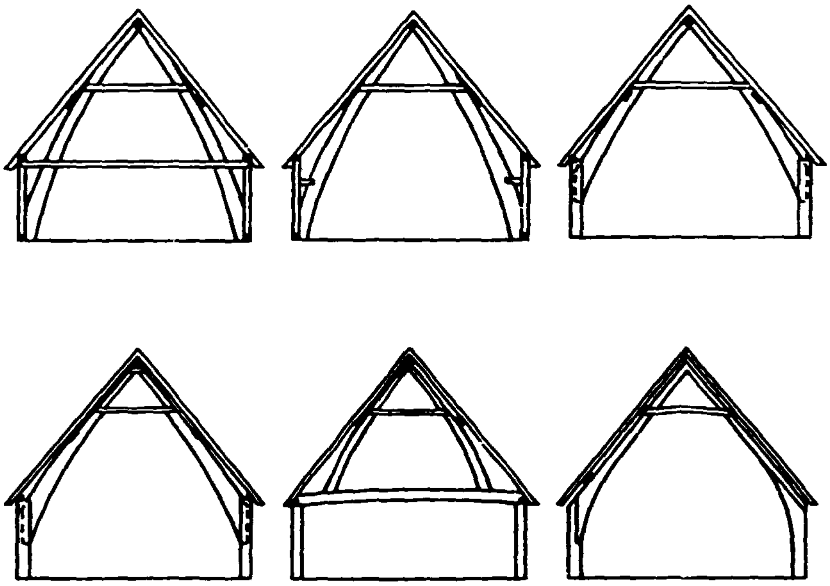

**Figure 2.5**

**Forms of cruck construction**

their green state, and apart from the main cruck frames, many of the timbers were taken from quite young trees, often only 35 to 45 years old.

Although primitive in essence, the cruck frame developed into forms which were no means crude. By the twelfth or thirteenth century, it had incorporated fully developed carpentry joints, Fig 2.5.

The original cruck types had frames right down to ground level. Sometimes the tips of the blades were merely butted to one another. In other cases, they were housed, halved, crossed over, or tied with various types of yoke or collar.

In more advanced forms of cruck construction, a tie beam was incorporated into the roof. The smallest types of cruck buildings had two frames only. Larger ones usually consisted of several bays, each about sixteen foot (4.9 m) long, with purlins and common rafters between.

The cruck frame building always incorporated a ridge purlin. It also had intermediate purlins and an upper wall plate. The purlins were housed into the cruck blades, a tradition that persisted for centuries, right through into early trussed construction.

As use of the system developed, walls were erected vertically to a projected wall plate which was cantilevered off the cruck

**Figure 2.6**

**Stokesay Castle, Shropshire, has a fourteenth century cruck trussed roof. Each blade represents a whole oak tree; with a sharp angle of about 35 degrees at the knee, the timbers had to be sought from craggy hillsides.**

frame by means of a spur, dovetailed into the cruck blades.

Developments from the simple cruck framed structure took several courses. In some cases, early forerunners of the roof truss can be envisaged in these forms of construction. In others, such as the base cruck roof, the action is essentially that of the portal frame.

Here, a pair of blades are connected by a collar, and this structure, the base cruck, supports a further tie beam. From this stage, a crown post or other higher-level support for the apex is strutted. Common rafters are then supported by this structure, through the usual purlins.

As well as overcoming span limitations, by making optimum use of the length of the cruck blades, such forms of construction gave clear unobstructed ground floor areas, suitable for tithe barns. Both base crucks and cruck trusses were also used in large fortified manor houses and halls. Although these developments from the simple cruck frame permitted more ambitious structures, they undoubtedly stretched the resources of the timber merchants, Fig 2.6.

## Box frame construction:

In box frame construction, the roof and wall frames can be built independently of one another. An essential feature of box frame is that the roof members are supported by runs of longitudinal timber framed walling, just as in modern timber frame construction, rather than having to be borne through a post and beam arrangement.

Box framing is based upon the bay system. A bay was probably either a direct unit of measurement, or at least a well-recognized standard dimension.

It is impossible within the scope of this paper to discuss all the various roof types associated with box frame construction. They have been classified by a number of authors into eight major groups. It is only possible to indicate a few principles of the main types.

In general, in addition to employing main frames in which all the members were maintained in a single plane, all forms of timber framing prior to approximately the second half of the seventeenth century had to rely mainly upon the transmission of compressive forces, as only the relatively weak dovetail and half lap types of joint were available to carry any degree of tension.

The compressive forces were passed by direct timber-to-timber contact, through joints cut entirely in the wood.

**Figure 2.7**

**Medieval box frame junction, using cleft heart-of-oak pegs**

Pegs, skilfully cleft from partially dried hardwood blocks, served mainly as locking devices. Fig 2.7. These pegs carried negligible shear forces, unlike modern timber engineering bolts, dowels and connectors.

## Development of roof framing:

'Single' framed roofs consist entirely of simple rafters and associated members which are not connected together longitudinally. The simplest of all is termed the coupled roof.

This merely consists of pairs of simple rafters, which are butted at their apex, and which rest on the wall plate at their base. The weight of

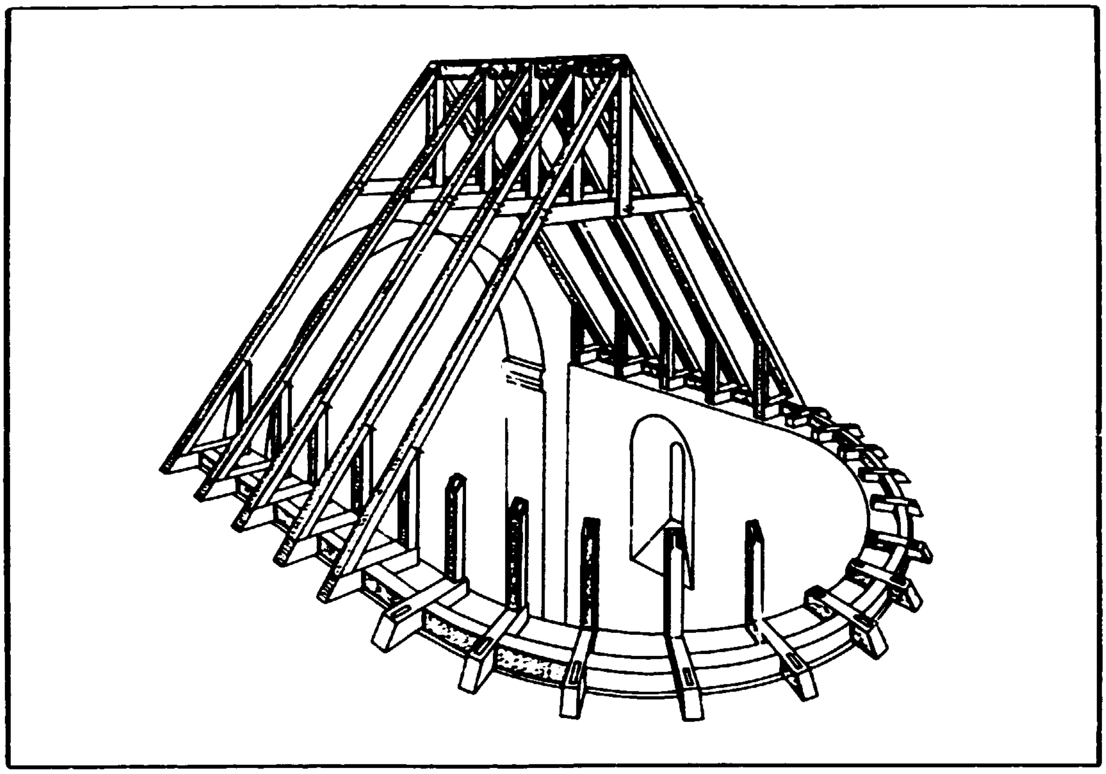

Figure 2.8

**Church of St Mary Magdalene, East Ham, Essex - early 12th Century roof of simple coupled rafters with high collars, ahlars, and apsed sanctuary wall**

the roof is transmitted through these members evenly, all the way along the wall plate.

A common rafter roof, possibly with the addition of simple collars, can span no more than about 6 metres without excessive deflection and outward thrust on the walls. A number of methods were used in medieval church and cathedral roofs to overcome such problems and to span up to 10 or 11 metres.

On roofs constructed on thick masonry walls, transverse members were added at wall plate level, and to these were attached vertical struts known as 'ashlars'. These had the useful function of stiffening the rafters at a point of high moment, spreading the reaction of the roof from the walls, and helping to reduce the effective span. Such roofs had little inherent bracing in their construction. Racking had to be prevented by means such as boarding, or by providing apsed ends, Fig 2.8.

Another favoured method was to employ a steep pitch of around sixty degrees, in conjunction with collars and scissor braces. The fourteenth century scissor braced common rafter roof above the nave of Ely Cathedral, Cambridgeshire.

was constructed in this way, Fig 2.9, and was only boarded over some five hundred years after its original construction.

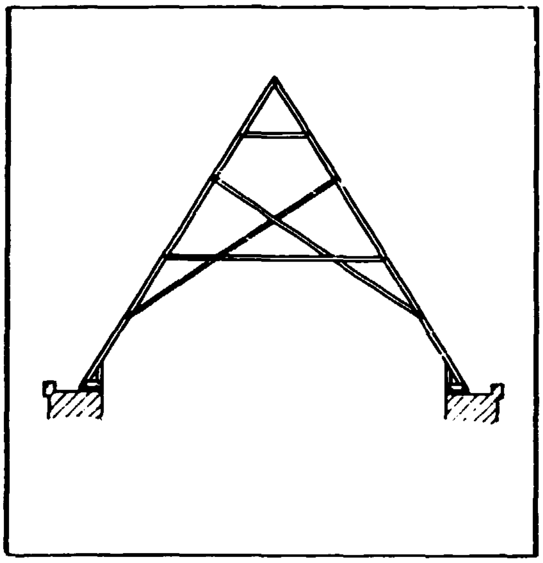

**Figure 2.9**

**Ely Cathedral, Cambridgeshire, Scissor braced common rafters**

The common rafter roofs of Westminster Abbey are also built in a similar manner, and span almost 11 metres, with rafters about 200 mm sq. Although scissor bracing is architecturally pleasing, and indeed is still sometimes chosen, it unfortunately creates a rather inefficient form of structure, requiring large rafter sizes.

In late medieval times, the open hall was a common style of living. Its arrangement was related to the feudal system of society. The open hall consisted of two-storey, two-bay construction. There was an open space in the middle, centring around the fireplace which vented in a simple hole in the roof. At one end of the building, known as the solar, was a more enclosed private area where the owner and his immediate family lived.

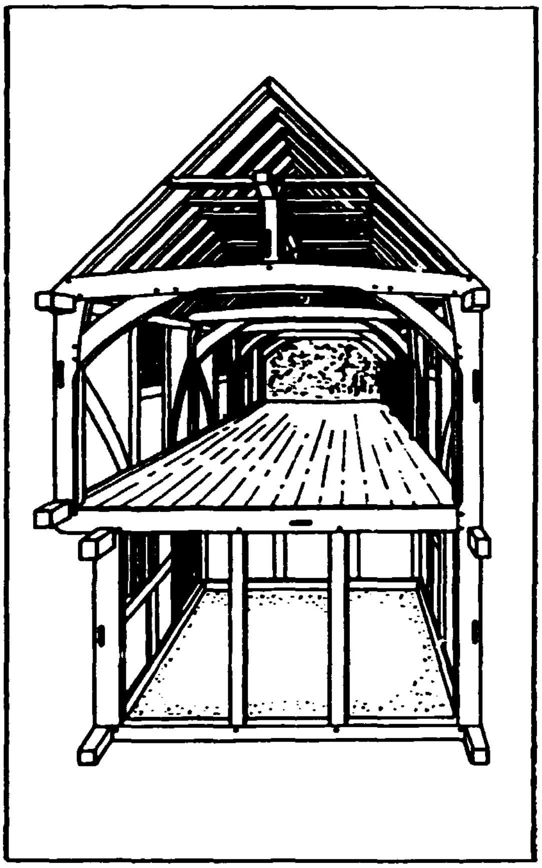

**Figure 2.10**

**Crown post roof, Crawley Market Hall, Sussex. A converted 15th Century manor house - Note the stout tie beams at eaves level**

The crown post roof was commonly employed for these open halls, Fig 2.10.

The crown post itself arose from the centre of a principal tie beam, located at each bay ending. It was braced to an upper collar, and at its head sat the central crown or collar plate, which ran longitudinally, in the same

**Figure 2.11**

**A crown post roof, Stanstead Mountfitchet, Essex**

sense as a purlin. This member in turn was used to carry the common rafters, by supporting a series of common upper collars.

Most authorities regard the crown post roof as belonging to the broad class of 'single' roofs, together with the simple coupled and collared roofs described above.

Although the crown plate fulfils a similar role to the purlins of the 'double' roofed types of construction, the arrangement is less than fully effective in transmitting along to the bay endings all of the load from the common rafters which are located in the central regions of the bay. The crown post roof therefore is seen as structurally transitional. The stout construction surmounting the transverse tie beam which crosses at the eaves of each bay is regarded as being structurally independent of this member. The tie beam serves to link the longitudinal walls and to prevent their spread, rather than forming the basis for any kind of primitive truss.

In several parts of England, the crown post roof can still be found within high quality medieval buildings in important towns. The roofs are often carved, and always incorporate skilled carpentry joints. Noteworthy examples are to be found in the South East of England, in the city of York, and in several towns in East Anglia, Fig 2.11.

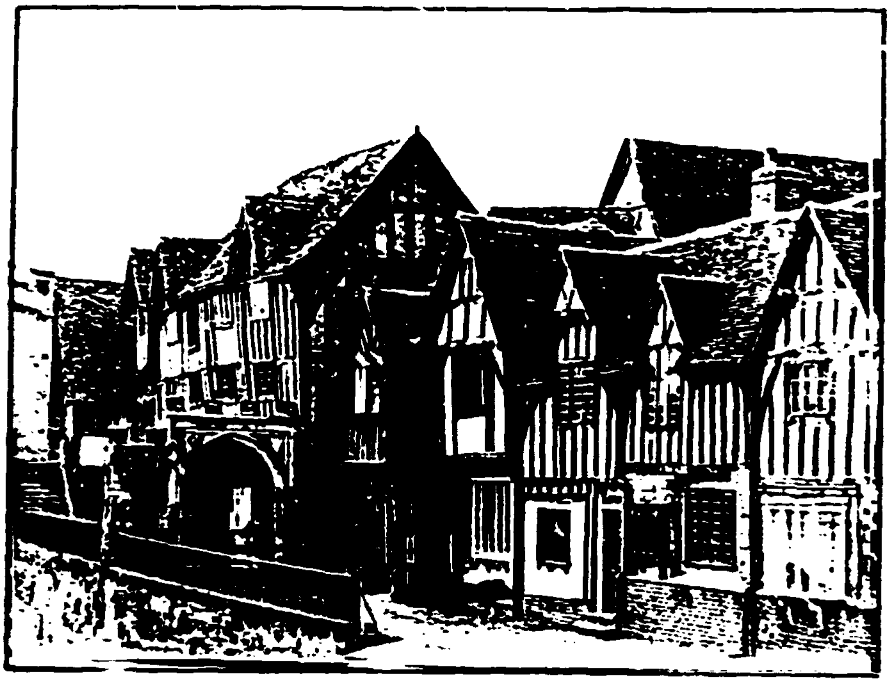

**Figure 2.12**

**A medieval street of timber framing - Warwick**

After about the year 1500, the double framed, or purlin roof, largely superseded the single rafter form in Britain. On the Continent, however, the simpler roof persisted regionally, right through to the last century.

The outward appearance of late medieval timber frame buildings must be familiar to anyone who has seen tourist pictures of Britain, Fig 2.12.

Fortunately numbers of these lovely buildings still stand, and in several English towns it is possible to see whole streets of them. Wall infill panels evolved from the use of materials such as wattle and daub, through lime plastered rubble, to brick which was used from the fifteenth century onwards.

The shapes of the wall frames varied. In the South of England, close vertical studs predominated, whilst further North, square panels were more usual, often with the addition of curved braces. Fig 2.13.

Important town buildings were often jettied, sometimes repeatedly. This was thought to be both to protect the occupants of the open ground floor, and also to gain extra space.

With the abandonment of the open hall, through social changes taking place during the sixteenth century, and the almost universal adoption of the double framed roof, the opportunity arose of utilizing the attic space thus created. Dormer windows were added, to light this roof accommodation.

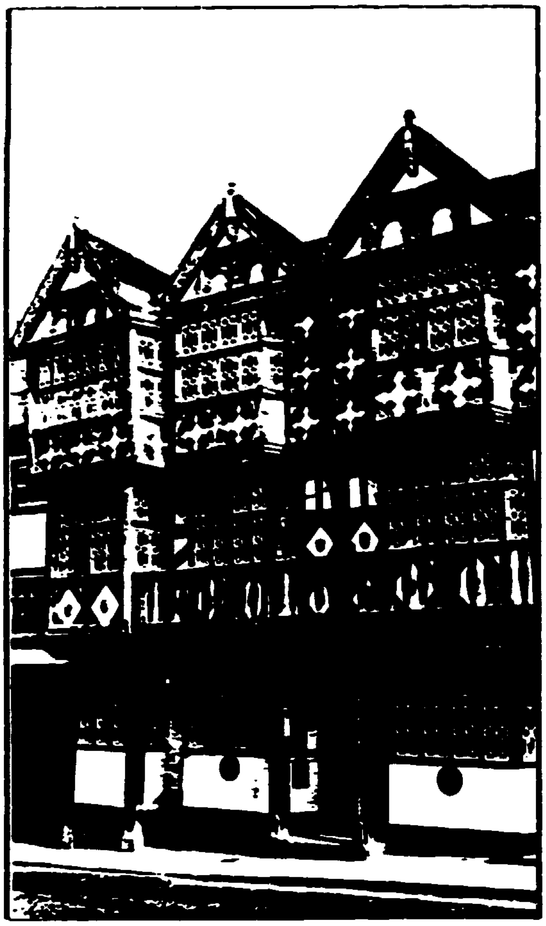

Figure 2.13

The Feathers Inn, Shropshire, curved bracing evolved into decoration

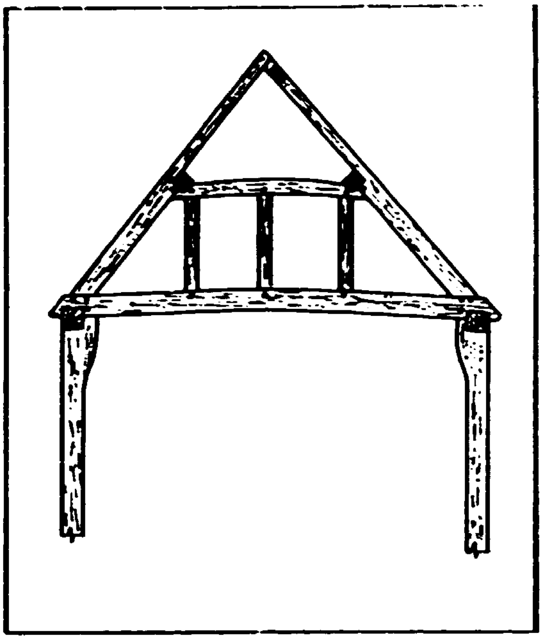

Figure 2.14

Clasped purlin roof

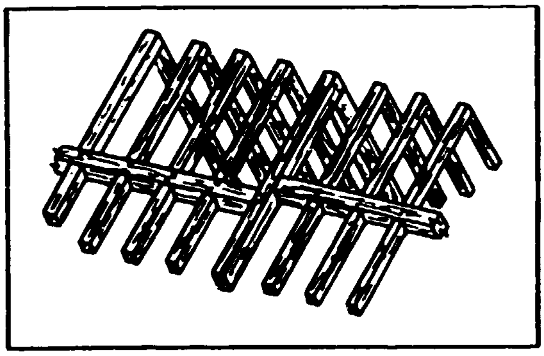

Figure 2.15

Butt purlin roof

There were several alternative principles used in connecting the purlins to the main roof frames. Two important types were the clasped purlin roof, Fig 2.14, and the butt purlin roof, Fig 2.15.

The latter appears the simpler form of construction, but it demanded a higher degree of carpentry skill. It was more common in Southern England and was regarded as a feature of high quality work.

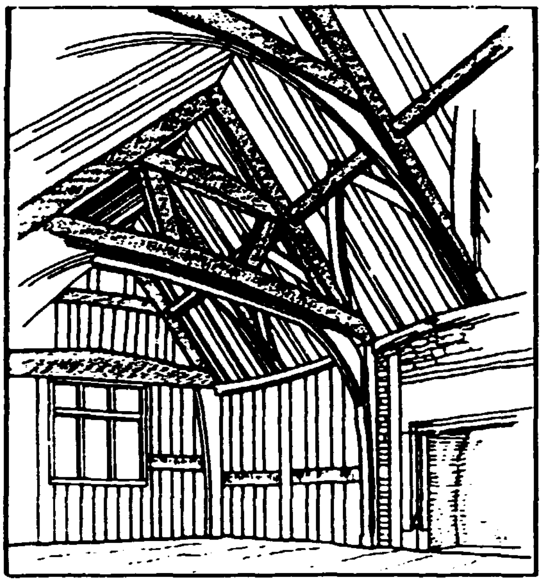

**Figure 2.16**

**Shell Manor House, Warwickshire - Sixteenth century roof of distinctive Queen post truss form**

In the clasped purlin roof, the principal rafter was cut with its upper face in line with the common rafters. The purlin was clasped beneath the main rafter in the birdsmouth at the end of the collar, the latter being further held in place with a strut.

**Origins of the roof truss:**

The clasped purlin roof incorporated the first recognizable form of roof truss. A few trusses dating from the sixteenth century are still to be found which can be said to bear some similarity to modern forms of truss, Fig 2.16.

An early type was the Queen post truss. Originally, this truss was used with trenched purlins, cut into the outer face of the principal rafters. In the Northern part of the country, the King post roof was more common. Elsewhere, the King post was not used until the seventeenth century. This is somewhat surprising, since it is a sound structural solution.

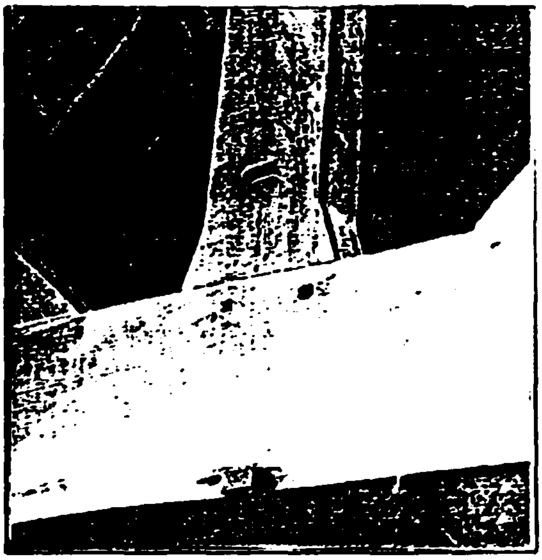

**Figure 2.17**

**Typical King Post to tie beam connexion**

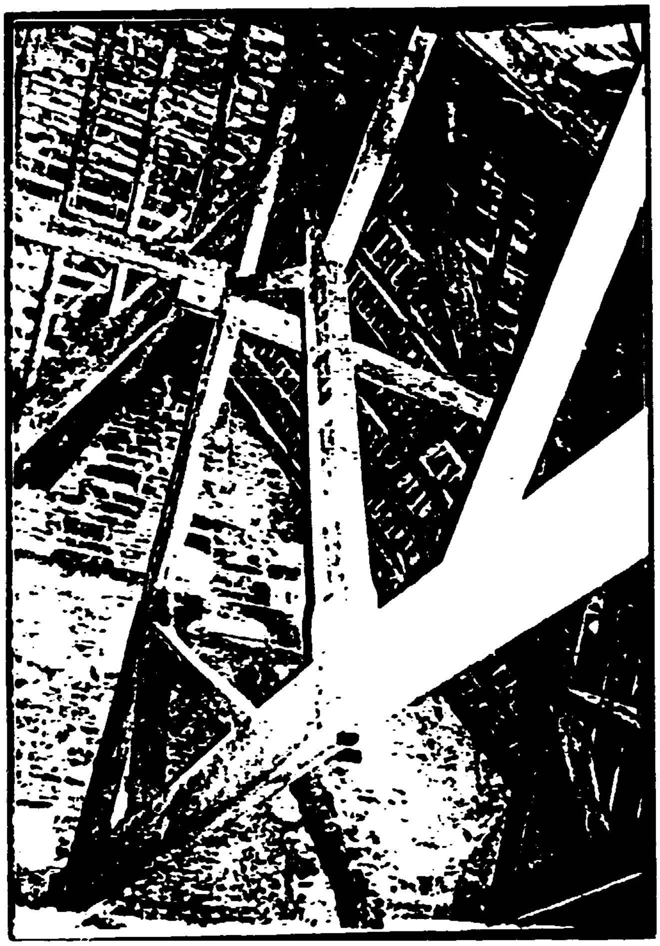

**Figure 2.18**

**Multiple King Post truss, 17th Century, Stokesay Castle**

The common rafters were generally of much lighter cross section. Normally they fell in their own continuous plane, outside and above the purlins.

From the seventeenth century onwards, buildings grew more ambitious in plan. Larger houses were constructed on what is known as the 'double-pile' principle, whose essential feature is the use of two rooms throughout the depth of the house at each floor level.

