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Note by Rosemary Devine: This is the last issue of *The Arup Journal* that I will be editing. The next issues should appear in September and November. However, if there are any changes in the production of *The Arup Journal*, I am sure that you will be told.

York Minster

David Mitchell

Part 2—The Minster

The Roman Headquarters Building (Principia)

The Minster is built upon the site of the headquarters building or principia of the Roman legionary fortress. Initially the principia was built of timber, rebuilt in stone by the IX Legion at the beginning of the second century A D and subsequently repaired and altered by the VI Legion on several occasions. The second century building was 250 ft. x 310 ft. overall including its external arcades.

In plan the principia would consist of a large open courtyard flanked on three sides by single storey buildings with open colonnades and on the fourth by a large cross-hall (215 ft. x c 115 ft.) backed by a series of smaller rooms. These were the administrative offices with the central room used as the sacellum, the legionary chapel containing a statue of the Emperor and the Legion's standards. (Fig. 1)

'The principia was the nerve-centre of the fort, as well as the most imposing building inside it. Beside the regimental chapel and the offices in which a wide variety and great quantity of paper work was performed, and the great hall in which the commandant addressed his officers and men, heard applications for leave, dealt with men on charges or even, in some cases, sat as district magistrate on matters brought before him by civilians from the surrounding district, the building included round its open courtyard accommodation for noticeboards on which orders could be posted, and the shrines or meeting-places for NCO's which formed a striking feature of the Roman Army, at least in the third century.' (1)

A legion was totally self-sufficient and contained, apart from its fighting troops, a complete range of specialists and artisans, engineers, masons, farriers, bakers, etc. From *The Ten Books of Architecture* written by Vitruvius in the first century B C it seems that architect and engineer are synonymous: *'There are three departments of architecture: the art of building, the making of time-pieces and the construction of machinery'.* (2) The architect was expected to be a highly professional, well educated man capable of designing cities, temples, theatres, breakwaters, aqueducts, sundials, water clocks, catapults and Hegetor's tortoise. *'Let him be educated, skilful with the pencil, instructed in geometry, know much history, have followed the philosophers with attention, understand music, have some knowledge of medicine, know the opinions of the jurists, and be acquainted with astronomy and the theory of the heavens.'* (2)

He prepared drawings, ground plans, elevations and perspectives, was skilled in setting out with string and compass using the principles of Euclidean geometry and was capable of levelling with dioptrae, water-levels or chorobates, the last being a 20 ft. straight-edge with a system of hanging plumb-lines. From the collapse of the Empire, it was to be a thousand years before architects with such sophisticated skills and wide-ranging knowledge were to be found in Northern Europe.

The rebuilding of the fortress in stone in the second century used the standard Roman methods of ground consolidation and construction. The walls were of squared stone facings with rubble and mortar infilling. This was the method of masonry construction used throughout the mediaeval period. It has presented problems in many cathedrals as the mortar can deteriorate with time giving the transfer of load from core to casing, with subsequent overstress and cracking.

At York the facing stones are of magnesian limestone from the upper beds (6 in. - 12 in. thick) of the Permian outcrops near Tadcaster and the rubble infill of ragstone; oolitic limestone, possibly from the Castle Howard area. For large details such as pier bases, millstone grit blocks were used, some weighing up to 2 or 3 tons. These may have come from the Bramley area. Stone from the three areas would have been transported on the rivers Ouse, Derwent and Aire.

The roofs were of timber covered with red clay tiles. Internally the walls were of painted plaster and the floors of 'opus signinum'—pounded tile mixed with lime on a base of crushed stone or tile.

The excavations under the crossing have uncovered part of the cross-wall with several pier bases and sections of walling. Evidence has been found of fires in the late second, third and fourth centuries. Pottery associated with these fire layers gives dates consistent with the wasting of the North in 196, 296 and 376 A D.

In the fourth century the cross-hall was reduced in size and a series of small rooms inserted into its north end and into the north-west arcade, presumably upon the introduction of the new army system when Eboracum became the headquarters of the Dux Britanniarum, resulting in an increase in senior 'civil servants' requiring offices.

In one of these rooms most attractive imitation marble painted plaster has been found with graffiti of which an unusual cursive R survives but of a type which can be paralleled from graffiti on plaster in Italy. Its significance is obscure.

After the fire of the late fourth century, there were a series of repairs and rebuilding of the Roman walls continuing after the departure of the Roman army and administration, and with a progressively deteriorating standard of mason craft. At one stage the north end of the cross-hall was partially converted to domestic occupation and a kitchen inserted on its north-west side, using a flue of a dismantled hypocaust to serve as a chimney. (Fig 2)

The excavations, to date, have been carried down to just below the floor level of the second century principia and just above the present level of the perched water table, standing about 15 ft. below the Minster floor. Details of the Roman foundations are therefore unknown although they are presumably mass concrete pads and footings between 3 ft. and 5 ft. deep. It is unlikely that timber piles or ground consolidation techniques were used, as it is thought that this area was comparatively dry during the Roman period, being the top of the rise above the river on which the fortress was built. The 6 ft. x 4 ft. moulded plinth of one base has been removed showing two layers of millstone grit each made up of several large blocks clamped together with large metal butterfly cramps. On one of the blocks of the upper layer, a line has been deeply incised, probably used for setting out. (Fig. 3)

In the corner of the principia nearest the north-west pier of the central tower one of the site investigation boreholes gave Roman material to a depth of 25 ft., i.e., 10 ft. below Roman ground level. As yet, despite several theories, this has not been satisfactorily explained.

Edwin's churches

Bede records that King Edwin of Northumbria after his conversion to Christianity by Paulinus in 627 built a small timber oratory and soon afterwards began the construction of a large 'square' church. It is thought that Paulinus brought masons from the Continent to construct the stone church as the vast majority of English buildings of this period were of timber. Indeed, the use of timber for many churches and secular buildings including royal palaces prevailed until the Conquest. The larger timber structures were sometimes strengthened with iron:

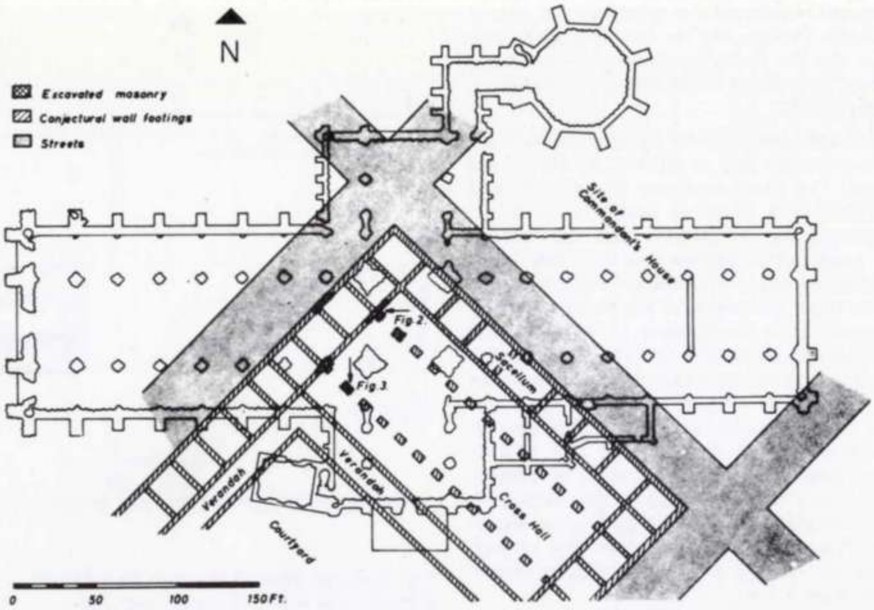

Fig. 1 Conjectural plan of part of the principia superimposed upon the plan of the present Minster. Illustrator: Margaret Woodward.

Fig. 2 above. Second century wall of the principia of the cross-hall with the flues of the hypocaust installed at a later date. The wall running into the picture is also part of later modifications. Behind this Roman work are the Norman foundations. (Published with permission of Royal Commission on Historical Monuments (England). *Crown copyright*)

Fig. 3 right. Foundation of a pier of the cross-hall after removal of the moulded base. The incised line at the bottom of the photograph is thought to have been used in setting out the building.
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'The warriors' hall resounded . . . the building rang aloud. Then was it great wonder that the wine-hall withstood the bold fighters; that it fell not to the ground, the fair earth-dwelling; but it was too firmly braced within and without with iron bands of skilled workmanship. . .' (*Beowulf*) (³).

The current excavations have revealed work of Saxon origin but, at present, its date is not certain. The main evidence of its form and construction is therefore Bede's description. (Although the translation uses the phrase *'the walls of a square church'*, the Latin 'quadratum' does not necessarily imply square in plan but could mean 'of squared masonry'.) However, it is reasonable to assume that Paulinus would build a church similar to the Kentish churches he knew well. These are all fairly small, the largest being SS Peter and Paul, Canterbury, founded as the chief church of an abbey by St. Augustine in 597. In plan it was approximately 80 ft. x 60 ft. overall, with a nave of 45 ft. x 30 ft. and with 2 ft. thick walls of Roman brick and 'opus signinum' floors. However, at York the church would be mainly of re-used Roman stone rather than brick.

Towards the end of the seventh century St. Wilfrid built churches at Hexham and Ripon and restored Edwin's Church at York; *'The Archbishop caused the roofs to be renewed and covered with lead, he filled the windows with glass which, while keeping out the birds and the rain, admitted light, he ordered the walls to be washed and whitened even beyond the whiteness of snow'. . . .* (*Eddius-Vita Wilfridi*). (⁴)

It should be noted that glass was very expensive and was not used for windows in secular buildings, even in the royal palaces until Henry III's reign. Similarly, lead was not used widely as a roofing material for major churches until the thirteenth century.

Aethelbert's Minster

About 780 during Aethelbert's incumbency a new basilica was built by his pupils Eanbald and Alcuin, who in a poem describes *'the grandeur of its height, the solidity of its piers and arches, the number of its aisles, the translucent beauty of its windows and the rich adornment of its thirty altars'*. (⁴)

Sections of Saxon walling have been found during the current excavations and are shown in Fig. 4. Fragments of imitation 'opus signinum' flooring, lime-washed external plaster, painted internal plaster, mouldings, lead wire for glazing and clips for roof fixing; all show distinct similarity with the late seventh century Northumbrian churches at Monkwearmouth and Jarrow. Traces of glass, presumably made molten by the fire of 1069, have also been found on certain stones.

Although the physical evidence, to date, is very limited, taken together with Alcuin's description it suggests a church similar in plan to that at Brixworth in Northamptonshire, *c.*670. (Fig. 5) This church is described by Sir Alfred Clapham as *'perhaps the most imposing architectural memorial of the seventh century yet surviving north of the Alps. It is an aisled basilica of four bays with a triple arcade . . . at the east end, opening into a square presbytery with an apse beyond'.* (⁵)

If this assumption is correct, the Minster would have had overall plan dimensions of 190 ft. x 65 ft. with a nave main span of 28 ft. centre to centre and aisles of 18 ft. centre to centre. The aisles may well have been divided into a number of chapels, porticus to contain Alcuin's 30 altars. The church's floor level was 3 ft. above the late Roman fifth century floor level and it was built of re-used Roman stone and plastered inside and out. There is evidence that this building was still standing in 1069.

As regards the technical skill of the designers and masons, Alcuin, in a poem on the saints of the city *'outlines the curriculum* (of the

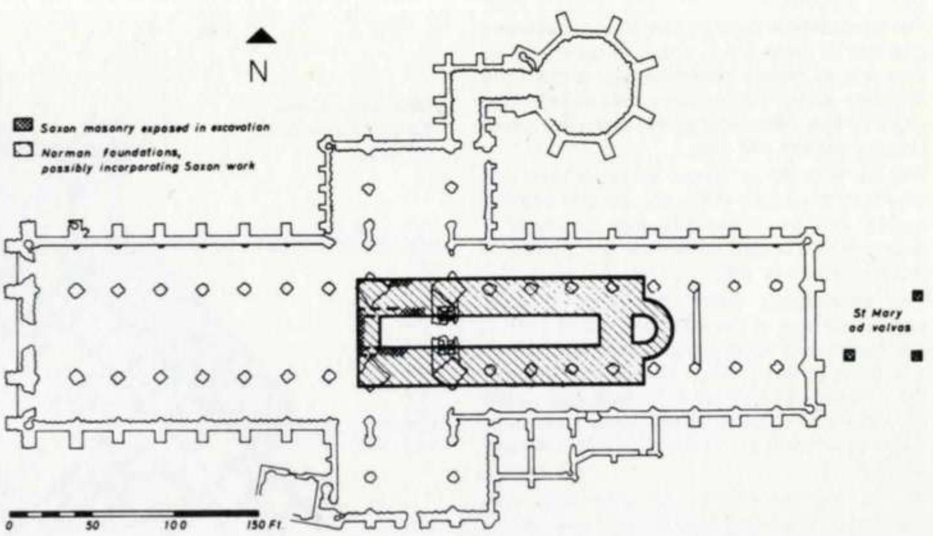


Fig. 4 above. Plan of Norman foundations showing the areas of Saxon walling. Illustrator: Margaret Woodward.