Carpenters had to develop new trussing methods to meet these requirements, and they were often based upon adaptations of the simplest King Post truss type, having more than one vertical strut.

The King post itself is a stout compression member, rising from the centre of the principal tie beam, Fig 2.17. It carries the ridge piece loadings, brought in by the ridge rafter which supports the tips of all the common rafters.

The King post triangulates the main truss, Fig 2.18. Secondary struts, originally more like simple braces in shape, spring from its base and meet on the underside of the principal rafters.

At this stage, furthermore, softwoods were beginning to replace oak and other hardwoods as the usual timber for such roofs, whilst joint details were beginning to make greater use of ironwork, giving higher capacity for tensile force transference.

Historical change:

As early as the sixteenth century, exposed timber framing began to be regarded as unfashionable, in comparison with 'modern' materials such as brick.

Hampton Court Palace and Hatfield House, Fig 2.19, are notable examples of major brick structures, which nevertheless contain elegant timber roofs exposed within the interiors of their halls.

There are a few timber framed buildings in which bricks were the original infill material, but these are fewer than is commonly believed. It was a favourite Victorian fashion to 'decorate' timber frame by replacing earlier infill with herringbone brickwork. Consequently, this is now often regarded as original.

**Figure 2.19**

**Hatfield House, Elizabethan Banqueting Hall - 'modern' brick construction with fine timber roof**

In bastions of timber construction, such as the West Midlands and the Welsh borders, where it was still considered dignified to expose the timber of the structure, buildings took on classical embellishments, whilst the bracing of the wall panels became so decorative, as in some instances to loose it structural efficiency.

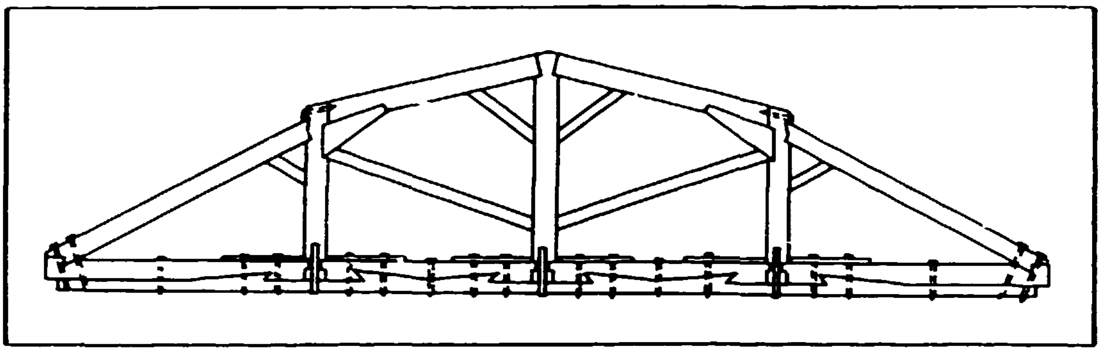

Figure 2.20

**Wren's trusses for the Sheldonian Theatre, Oxford, 1669. At 21 metres span, with a low pitch and a leaded roof, these had composite lower chords**

**Renaissance architecture:**

The revival of art and letters under the influence of classical models was known in Europe as the Renaissance. It had its origins as early as the fourteenth century, but in architecture its culmination in Britain was in the great buildings of Wren, Gibbs and Hawksmoor.

The Regency period of the early eighteenth century extended fashionable classicism. Many a timber frame town house has been rediscovered behind a classical facade added during that era.

By approximately these times, roof trusses based on the King post principle adopted more or less standardized jointing details, incorporating patented metal fixings.

In many cases, such trusses were extended to form several bays, and to carry the heavy loadings due to lead sheeting on the lower pitches dictated by architectural style.

Composite elements started to be used, Fig 2.20, and Fig 2.21. Softwoods and hardwoods, usually oak, were sometimes found in combination with one another.

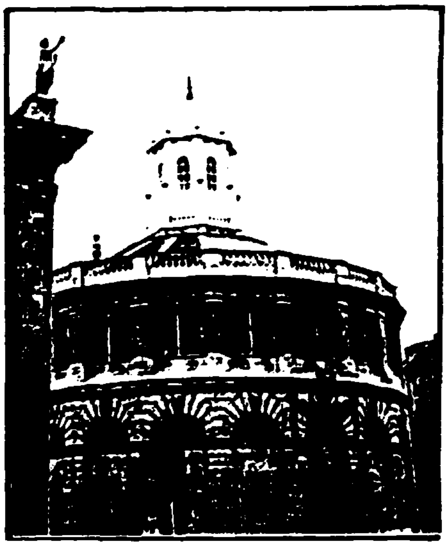

**Fig 2.21**

**Sheldonian Theatre**

**Foundations of engineering:**

The foundations of modern structural calculations had been laid by the eighteenth century. In order to be able to calculate structures, three aspects are involved.

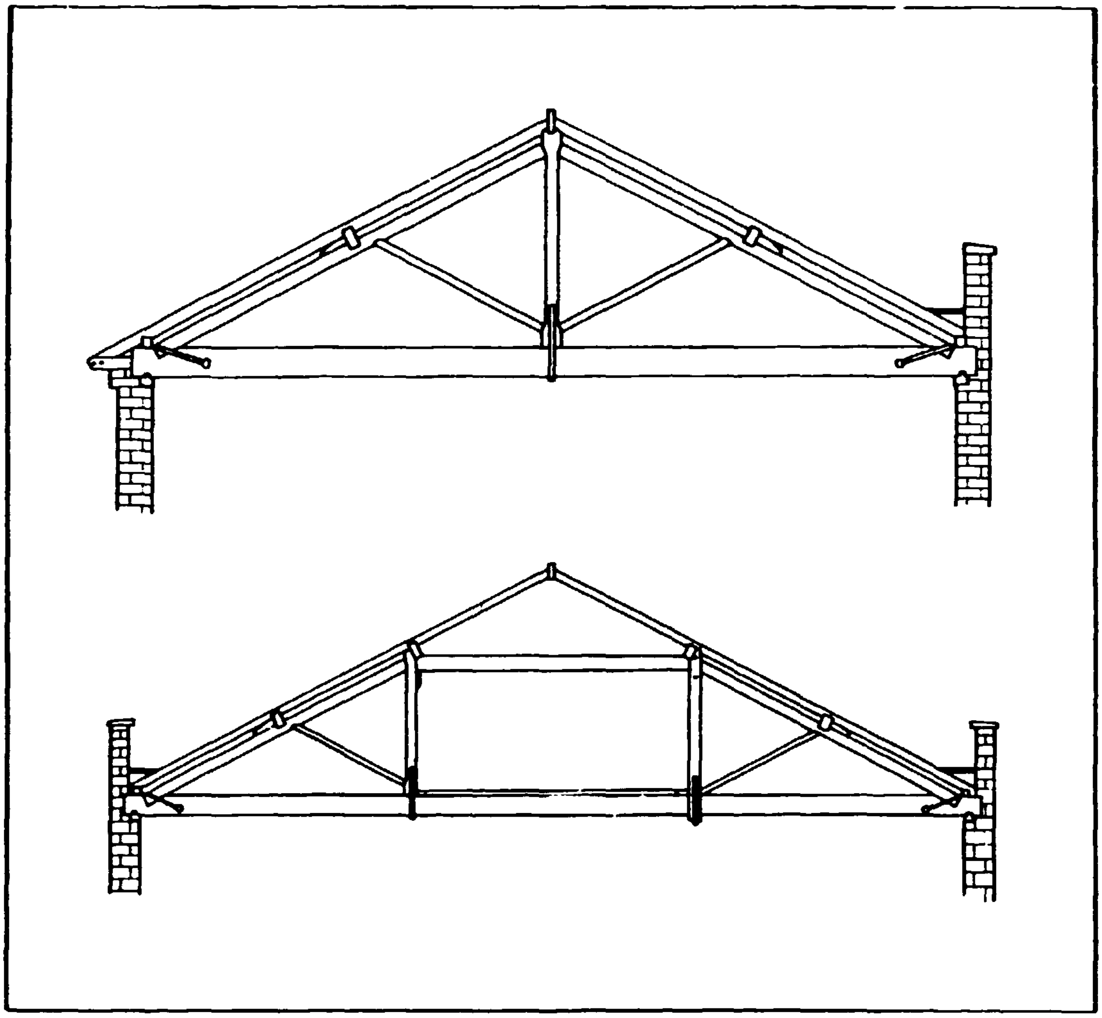

Figure 2.22

'Engineered' King and Queen post truss designs published by the Tredgold brothers, 1820

Firstly, the principles of statics are required, and these had been firmly established by Isaac Newton.

Secondly, information on materials' properties, are necessary. These had been initiated in the case of timber by French academics, who conducted surprisingly large-scale tests.

Thirdly, applications rules are required, or as we would now say 'codes of practice'. These have as their basis textbooks such as Tredgold, Fig 2.22, based in part upon experience but also drawing upon sources such as Palladio, in Italy, for theory.

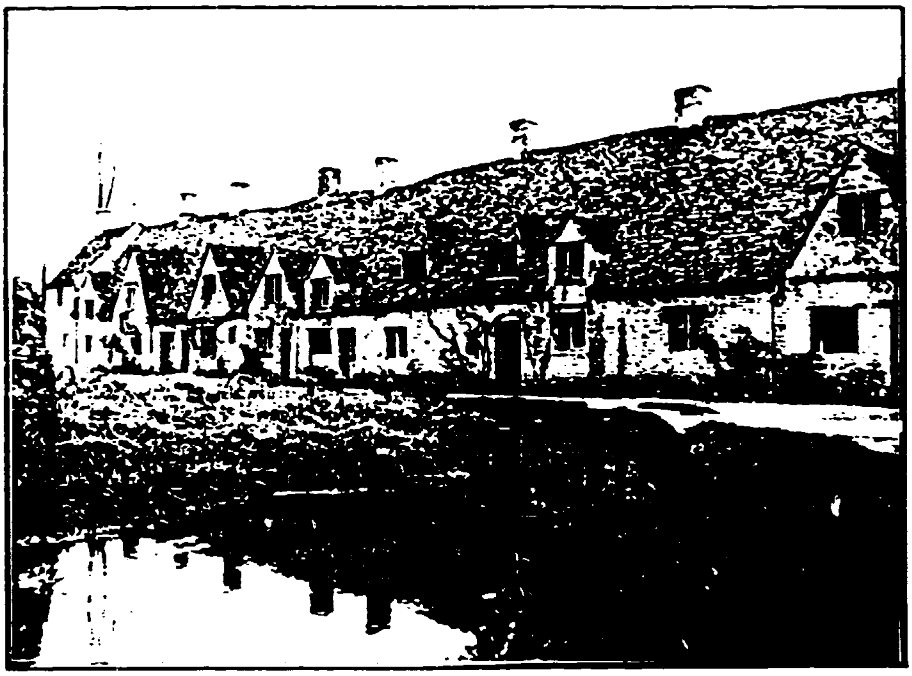

Figure 2.23

**Weavers' cottages, Bourton, Gloucestershire**

Serial manufacture had its origins in 'cottage industries'. Weavers' cottages, for example, Fig 2.23, are still preserved in many English towns and villages, having steep pitched, dormered roofs and large windows.

The industrial revolution marked the birth of the 'manufactory' or 'factory' for short, Fig 2.24. Industrial buildings involved much heavier loadings, due to both the machinery, goods and power sources. By the standards of the day, long clear spans were required, and stronger members had to be provided both in floors and in roofs. Mechanized sawing produced the necessary beams of pine, now orientated in the optimum manner with depth much greater than breadth.

Victorian mill construction also entailed considerable use of standardized iron bracket work, bolted details for timber joints, and tightening and locking devices.

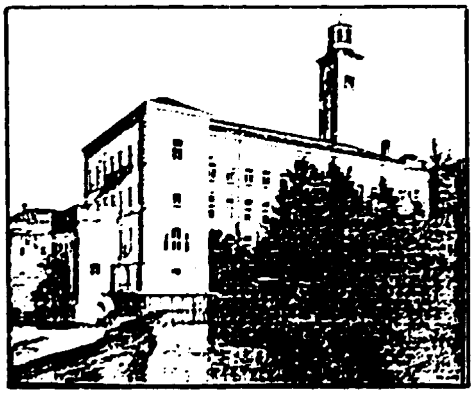

**Figure 2.24**

**The New Mill, Saltaire, Bradford, 1868 - typical Italianate Victorian mill construction**

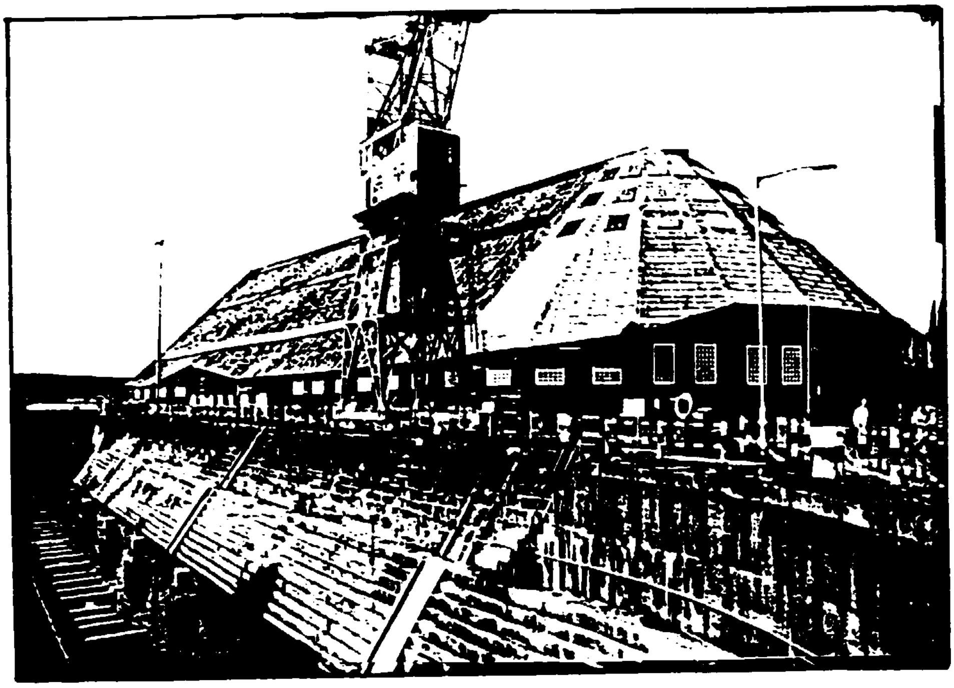

Figure 2.25

Chatham Naval Dockyard, Kent - Covered Slipway.
Large timber structures such as these, built to protect sailing ships during construction, were amongst the earliest instances of industrial timber structures

In the south of England, examples of large industrial structures in timber included the Covered Slipway Number 3 for the naval shipyard at Chatham, built in 1837, Figs 2.25, 26.

Whilst it is possible to cite other notable examples of structural timberwork undertaken during the Victorian era, it must be admitted that in Britain the material was beginning to suffer from being regarded as 'second rate'.

The problems of promoting timber as a serious medium for large structures, even at this present time, can be traced in part to the pride of the Victorian iron masters, mill owners and industrialists in their 'new' materials.

Figure 2.26

Chatham, covered slip interior, showing large timber roof

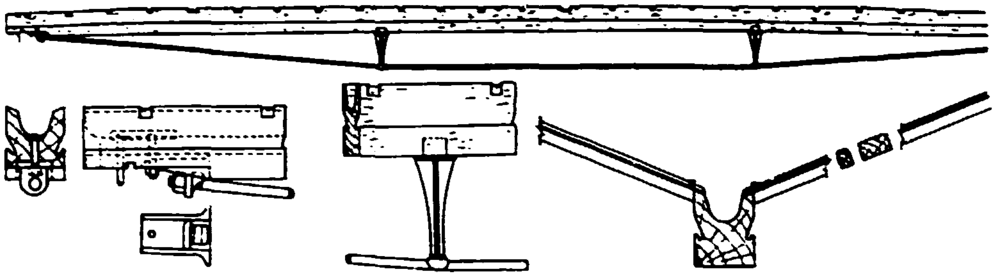

Figure 2.27

Details of composite timber and malleable iron construction in the Crystal Palace, 1851

Victorian ingenuity:

The 'Grand International Building of 1851 for the Exhibition of Art and Industry of All Nations', later known as Crystal Palace, was first built in Hyde Park, in the centre of London.

A prestigious competition was held for the design of a worthy structure to contain this great Victorian exhibition of trade and industry.

The winner was Joseph Paxton, an unknown provincial designer of glasshouses for country mansions. Paxton's scheme was revolutionary in several ways. It was bold, large, and innovative. It was a 'first' in terms of a prefabricated structure of anything like the size concerned, and it employed a great deal of timber, nearly all of it structural.

However, used to the demands of lightness, both in the sense of lacking mass, and also in the sense of allowing the maximum of light to penetrate the acres of glazing involved, Paxton combined structure with glazing joinery.

He even used a special patented structural ridge piece, having a complex machined section in timber, which doubled up as a rainwater channel, Fig 2.27.

The structure was erected within six months, and covered 70 000 square metres of ground. Its height was 22 metres to the upper eaves level, and it was crowned with a glazed barrel vault, which consisted of prefabricated timber modules, having a 22 metre span, Fig 2.28.

The entire structure was in fact modular, based upon an 8 foot (2.44 m) grid. The extensive prefabricated timberwork was often

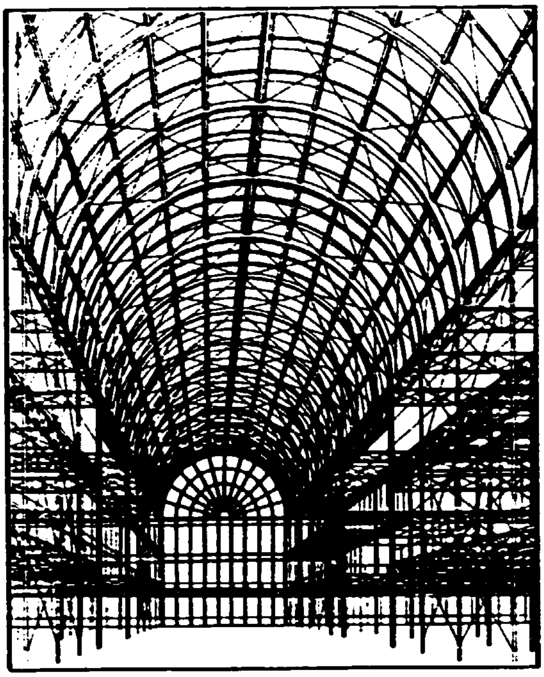

**Figure 2.28**

**Crystal Palace, interior perspective showing glazed barrel vaults**

composite, for example spruce and oak were combined in some of the members. Timber was also used in conjunction with malleable iron, to form lattice girders, and the pretensioned timber purlins had iron tie rods.

The glazed timber vaults contained vertically laminated curved members, Fig 2.29. These were connected with bolts, and the whole assembly was stiffened with diagonal metal tie rods.

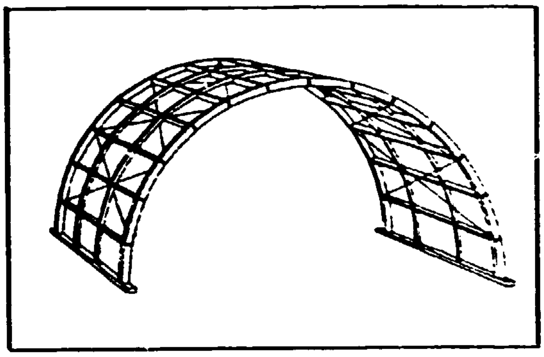

**Figure 2.29**

**Prefabricated barrel vault construction in vertically laminated timber**

After the Great Exhibition, the Crystal Palace was dismantled and removed to a South London site where it stood until 1936, when unfortunately it was destroyed by fire.

## Glued laminated timber:

Small-scale uses of wood adhesives have been known since prehistoric Egyptian times, and the technique of building up timber elements by assembling layers of boards is also extremely ancient.

According to extensive studies into the history of timber engineering which have been made by Dr L G Booth of Imperial College, London, the beginnings of modern glulam may be traced to the start of the nineteenth century.

There are possibly earlier contenders for the foundations of structural laminating, such as De L'Orme in France, but so far as glulam is concerned, it seems that the method has its origins in bridge engineering, rather than in roof structures.

Horizontally laminated timber arch bridges with spans of up to 200 ft (30 m) were first developed by an engineer called Carl Friedrich von Wiebeking, working in Bavaria during the period 1807-9.

Wiebeking achieved a remarkable construction record of completing nine large bridges during those two years. Most used thick bolted laminations, a technique now known as mechanical laminating, which is still popular for bridges today.

However one of his bridges was certainly glued. The ribs of this structure were formed from oak boards, two inches thick, with staggered butt joints. These boards were curved over formers by the side of the bridge site, having been warmed over a coal fire. He had previously proved the strength of such glulam beams by making tests on full-sized laminated specimens.

The lack of durability of the early adhesives was undoubtedly a frustration to designers. Had they been more reliable, the ability to laminate with glues would have been a great advantage to shipwrights, as well as to bridge and building engineers.

Claims for so-called 'waterproof' adhesives, which were based on substances such as rubber compounds, can be noted in Admiralty patents filed in Britain in the nineteenth century.

**Figure 2.30**

**Laminated arched roof at Worsted mill in Bradford, constructed about 1875 and in use for about ninety years**

As laminated timber construction progressed, there were more frequent examples where the joining of the layers was achieved by mechanical methods, rather than by glues, Fig 2.30.

Nevertheless, occasional nineteenth century glued laminated timber can be found on record, such as the roof of the wedding ceremony hall at Southampton Registry Office, Fig 2.31. This was fabricated around 1860, and belongs to a building which is still in use.

Formerly part of a grammar school, the roof consists of circular glulam arches from which principal rafters are strutted, together with a small crown truss type of apex.

Famous railway engineers such as I K Brunel, were also familiar with laminated timber and they made use of it, not only for outstanding railway bridges, but also for building structures.

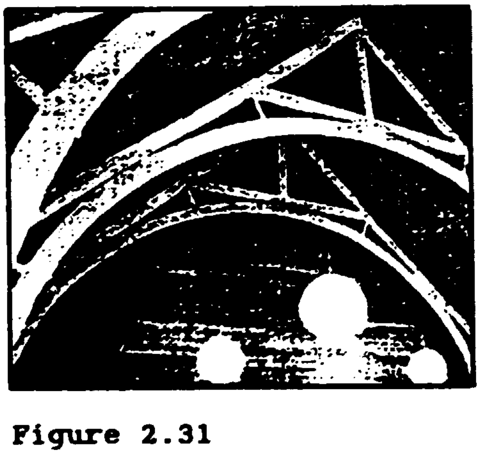

**Figure 2.31**

**Possibly the oldest glulam roof in the world, Southampton, 1860**

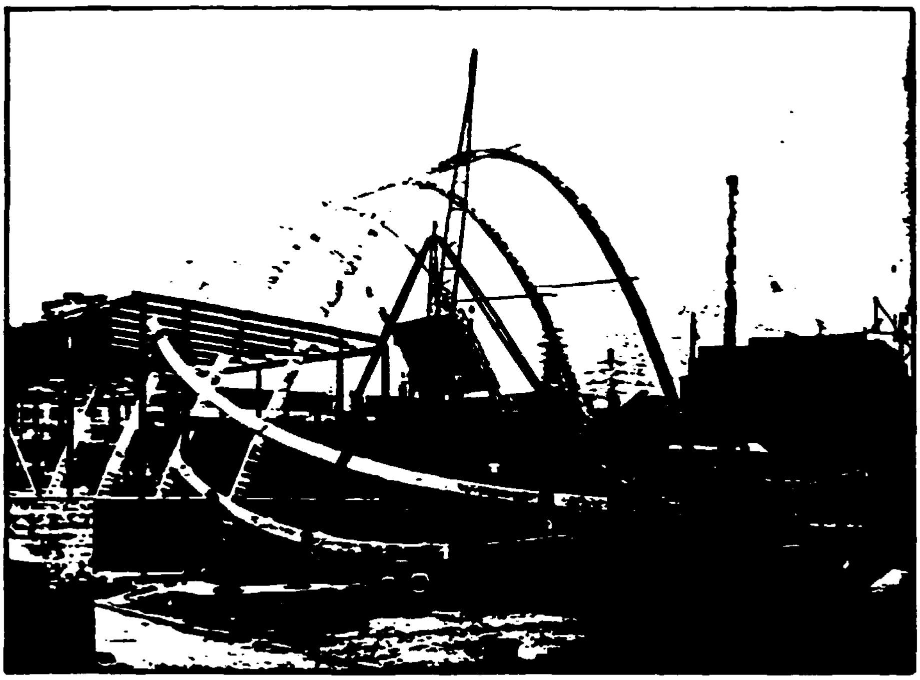

**Figure 2.32**

**Glulam arches for Festival of Britain entrance, 1951**

For nearly another century, however, glulam development awaited the availability of truly waterproof adhesives.

In 1906, the German, Otto Hetzer, working in Weimar, obtained a patent in order to start to commercialize glulam manufactured with casein adhesive. So successful was he that his name was still being associated with glulam construction in Switzerland, when a TRADA study visit was made there in 1962.

Switzerland was one of the first countries to use 'modern' glulam. Following a tour of Europe in 1936, Wilson of the Forest Products Research Laboratory USA, wrote that the most extensive use of glulam had been in Germany, Sweden and Switzerland, but that it was only just being introduced into the USA.