Fig. 5 right. Plan of Brixworth church, Northamptonshire. (Photograph by P. Beckmann from CLAPHAM⁽⁵⁾)

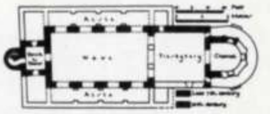
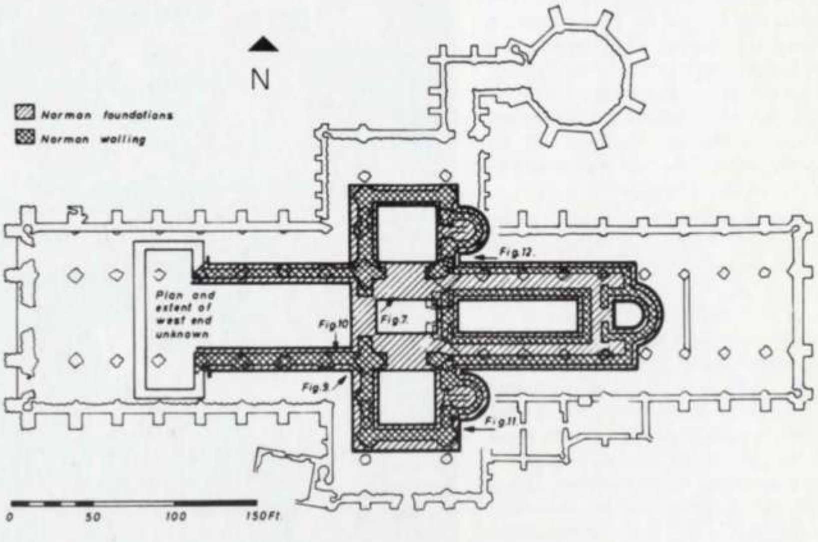


Fig. 6 below. Conjectural plan of the Norman Minster *c.*1100. Illustrator: Margaret Woodward.



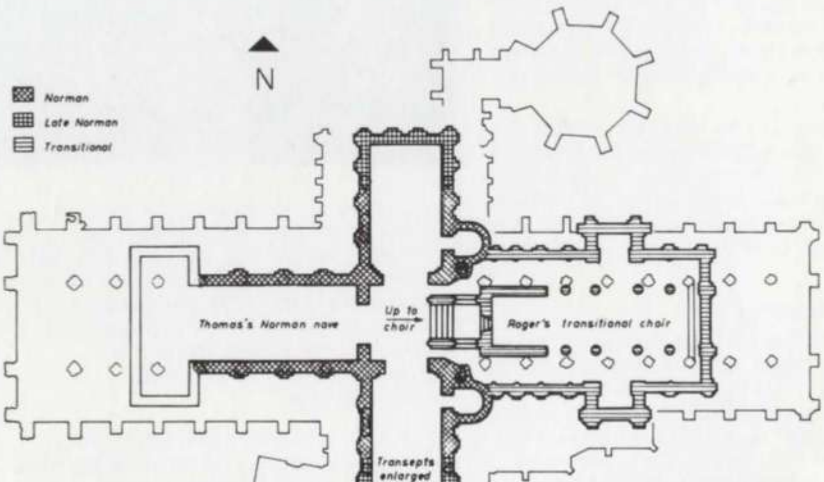


Fig. 13 Conjectural plan of Minster *c.*1200. Illustrator: Margaret Woodward.

Fig. 15 below. Conjectural plan of Minster *c.*1250. Illustrator: Margaret Woodward.

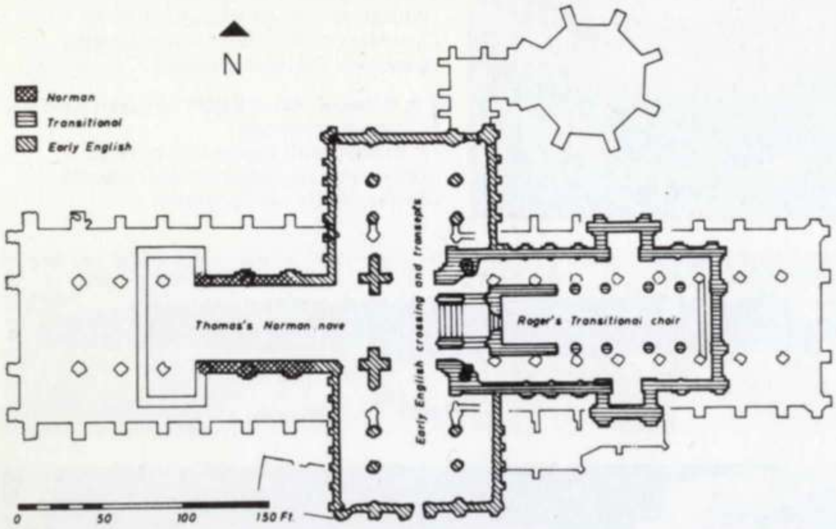


Fig. 21 Conjectural plan of Minster *c.*1350. Illustrator: Margaret Woodward.

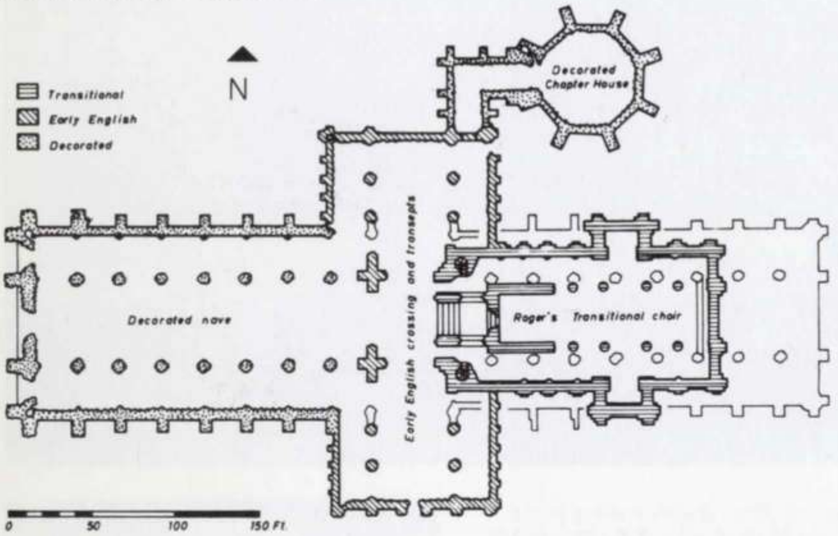
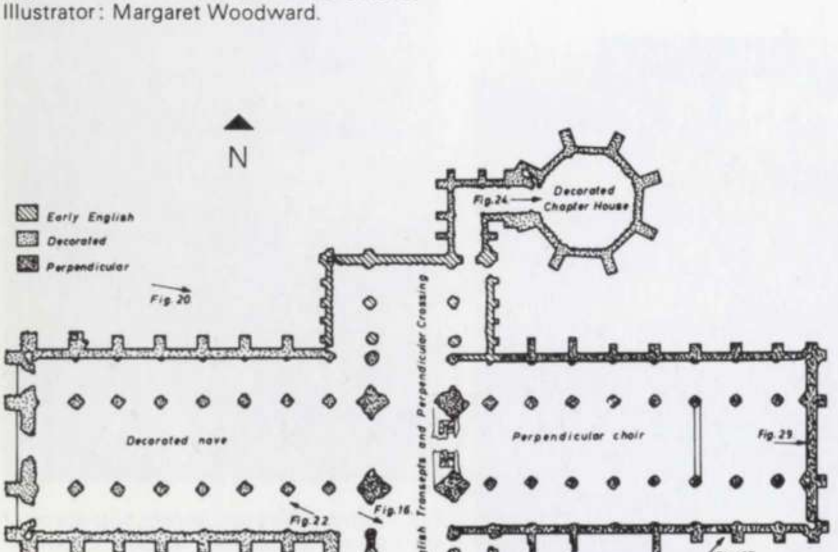


Fig. 25 Plan of completed Minster *c.*1500. Illustrator: Margaret Woodward.



school at York) *which included grammar, rhetoric, law, poetry, astronomy, natural history, arithmetic, geometry, the methods of calculating the date of Easter, and the study of the scriptures.'* (6) However, in general, it seems that the practical application of such subjects as geometry was weak and that setting out and standards of masonry were not high during this period, although particular evidence from York is fragmentary.

The Norman Minster

After the disastrous fire of 1069, Archbishop Thomas initially repaired the Minster but ten years later demolished it and started to rebuild from the foundations. No major part of this Norman building remains above pavement level but sections of walling and parts of staircase turrets are found adjoining the central tower at triforium level (about 50 ft. above pavement level). However, much of the present foundation is now thought to be of this date, whereas in the past the majority of architectural historians have considered it Saxon.

The latest conjectural plan, and it is necessary to stress its transient nature, is shown on Fig. 6. This shows a cruciform plan with a narrow aisled choir with an apsidal east end—transepts each with a single apsidal chapel, and an aisleless nave with a very large span, necessitating a crossing of similar dimensions. (The long transepts as shown on Fig. 13 may have been part of Thomas' Minster or early twelfth century additions—the tooling both on the north end wall of the north transept and on the staircase turrets (Fig. 31) is finer than that in the crossing (Fig. 9) though not as fine as that of Roger's Transitional choir.) (Fig. 12) Aisleless naves with clear spans similar to York's (45 ft.) built before about 1075 are found at Angers about 1010 (52 ft.), Speyer about 1030 (44 ft.), Hersfeld Abbey in Central Germany about 1037 (43 ft.), Reims St. Remi about 1041 (43 ft.) and Milan St. Ambrogio about 1070 (42½ ft.), but not in Normandy. Apart from York the largest span in England was Old St. Paul's in London (38 ft.).

The main foundations are continuous sleeper walls of rubble masonry and lime mortar about 6 ft. thick and up to 22 ft. wide, faced with squared stones and reinforced horizontally in both directions with oak balks roughly 18 in. square in section. These were discovered by John Brown in the nineteenth century and further investigated by Sir Charles Peers in 1930, and again in the present excavations. (Figs. 7, 8) By floating rods along ducts left by some of the balks which had rotted, it was shown that the foundation was continuous from the choir to the crossing and into the nave.

Inherent in the conjectural plan of the Saxon basilica (Fig. 4) was the assumption that the foundation sleeper walls of aisle and nave were incorporated into the wide Norman foundations. If this is correct it would be the first of several examples at York of the plan of a previous structure being a major factor in the design of the new building.

The masonry facing to the foundations is of indifferent quality with wide mortar joints utilising re-used Roman material, a mixture of oolitic and magnesian limestone and millstone grit, sometimes reworked with coarse diagonal axed tooling. (Fig. 9) Fragments of most beautiful Saxon crosses are also incorporated into these walls.

'The Norman date of these foundations is well established by associated pottery, the tooling on some of the stones, and the eleventh century date of one of the incorporated Saxon crosses. It follows that the walls on the foundations including the herring-bone walling in the crypt which has been said to be Saxon, are of Norman date. Similar herring-bone walling has been recently excavated in the north-south cross-wall on the west side of the crossing and in both the north and south

walls of the nave (Fig. 10) *where it is closely associated with Norman tooling. The same kind of walling associated with similar foundations and also of late eleventh century date occurs in the early Norman work at Richmond Castle.'* (*Herman Ramm*).

The limited physical evidence suggests that the structure of the building was simple and austere with little architectural ornament. It was plastered inside and out with the walls limewashed with false masonry joints painted in red. (Fig. 11) This treatment was presumably to keep the weather out of the wide joints and to disguise the variation in colour and size of the re-used stone. With the great improvement of masonry during the twelfth century this treatment for external walls was discontinued. Internally the plasterwork might well have been decorated in places with brightly coloured frescoes. The aisleless nave was stabilised with simple pilaster buttresses with engaged internal columns, 2 ft. in diameter.

The newel staircase in the north-east corner of the crossing was carried on a voussoir arch spanning across an earlier grave. (Fig. 12) On excavation only bone traces were discovered. This was not unexpected as the arch was walled up when Roger's choir was built in the twelfth century when the body was presumably translated. To merit this treatment the grave's occupant must have been of some importance, perhaps a Saxon king or saint.

Transitional Choir

The most striking difference between Saxon and Norman churches is that of scale. This is symptomatic of the eleventh century revolution in building.