Wilson gave details of a number of the structures which he had inspected in Switzerland. Some, such as the dome of the University of Zurich, had been manufactured as far back as 1913.

By 1937, urea formaldehyde (UF) adhesives had become available on a commercial scale. These could offer the potential of glulines stronger and more durable than the timber itself. Wartime requirements for laminated marine and aircraft components gave impetus to such adhesive developments.

Under such exacting conditions, casein, which was certainly surprisingly waterproof, considering its basis of manufacture, was nevertheless found to be inadequately durable.

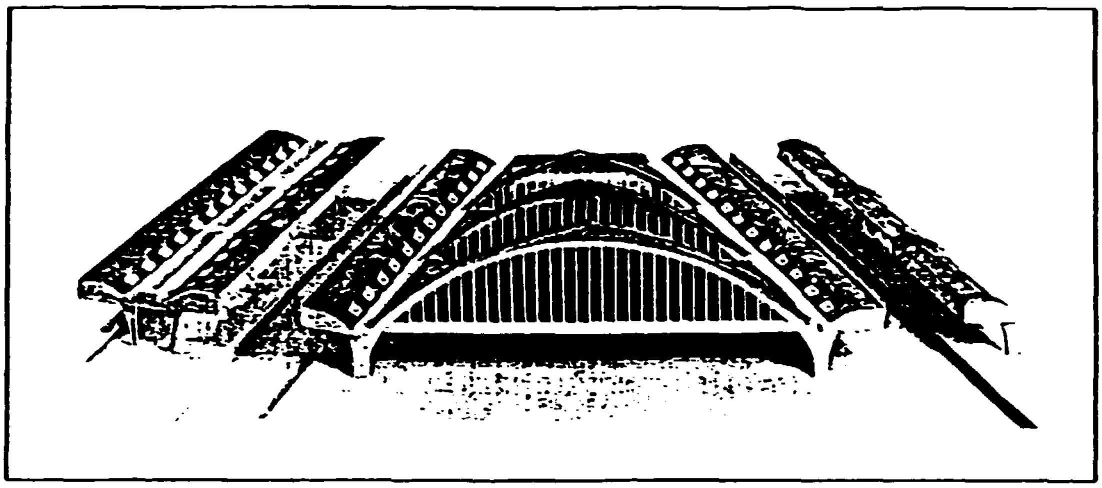

**Figure 2.33**

**Structural model of conoid roofs, Oxford Road Station, Manchester**

By around 1943, the modern family of synthetic resin adhesives was completed by the large-scale introduction of resorcinol formaldehyde (RF) and phenol formaldehyde (PF) adhesives.

In Europe, the 1950s were an exciting era of recovery and redevelopment, in which individualism flourished. The 'Festival of Britain' embodied this spirit.

A group of professionals and timber enthusiasts, who won a competition for the design of the entrance to the Festival, employed for the purpose an elegant and exciting glulam structure, formed with parabolic arches, Fig 2.32.

On the Continent, the same period showed interesting developments in Switzerland, the Netherlands and Belgium, with Germany and France lagging.

Problems with glulam in Germany were ascribed to a temporary setback caused by lack of confidence through a series of glueline failures. These were attributed to the effect of acid hardeners on the wood fibres.

The loss of key personnel, particularly skilled foremen and craftsmen, caused by the recession and the war, was also a serious problem.

Strict control was subsequently set up under the aegis of the Otto Graff Institute, Stuttgart, and technical promotion and development has since then boosted German glulam usage back to the leading position in Europe, now about twenty times that of the UK.

In public buildings, roof forms consisting of strict geometrical surfaces such as shells, hyperbolic paraboloids and conoids, featured strongly during the 1950s. These frequently made use of glulam. Examples such as Oxford Road Station, Manchester, Fig 2.33, are still in daily use.

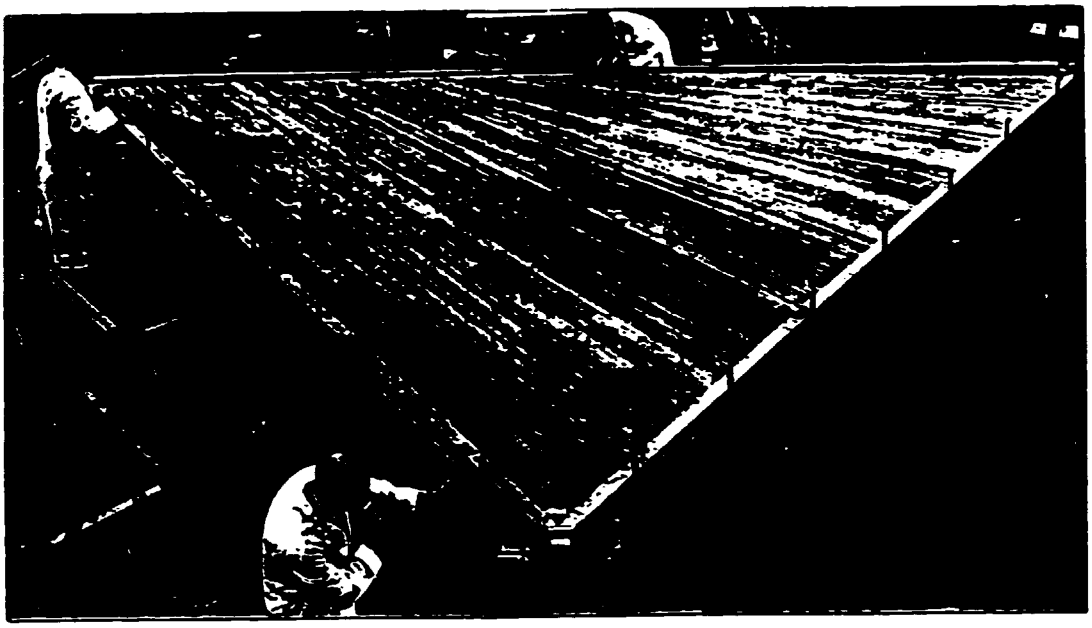

Figure 2.34

Hyperbolic paraboloid shell roof being prepared for test, TDA Laboratories, 1956

Outstanding examples of hyperbolic paraboloid shell roofs, Fig 2.34, included the multiple paraboloid shell roof for the Royal Wilton carpet factory, in 1957, and an attractive conference hall for the Scott Bader company in Northamptonshire, built in 1959.

In more conventional form, the merits were realized of glued laminated timber to construct, for example, portal frames for factories, Fig 2.35.

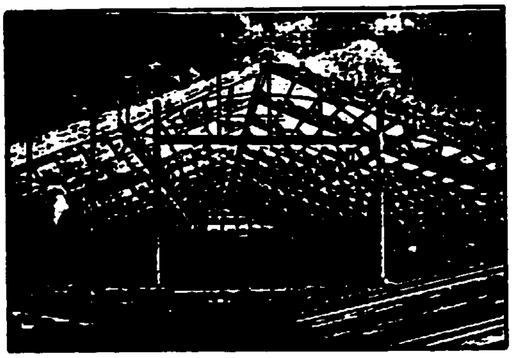

Figure 2.35

Glulam factory under construction, Grangemouth, Scotland, 1959

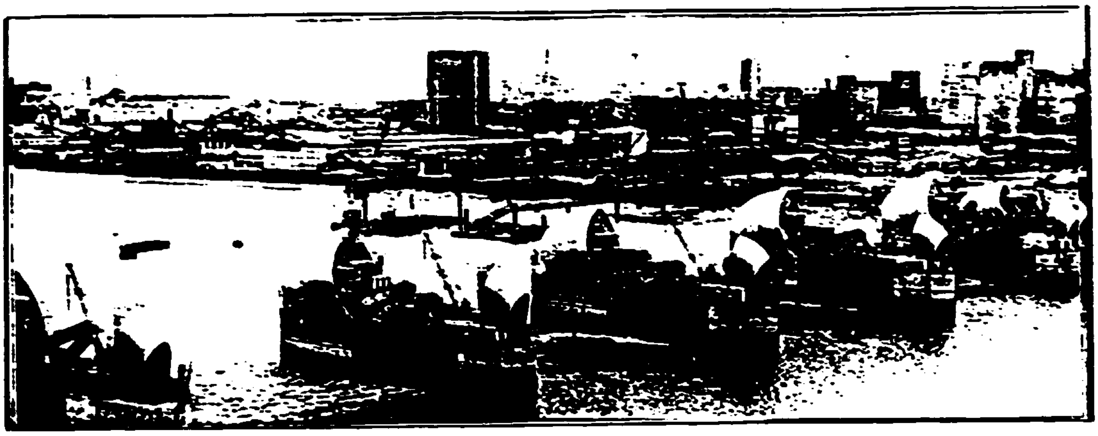

Figure 2.36

Roofs of the Thames Flood Barrier, constructed from glued laminated iroko arches

Recently, some very large building structures, domes 150 metres in diameter for example, have employed glulam. Although none so large have yet been located in Britain, glulam continues increasingly to be used here. Applications range from the Thames Barrier shells, Fig 2.36, to beautiful buildings such as that housing the Burrell Collection in Glasgow, Fig 2.37.

Figure 2.37

Burrell Collection

## CHAPTER 3

## Traditional pitched roof construction

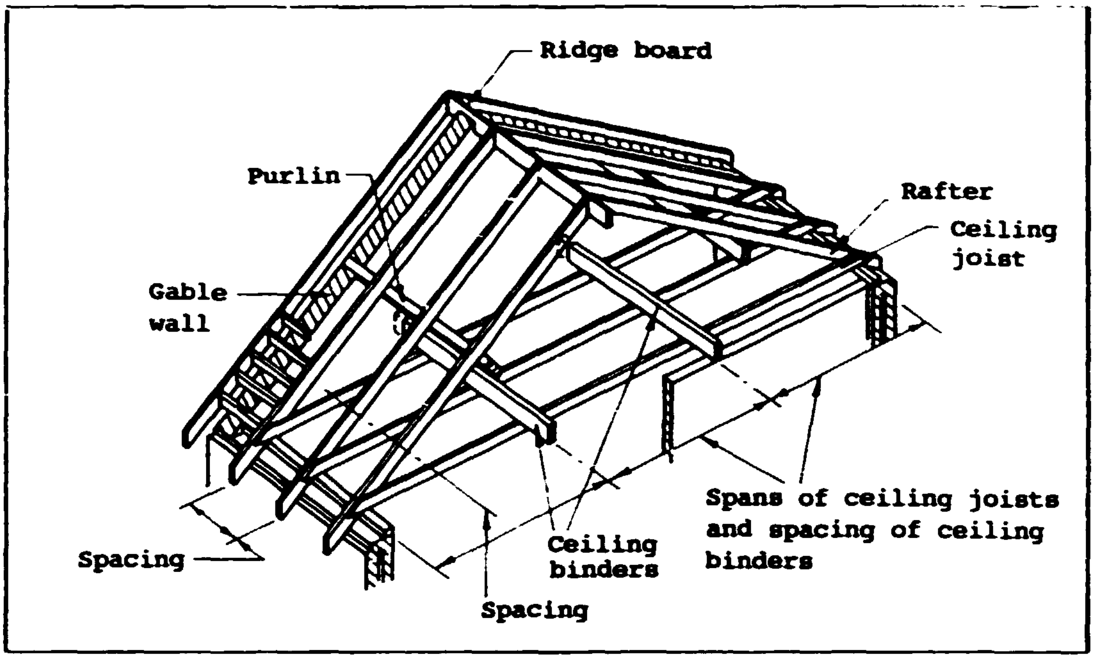

Fig 3.1

Typical example of simple pitched roof construction, illustrating main terms for components

This Chapter deals with the modern design principles of traditional pitched roof construction. This is construction using purlins, rafters ceiling joists and other members, which are generally cut and fixed together on site, as opposed to roof construction based upon the use of prefabricated trussed rafters.

The members involved in traditional pitched roof construction are generally made of solid timber, although in some instances, such as larger purlins for example, the design methods could be applied to glued laminated timber (glulam), or other modern composites such as laminated veneer lumber (LVL).

Roofs such as these are often described as 'cut roofs'. Although 'traditional' in the sense that they have evolved from carpentry craft practice, which was reviewed in Chapter 2, cut roofs are now designed using engineering calculations.

They are a form of construction which is still very much in use, despite being essentially quite primitive. Also they contain elements of structure which many have found surprisingly difficult to analyze.

In addition to the fact that due to their continued usefulness cut roofs form a suitable subject for study in their own right, a knowledge of their design principles is helpful in order to be able to apply trussed rafter construction satisfactorily. This is especially the case when adaptations are required to the latter, when non-standard features are required, for example.

A typical example of a simple pitched roof is shown in Fig 3.1, which illustrates the main terms used in conjunction with the components of this type of construction.

In Britain, the sizes of many of the elements of a cut roof are prescribed in documents which accompany the Building Regulations. The design of all new roof structures in England and Wales must conform with the requirements of the Building Regulations 1985. In Scotland, Building Standards (Scotland) Regulations 1981 to 1986 apply, whilst Northern Ireland uses regulations similar to those of England and Wales.

The statutory documents, that is to say the regulations themselves, state the functional requirements with which the design must conform. For trussed rafter roofs for example, these functional requirements can be met by designing in accordance with BS 5268: Part 3. For cut roofs however, there are a number of span tables given in what are termed 'Approved Documents'.

The Approved Documents span tables can be used to size the individual timber members in a cut roof, thus ensuring structural adequacy and hence compliance with the regulations.

The methods used to calculate the span tables in the Approved Documents have become established over the period since Model Byelaws and town and city building regulations began. In London, for instance, laws controlling building methods can be traced back to as long ago as the rebuilding subsequent to the Great Fire (Rebuilding Act, 1667).

The design methods upon which the modern Approved Documents are based have been studied by government departments concerned with construction, and by British Standards Institution technical committees. They have recently been set down in publicly available standards, as explained below.

Meanwhile, the Approved Documents which are issued by the same body as that which publishes the Building Regulations themselves, are an invaluable design aid for cut roof construction. Other publications based upon the Approved Documents methods of calculation are also available from TRADA. These are prepared by means of specially written computer programs, whose calculations follow the approved procedures.

To date, there has been little demand for computer programs which can guide the user to select on screen his own solutions for a particular form of cut roof construction. To write such programs would be a relatively easy adaptation of the existing types which generate tables. On the other hand, selection from printed tables which have been calculated by computer is also quite an easy matter for the user, so it is doubtful whether there would be a great call for such software.

The general principles for the design of structural timber members are stated in BS 5268: Part 2. Using this guidance, it is possible for span tables to be prepared for a wide range of simple timber members, including those needed in cut roofs. Hence the span tables for members comprising traditionally framed roofs, which are given in the Approved Documents, were calculated using design recommendations having their basis in the main structural timber code.

However, experience showed that different interpretations of these Part 2 recommendations led to inconsistencies in span tables published by various organizations. These variations amongst span tables were not necessarily due to errors. In the wording of a structural code of practice, it is quite normal to leave certain decisions to the designer's judgement.

Obviously however it is desirable that in the case of span tables for common elements of small buildings such as cut roof members, arbitrary differences should not exist. Accordingly it was decided to eliminate such differences of interpretation by recommending in detail the design equations and the loadings to be used in the preparation of the joists and cut roof span tables.

This was dealt with by preparing a complete series of sections of a new part to the structural timber code, numbered BS 5268: Part 7. This part of the code was written to ensure that different organizations would produce span tables on a consistent basis.

Part 7 is not necessarily intended for direct use by designers for individual designs. In most day-to-day work on residential accommodation of up to three storeys, and on similar sized non-residential buildings, designers will be able to work to the span tables which are in turn based on Part 7.

Routinely, structural calculations or checks on simple carpentry members such as joists and rafters can adequately be performed with very elementary calculations.

The loading conditions and design equations which are described for the various elements included in Part 7 are quite elaborate and comprehensive however, since they are intended to be incorporated into computer programs which will generate span tables giving optimum economy.

**Sections of BS 5268: Part 7:**

The sections available within BS 5268: Part 7 are as follows:-

| | |
|---|---|
| Section 7.1 | Domestic floor joists |
| Section 7.2 | Joists for flat roofs |
| Section 7.3 | Ceiling joists |
| Section 7.4 | Ceiling binders |
| Section 7.5 | Rafters |
| Section 7.6 | Purlins supporting rafters |
| Section 7.7 | Purlins supporting sheeting or decking |

Of these, Sections 7.3, 7.4, 7.5, 7.6 and 7.7 are relevant to cut roofs of pitched form, as discussed in this Chapter.

As already mentioned, the timber stresses and moduli to be used for span tables following the methods given in BS 5268: Part 7 are those recommended in BS 5268: Part 2. The latter provides grade stresses for very many combinations of species and grade. Hence it is impractical to publish in the British Standards themselves span tables for all of the possible combinations of species, grade and size that may be required.

The approach adopted therefore is to give the basis for the calculations, along with sample span tables for a few important strength classes, grades and standard sizes. Part 7 recommends the formats that span tables published by other organizations should follow. Since there are many combinations of geometry and materials for each of the member types covered, computer programs which were prepared by TRADA were used to generate the sample outputs and the sample span table formats.

**The role of the cut members in the complete roof:**

Traditional carpentry textbooks tend to take the reader progressively through cut roof construction, beginning with 'simple couple' roofs, through 'close couple' and 'collar' roofs, to 'double roofs', a term for those incorporating purlins. These forms follow the customs of carpentry already described in Chapter 2.

The Approved Documents, and more recently the Part 7 span tables, have brought a greater measure of uniformity to cut roof design. However it is still found necessary in some instances to employ individual carpentry skills in providing roof shapes which go beyond those indicated in Figure 3.1.

Examples of such shapes include attic roof construction, and cut roofing infills in trussed rafter roofs, which entail hip ends and valley intersections. These will be discussed more fully in Chapter 5.

Other instances in which these long-established dimensioning rules are used for the common roof elements shown in Figure 3.1, whilst at the same time taking advantage of more modern methods for the construction of the principal trusses. occur with the bolted and connectored prefabricated trusses described in Chapter 4.

Such forms of construction, hybrids between traditional and fully prefabricated methods, are well worth considering in a number of developing country situations, where the expensive modern plant, required to fabricate trussed rafters with punched metal plates, is not yet installed.

Figure 3.2 shows a purlin, common rafters, ceiling ties and a ceiling binder. However instead of being supported via the purlins just by cross walls, the common members are borne on purlins resting on a standard type of bolted truss. To the right of the illustration, the purlin and binder are supported by a cross-wall, in the more conventional manner, as in Fig 3.1.

In Fig 3.3, the complexity of the roof is taken a stage further, since half-trusses are added, to provide a hipped end, with infilling by means of loose, or cut common rafters. Deep, slender plate-like members, called 'hip rafters', are incorporated at the corners of the roof. The main purpose of these is to transmit a smooth thrust between the compressive rafter members in one roof plane, and those in the adjacent surface. The shortened rafters are known as 'jack rafters'.

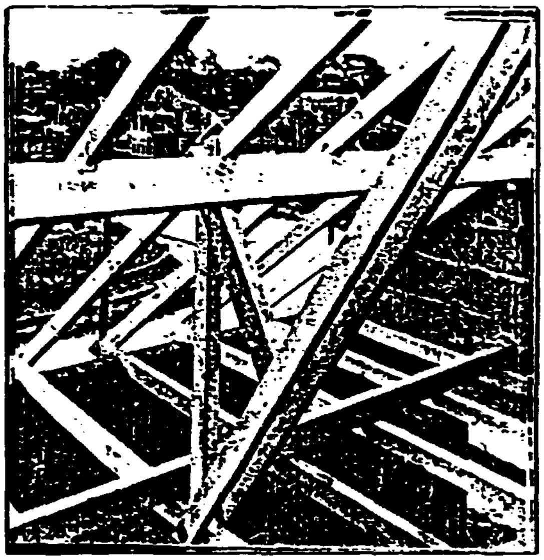

**Fig 3.2**

**Common cut roof members supported on purlins carried on a bolted truss**

Such forms of domestic hipped roof were very popular during the post-war reconstruction boom in Britain. The model illustrated in Fig 3.3 was exhibited as long ago as 1947, at the Building Trades Exhibition, Olympia, to promote the merits of partially prefabricated construction using TDA trusses.

Millions of such roofs still serve well, covering a large proportion of the housing stock of Britain, a fact worth bearing in mind when dwelling upon more 'modern' methods. One of their special merits is that the structural form is inherently very stable, and hence these roofs required no special addition of bracing members.

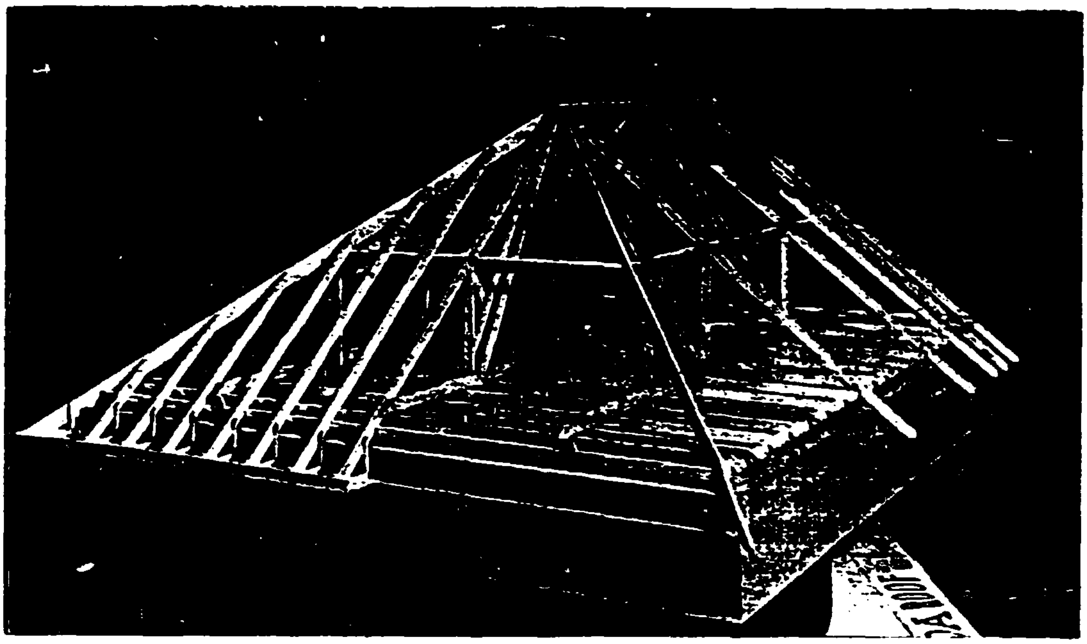

Fig 3.3

**Hipped roof using bolted trusses, half-trusses, and purlins with common cut members**

Trussed and common raftered roofs are really just more modern, engineered versions of several of the forms of domestic roof construction described in the previous Chapter. Hence it can be appreciated that in experienced hands, BS 5268: Part 7 provides a valuable basis for such further needs, as well as just enabling member sizes to be looked up for the exact simple type of roof shown in Figure 3.1.

Features of BS 5268: Part 7:

Comprehensive discussion of BS 5268: Part 7 would be beyond the scope of this paper, however salient features are presented as follows:

Part 7.3 Ceiling Joists:

This section of BS 5268: Part 7 recommends a calculation basis for permissible clear spans for ceiling joists to be used in situations where there is access to the roof. The joists are limited to a maximum spacing of 610 mm centre-to-centre. The design calculations are based on engineers' bending theory, and are consistent with the recommendations of BS 5268: Part 2. For example, the deflection due to bending and shear is restricted to 0.003 times the span.

The lateral load distribution possible with the majority of ceiling types is not sufficient to allow stresses to be increased for 'load sharing', hence this is not included. However there is a concession to the fact that long experience has shown that it is satisfactory to use the mean modulus of elasticity in the equations for limiting deflection.

For roof pitches greater than twenty degrees, which covers the majority of cases, the axial tension induced by the rafter thrust is ignored in the design of the ceiling joist member itself. The code warns however that there is significant tension in such members, so far as the design of the connexions is concerned.

As with all sections of Part 7, loadings follow BS 6399. Uniformly distributed dead and imposed loads are involved, as well as a 0.9 kN concentrated load in a single position.

Bearing lengths indicated are the minimum necessary to ensure that the permissible compression perpendicular to the grain stress is not exceeded in the joist. Practical constructional considerations may demand longer bearings.

Section 7.3 continues by detailing the loading equations; stress equations in the form of polynomials to be solved for span; and deflection equations under point and uniform loads which incorporate both bending and shear effects. Sample calculations for a ceiling joist are provided, together with specimen span tables.

Section 7.4 Ceiling binders:

The function of the ceiling binder is to give intermediate support to the ceiling joist over its eaves-to-eaves span, Figure 3.4.

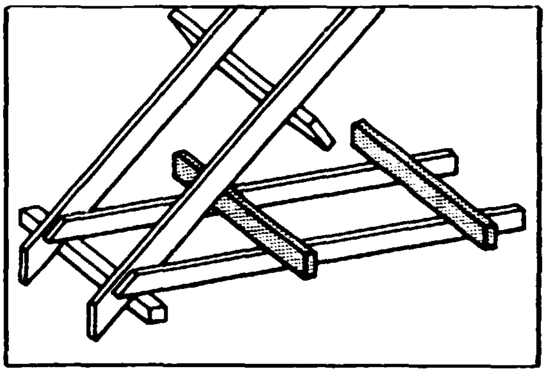

**Fig 3.4**

**Location of ceiling binders in a typical cut roof**

The method of calculation given in the Section is for single span binders supported at each end by external or internal walls. The roof space is considered to be accessible; this affects the loading.