'Whether or not we attach major historical significance to the millennial hypothesis—that men who believed in the end of the world at A D 1000 would devote scant attention to grandiose material projects—it is a fact it was the eleventh century that witnessed a profound change in outlook.' (7)

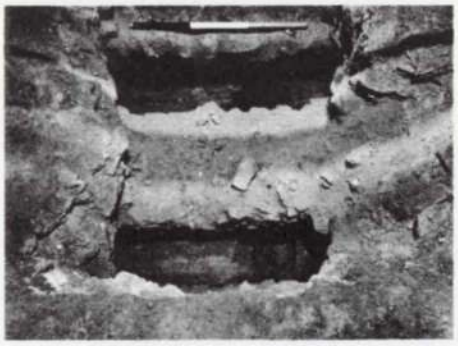


Fig. 7 left. Section of Norman foundations from above showing the east-west ducts left by the rotting of the oak balks and the remains of a lacing balk which run north-south at about 9 ft. centres.
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Fig. 8 below. An oak balk removed from the Norman foundations
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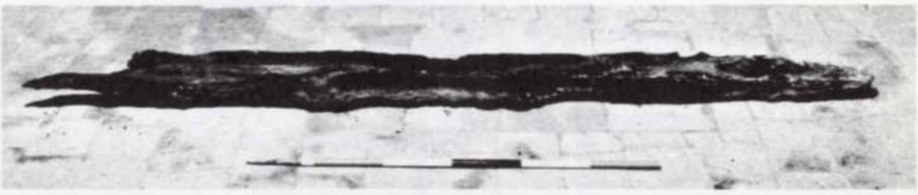

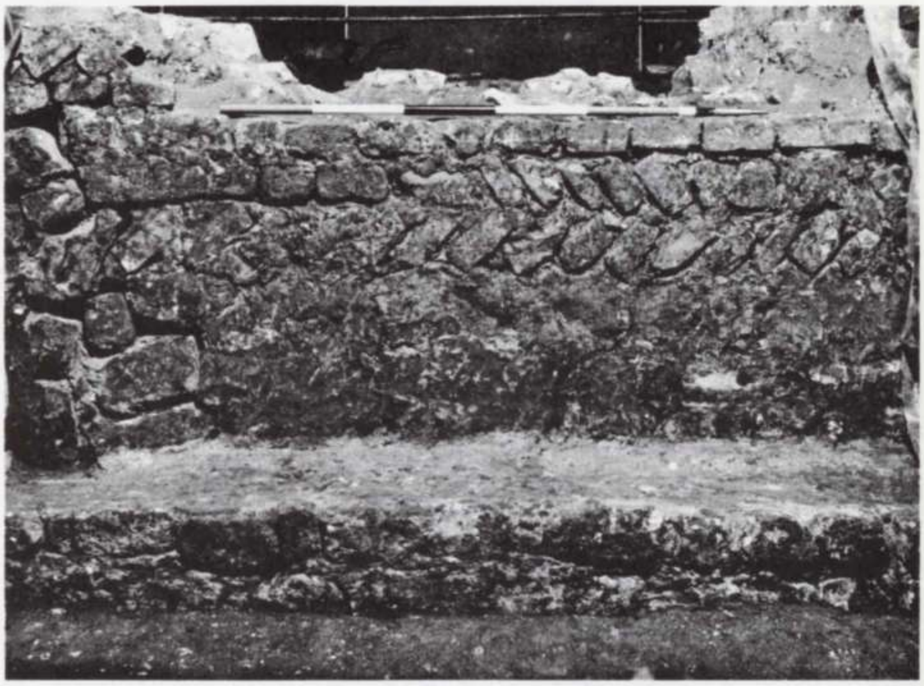

Fig. 10 above. Herringbone walling in the inside of the Norman wall at the east end of the nave, on the south side.
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Fig. 9 below. Junction of the south wall of the Norman nave and south transept, showing the top of the foundations and the first 3 ft. of the external walls. Superimposed on these walls is the Perpendicular south-west pier of the 15th century central tower.
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Fig. 11 above. Norman pilaster buttress on the east wall of the south transept showing limewashed plaster with imitation masonry joints painted in red.
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Fig. 12 right. Voussoir arch across grave in north-east corner of the crossing. The finely tooled masonry top left and clustered columns bottom right are the remains of the blocking wall of Roger's Crypt built in the second half of the 12th century. (Published with permission of Royal Commission on Historical Monuments (England). *Crown copyright*)

Fig. 14 right. A large transitional pier from Roger's Crypt. (Published with permission of Royal Commission on Historical Monuments (England). *Crown copyright*)

'A revolution was in progress, or rather a series of revolutions. The first stage is marked by the desire to build on a large scale, even if crudely . . . The second stage, far more concerned with niceties of design and capable of even larger buildings, occupied the second half of the century. About the year 1100 this second stage was itself overtaken by a third wave of still greater accomplishment.' (7)

John Harvey, who is quoted above, attributes the revolutions to contact with the Islamic world: The first and second stage by the Norman campaigns in Southern Italy (1030's) and Sicily (1060-90) and by the capture at Barbastro in Aragon in 1064 of several thousand Moorish prisoners. These almost certainly included *'a substantial number of craftsmen who possessed a degree of technical skill hitherto unknown north of the Alps and Pyrenees'*. (7) (It is known that the skill of prisoners was utilised in the west, Neath Abbey being built by the Saracen master mason 'Lalys' in 1129.)

The third stage of the revolution with its greater accuracy of setting out and improved workmanship is connected with the translation of Euclid's *Elements* and other texts from the Arabic into Latin by Abelard of Bath about 1120. This new acquisition of classical geometry swept through Europe in ten years. These developments coincided with the introduction of the pointed arch into Europe from an Islamic source and the birth of the Gothic style.

During the period 1154-81 Archbishop Roger repaired the nave of Thomas' church damaged in the fire of 1137 and built a new choir. (Fig. 13) It was Transitional in style, of the highest workmanship, as can be seen from the remaining piers and walling in the crypt: good examples of the changes which had taken place during the twelfth century. (Fig. 14) The masonry was of newly quarried magnesian limestone generally of a size which could be manhandled. The earlier foundations were utilized but must have been extended to the east and locally to the north and south. The choir was two-storeyed with steps leading up to the chancel and down to the crypt. This served two purposes—to give the high altar added prominence and to allow easy circulation of pilgrims past the shrines of saints or collections of relics in the crypt, which proved a most lucrative source of income. The new choir had either choir transepts or eastern towers, and Thomas' apsidal east end was probably replaced by a square-ended chancel as in most English churches of this date. This peculiarly English preference for square east ends is attributed by Pevsner to the *'English dislike of subordination. Parts . . . remain co-ordinated, added to one another, and in addition box-shaped rather than rounded'*. (8)

Early English Transepts

Between 1225 and 1250 the transepts and crossing were rebuilt and a lantern (or tower) constructed. Their plan is shown in Fig. 15.

Although it is impossible to establish the design criteria and their comparative weighting in the designer's mind from the finished building, certain inferences may be drawn.

It was clearly decided that the foundations to Thomas' transepts should be used where possible in the new work and that rectangular transepts of three bays should be constructed. The decision to build double-aisled transepts on a much larger scale than Roger's choir was presumably the client's who envisaged this as the first stage of a comprehensive rebuilding programme. Although this project took longer and a different architectural form than was envisaged, its fruition in the fifteenth century gave a cathedral with the 'classic' English plan with double-aisled choir, transepts and nave with central and western towers. It should be noted that 'classic' does not imply common, as very few English cathedrals conform in all respects to this plan. For example, double-aisled transepts are a comparative rarity in England although the norm in France. The only Norman examples are at Westminster and Ely and *'even in Gothic days but few of our abbeys or minsters indulged in the luxury of a double-aisled transept: Old St. Paul's; the Cistercian Abbey of Byland c.1170; Beverley and York c.1240; Westminster, 1245 (north arm only); Chester c. 1330 (south arm only); are the chief. It is found also in a few parochial or collegiate churches; e.g. Faversham; Patrington; St. Mary Redcliffe, Bristol'*. (9) It is interesting that four of these nine examples are in Yorkshire.

The transepts were built in the Early English style with the normal three storeys, arcade, triforium and clerestory. (Fig. 16) The arcades were positioned on the lines of Thomas' load-bearing walls with the eastern aisle wall built at a tangent to the apsidal chapel and the western aisle wall built on a new foundation. The arcade piers have clustered shafts of alternative stone and Purbeck marble with horizontal mouldings of marble or limestone at base, capital and midway between the two. These horizontal mouldings are a decorative device said to derive from the use of iron bands to restrain clusters of timber columns. However, at York, a moulding, presumably by its profile from a demolished Early English central tower pier, has been found in the excavation. From this, it seems that these horizontal bands are the exposed perimeters of flat slabs, the same diameter as the pier. (Fig. 17) They obviously serve a valuable structural function in tying the cluster columns together and the ashlar casing to the rubble core. The period's delight in contrasting materials is exemplified in a contemporary Latin poem describing St. Hugh's building of the new Gothic Cathedral at Lincoln from 1192:

'The dark Purbeck marble contrasts with the freestone, and instead of having a rough grain, shines with a high polish'.

'As for the slender shafts themselves, surrounding the great columns, you might think them a group of maidens in a round dance.' (10)

The relationship of triforium to clerestory is conditioned by the structural demands of vaulting the roof. The height of the triforium is defined by the width of the aisle and the slope of the roof. This is typically steep due to the wet northern clime and the roofing material which would have been either tiles or flat stone slates. (Fig. 18) Thus the large span and steep slope result in a tall triforium. Its architectural treatment is stylistically similar to Whitby Choir with its single semicircular containing arch with two pointed intermediate arches and four lower arches. (Fig. 17)

Within the triforium chamber underneath the aisle roof are internal flying buttresses (struts) to transfer the main vault thrusts to the external buttresses. These are of a pattern that first appeared in Durham nave which was finished in 1133. This method of abutment inevitably conditions the height of the clerestory which must be comparatively low due to the transfer of thrust from the springing of the vault to the internal flying buttresses. This reasoning and the conservatism of the North resulted in the low clerestory of five bays, three of which were glazed.

The way to increase the height of the clerestory and thus the light inside the building is to increase the height/span ratio of the building and utilise external flying buttresses. (Fig. 19) This, of course, was the classic Gothic solution. It is interesting to note that the transepts of York and Amiens were being constructed concurrently. York has a height/span ratio of approximately two and Amiens, employed a more highly developed skeleton construction system with external flying buttresses, a little over three.

In the north transept the problem of lighting was solved in the 'revolutionary treatment' of the north wall by the suppression of the three normal storeys into one in the form of huge lancet windows, the Five Sisters. (Fig. 20)

Pinnacles were built on the corner buttresses but not on the flanking buttresses. This was quite normal as corner pinnacles had been employed widely in the Norman period, but flanking pinnacles were not used extensively in this country until the fourteenth century; *'the early practice was to give a flanking buttress no finial except a saddle-back roof to keep the rain out of the joints. This then was the first step towards a pinnacle; a mere gable; e.g. in Whitby Choir; in York Transept . . .* (9) (Fig. 18) Amiens had fully developed pinnacles in about 1230. Both types, apart from their decorative properties, serve the same function of providing an extra vertical component to 'straighten' the thrust line towards the top of the buttress.

As previously mentioned, the stone vaults over the main spans (the aisles have masonry vaults) whether for reasons of cost or timidity were never completed although some stone springings were provided. The wooden vaults are an anathema to the 'structural truth brigade', Bond in 1905 is its admirable spokesman; *'Whether vaulted or semi-vaulted in wood, such roofs are objectionable as being a reproduction in one material of forms which arose out of the nature of another'.* (9)

Of the Early English lantern, very little is known save that it was famous for its beauty when it collapsed in 1407. The archaeological dig has revealed that extra footings were added to carry this lantern on the west side of the crossing. The excavations have also shown that the bells for this lantern were made in a foundry in the north transept, the collapsed moulds of two bells, being discovered at Norman floor level. Piles of masonry have been found in the same area which may have been packings around the shear legs used in handling these bells.

Decorated Nave and Chapter House

A new nave to replace Thomas' Norman nave was begun in 1291 and finished in 1343. Its design probably by Simon the Mason was conditioned by this aisleless nave. Simon positioned the main arcade piers on the line of the Norman walls to give a main span of 52 ft. centre to centre and chose an aisle span and arcade spacing of 26 ft. centre to centre, resulting in square aisle bays and double square main bays. (Fig. 21)

Apart from its scale and its wooden vault, it is quite different from the transepts. The method of abutment (as once more it seems a stone vault was contemplated) and thus the division of its three storeys, is quite different and the tracery and mouldings are in the Geometric Decorated Gothic style rather than the Early English.

The arcades are of similar size but the triforium is an interesting step in the development from a large triforium, as in the transepts, to its final elimination in the late Perpendicular churches such as Bath Abbey; *'to reduce the height of the triforium stage, the lean-to roof (of the aisle) is much flattened to minimise its importance, a blank wall is built in front of it and the jambs and clerestory mullions of the windows are brought down to the sill of the triforium (c.f. Southwell 1233 and St. David's 1190). The result is, to the eye, to make the internal elevation, one of two storeys, instead of the traditional three.'* (9) (Fig. 22)

In fact this development from three to two storeys is the effect on architectural expression of change in material and structural system. For example, at York with the use of lead as a roofing material the slopes of the aisle and main roofs are reduced. Thus from the utilisation of the same overall height a large clerestory results. If a masonry vault is envisaged this necessitates an abutment method employing external flying buttresses and flanking pinnacles. It does seem that provision was made for a masonry vault although the question of the existence of flying buttresses as part of the original design is a vexed one, for they were rebuilt in about 1902 after being dismantled in the eighteenth century. (Figs. 20, 23) With the employment of lead as a roofing material shallower roof slopes were made possible, as the lapped joints of lead sheets were more efficient at keeping the rain out than tiles or shingles, and advisable owing to the 'plastic flow' of the sheets under gravity which tended to tear the sheets from their fastenings. *'In the fourteenth and fifteenth centuries the output of lead in England was at least equal to that of Central Europe and in fact was the greatest of any single kingdom or country in the world.'* (11)