The usual references to BS 5268: Part 2 and to deflection limitations are made. Load sharing is not assumed for stress, nor for stiffness, unlike the case with ceiling joists. Hence the minimum modulus of elasticity is used.

Clauses follow on loading conditions, design loads, limitations of bending stress, shear stress, deflection and permissible clear spans. The format of the document is similar to Section 7.3.

**Section 7.5 Rafters:**

Section 7.5 recommends a calculation basis for permissible clear spans for rafters. The rafter member extends the full distance from eaves to ridge.

The rafters described in the Section are for use in roofs with a slope of fifteen to forty five degrees. These pitches cover the majority of applications. The maximum spacing of the rafters is 610 mm. It is assumed that the tiling battens are capable of providing lateral load distribution and lateral support to the rafter, hence the load sharing modification factor given in BS 5268: Part 2 is used for stresses, and the mean modulus of elasticity is applied in the deflection calculations.

The uniform and concentrated loads of BS 6399: Part 1 are considered. Provision is made for a uniformly distributed imposed load derived from BS 6399: Part 3.

The types of rafter covered in the Section are shown in Figure 3.5. The references to BS 5268: Part 2 and to deflection limits are as given in other sections of Part 7. The calculations relate to pitched roofs having a single purlin on each side of the ridge. The rafter may be continuous or non-continuous over the purlin. The purlin is perpendicular to the rafter, and is centrally placed, so that the upper and lower portions of the rafter have equal spans.

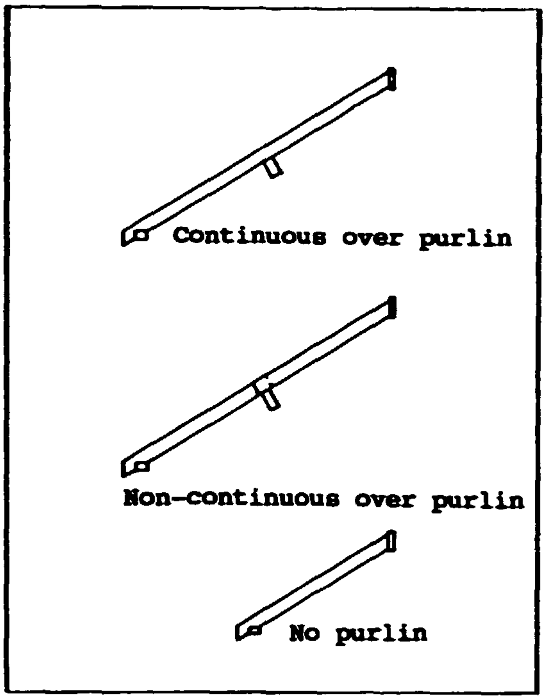

**Fig 3.5**

**Common rafters**

It is assumed that the ceiling joists will be used to transmit to complementary rafters the horizontal component of thrust occurring at eaves level, Figure 3.1.

The constituents of the roof loads are described in detail, these are imposed loads, dead loads, and self-weight. The loading conditions for design are then prescribed. These consist of a uniform imposed load condition, a point imposed load condition and a long-term load.

Explanations of the design formulae are then given. They are derived for the form of construction already described. It is important to note this, since formulae can only be set down once the geometry of the structure is closely defined. The formulae differ for the three types of rafter shown in Figure 3.5.

For simplicity, rafters without support are treated in the same way as non-continuous rafters, with slight conservatism. The spans derived in this way are also recommended for jack rafters. Section 7.5 details the loading equations: stress equations and the deflection equations under point and uniform loads. The equations include both bending and shear effects. Sample calculations for rafters are included, and specimen span tables are provided.

**Section 7.6 Purlins:**

Section 7.6 of Part 7 gives recommendations for calculations for purlins supporting rafters in pitched roofs. The purlin is the beam which runs parallel to the eaves, giving intermediate support to the rafters. Figures 3.1 and 3.2 show the location of purlins in typical pitched roofs.

The calculations given in the section are for single spans, or for two-span continuous purlins. The major axis of the purlin is arranged perpendicular to the rafter slope. This is not always done in practice, but it is the recommended arrangement, since it is structurally more efficient.

The loading assumptions for the Section are as for the other elements of the pitched roof, already described. The purlins are treated as principal members, with no provision for load sharing.
It is necessary to make an assumption as to how the rafter spans are divided in order to calculate the purlin loadings, hence these are treated as two equal spans.

The three loading conditions: uniform imposed load; point imposed load, and long-term load are prescribed in detail. For each of these, the equations for the load are resolved perpendicular to the roof plane.

Formulae are given for permissible spans for purlins of the type described, the permissible effective span being the shortest resulting from the calculations for bending strength, shear strength and deflection. Sample formats for purlin span tables are provided, so that those wishing to produce data in conformity with the standard may follow this uniform method.

**Section 7.7 Purlins supporting sheeting or decking:**

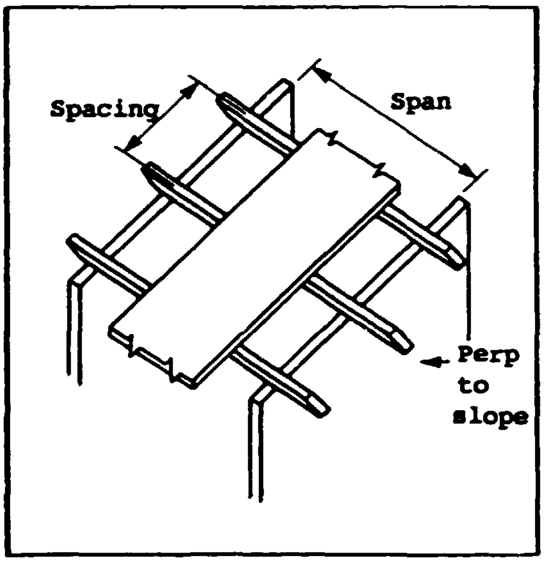

Fig 3.6

Purlins supporting sheeting or decking

Purlins supporting sheeting or decking in pitched roof construction differ from those supporting rafters, as described in relation to

Section 7.6. above. Purlins of the type covered in Section 7.7 of the Code are normally supported by external or internal walls, as shown in Fig 3.6, although it is possible for these supports to be in the form of solid or glulam beams, or trusses, such as those discussed in the following Chapter.

The major axis of the purlin is assumed to be perpendicular to the roof slope. This is by far the most common arrangement when such purlins are used in conjunction with trusses, at fairly wide centres, such as from 1.2 metres to 4.8 metres.

This form of construction is frequently useful in fairly simple tropical building designs such as classrooms, workshops and community buildings. Fig 3.7 shows a typical application of purlins of this type.

Fig 3.7

Typical application of purlins supporting sheeting

The information and recommendations given in this Section of the standard generally follows broadly similar lines to that described above for domestic purlins, although in detail the calculations differ.

**Extending the principles of BS 5268: Part 7:**

It has been shown that by designing traditional pitched roof elements in conformity with BS 5268: Part 7, compliance with the Building Regulations can be achieved, without the necessity for employing a structural engineer. Often however the principles of Part 7 need to be extended for forms of roof construction which go beyond the simple type shown in Figure 3.1. The degree to which this may also be done without a knowledge of engineering is to some extent a matter of judgement. Prudence would obviously suggest that adaptation should be undertaken with caution.

A simple hip roof can be formed from timbers cut on site with only the addition of a hip rafter, plus jack rafters, which are cut to a compound angle at the tips, using a carpenter's square. This will create a roof similar to that shown in Fig 3.3, but using entirely loose members rather than trusses in combination with cut construction.

The purlin requires alternative support at the hip end, in place of the usual gable wall. This support is normally provided by propping from a load bearing wall. At the wall plate corners, an angle tie, and a dragon beam were traditionally added, in order to contain the substantial outward thrust from the hip, Fig 3.8.

Valley structures are another common feature. In a simple cut roof, the intersecting roof or dormer is formed by means of valley jack rafters, which are supported on a valley board. This is fixed over the rafters of the main roof.

Attic roofs using site cut timbers require greater extrapolation from the principles just stated. Consequently they are probably better constructed nowadays using trussed rafters, the system owners having a number of standard solutions available.

Another alternative is the TRADA 'Room in Roof Construction', which involves the use of stressed skin panels and which makes special provision for the tying together at the eaves of the components concerned.

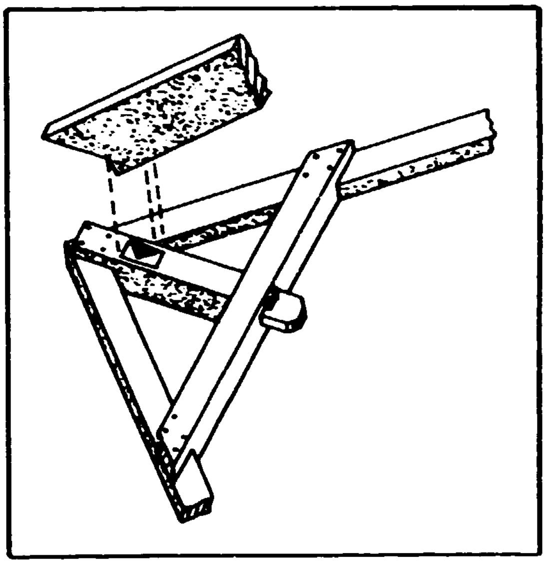

**Fig 3.8**

**Corner details in a hipped ended cut roof, showing dragon beam to prevent spread**

# CHAPTER 4

## The development of the bolted and connectored roof truss

### Origins:

Soon after its formation in 1934, the Timber Development Association (TDA), which was the immediate forerunner of the Timber Research and Development Association (TRADA), took up the development of more economical means of producing timber roof structures.

A little earlier, the British Forest Products Research Laboratory (FPRL) had been formed, originally as part of the Royal Aircraft Establishment. Many aircraft of the time were constructed from timber. The use of wood in aircraft structures may be thought to have had its culmination in the famous Mosquito design, but even some of the early jets, such as the De-Havilland Vampire, contained important structural timber parts, Fig 4.1.

Fig 4.1

Timber and plywood were important structural materials for aircraft, even in early jets, such as this De-Havilland Vampire

The method of construction was stressed skin, and both ribs and formers, and the skin panels themselves, were made from timber and plywood.

Alongside these important developments in timber construction in the aircraft industry, the structures in which the aircraft, balloons and airships were housed and serviced were often of a major size. Several record-breaking spans were constructed. These were nearly always formed using bolted, connectored trusses, arches, built-up columns and trussed frames, Fig 4.2.

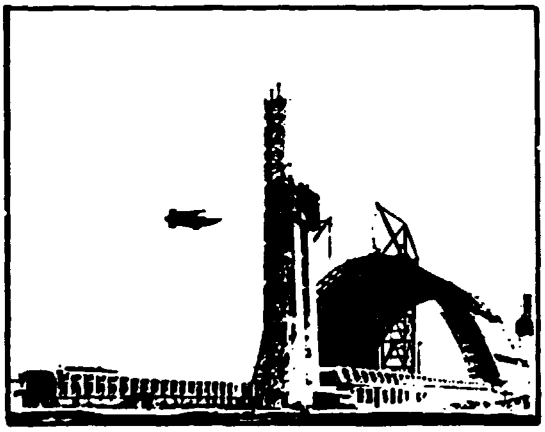

Fig 4.2

Large spans such as this airship shed were built using bolted and connectored timber construction

The first types of timber connector were probably invented in Scandinavia. Certainly the round toothed plate connector was a Norwegian device. Fig 4.3. Quite soon after these first developments, separate types were invented in Germany.

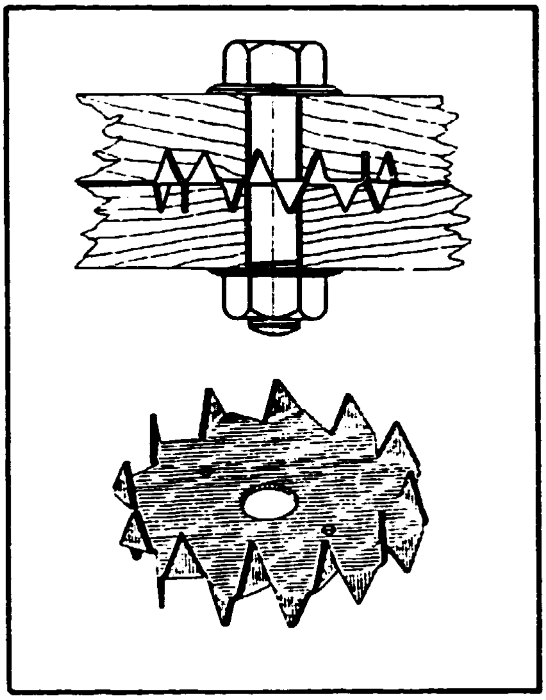

Fig 4.3

**Round, double-sided toothed plate connector**

During the 1930's, study teams travelled to Europe and Scandinavia from North America and witnessed timber engineering methods playing an important role in redevelopment after the First World War and the depression.

There were important research publications on timber bolted and connectored joints issued by the Forest Product Research Laboratory, Madison, USA. These have continued to serve as the basis for timber code recommendations for timber bolt and connector design, until very recently.

**Post-war developments:**

In Britain, there was a great shortage of all forms of building materials as a consequence of the Second World War. Licences were required in order to obtain permission to build and to be able to obtain materials.

Amongst the methods proposed to overcome these difficulties with respect to timber was the first introduction of tropical hardwoods intended for structural purposes. These were mixed hardwoods described in terms of an elementary grouping system.

One of the countries of supply was Malaysia, or rather Malaya as it was known at the time. In some instances, bolted and connectored frameworks were made in Britain from these mixed Malayan hardwoods. Fig 4.4. Sometimes problems

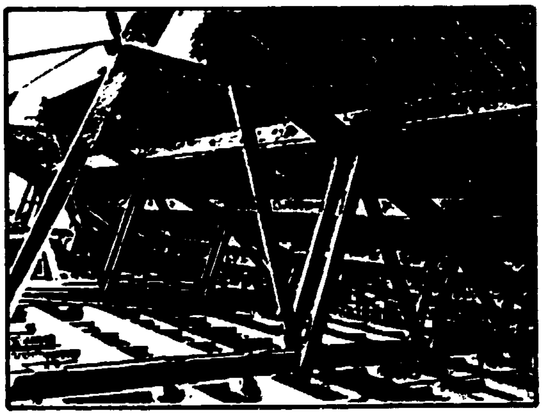

**Fig 4.4**

**Bolted trusses for the roof of a spa, using Meranti members**

arose, because the different grading characteristics of tropical hardwoods were not fully realized.

Roof solutions had already been identified by pre-war studies initiated by the TDA, and there was even a small amount of effort continued throughout the war period. When the time came to rebuild therefore, not unnaturally, a programme to develop standard designs for prefabricated bolted and connectored roof trusses received high priority.

A range of roof designs were developed and tested using principal trusses jointed with bolts and connectors, together with nailed secondary parts, purlins and rafters.

Where previously simple bolts, nails and devices such as 'joggles' would have been used in traditional trusses such as the kingpost type, the TDA truss designs all used bolts with various types of connector, mainly the toothed plate, or the split ring.

Joints formed from side-lapped members were invariably employed, so that the individual connector unit (a bolt, plus the set of individual connectors on its axis) would be loaded in single or double shear.

This was a distinguishing feature of the bolted and connectored construction method, Fig 4.5, as opposed to both earlier carpentry frames and later truss plated rafter systems, where members lying all in one plane were possible.

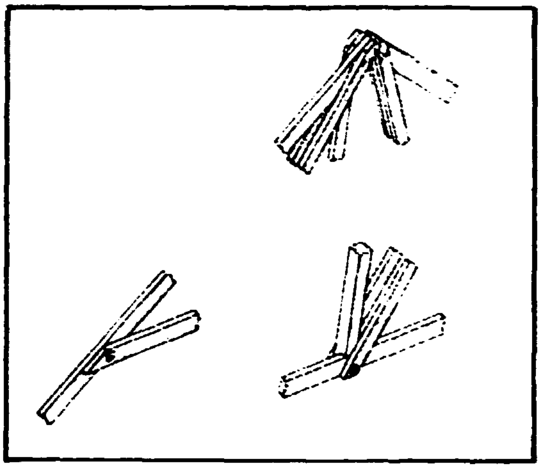

**Fig 4.5**

**In bolted and connectored construction, the individual members of the truss do not all lie in a single plane**

Connectors allow the forces which must be transmitted by the timber joint to be shared over a larger area of the faces of the connected members, Fig 4.6.

By contrast, in a plain bolted joint, there are great concentrations of stress around the area where the bolt bears on the truss members. Hence the bolt tends to crush and cleave apart the timber at quite a low value of force.

Properly constructed connectored joints also tend to be more rigid, that is to say there is less joint slip, and less deformation due to tolerance being taken up as the joint tightens under load.

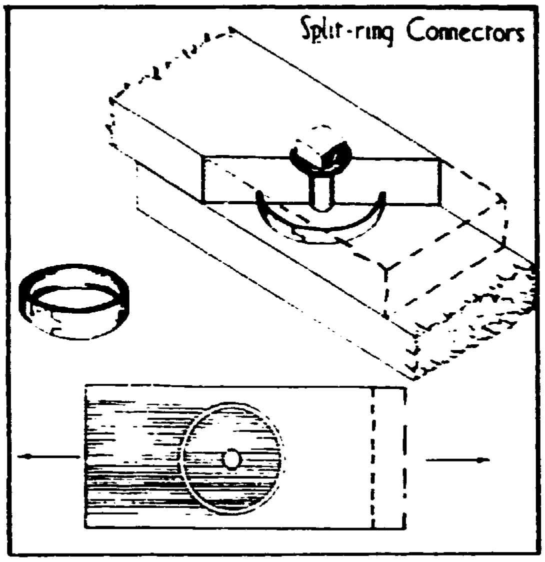

**Fig 4.6**

**Connectors such as this split ring spread the shear forces over a greater zone than a plain bolt**

The initial bolted and connectored designs were mainly intended for domestic purposes. The trusses were known affectionately as 'TDA trusses', and are still described as such from time-to-time today, since a number of the standard types are still used.

At first, the urgency was to develop the designs by a combination of calculation and testing, Fig 4.7. They were issued as dye line prints, in order to get them into use as quickly as possible.

Gradually, documentation work caught up, and by around 1950 printed design sheets with construction details and instructions were being issued.

Structural calculations were prepared for each standard design, using graphical techniques to calculate forces and deflections. Joint design details were calculated and listed by the draughtsman in tables which accompanied the master drawings.

The first standard domestic connectored roof truss designs were known as types 'A' and 'B'. These had pitches of 40 degrees and 35 degrees respectively, and covered spans up to 30 ft (9 m).

During the later 1950's and early 1960's, the trend was to lower roof pitches. Later it was later discovered that this was to the detriment of both performance and appearance; however it was seen as an economy at the time.

As a consequence, further 'TDA' truss types were introduced. The 'C' range gave pitches from 22 to 30 degrees and spans of up to 32 ft (10.8 m). Around 1965, the types 'D', 'E' and 'F' ranges were published. These used a slightly different truss member layout. They went down to 15 degrees in pitch, and up to 40 ft (12 m) in span. The construction details on the design sheets permitted some flexibility in pitch and span, within stated limits.

A range of trussed rafter designs were also introduced at about the same time, since these components were just becoming known in Britain, having already been used in North America for five or ten years.

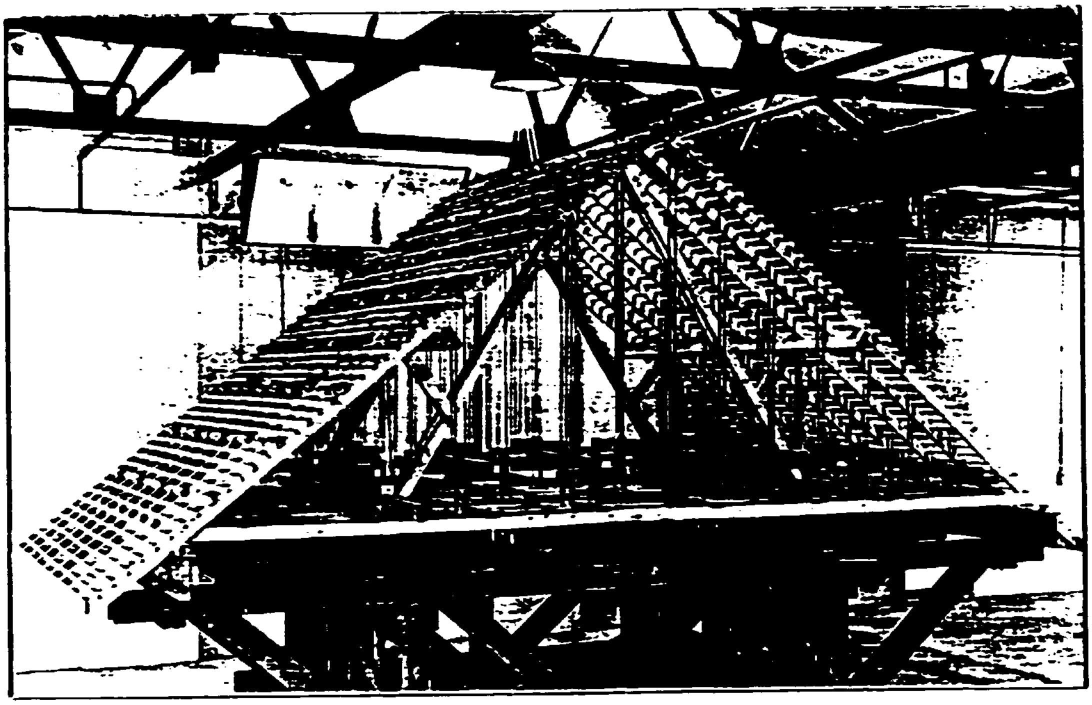

Fig 4.7

A standard TDA trussed roof design under prototype test

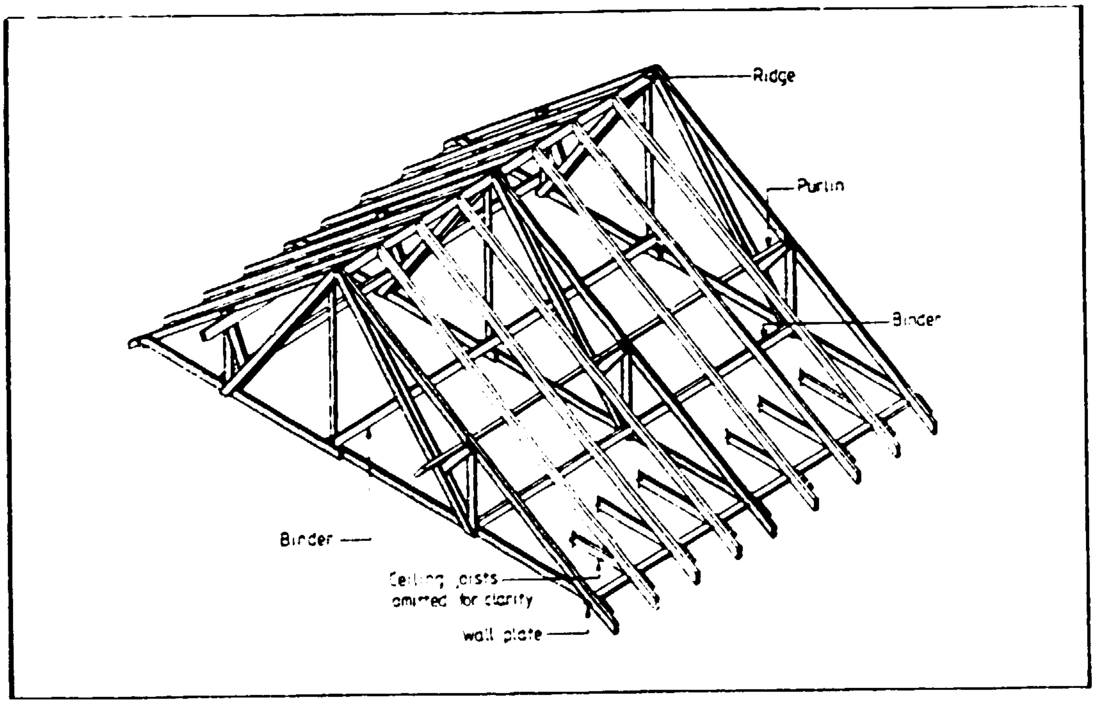

Fig 4.8

Roof construction using standard TRADA bolted and connectored trusses

The bolted trussed rafters were more frequently used for classrooms and similar small-span institutional buildings, rather than for housing. As such, they were often required to carry a light roofing, such as plywood or boarding with three-layer felt. School buildings and other social re-building was of course an urgent priority at the time.

These bolted and connectored trussed rafters were spaced at close centres, commonly 2 ft (600 mm), without intermediates, in just the same way as the later punched metal plate fastened trussed rafters would be arranged.

In this respect they were quite unlike the TDA, and later, TRADA trusses. These were much more common at the time, and were always widely spaced, usually at 6 ft (1.8 m) centres, Fig 4.8. The standard domestic bolted and connectored trussed roof construction also included common rafters carried on purlins between the trusses, and binders which were designed to support common ceiling joists which were placed between truss centres.

Many of the standard domestic bolted and connectored roof truss designs are still available from TRADA, Fig 4.9, and there is a regular demand for the standard design sheets. The designs are often preferred for smaller building projects, where only a few trusses are to be built in a particular style.