It has been said that the nave was vaulted in wood for one of three reasons: timidity due to the slenderness of columns and walls; the technical inability to vault such a large span; economic considerations. The reason may

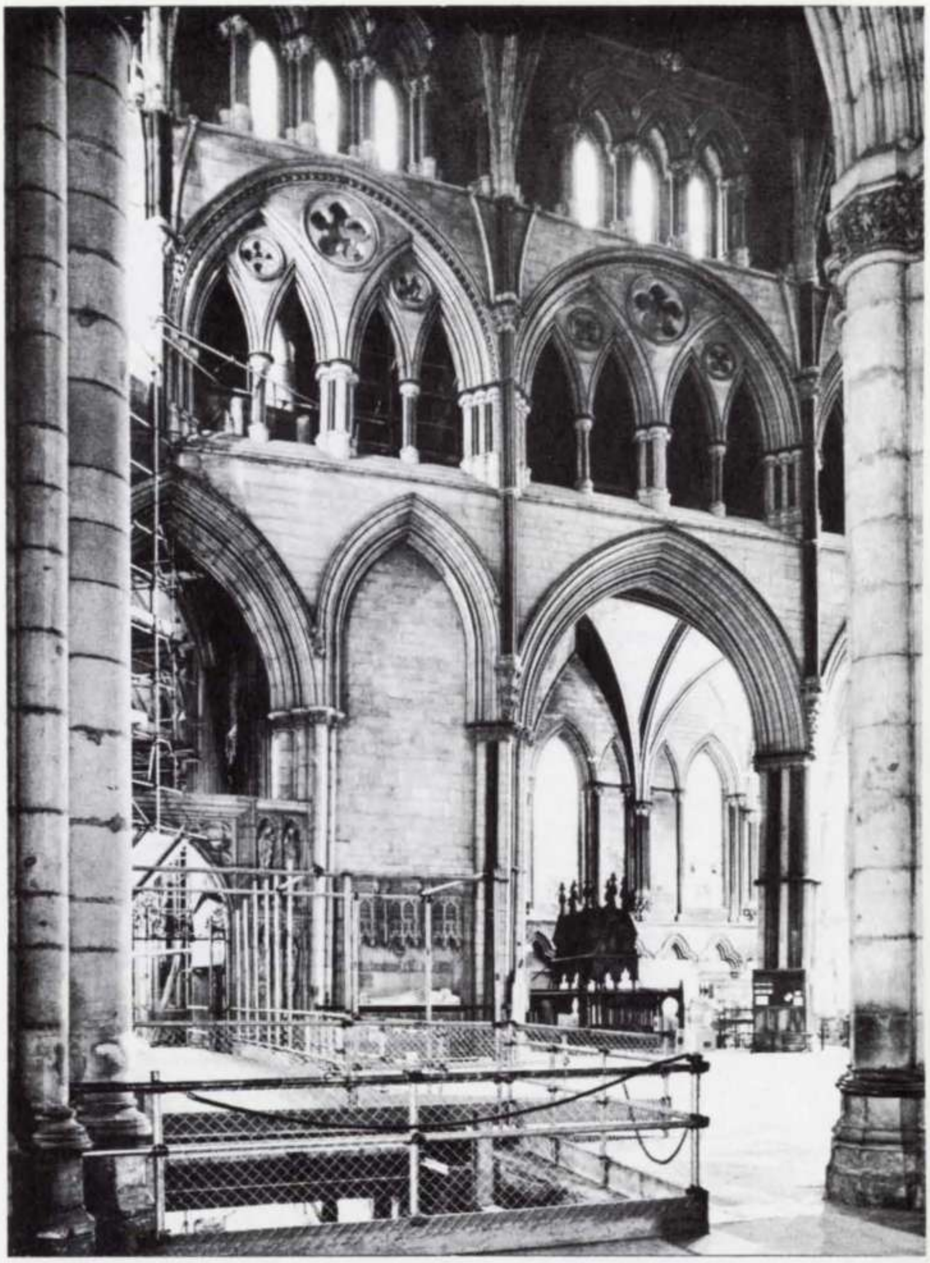

Fig. 16 above. Early English south transept from the south aisle of the nave. The furthest left arcade bay and its narrow neighbour were rebuilt in the Early English style in the 15th century and the narrow arcade arch blocked up in the 18th century.
(Published with permission of Shepherd Building Group Ltd.)

Fig. 17 below. Early English 'slab moulding' which ties together a group of clustered columns. (Published with permission of Royal Commission on Historical Monuments (England). *Crown copyright*)

have been a combination of all three but the stresses in the nave columns are comparatively low and Lincoln Presbytery (1255-80) had a ribbed vault with a clear span of 40 ft. It is also significant that other major Yorkshire churches of much smaller spans than the Minster were vaulted in wood during this period, e.g., Ripon choir started by Romanus in 1286 and the choir of Selby Abbey (1280-1340) which has provisions similar to York's for a stone vault. This tends to suggest there was a northern preference for the use of timber and that it was linked to latent conservatism or economic considerations.

The wall of Thomas' aisleless nave was replaced by an arcade and an aisle wall built on a new foundation a bay width outside this line. The two operations could have proceeded simultaneously with the outside wall being constructed while sections were cut out of Thomas' wall for the construction of the arcade piers which are approximately 8 ft. in diameter, the thickness of the Norman wall. Arches could have then been constructed with the minimum of centering supported off the existing wall. This formwork would have then been struck after about a year (mediaeval mortars were very fat) and the remaining sections of wall demolished. The aisle vault (in stone), triforium and clerestory would have then been completed. Evidence that the arcade was built in a manner similar to this descrip-