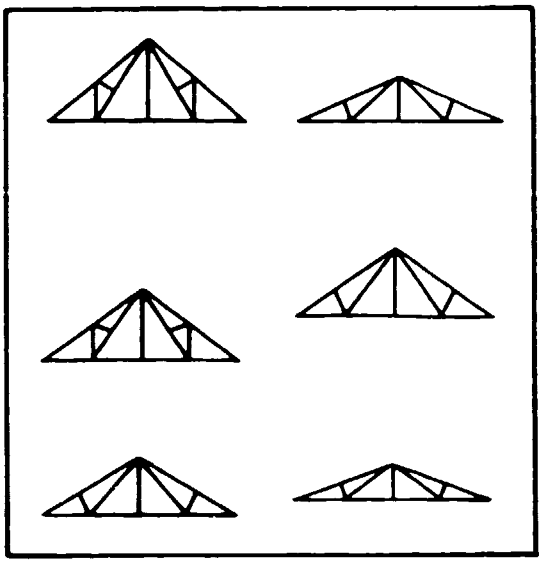

**Fig 4.9**

**This series of standard bolted and connectored truss designs is still available from TRADA, in spans from 5.0 to 12.0 metres, and in a range of pitches and roof weights**

**Industrial trusses using bolted connectored joints:**

In the 1950's and 1960's industrialized building methods were believed to be part of the solution to rapid rebuilding programmes. There was also a strong belief in the timber trade that in order to promote the material, faith should be shown in its use by reconstructing timber storage sheds and the like using one's own medium.

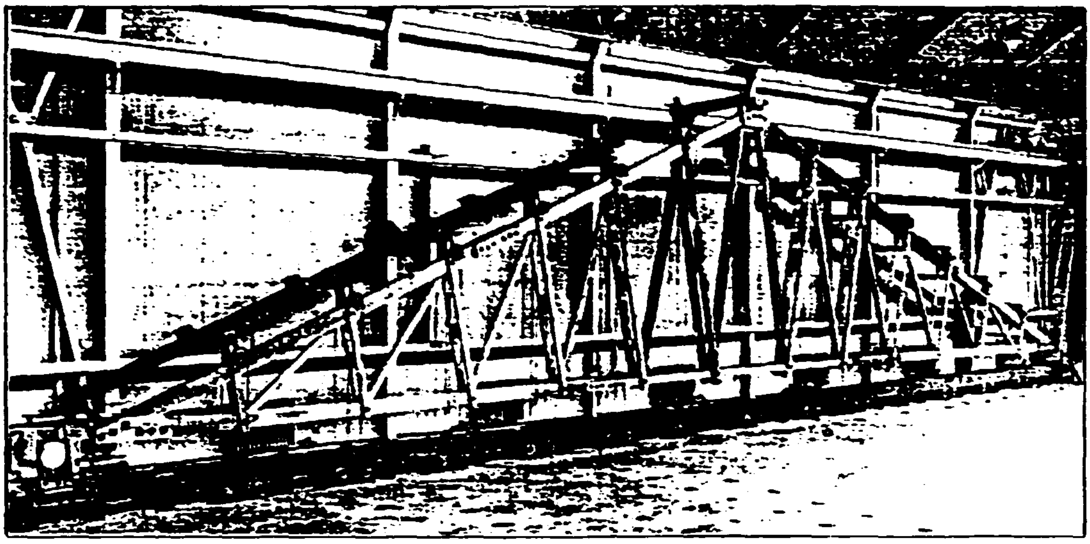

Fig 4.10

A standard bolted and connectored industrial truss design of 17 m span undergoing prototype testing

Consequently numerous industrial connectored truss types were also designed, tested and built Fig 4.10.

Demand was more varied than for the domestic types, and many were retained simply as ink drawings, with typed instruction sheets, which could be copied and sent to enquirers as demand arose. These standard designs could be purchased for pitches of 22.5 degrees up to 30 degrees and for spacings from 11 to 14 ft 3.35-4.25 m with spans up to 66 ft (20.1 m).

Impressive areas were often covered by bolted and connectored trussed roofs such as these and in a number of cases special projects were set up to design, test and build one-off designs Fig 4.11 and 4.12.

**Nail gusseted portals:**

Later, the industrial truss types were supplemented by standard design sheets for nailed ply gusseted portal frames. These gave spacings from 3.6 m to 4.8 m and spans up to 12 m as standard.

These solid timber, ply gusseted portal frames were extensively developed. Some of the first specially-written computer programs were produced for these designs at TRADA, and later a postal computer design service was provided for TRADAFARM members, using pro-forma computer input sheets.

Occasionally these portal designs were adapted for purposes other than agricultural and industrial buildings. In one instance they were used for a school for example, Fig 4.13.

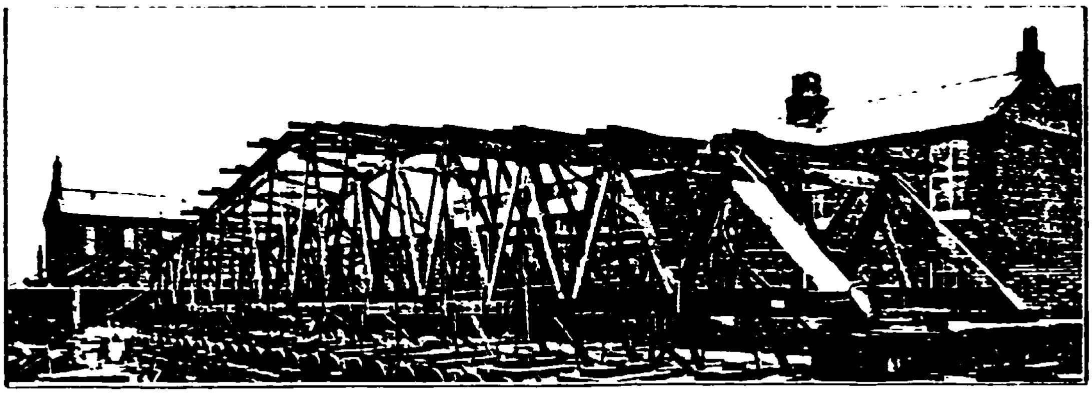

Fig 4.11

A pair of Warren trusses of 26m span under prototype test

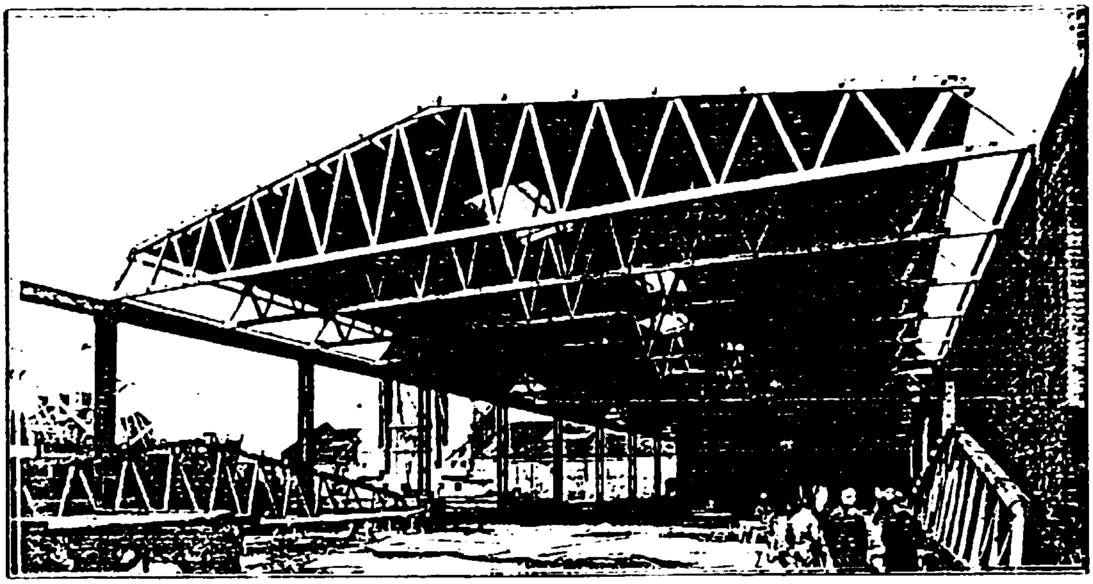

Fig 4.12

Warehouses under construction for Mersey Docks and Harbour Board, using trusses shown above

These portal designs have also proved eminently suitable as industrial buildings in the tropics, for applications such as sawmills, sawdoctors' shops and general-purpose mechanical workshops and woodworking shops. As such, they are frequently specified and adapted as one-off designs.

A case has recently arisen in which building designs of this type have been provided for a Wood Use Centre in Honduras, for example.

The standard portal designs are also still available and have been checked for validity to the latest codes.

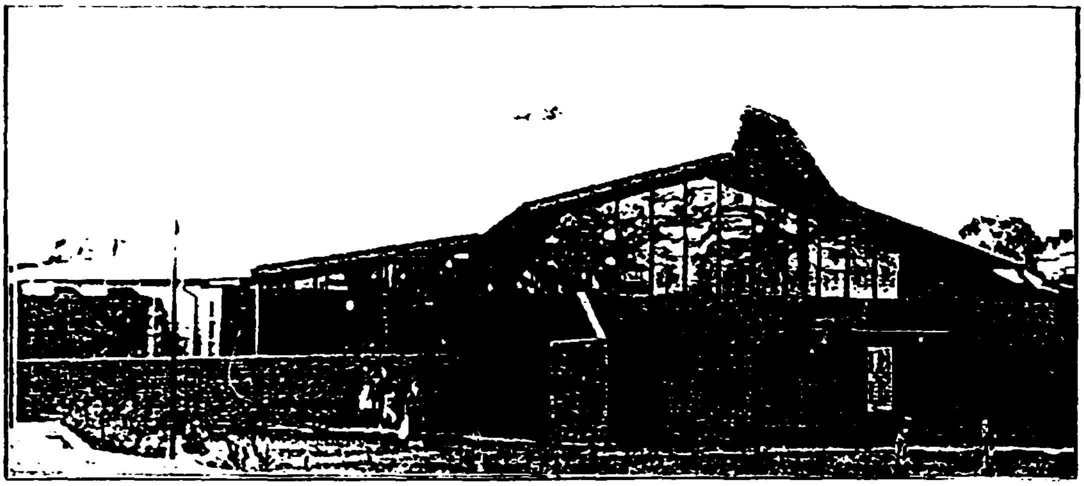

Fig 4.13

**Nailed gusseted portals for classrooms and assembly hall, Stakes Hill School, Hampshire**

Recent developments:

A standard design information pack has recently been published, giving drawings and instructions for a 'room in roof' method of construction. This is based on a stressed-skin panel design. It uses rafters formed into panels covered by nailed structural plywood sheathing. These panels butt together at the ridge, and are supported at their base by a timber plate with a shaped cross-section, Fig 4.14.

The whole assembly is provided with rigidity, and prevented from spreading, by means of a bolted collar tie. Such forms of panellized roof construction, which may be jointed effectively with mechanical timber fasteners such as nails, bolts and connectors, lend themselves ideally to factory prefabrication and hence to fast and efficient on-site construction.

'Room-in-roof' construction is especially favoured in the Netherlands, and in Scotland. Also it has always been employed quite extensively in the Scandinavian countries. It provides a large volume of habitable space in proportion to relatively low standard costs, and is amenable to the inclusion of large quantities of thermal insulation.

Recently, extensive research programmes by TRADA, PRL and several technical trade associations have brought about developments in several new forms of structural panel product. These materials have been rigorously assessed to ensure that they have adequate moisture resistance, strength and durability. They lend themselves therefore to further opportunities in the application of panellized roof systems, both for domestic use and for larger buildings. New designs based on these principles are likely to be of pitched rather than flat roof form.

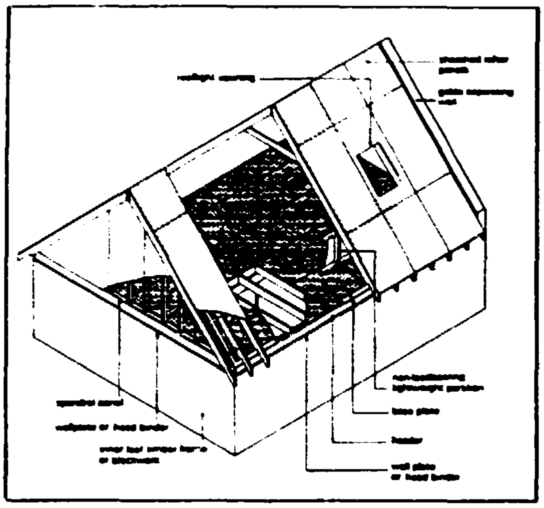

Fig 4.14

**Room in roof construction, using nailed stressed skin panels**

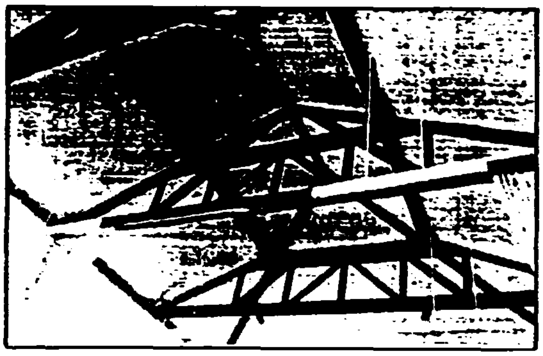

Fig 4.15

**An example of a roof in which the architect has chosen deliberately to express the structure of connectored trusses**

Reverting to the current use of the more traditional plane frameworks, it has to be said that in Britain trussed rafter systems are now so well developed, and so well proven in use for non-domestic as well as for housing applications, that there is little merit in preferring bolted and connectored assemblies for spans up to about 18 metres, unless there are special reasons.

However this is not uncommonly the case. The special reasons may include the need to carry exceptionally heavy loadings; the desire for 'historical authenticity'; a call for 'traditional' trusses, or simply preference on the part of the architect for an 'expressed' structural roof, Fig 4.15.

For large, framed roofs, using either trusses made from hardwood of exceptional cross-section, as in the case of the recent North Transept roof reconstruction following the fire in York Minster, Fig 4.16, or when using glulam members, timber connectors are likely to remain in use for many years to come.

When bolted connectored trusses are formed using hardwood or glulam members, the trusses often need to be detailed and manufactured with great attention to their external appearance, since the truss remains exposed forming a feature of the internal architecture of the structure.

It is common for bolted and connectored joints to include a number of connectors, both

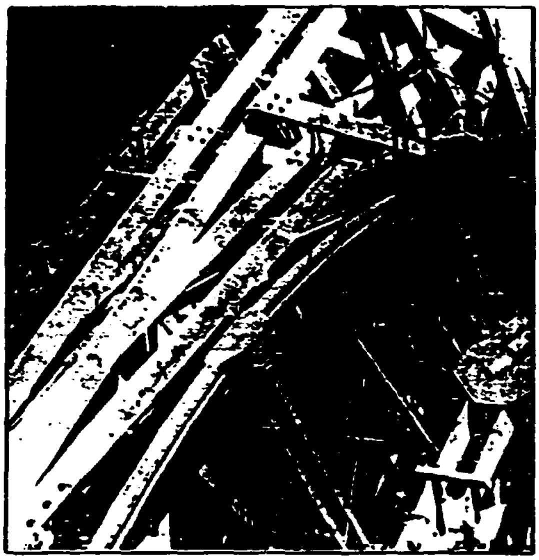

**Fig 4.16**

**Oak trusses using specially fabricated stainless steel shear connectors, for York Minster roof**

It is common for bolted and connectored joints to include a number of individual connectors, both several on one bolt, in the case of multi-member nodes, and also in many cases a pattern of several connectors in the face of each member, Fig 4.17. Since the diameter of the connectors may be quite large in relation to the width of the joined members, there is a considerable amount of skill in arranging the details of such joints.

When EC5 is adopted, it can be expected that there will be new computer programs facilitating the design of such joints. A European Standard (CEN) Working Group has been formed in 1990, to ensure that when harmonization measures are effected, data will still be made available to designers for the use of traditional connectors.

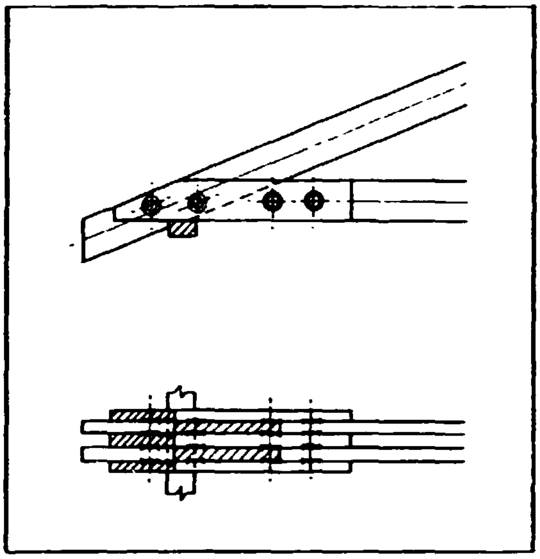

**Fig 4.17**

**The complications of joint design using timber connectors provide an ideal application for computer-aided design in the field of timber engineering**

# CHAPTER 5

## The design of trussed rafters and trussed rafter roofs

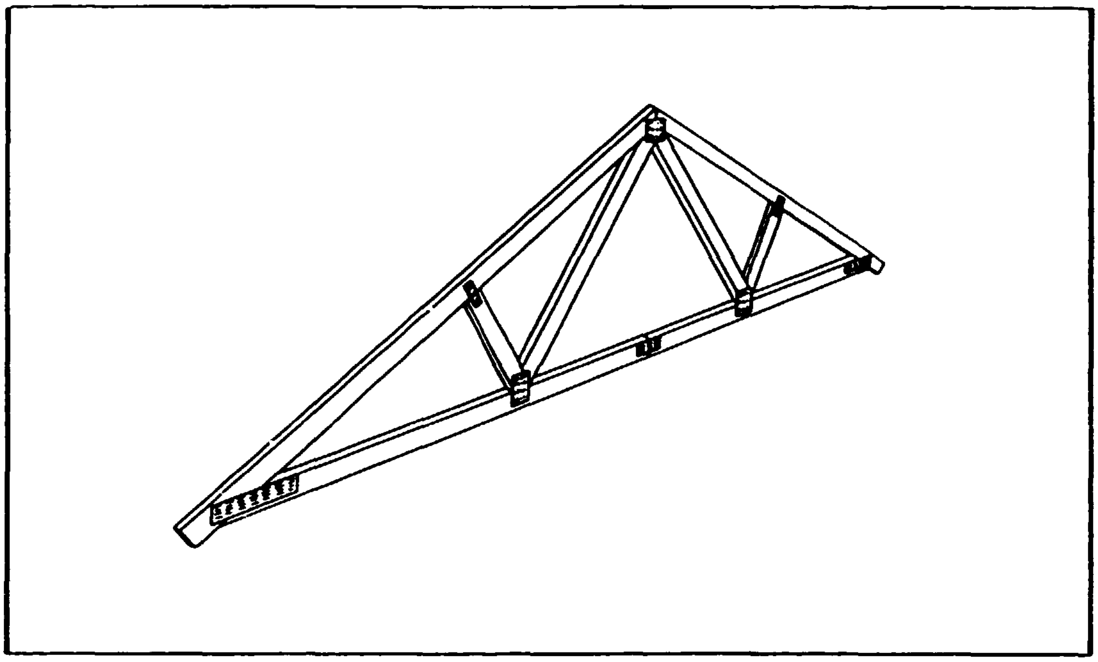

Fig 5.1

A simple symmetrical Fink or 'W' trussed rafter, viewed as a single component

Trussed rafters are lightweight triangulated roof frames, spaced at intervals generally not exceeding 0.6m, and made from timber members of the same thickness throughout, Fig 5.1.

These members are fastened together in one plane. The normal method of connecting them is by means of punched metal plate fasteners. These are metal plates with integral teeth, Fig 5.2.

Various proprietary patterns are available. The plates are required to be galvanized to certain standards, or to be manufactured from stipulated types of stainless steel.

The British 'Code of practice for trussed rafter roofs', BS 5268: Part 3: 1985, is a well-proven and comprehensive standard for the design of trussed rafters. It also contains important recommendations for complete trussed rafter roofs built using these components.

These recommendations are based upon the results of extensive research and testing. Non-domestic roofs

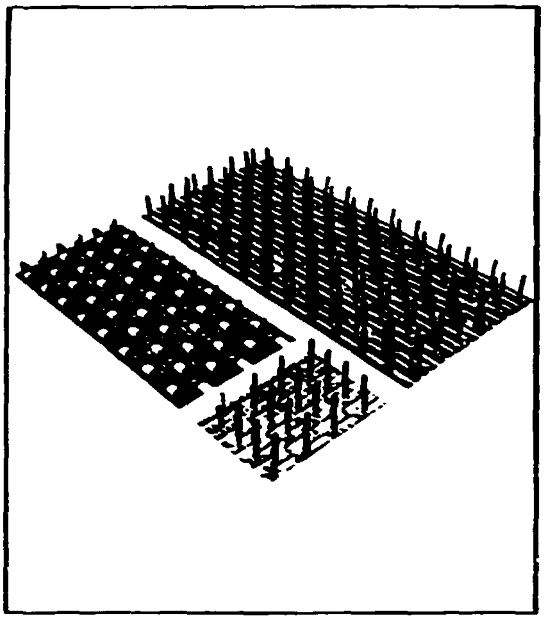

Fig 5.2

**Punched metal plate fasteners with integral teeth**

now represent a major sector of the trussed rafter industry in Britain and in other parts of Europe, and the code also refers to these.

Trussed rafters are normally designed to span between external loadbearing walls without the need for intermediate supports.

They are often described as 'highly engineered' components. Because of this, their successful use depends upon the careful observance of proper specification and selection of materials; control of production and handling; correct erection procedures, and adequate bracing of the whole roof structure.

The connexions of the trussed rafter roof to the supporting structure, and through this ultimately to the ground, are equally important.

**Design considerations:**

BS 5268: Part 3 contains two major sections devoted to design. The first of these deals with the design of the trussed rafter as an individual component, and the second with the overall trussed rafter roof design.

The code states that three methods are equally acceptable in establishing the structural adequacy of trussed rafters. These are as follows:

**1. Engineering calculations**

This method itself comprises two sections. Firstly, the code presents in great detail a method of simplified analysis, which is to be used for the common configurations of fully triangulated trussed rafters.

This method has been derived from a knowledge of the performance of the components both under test and in actual use. By following it, designs will be obtained which correspond with those recommended in permissible span tables, which are also included in the code.

In this simplified analysis, axial forces are determined assuming a pin-jointed framework. Bending moments are determined assuming that members are continuous throughout their length, with pin supports at the nodes. Deflection at the nodes and partial fixity at the joints is allowed for by a reduction of ten percent in the bending moment at the nodes.

A table of bending moment coefficients in accordance with these assumptions is provided, for a series of common configurations.

Secondly, as an alternative to the simplified analysis, a so-called rigorous analysis is permitted. However when a standard configuration is proposed by the user of the programs provided by the trussed rafter system owners, these normally follow the simplified analysis. Nevertheless, they will follow the rigorous analysis for non-standard designs. This avoids conflict between 'designed' and tested spans, as given in the code tables, for conventional configurations.

The rigorous analysis procedure applies normal structural engineering plane frame analysis procedures, with certain assumptions stipulated by the code, unless other evidence is available. For example, zero fixity at the joints should be assumed, if alternative specific data are not available.

The design of the individual members of trussed rafters follows normal timber engineering principles, but it includes some additional considerations. For example, there is a check against buckling in the direction perpendicular to the plane of the rafter, Fig 5.3, which takes account of the results of tests, and which uses an adaptation of the normal combined stresses summation equation.

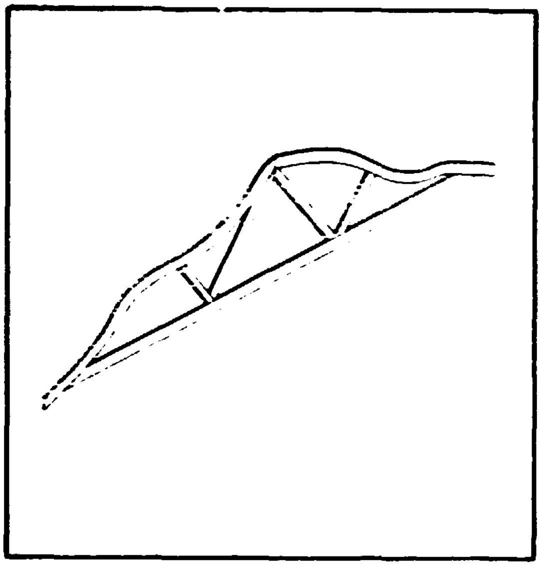

**Fig 5.3**

**Buckling in the plane perpendicular to the rafter**

**2. Load testing**

The code also contains a section on load testing, which is an equally acceptable alternative to the two types of theoretical analysis. It may also be necessary to test trussed rafters where a complex and unusual design is required, or where there is doubt or disagreement as to whether the design or the materials or fabrication comply with standards.

Generally speaking, tens or perhaps hundreds of thousands of conventional trussed rafters have now been tested

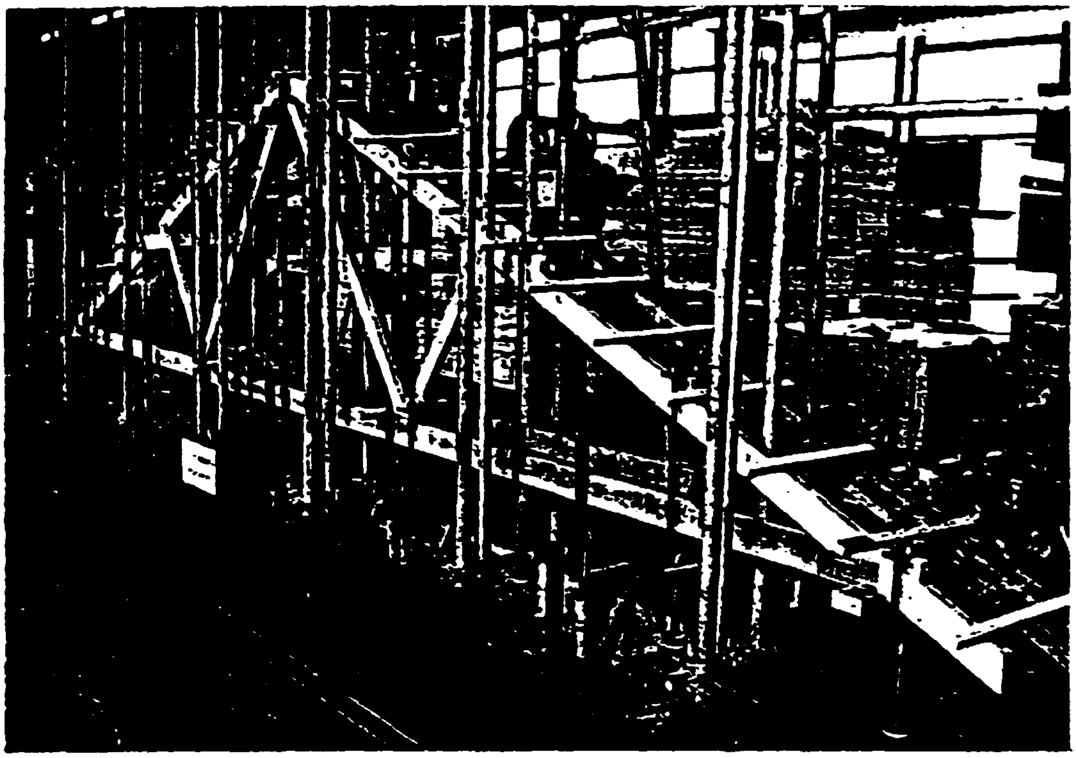

**Fig 5.4**

**A conventional, standard trussed rafter under prototype test**

since the inception of the method, Fig 5.4, and such procedures are now normally confined to unusual configurations, and to quality control testing.

**Span tables:**

The first British code of practice for trussed rafters contained simple span tables. When BS 5268: Part 3 was published in 1985, revised span tables based on testing and service experience were included, for a range of combinations of grade and species. These covered machine stress graded softwoods, including British-grown material, and visually stress graded softwoods, grouped into strength classes.

**Materials for trussed rafters:**

Confidence in the performance of trussed rafters is strongly dependent upon close attention to the specification and control of materials, and it is essential to build up trust and knowledge in species properties; grading; sizing standards and in finger jointing and fastener technology. In brief, these aspects may be covered under four headings:

**1. Timbers**

Suitable timbers for trussed rafter manufacture must be fully defined in terms of structural properties, and should be capable of forming satisfactory joints. The latter depends upon the types of fastener used. There is evidence from other countries, where it is necessary to make use of hardwoods, that trussed rafters can be fabricated with these, provided that heavy-gauge punched metal plates are employed.

## 2. Grading and sizes

Because of the exacting strength requirements of trussed rafters, stress grading in accordance with BS 4978, or other rules such as certain North American ones, is mandatory for trussed rafters in Britain. In addition, there are certain extra requirements for straightness and freedom from twist, cup and wane, which are stated in the trussed rafter code itself.

Timber is also required to be sized in accordance with BS 4471: Part 1, and there are strict limitations on deviations in the finished thickness and depth of members.

## 3. Finger joints

It is an advantage to be able to finger joint trussed rafter stock, since in this way high grade and stiffness material may be ensured more economically. Finger jointed timber is admitted in trussed rafters in Britain, provided that it complies with certain requirements, and provided that the finger joints are manufactured in accordance with a standard covering the subject. There are modification factors for finger joint efficiency ratings, which allow for the possible effect of plates being pressed into an actual finger-jointed region of the truss member.

## 4. Fasteners

Clearly there must be strict control over these critical items. Punched metal plate fasteners with integral teeth, and perforated plate fasteners must be made from a stipulated grade of hot-dip galvanized plain steel sheet or coil. Alternatively where a greater resistance to corrosion is required, bare austenitic stainless steel of a grade defined in BS 1449: Part 2 may be used.

Minimum mechanical properties are laid down for the plate material, and there is a restriction upon the type of manufacturing process used for the steel. There is also an absolute minimum restriction upon the gauge of steel to be used (0.9mm).

## Sizes and spans:

Irrespective of the required member sizes calculated following framework analysis and member design, it is desirable to place practical limitations on the cross-sectional size to length proportions of the complete members, and on the distances between the nodes of the truss. This ensures robustness during handling and erection and avoids 'theoretical' justifications for spans going beyond those shown by experience to be satisfactory.

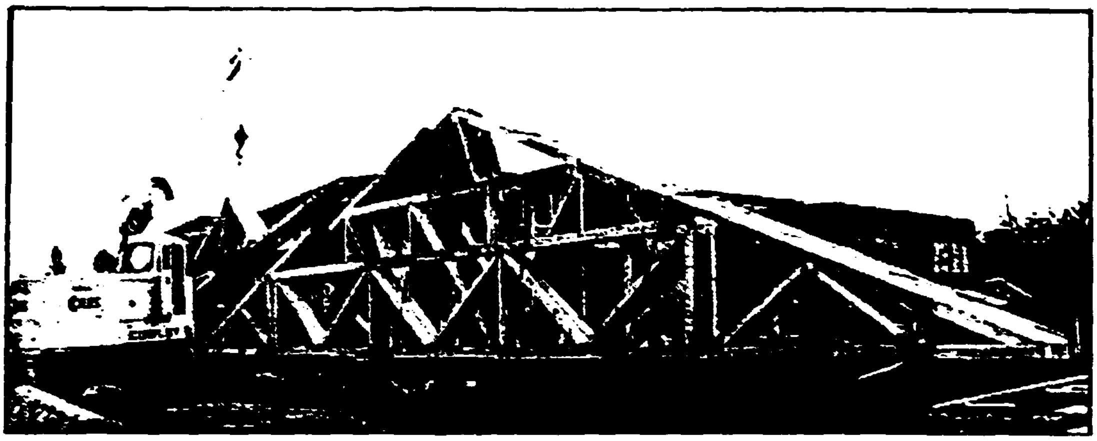

Fig 5.5

**Trussed rafter sets, including hip components, of 18.8m span. Such sizes are close to the upper limit for trussed rafter construction**

The trussed rafter system owners also place practical and 'experience' limitations upon applications of the design method. Broadly speaking, it is unusual to find trussed rafters in use for spans beyond about 20 metres, Fig 5.5. At greater spans than this, one would normally expect the designer to be considering the use of glulam, or similar structural composites.

Delivery and erection considerations, rather than structural performance, also tend to place an upper limit on trussed rafter heights. Methods such as 'top hat' trusses, Fig 5.5, have been devised for tall roof structures.

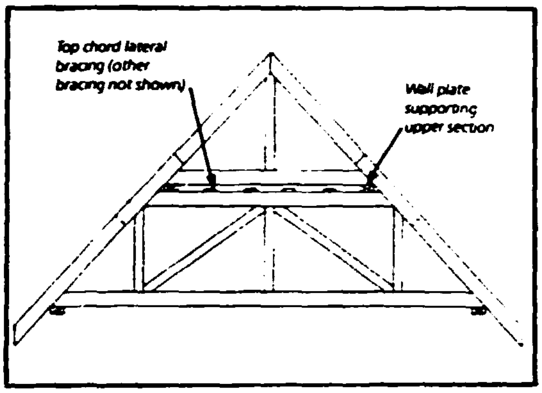

Fig 5.6

**'Top hat' trussed rafters**

The code also places limits upon span which are related to the finished member thickness. The common member thickness (rafter or tie breadth) of 35mm is restricted to a maximum span of 11.0m. For a finished member thickness of 47mm, spans of up to 15.0m are allowed. Larger spans are achieved by means of what are known as 'multi-ply' trusses. These consist of two or more frameworks, similar to an individual truss, which are rigidly joined together by means of mechanical fasteners, to provide a complete component, Fig 5.7.

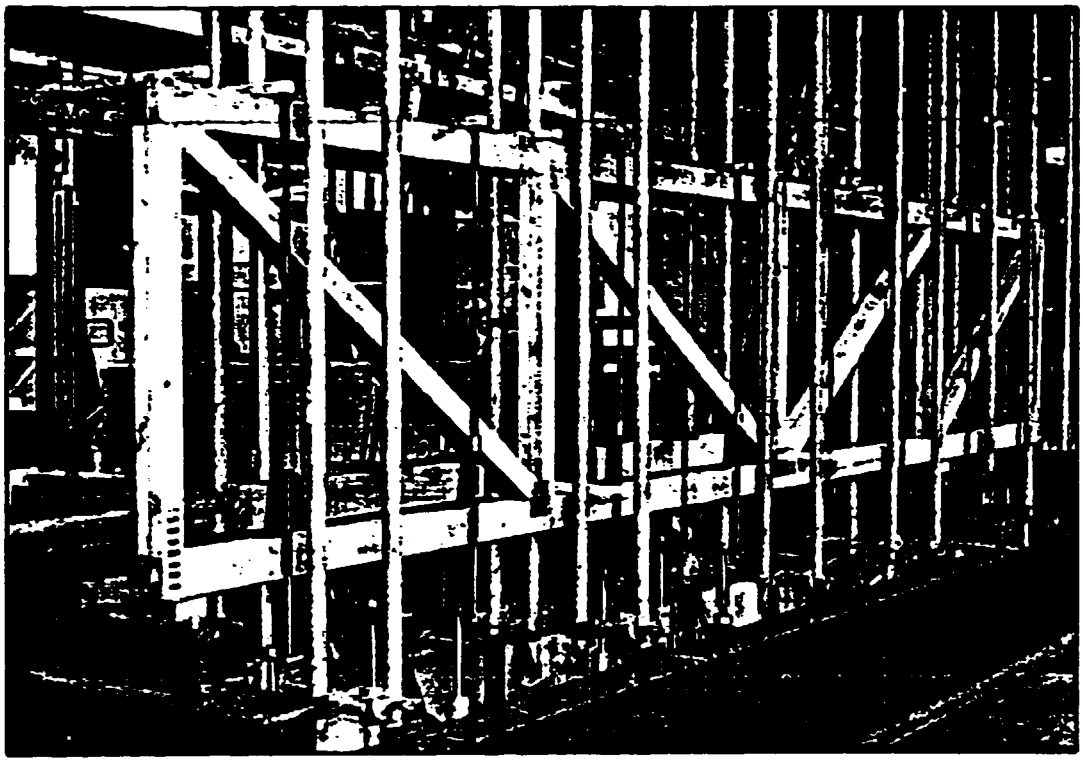

**Fig 5.7**

**A flat topped girder truss, formed with twin-ply members**

## Trussed rafter roof formations:

Nowadays, a building which is simply rectangular in plan, roofed with a parallel ridge and with plain gabled ends, is the exception rather than the rule. Trussed rafters can provide an economical structural solution to a great variety of roof shapes, giving the architect much freedom of design. Amongst the most important variations in roof formation are the hipped end, several types of 'T' intersection, and the scissor truss and dormered truss families. Some of these are briefly discussed below:

### 1. 'T' intersections and valleys

A 'T' intersection occurs when two ridge lines are required to intersect at ninety degrees, Fig 5.8. The ridges need not necessarily be at the same height as one another. Even the pitches need not be equal. Solutions have been found to all such variations, generally based on similar broad principles.

The intersection between the two roofs is constructed using a set of diminishing valley frames. These are slightly adapted symmetrical trussed rafter frames.

The valley frames transfer loading in a reasonably uniform manner onto normal trussed rafters, forming the

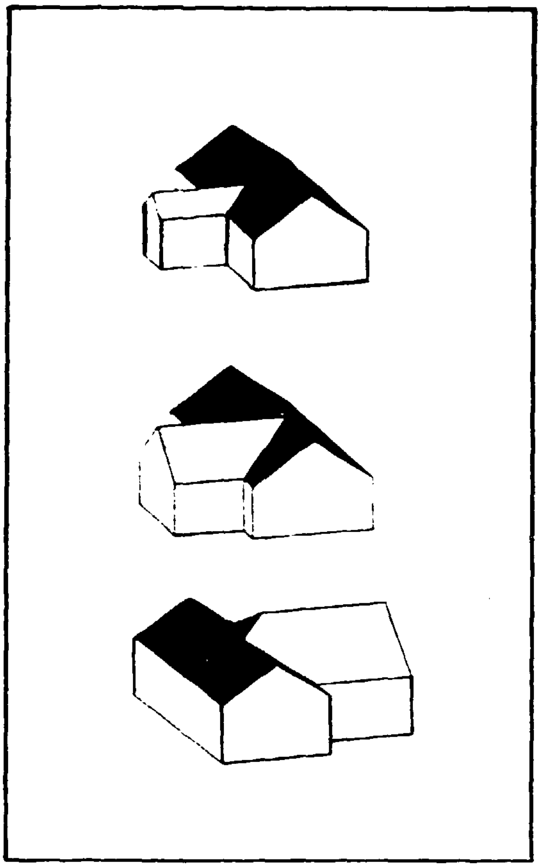

Fig 5.8

'T' intersections

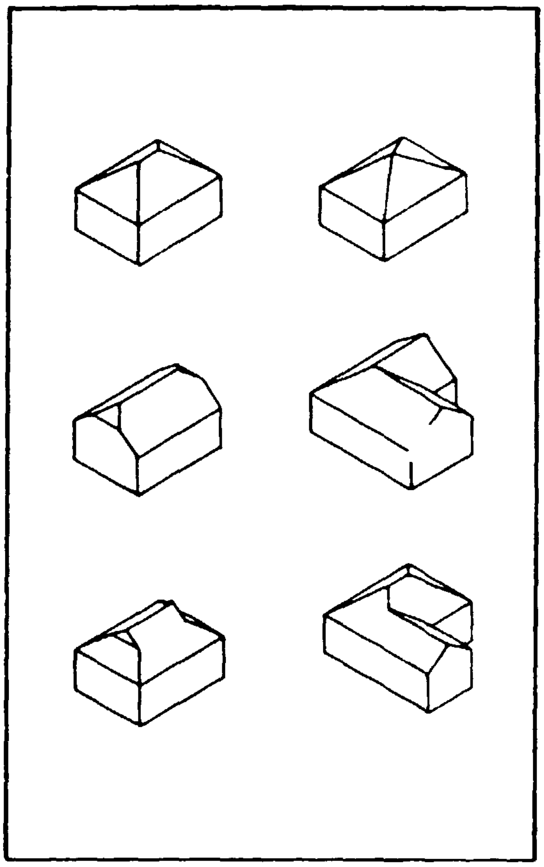

Fig 5.9

Hipped roof variations

intersected roof below, and bracing is rearranged accordingly. Often it is required to construct a 'T' intersection without a load bearing wall at the crossbar of the 'T'. In this case, a strong girder truss is designed, using multi-ply chord and web members.

## 2. Hipped roofs

There are four basic variations on the simple hipped roof, and in addition, such forms may be combined with corners, to provide 'L' shaped plans, and with 'T' intersections, Fig 5.9. In all cases, the hip system is the preferred solution, rather than site-built infill.

For domestic and other small structures up to twelve metres span, the trussed rafter system owners have standard solutions for hips. Above this, specialist structural engineering advice is recommended, Fig 5.10.

Roofs including hipped ends should normally be pitched at a minimum of twenty two

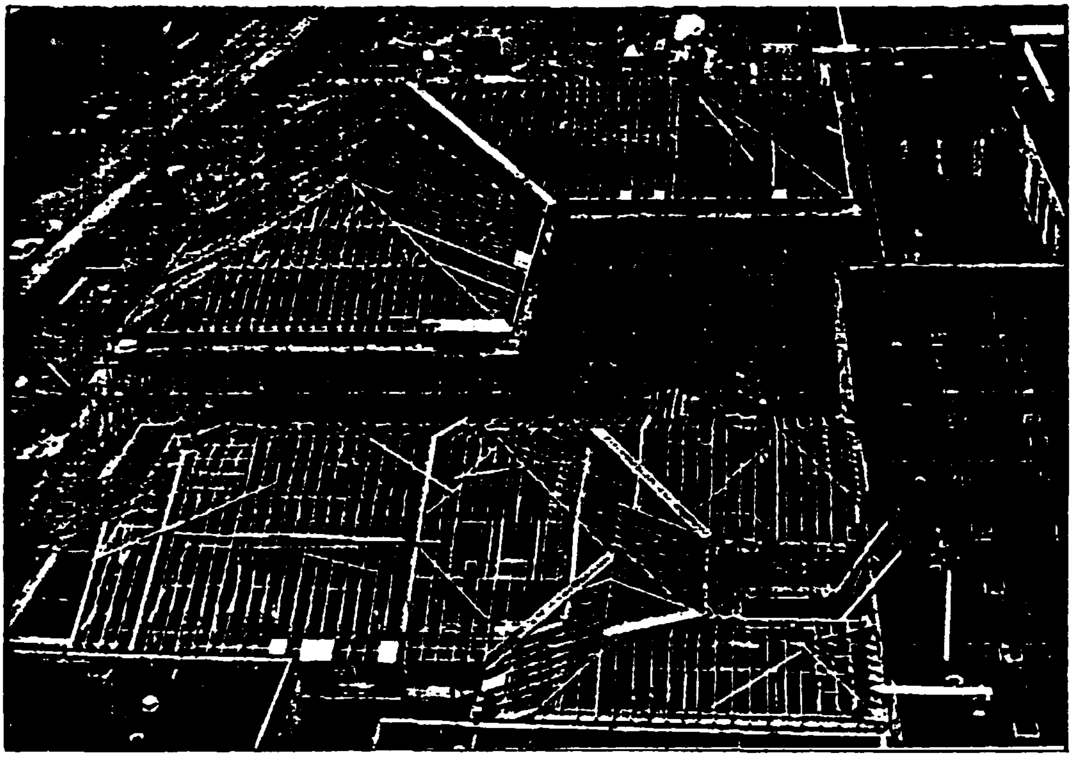

Fig 5.10

**Large trussed rafter roof contract for hospital, involving spans greater than 18 metres, and complex hip structures**

degrees, to ensure that adequate height is available for economical hip girders. The positioning of the hip girders should be planned to benefit from load bearing walls, and to avoid clashing with chimneys and large wall openings.

Broadly speaking, all hip systems are based on a combination of hip girders, which are rather like strong, flat topped trusses, and intermediate monopitch trusses. It is impossible to describe all variations on hip framing even briefly. However a short description of the 'Gang-nail' 'Standard Centres' hip will give a typical example:

This hip system comprises a number of identical flat-top trusses, and a multiple girder of the same profile, Fig 5.11. This girder supports monopitch trusses off its bottom chord. The hip and monopitch trusses contain 'flying rafters'. These are slightly overlength, cantilevered rafter extensions which are trimmed to their exact required length as the roof is fitted together on site.

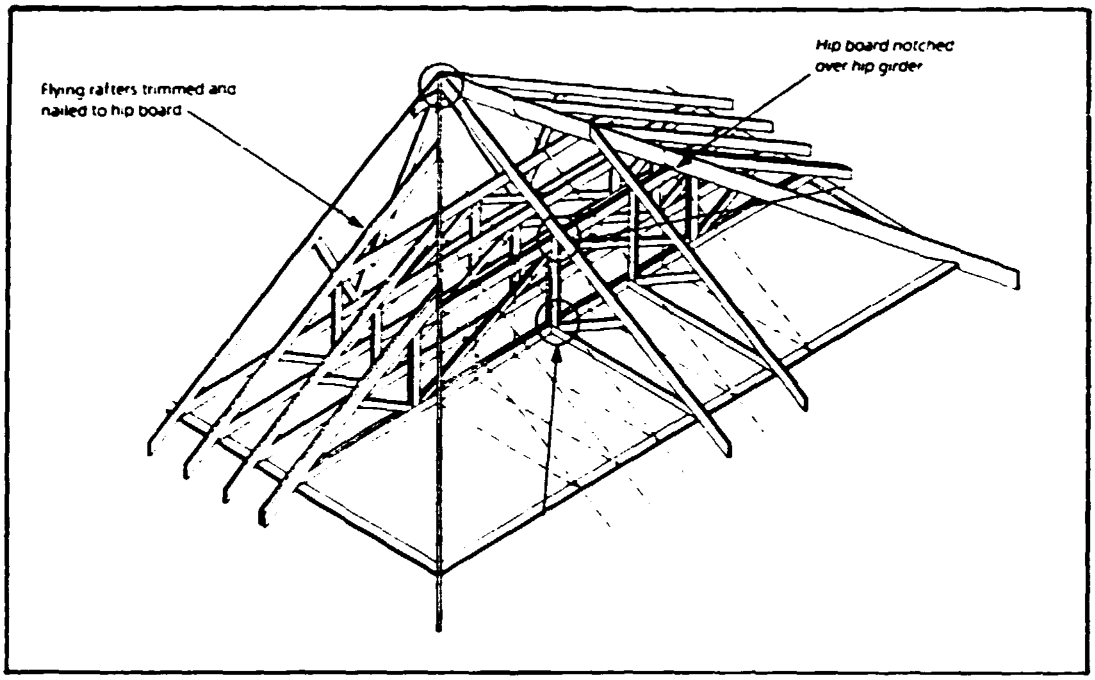

Fig 5.11

The 'Standard Centres' hip system

## 3. Attic trussed rafters

The attic trussed rafter, Fig 5.12, has to fulfil the structural duty of both the normal truss and also provide the ceiling joists of the 'room-in-roof' space.
In addition, due to the large aperture provided for the living space, there are less opportunities for structurally efficient triangulation. Consequently member sizes are considerably larger than in normal trussed rafters.

Timber of 44 mm or 47 mm thickness is usual, with depths ranging from 145 mm to 245 mm. As an indication of spans and pitches, from 9 m span to 11 m span is a good range at 35 degrees pitch, whilst at 45 degrees, 6 m to 10 m can be considered.

Cases outside these have to be treated as special designs.

It is easier to construct attic roofs with gabled ends, although hips are possible. Dormers should be restricted to 1200 mm width if possible, in order to economize on girder sizes.

The transportable height of the attic truss set is another important cost consideration. Where possible, this should be restricted to a maximum of 4.0 m.

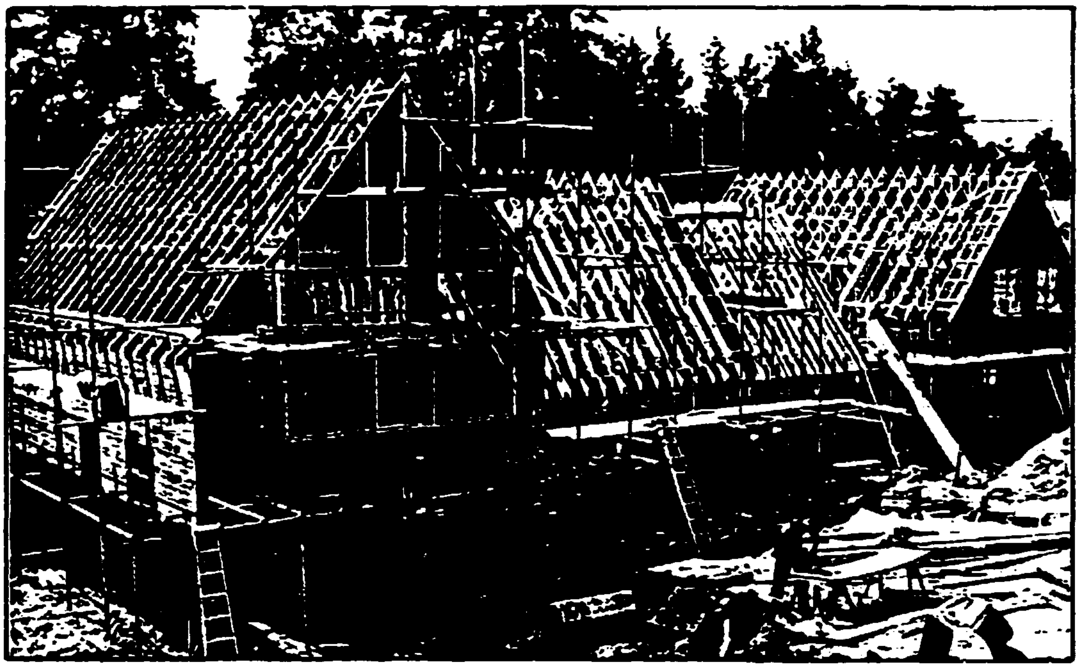

Fig 5.12

**Housing incorporating attic framed trussed rafters**

**Bracing:**

All roofs require permanent bracing. Although it had always been the case that in order to provide a stable and satisfactory structure, the roof needed to be braced in various ways, it became evident that there are less hidden reserves in a trussed rafter roof than in some of the more traditional forms.

Also these components proved so versatile that there was a tendency to stretch their application to new limits, without giving full thought to the principles of sound structural design.

For these reasons, the areas of responsibility of the trussed rafter designer and the building designer were considerably clarified, when the British trussed rafter code was revised in 1985.

From experience in the use of trussed rafter roofs in Britain, standard bracing methods for the majority of normal domestic roofs up to twelve metres span have now been worked out in considerable detail.

Since it is not practicable to expect a professionally qualified structural engineer to approve every small building design, the code prescribes such details. It also states the limits to which they are applicable in terms of factors such as span, roof shape and pitch, and site wind loading conditions.

Roofs which exceed these parameters are required to have a professionally engineered solution to ensure both stability and wind resistance.

Roof bracing serves three distinct functions:

### 1. Temporary Bracing

This refers to bracing used to restrain the structure during erection, Fig 5.13.

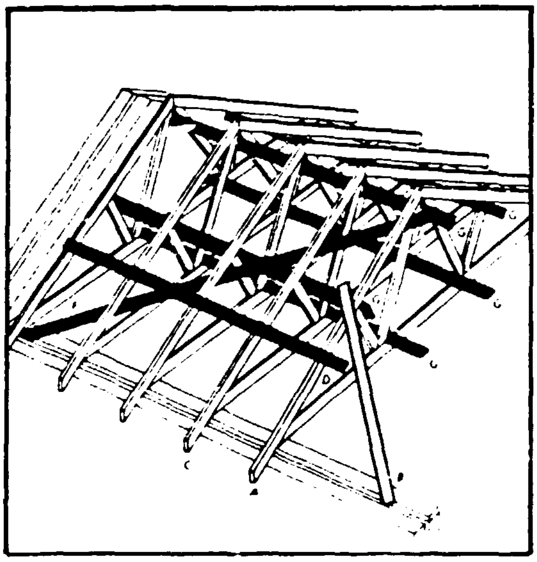

Figure 5.13

Temporary bracing

### 2. Stability Bracing

This is permanent bracing, which holds the trussed rafters upright, in plane, and parallel to one another. It serves a very important function in restraining members subject to compression, thus preventing lateral buckling.

The members which must be braced in this way include rafters and other compression members, especially in larger monopitch trusses, which can be quite long.

For the majority of conventional trussed rafters, Fig 5.14, stability bracing consists of five basic elements, as follows:

a) Longitudinal Bracing

b) Rafter Diagonal Bracing

c) Tiling Battens

d) Web Chevron Bracing

e) Lateral Web Bracing

The last two items are only necessary with larger spans, for example web chevron bracing is only required for duopitch spans greater than eight metres. It is the triangulation of the diagonal bracing members that adds a great deal to the stiffness of the roof framework.

The diagonal bracing of attic trusses can often be achieved by adding plywood to the undersides of the rafters. Internal linings and partitioning may also be designed to play a structural role.

Where the internal layout cannot be adapted to follow the precepts indicated above, or where large rooms are required, cross wall girders or glulam beams can be combined with attic trussed rafters. Outward thrusts from the attic frames must be accounted for, and connexions carefully designed.

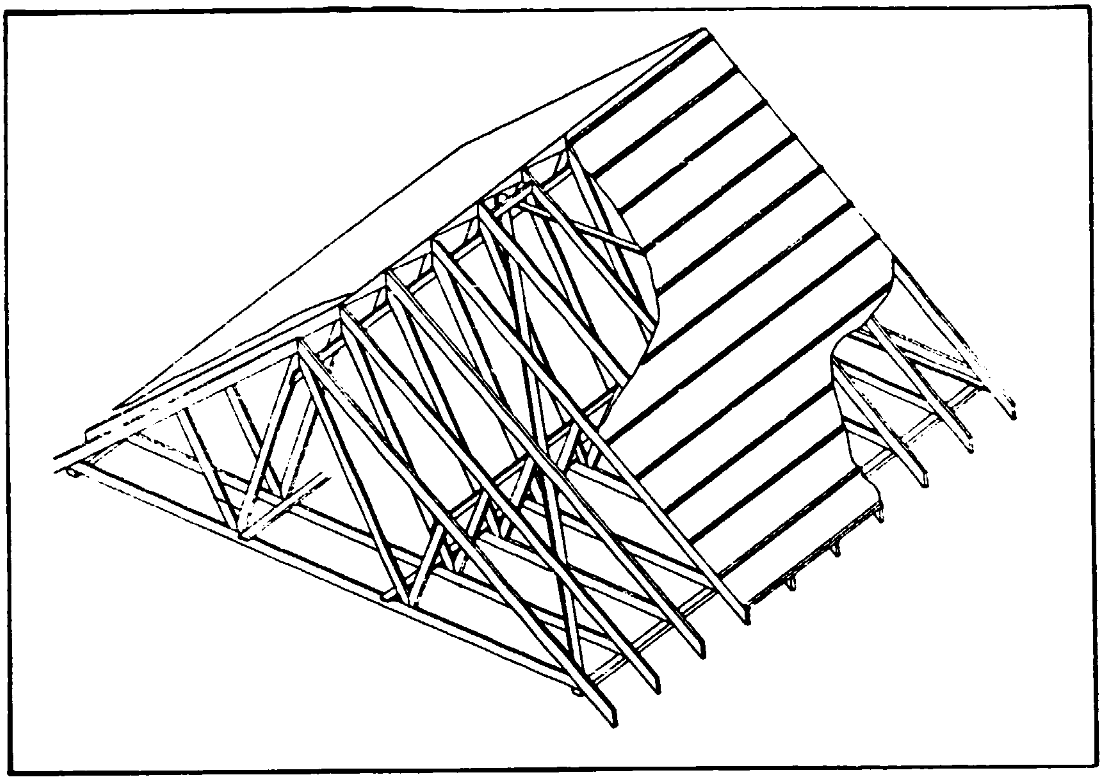

Fig 5.14

Stability bracing

### 3. Wind bracing

Extra bracing may be required to withstand wind forces on the walls and roof. Whether or not the walls of the structure are able to resist wind loading alone, there is always a connexion between the walls and the roof to be taken into account.

In addition, the roof structure itself receives a portion of the total wind loading on the building. Wind bracing thus has to be designed with careful consideration of the building construction as a whole.

For a wide range of domestic structures it has been shown that the standard stability bracing described above will also function adequately as the wind bracing. However, trussed rafters are used for a wide range of roofs beyond this scope.

There are several options available for the wind bracing of these larger roofs. Applying standard engineering principles, a triangulated bracing system can be designed using solid timber members and site connexions.

Although adequate for smaller roofs, this often presents fixing problems. A good alternative is to provide diaphragm action, using structural plywood or a

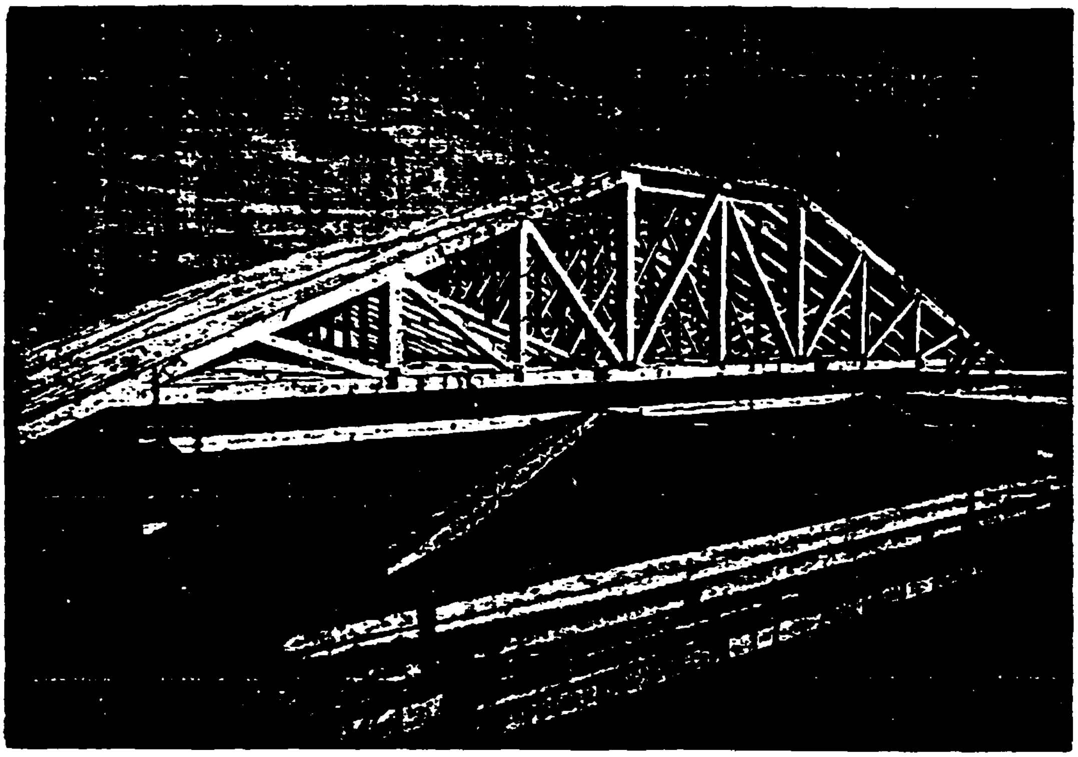

Fig 5.15

Horizontal wind girder, fabricated with punched metal plates

similar material. In Scotland, boarded sarking was traditional in all roofs, consequently the substitution of this by a structural plywood can be cost effective.

Another very satisfactory means of providing wind bracing in larger roofs relies on the use of wind girders, Fig 5.15. These are fabricated using punched metal plates in exactly the same way as the trussed rafters themselves, but they are a component which is installed in a horizonal plane.

Wind girders span between the cross walls of the structure, and transmit the wind forces from one part of the structure to another, relieving the roof trusses of this role. Decisions have to be taken by the structural engineer as to the amount of horizontal deflection permitted at the eaves of the walls in this type of arrangement.

As already indicated, the British trussed rafter code is very specific about areas of design responsibility for bracing. In general, responsibility for stability and wind bracing rests with the building designer, whereas the trussed rafter designer specifies the bracing necessary to provide restraint to his components.

**Structural design programs:**

The major trussed rafter system owners provide extensive suites of computer programs for their customer networks. These customers are known as 'fabricators'. They are the firms, normally integrated within the timber merchandising and building supply industries, who provide trussed rafter components and other parts of the complete roof system to the builder.

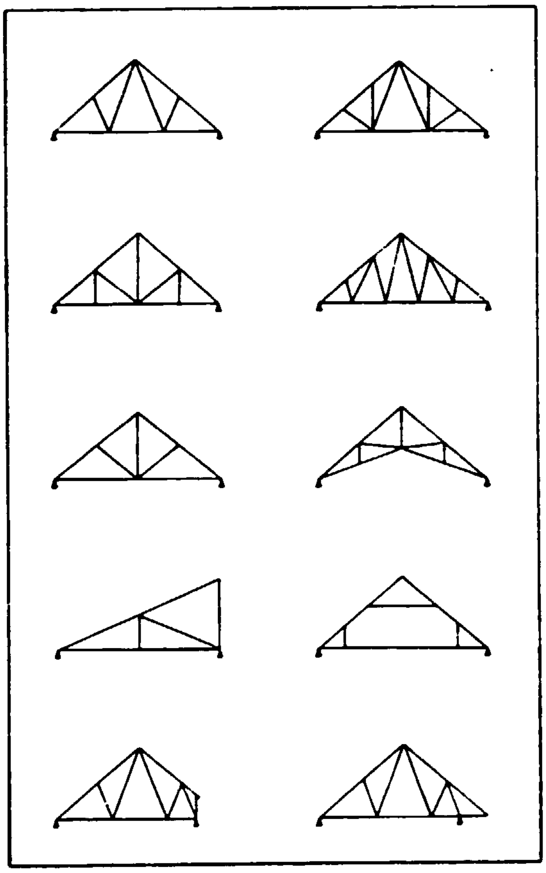

Fig 5.16

Typical truss shapes from a system owner's library

Generally the complete design suite of each system owner consists of several programs. The parts relating strictly to the structural aspects of the design can be described as either performing a 'simplified analysis' or 'rigorous analysis'. In some cases, as for example with Gang-Nail's 'Concept 2000' design suite, the simplified analysis is further subdivided.

In this case, a method known as 'Superfast', which rapidly yields pre-computed design solutions which are accessed by the program code, may be selected for many of the most common configurations. Such computer programs will generally guide the user towards a suitable profile selected from the system owner's library, Fig 5.16.

When the simplified analysis program is run, it will first produce a header sheet of output giving basic job reference information. If the truss being designed can be solved by reference to the standard span tables included in the code, then the programme will indicate this by the words 'Tested Truss'. Information will continue giving plating and bracing details. Otherwise computer calculations will be made based on a method giving comparable levels of safety to the standard trusses.

There are standard ways of referencing the dimensions of trussed rafters, and the design programs refer to these in their output. This information is reported together with the truss member sizes; left and right top chord pitches; number of

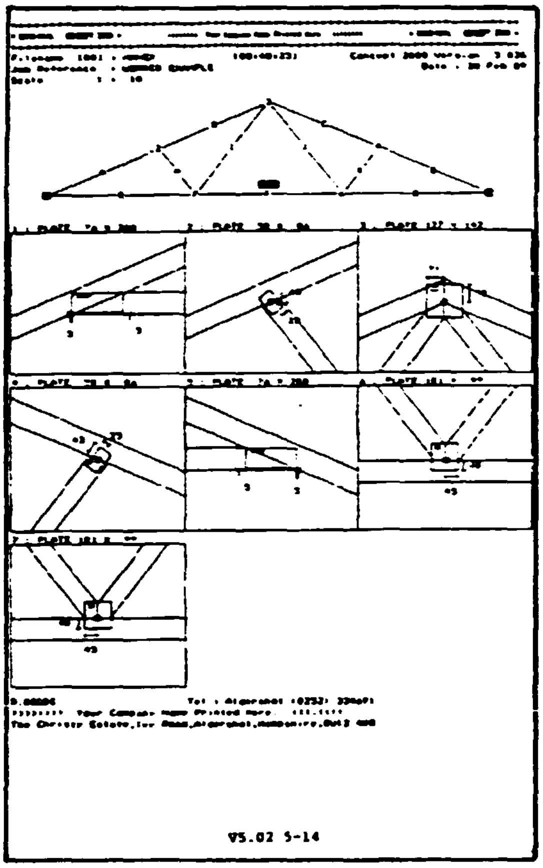

Fig 5.17

Example of standard plotting output

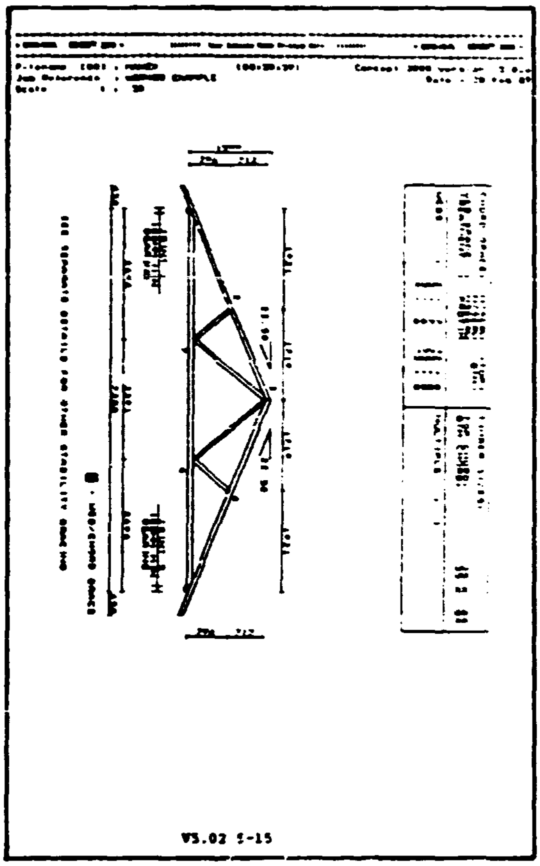

Fig 5.18

Example of standard plotting output (cont)

trusses required in the roof section concerned, and finally the truss centres. All of the loadings selected by the user of the program during his design session are listed in the output.
The grade and species of timber used for the top chord, bottom chord and web members is also indicated. Following this, the plate file is referenced indicating the type and gauge of connector plate to be used. If non-standard heel joints are required for the design, these are indicated. Rafter overhang details may also be given.

Although fully detailed design drawings are no longer necessary when using the software and equipment provided by system owners for trusses within their normal library ranges, simple line diagrams are normally included in the standard output, as an additional form of error checking. These diagrams may either take the form of a 'star plot' sketch (not to scale), or a scaled linear sketch if a computer graph plotter is available. Figs 5.17 and 5.18 show

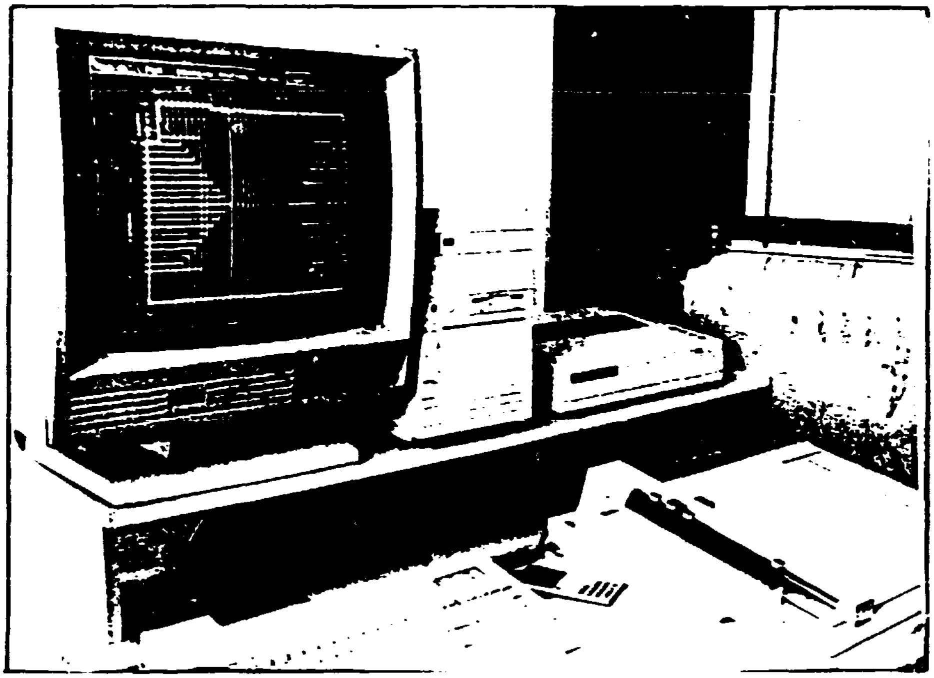

Fig 5.19

**A roof plan and truss layout on-screen on a microcomputer**

examples of standard plotting outputs for a worked example using Gang Nail's Concept 2000 software.

The analysis program finally outputs the essentials of the design calculations. It gives the bending moment coefficients calculated for the design, at each joint and panel position in each chord member of the truss. Applied stresses and forces are also listed. Only the worst cases are given for the chord members. For web members, a full output is provided for each duration of load case. Trussed rafter system owners normally refer to the index computed by summing the stress ratios due to flexure and axial forces as a combined stress index (CSI). This CSI and also the direct stress index is listed. The maximum local deflection of each member between the nodes is given, together with its slenderness ratio. The deflections are also stated at each joint considered in the analysis, together with the support reactions for each load case.

**Software for the complete trussed rafter roof:**

Other aspects of the structural roofing service which are computerized, in addition to the structural truss design, include the overall roof design. In this case one is considering the shape of the roof in terms of building plan, sections and elevations; truss and girder cutting, plating, jigging and estimating information; drafting for the creation of fabrication drawings and architectural plans, and management information such

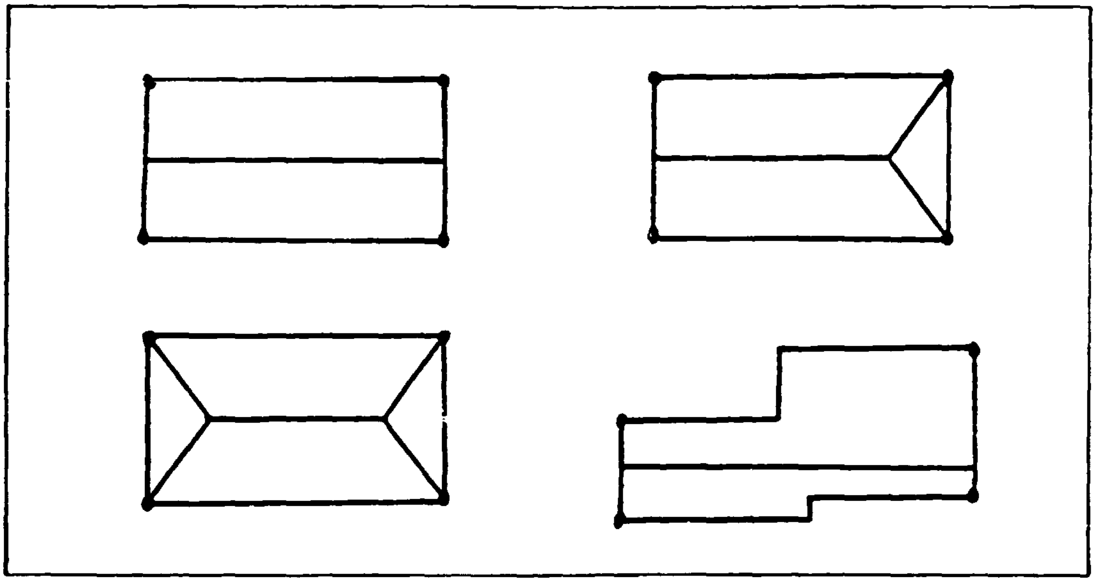

Fig 5.20

'Sections' as defined in the program 'ROOF'

as plant planning and performance, materials management, transport costing, and sales analysis.

A typical whole-roof design program is that contained in the Gangnail Concept 2000 suite. One of the important programs in this set, known simply as 'ROOF', is intended to take off a complete schedule of roof trusses, girders and ancillary roof materials from a description of the roof perimeter. A roof plan and truss layout drawings are also produced. These may if required include intersections, various types of gable, hips and valleys.

The ROOF program produces a roof plan of a complete building, or even a building complex. A fairly simple example of a roof plan and truss layout is shown as it would appear on-screen on a computer in Fig 5.19. In this example, quite a large span, hipped ended roof is indicated.

Roof truss profiles are also indicated as part of the output, and files containing information about them can be transferred to other programs within the suite, for steps such as structural sizing, and fabrication detailing.

The roof shape is entered by the user of ROOF through simple graphical routines. For the purposes of operating the program, the overall roof shape is subdivided into areas which are rectangular in plan. The roof sections of these subdivisions are stipulated by the user during the design process. In the special definition used in the program, 'sections' are zones of roof containing a single ridge line, together with prescribed end conditions, Fig 5.20. The results of the program, including the truss layout drawings, and the truss schedules can also be related to these sections, as defined during the design process. Internal walls and girders, capable of providing potential support points for the trussed rafters, are taken into consideration in defining the sections.

A real trussed rafter roof seldom consists merely of a rectangular plan with a simple set of symmetrical duopitch trusses in parallel all along the roof. At the very least, there is likely to be a chimney or other opening at some point. This will involve the use of what are known as 'stubbed' trusses. More frequently, buildings often include trusses which are cantilevered, or which intersect walls and girders. The ROOF program automatically ensures correct truss modification at all such points.

When beginning a new design, the user of ROOF will usually input data concerning the roof plan and shape by reference to a plan layout defined on the screen. A provision exists, however, to retain files of partially defined roof configurations, known as 'parameterized shapes'. These can be data relating to commonly used building types, and 'building block' plans, such as a common core shape with alternative additions. Hip and corner solutions are offered to the program user in a similar manner to the other facilities. They can be edited as desired, and a schedule of all the trussed rafter components can be produced for each hip and valley in the roof.

The 'roof general file' contains many of the user-set default values. These can be overwritten during individual job input, but by a wise selection, the user can greatly speed up his operation of the program. Perimeter wall data, for example, can be kept in the general file. These stipulate the thicknesses of the brickwork or masonry, the standard wall plate thickness, and similar values, so that a datum point can be established for the truss setting out values. Eaves conditions default values are another option that can be set in the general file. A default truss overhang value, typically 600 mm, can also be set, together with a default type of overhang cut.

'Section data' relate to an important menu which governs many of the truss design features in the roof section under consideration at any particular time. Examples of section data include the default pitch, typically 30 degrees; the truss family; truss centres, very often 600 mm; the standard water tank load; the default timber thickness and grade typically 35 mm, M75 grade.

The term 'truss family' refers to the choice of a series of trussed rafter forms such as duopitch fink; monopitch; flat; attic; asymmetric; scissor; raised tie, etc. Within each of these main families of configurations, it is still necessary for individual designs to be sized at a later stage. However, ROOF can work with the section

data provided, including the truss family's outer profile. The valley and gable setback dimensions and the hip type also have to be selected.
A wide variety of hip types are common, and ten types of hip are provided as standard options by the program.

Load cases are also selectable from a menu. The information chosen relates mainly to the weight of roofing required, such as concrete interlocking tiles, heavy tiles, or asbestos tiles. Although there are options to select top and bottom chord live loads, these are more uniformly standardized by the loading code.

Some details of fabrication data are quite standard for a given manufacturer. These include selection of timber treatment, such as by the 'Protim' or 'Vac-Vac' methods, or untreated material. A reference is made to a standard plate file in the fabrication section of the general file. The standard plate file contains details of the normal galvanized plates and the stainless steel plates which the fabricator carries in stock, giving their gauges and sizes.

As in the case of the description of the general file selection procedures, the following discussion of the normal input method is not intended to be fully comprehensive, but rather to give an indication of the functioning and capability of the program.

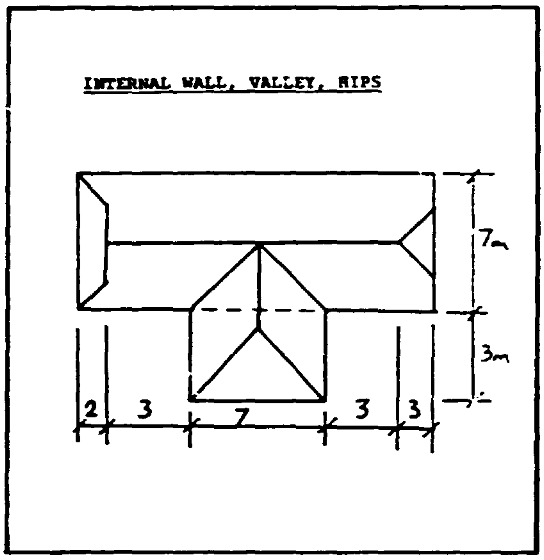

Fig 5.21

**A sketch roof layout, as a starting point for program 'ROOF'**

Where a new roof shape is to be designed, 'input by plan' is the normal method of data entry. This method is also used to create a new 'parameterized shape' of roof. For example, Fig 5.21 shows a sketch with dimensions of a roof with an internal support wall, valley and hips which could be used as the starting point for a typical design using ROOF.

The overall dimensions of the roof plan, including an allowance of about two metres for a border, need to be stipulated. A starting point for plan input then needs to be chosen by the user for commencing to draw the plan on the screen. Normally, this will be a 'bottom left' position on the building plan shape. The external wall perimeter is entered in its

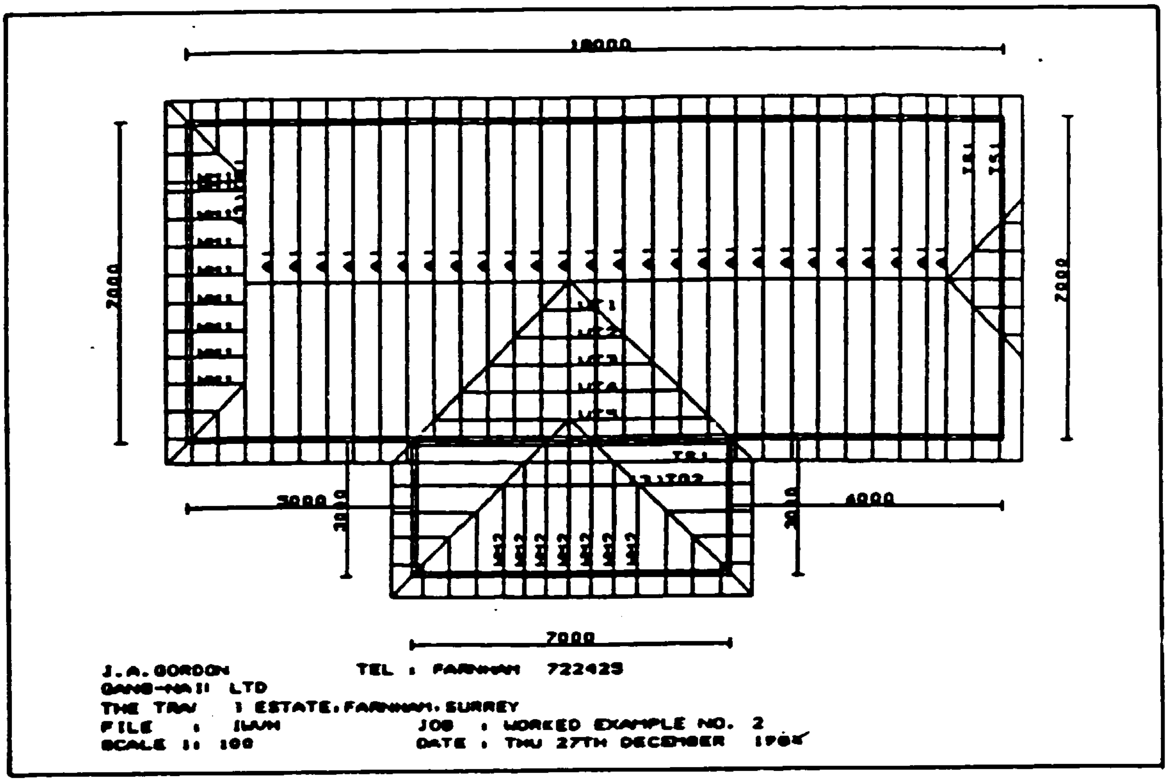

Fig 5.22

**A roof truss layout drawing, one of the principal outputs from the program 'ROOF'**

entirety. Each external wall is described in turn, using a clockwise sequence starting from the selected origin.

To assist input, the program always tries to close the perimeter in a clockwise manner. Keyboard directional and dimensional defaults always tend to anticipate this function to close the shape. Because it may be necessary to include recesses or re-entrant shapes in the plan, the user has the option to override the program choice. If an error is made during a drawing, a single key permits stepping back a chosen number of stages, without the necessity for complete re-entry.

Once the perimeter and node points have been input, the program re-scales the perimeter to one of the pre-selected standard scales. Sequential reference points are then indicated on the screen. The inner and outer wallplates, brickwork thickness and dimension lines are all added, obeying menu selections.

The initial screen plot of the roof perimeter, created by the steps described above, is edited into a completely dimensioned roof layout, by executing a series of functions in a sequence prescribed by the software.

After the complete perimeter has been input, the user may decide it is necessary to include additional nodes, other than those automatically formed at the corners in the perimeter. Reasons for this may include the requirement for a new node at a girder support position along a wall, or at the intersection point between a perimeter wall and an internal loadbearing wall. A boundary modification option is available in the roof data menu to permit this. A 'redraw' or 'tidying up' facility is also available at this stage.

Any girders not included during the perimeter input stage must be positioned before the design can be completed. Once this is done, the roof sections can be fully defined. The principal sections are defined before any secondary ones. For example, in many buildings, there will be a main accommodation area, which is essentially a large rectangle in plan. Once the main sections are defined, the program can calculate the intersection zones between them, and assign the relevant data to each sub-file. After this step, the program can, if necessary, be used to close the data into a 'parameterized file'. Otherwise the user proceeds to stipulate his required outputs, which may be to the screen, on a printer, or to a graph plotter.

The principal outputs of the ROOF program are a roof plan drawing, a roof truss layout drawing, Fig 5.22, truss profiles, and a truss take-off schedule. Transfer files are also created, so that a general drafting program can receive the output to generate drawings on a graph plotter or similar device. Listings are also produced of the ancillary items required to construct the roof, such as the truss clips, hangers and shoes, and the soffit and barge board sizes.

## CHAPTER 6

## The future

### European Harmonization:

The Eurocode No 5:'Common Unified Rules for Timber Structures', is one of eight Eurocodes being prepared to promote the aims of the Common Market by removing obstacles due to differing structural design rules.

The Eurocodes are a major aspect of the European harmonization process. They provide common technical rules for the efficient application of the intentions of the Construction Products Directive (CPD) with respect to design.

It is anticipated that their use will first be introduced mainly as an alternative to national rules for public contracts. Their gradual introduction for all other contracts is expected to follow later.

Many of the supporting documents for EC5 are well advanced and are being agreed as CEN drafts (European Committee for Standardization, in English). The standards organizations of the individual countries within the Community will publish these 'Euro-norms' (ENs) with corresponding national numbers. Thus the system of British Standards, French (AFNOR) and German standards (DIN) is likely to continue for a considerable time to come, although these standards may only amplify, not conflict with, those commonly agreed.

The present EC5 is also a draft at this stage. The drafting work drew largely upon studies which have been undertaken for more than twenty years in Working Group W18 (Timber Structures) of the CIB (International Council for Building Research Studies and Documentation).

Comment upon the EC5 draft has been thorough, detailed and in-depth. A second, substantially revised and printed draft in English is expected to appear by about April 1992. Subsequently it is hoped that this will be adopted as a voluntary but legal code (ENV). This could be applicable from April 1993.

Currently, progress towards European harmonization in the structural timber field continues quite rapidly. An important political development is that member countries of the EFTA group are now fully participating in this work, in addition to the twelve Member States of the Community.

Amongst these, Finland, Norway, Sweden and Switzerland have considerable structural timber proficiency, as well as being, in some cases, very important suppliers to the other member countries within the group.

Hence when harmonization is achieved, the nations adopting these codes and standards will not only represent the largest coherent economic bloc in the world, but will also form a grouping of great significance for timber supply and demand.

**EC5 design philosophy:**

Like all the other Eurocodes, EC5 is a limit states design code. 'Limit states' are states beyond which a structure no longer satisfies the design requirements. For instance, there are limit states for ultimate strength, and for serviceability of the structure.

Buildings are required to withstand 'actions' (generally speaking, equivalent to 'loads') with an acceptable probability of risk. Actions are divided into permanent, variable and accidental effects.

Because timber is load-duration sensitive, durations of actions must be also be defined. Partial coefficients are applied to the values of the actions, to take account of unfavourable deviations of estimated effects and to allow for uncertainties.

In the design process, design values of actions are compared with the design resistances of the proposed structure.

In limit states design, material properties are stated in terms of 'characteristic values'. These are defined by means of standardized tests, followed by agreed statistical procedures. Both of these steps are laid down in the ENs which support the code.

The design value of a timber material property is derived by multiplying the characteristic value by a partial coefficient for material properties. In addition, account is taken of duration of load, moisture content and similar effects, some of which are peculiar to timber.

**Trussed rafter guidelines for Europe:**

A notable omission from the first draft of EC5 was that there was no section dealing with the design of trussed rafters. Consequently trussed rafter 'guidelines' were initiated by a sub-group of WG18, at its meeting in Berlin in September 1989. These have now been broadly adopted, and are in the process of being finalized by the EC5 Editorial Group, with national inputs from various concerns.

**Scope of the guidelines:**

Unlike the British trussed rafter code, the EC5 draft guidelines are confined to the design of individual trussed rafters, treated as what are termed 'plane frames' in the strict structural analysis sense.

The design of the truss is treated in three phases, although it is noted that often these three phases may not be followed sequentially but that iterations may be involved. These three steps are as indicated overleaf:

1. Static analysis of the framework
2. Strength verification of the timber members
3. Strength verification of the connexions

The draft concentrates on trusses jointed with nail plates, and assumes that the plane frame analysis phase will be carried out using one of the many existing general structural plane frame analysis programs.

The strength verification of the timber members may in principle be carried out as described in general timber codes, such as the main sections of EC5. Only certain aspects of this which are peculiar to trusses have therefore been added.

The strength of nail plates has been discussed in several CIB papers, and the guidelines adopt some of these recommendations.

A recent addition to the guidelines has been the adoption of a simplified analysis for fully triangulated statically determinate trusses. The method used is quite similar in principle to the simplified method which is given in BS 5268: Part 3.

**Frame analysis:**

Typical of the assumptions made in generally available linear elastic plane frame analysis programs are as follows:

1. Linear elastic behaviour of the individual members and of the structure as a whole.
2. First order method of analysis - this means that non-linear changes in the geometry of the structure under load are not taken into account iteratively by the program.
3. Members are modelled as straight beam elements.
4. Most programs permit deformations in the joints to be included in the deflection predicted by the analysis. This is done either by adding a prescribed slip at selected nodes or by including spring elements in the model.

Methods of allowing for slip in the connexions are of practical importance in attempting realistically to model the behaviour of trussed rafters using standard plane frame analyses, since the degree of fixity and the stiffness provided by nail plates impinges upon the strength verifications made as a result of the analysis, as well as affecting the serviceability (deformation) considerations.

Because of limitations, there are only two realistically applicable possibilities for modelling slip. These are as shown overleaf:

1. Prescribed slip

From tests on nail plates, the load-slip behaviour in absolute terms (so many millimetres or so many radians per Newton or Newton metre) is prescribed for each nail plate type.

Load-slip curves are generally quite non-linear, but when the connexion reaches the ultimate load that will be used as the basis for design values, a corresponding slip may be assumed.

If it is also assumed that the plates will normally be used efficiently, so that plates of a larger area will be used at nodes where members carry greater forces and moments, then the slip that will occur in practice can roughly be equated to the plate type, by linear interpolation, independent of plate size.

Even with such crude assumptions, there are still difficulties, since not for every load case in a given member will the nodes concerned reach their ultimate value divided by the accepted load factor.

2. Elastic spring elements

Many elastic plane frame analyses permit elastic spring elements to be associated with the nodes (mathematically, this merely entails adjustments to the stiffness matrix).

However, in common with nearly all mechanical timber fasteners, punched metal nail plates used for trusses deform non-linearly, both under test and in the real structure. Hence stiffness constants for the joints must be stated as a secant modulus.

This means that for each load case under analysis the designer needs to indicate the relative strength utilization. The stiffness matrix which is being operated upon by the mathematical 'inner workings' of the program has to be updated, hence again analytical iteration is inferred.

**The frame model:**

The frame model is an idealization of the real structure which is capable of being analyzed by the computer program. As such, it should represent as nearly as possible the real structure, particularly with regard to intersections of centre lines of the real members, and the real stiffnesses of the connexions. However, certain simplifications are essential.

Beam elements are used to model the real linear members; fictitious beam elements model some of the constraints within the connexions (including allowances for non-intersection of some real members' centre lines, due to the width of the real members); spring elements model the elastic behaviour of the connexions.

As the intention is to represent as nearly as possible the elastic behaviour of the real structure, it is preferable in the frame model to state mean values of stiffnesses. This is not always understood, since for some purposes during the design process, engineers use lower bound (eg fifth percentile) characteristic values of such properties.

In providing the computer program with the geometrical data of the framework to be analyzed, chords should always be modelled such that beam elements lie along the centre line of the actual members.

For internal members, such coincidence is not always possible with a single model, however the beam elements should at least extend from nodes which lie within the actual cross section of the timber used.

Connexions:

Connexions can be modelled in several ways, and the choice depends upon the interpretation by the user of the static behaviour of the real connexion. The following main possibilities exist:

1. Pinned connexions
2. Completely stiff connexions
3. Spring elements

Prescribed slips can be included in the data relating to any of these three types.

The guidelines suggest that pinned connexions should be used in the model if the rotational stiffness of the connexion between two timber members is smaller than the stiffness of the members themselves.

Sometimes for the purposes of analysis it is necessary to treat a continuous timber member in the real structure as two or more beam elements terminating at common nodes. Where this is the case, the connexions at such nodes are treated as completely stiff.

Completely stiff connexions are also involved if the rotational stiffness of the connexion between two timber members is greater than the stiffness of the members themselves.

Constraints in the connexions of the real structure, such as contact areas between adjacent timber members, are modelled using fictitious beam elements. These elements should be located such that they coincide as near as possible with the real force transfer path.

As the fictitious members are quite short, the results of the analysis are not sensitive to their stiffnesses, and arbitrary values may be assigned to them. Fictitious elements may require coupling by pinned or fixed connexions.

**Static analysis:**

Different static analysis approximations are suggested for the serviceability limit state and the ultimate limit state.

As regards the loadings required as input to the analysis, the guidelines indicate that 'relevant codes' should be referenced. Unified structural loading codes for Europe however are some years away from being available.

There are some suggestions giving guidance on when to approximate a series of concentrated loads by a uniformly distributed load. Large concentrated forces must of course be applied where they act in reality.

Supports are generally treated as simple pinned or rollered arrangements, in keeping with normal structural analysis, unless there are special conditions such as a non-stiff support structure that would influence the internal forces in the truss under analysis.

**Strength verification:**

The intention of the guidelines is that the strength verification of the timber members in the trussed rafter should broadly follow the principles of the main EC5 document.

However it is recognized that there are several aspects of the strength checks required for a trussed rafter that are special or that need assumptions to be stipulated. Effective column lengths are one such aspect. Basing effective column lengths on the distance between points of contraflexure is a common recommendation, and this is included in the guidelines for certain conditions.

Reduced column lengths related to the bay lengths or to the largest adjacent bay length are also included, for the design of fully triangulated trusses. These rules apply where members are taken as continuous over several bays, which is the most common situation.

**Plate strength verification:**

Clauses have also been drafted describing the strength verification procedure for the nail plate connexions in the truss. The data to be found on punched metal plates in sources such as Agrement Certificates may still be used.

Design modification factors for plated joints relating to aspects such as load duration and moisture effects are still not well validated by research. Capacities of the steel sections of the plates themselves however are well known.

**The development and future of structural computing in general:**

To conclude, a brief section of this final Chapter considers the development and future of structural computing in general, and offers some thoughts as to where this is likely to lead with respect to timber roof design.

**Hardware developments:**

The first generally programmable electronic computer was known as 'EDSAC'. This machine, which first ran at Cambridge University in 1949, was distinguished from earlier types by the fact that its programs were held in an internal memory of the same type as the memory designed to store data. This interchangeability of program and data in memory was a major innovation which proved to be the key to further developments.

The fifties saw computers develop, relatively slowly by modern standards. 'LEO' (Lyons Electric Office) was the first computer used for commercial purposes.

In 1953, the journal 'Engineering' carried a milestone paper by Dr. R K Livesley entitled 'Analysis of Rigid Frames by Electronic Digital Computer'. Previously it had been necessary for structural frameworks to be analyzed by laborious hand calculations, using tabular methods to organize the matrices.

The Elliot company published details, and issued copies on punched paper tape, of a program that would nowadays be regarded as a 'package'. This was based on the Livesley paper.

It was well documented, with a simple but clear and thorough explanation of the program, a worked example, and a standard data entry sheet. The program was intended for the elastic analysis of rigid jointed plane frameworks, the user specifying details of the geometry and the forces at the nodes. The sample problem had twenty joints, thirty four members and one load case.

It took 6 minutes 40 seconds to run on an Elliot 803 computer. Nowadays such a problem would run on a desktop microcomputer so rapidly that the results would appear to flash up on the screen the instant the user hit the 'Enter' key.

The 1960's were the decade in which mainframe computers became fully established and much more widespread in use, both for commercial and for scientific applications. It was also the time when IBM dominated the industry. There were mainframe machines of importance other than the IBM 360 and 370 series however.

Notable amongst these were the Control Data Corporation's CDC 6600 series, upon which much software of structural and civil engineering importance was available.

In Europe, contributions to progress were mainly through improvements in high level programming languages. These aspects had a permanent influence, not only by encouraging better structured languages such as Pascal, but also upon later machine architecture such as the modern 'RISC'systems.

Most of the early timber engineering design aids produced and published by TRADA from 1965, until about 1972, were developed and run on a postal bureau basis, using the London University Atlas computer.

Each of these machines, of which only four were built, occupied a large air-conditioned room, and required many large magnetic tape decks and other bulky peripherals.

The actual program code was prepared on punched paper tape, using a fairly primitive keyboard machine known as a 'Flexowriter'. Great care had to be taken in coding a program, since a minor error such as the omission of a single comma in a statement would cause several day's delay in developing a compilable program.

It seems almost incredible to recall that at the beginning of the 1960's, the 'large' mainframe (about as powerful, in memory terms, as an average PC nowadays) depended upon valves, rather than microchips. Memory, often called 'core' at the time, did actually consist of a matrix of wires and rings of semiconductor material, or 'cores'.

Towards the end of the mainframe era, remote processing began to become affordable, through the use of modem links, and public services telephone networks.

By the mid 1970's, such operations had been switched to in-house mini-computers, using early models of the highly successful Digital Equipment Corporation (DEC) range. This made it possible to harness the computer for operations such as the logging and analysis of research results, as well as the development and running of 'personal' software, both being types of operation which would previously have been too expensive for other than high technology laboratories.

Many of DEC's scientific and engineering users have migrated to microcomputers, in recent years, now that these have attained far greater power than the 'hobby' machines through which the technology and operating software was first introduced, around 1980.

Ever since computers first became available for general use, their technology has continued to develop at a rate much faster than other modern inventions such as cars, aircraft, and even other electronic devices, including televisions.

Thus it is by no means extravagant to expect that in ten years time, a commonly available machine the size of a present-day 'IBM PC', or probably an even more compact device, will operate at ten times or more the speed, and will have thousands of times more mass storage capacity.

The prediction concerning microprocessors is that for so long as such devices are based merely upon improvements on present technology, the day is rapidly approaching when performance will reach a plateau. This is because speeds will start to become limited by the physics of circuit design, for example heating effects, preventing further miniaturization.

It seems inevitable that the time will come when limitations will have to be overcome by means of major revisions in machine architecture. At present, the conventional wisdom is that once i586 processors operating at about 50 million instructions per second are commonplace, then techniques such as symmetrical multi-processing will be usual in desktop-sized machines.

At present, such methods only operate on 'supercomputers' such as the Cray X-MP machine, which is used to make predictions for the next ten days' worth of weather in the entire northern hemisphere each time it is run.

In the longer term, prospects for ultra high speed computing are thought to lie in circuitry based on light, rather than electrons, since laser beams can transmit signals at the same theoretical speed as electrical charges, but at far greater efficiency and without overheating. To this end, research is already in hand on new materials upon which miniaturized light circuits can be based.

**Future applications:**

Whenever prognostications of great increases in computer power are made, the natural reaction is to question why such facilities could possibly be useful for such mundane applications as those in the building industry. However experience teaches that computer users swiftly become accustomed to whatever power, computing speed and storage is provided, and soon begin to demand more.

Take the mundane example of sizing, drawing, scheduling and costing all the trusses and components in a roof, for example. As has been shown, in a modern, reasonably complex building, there can easily be up to about twenty different major components.

At present, fabricators are normally unwilling to price a job of this nature whilst the client waits on the telephone. However, with greater speed, power, and communications, such as multiplexed computer-facsimile networks, 'real time' response is likely. The reliable remote exchange of technical drawings in the form of paper sizes and quality of detail that are required for engineering work is another barrier that will soon be overcome to assist such rapid response.

Computer-aided drafting and design are no longer new. On the other hand, they are still not commonplace in the 'lower tech' industries such as building. This is almost certain to change in the second half of the 1990's.

It has been said that most CAD users could make good use of the predicted 1995 type of microcomputer this very day. Additional processors on the mother board and on the communications and I/O devices are likely, to provide the types of machine required to put Autocad networks in every drawing office.

The British Standard used in all drawing offices, BS 1189, is about to have a new Part 5 added which will deal exclusively with CAD. Predictably, in about five years' time, drawing boards, compasses and templates will seem as quaint as slide rules do now.

Recent improvements in microcomputer operating systems are permitting better facilities to be put at the CAD designer's disposal at modest cost.

Program exchange techniques are becoming available on simple operating systems working on smaller but powerful machines. These link the actual CAD design software and its database with ancillary programs and data.

Thus whilst working on a set of drawings on screen, the designer can make changes which will not only affect the object he is viewing, but will also generate updated tabular and file-listed information in real time, as he affects the changes.

For example, alterations in the geometrical ratios of an engineering component will bring about corresponding changes in its areas, mass and geometrical properties, all held in an operable spread sheet file. The spread sheet data can if necessary be viewed on part of the screen at the same time as the drawings. Drawing management facilities are also found, which keep up to date extensive information on sets of drawings. Drawings can thus be searched by project, drafter, revision date, budgeted time and so on.

If everybody designs and 'draws' with the computer, then we shall no longer wish to rely upon the post or the low resolution 'fax' machine to exchange drawings.

DXF (drawing exchange facility) is the name of a well-advanced technology that is expected to become established to pass and receive 'drawn' technical information.

At present, although Computer Aided Manufacture (CAM), so often linked with the acronym CAD, is likely to find its way gradually into the higher technology areas of the building industry, such as factory prefabrication, it is inconceivable that for some years yet, the drawing will be eliminated from the site.

With the trend towards companies and groups enlarging and integrating, and everybody storing more and more information, communications bottlenecks can be expected.

Very advanced and expensive communications facilities such as fibre optics cables, have had to be installed in large commercial buildings such as Lloyds Exchange, simply in order to give an acceptable response to the required data transmissions made possible by hundreds of present day desktop machine operating on the same premises.

Optical disc controllers (operating like music compact discs) are now offered for sale interfaced with microcomputers costing less than £ 2000. This provides a very compressed method of storing large databases.

Initially such systems have been used mainly in the field of information technology, in order to access encyclopedias, atlases and similar.

As an example of a technical application, however, a database giving basic wind speeds and basic snow loads at geographical locations specified by means of Ordnance Survey grid points is shortly to become available to structural engineers in the UK. Such applications certainly demand innovative methods of storage, access and retrieval.

When the computing power available at the individual workstation is considered, there are aspects beyond mere machine power and speed.

A major constraint has now become the screen itself. For a combination of technical and economic reasons, screen technology is unable to progress at the tenfold or thousandfold rate of microchip technology.

Again, the laws of physics come into play. Glass screens involve problems with weight, heat dissipation and sheer cost of manufacture. When twenty inch flat television screens become affordable for every home, then corresponding improvements in the computer screen are likely.

Other screen techniques, such as liquid crystal displays (LCD), used for 'laptop' computers, can only be described as disappointing at present. Improved colour LCD displays built into the surface of the desk itself are forecast, for those who relish and will be able to afford such devices.

Users of specialist software are demanding the change from older-style screen presentations, as they become accustomed to more lively software presentation through their familiarity with the more universal management programs, such as the Lotus 1-2-3 spreadsheet, and advanced word processors, such as WordPerfect.

However, it is becoming evident that serious limitations are now being placed upon effective use of the computer by constraints involving human performance.

Aspects such as screen size, layout and illumination, and human data and program entry and modification techniques, as well as operating system and communications network design, need to play a major role in achieving further improvements.

These steps are likely to be seen in all specialist applications of microcomputers, including their use for timber engineering design and construction software. Hence those contemplating offering new systems and software need to be ever mindful of such trends.