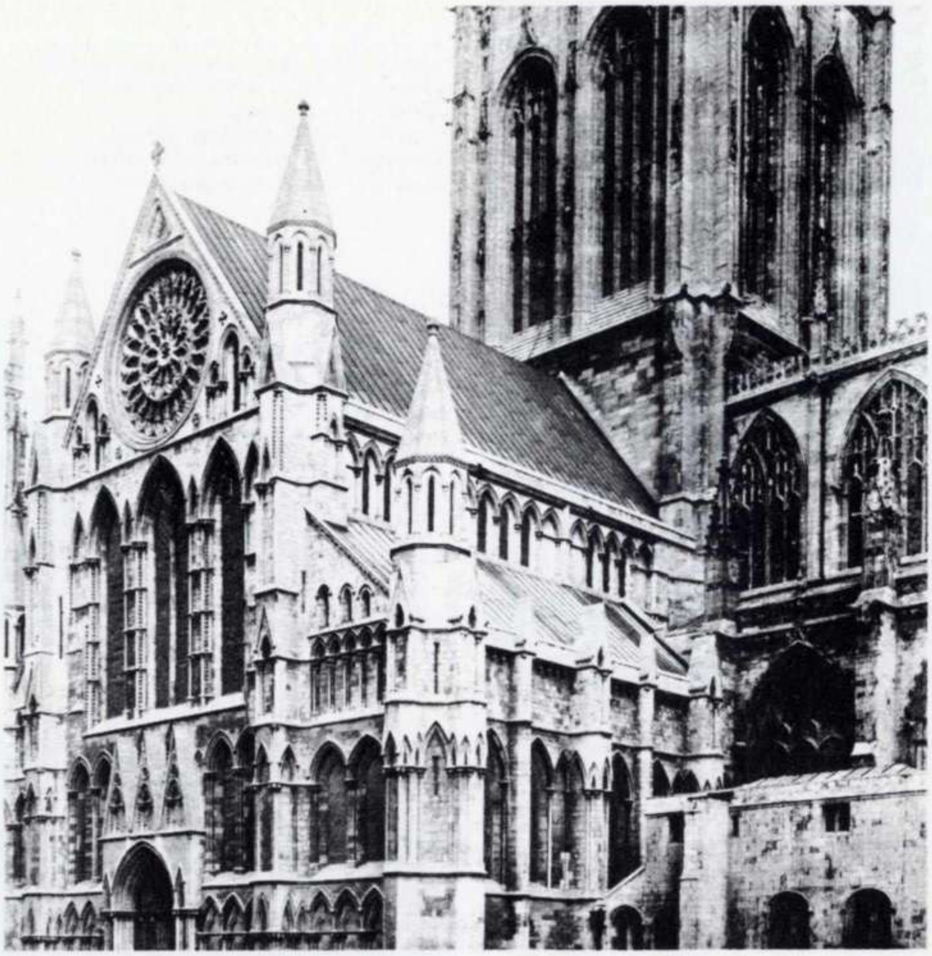

Fig. 18 above. South transept from the south-east. (Published with permission of Royal Commission on Historical Monuments (England). *Crown copyright*)

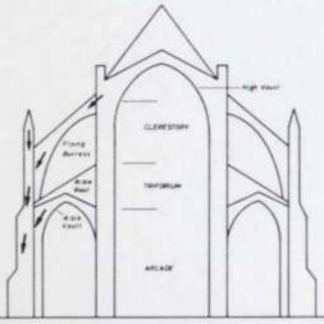

Fig. 19 left. Diagram of the 'classic' Gothic cathedral showing the function of the flying buttress.
Illustrator: Eleanor Grover

Fig. 20 below. The Minster from the north-west painted by Paul Sandby Mann *c.*1800. From left to right the chapter house and vestibule, the north transept with the Five Sisters window, the central tower, the nave and the western towers. (Published with permission of Royal Commission on Historical Monuments (England). *Crown copyright*)

Fig. 22 left. The nave looking north-west from the south aisle showing the geometric decorated tracery and the treatment of triforium and clerestory.
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Fig. 23 below. The Minster from the south drawn by Wenceslaus Hollar in the 17th century, showing provision for flying buttresses on the nave.
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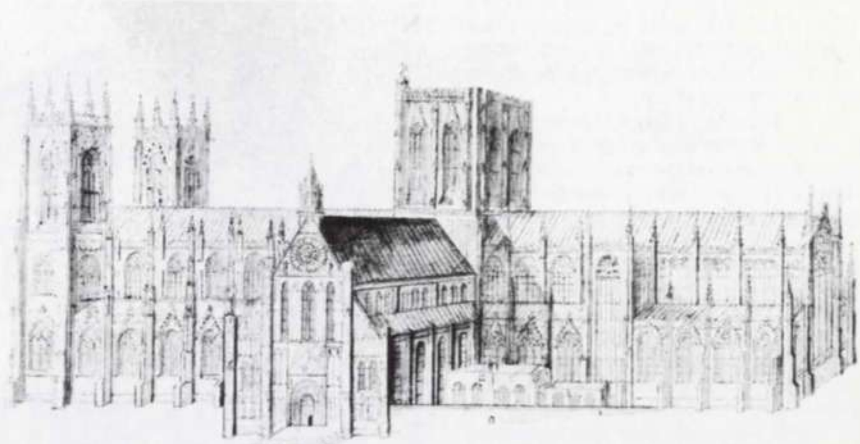


tion, is the Norman masonry found in the triforium and spandrels of the arcade which seems to be in situ rather than re-used.

The roof from which the vault is suspended was constructed between 1354 and 1370 by Philip of Lincoln, the master carpenter.

The octagonal chapter house has a timber vault similarly suspended from a very indeterminate roof structure: *'essentially based upon the tie beam and king-post truss, the roof is not a constructional novelty but is a remarkable example of prefabrication on a very large scale.'* (¹²) This use of timber enables the central pier, which is a feature of the masonry vaulted polygonal chapter houses such as Worcester, Lincoln, Salisbury and Wells, to be omitted giving an unrestricted space.

The building is remarkable for its scale and beautiful glass walls. (Fig. 24) The sculptural details of the stalls and canopies are no less remarkable, as, in a slightly incongruous way, are the external buttresses.

Perpendicular Choir

During the first half of the fourteenth century the Perpendicular style developed in England. Its main features were the uniformity and repetition of bay design, concern with natural lighting, and greater co-ordination between both the individual parts of the cathedral and its three storeys—arcade, triforium and clerestory.

In 1361 the Archbishop and Chapter decided to build a new choir as Roger's choir seemed 'rude' in comparison with the beauty of the nave. In the same resolution they made the very Perpendicular statement that *'every church ought to have its parts consistently decorated.* (⁴)

The work appears to have started with the demolition in 1362 of the Church of St. Mary ad Valvas which stood to the east of Roger's choir (the parish boundary passing through the third bay of the present Perpendicular choir). Excavations outside the east end have shown an early twelfth century Norman wall and Saxon foundations, which continue beneath the Minster's east wall. It is assumed

Fig. 24 The interior of the chapter house. (Published with permission of Royal Commission on Historical Monuments (England). *Crown copyright*)

that the eastern bays were built leaving Roger's choir intact. The foundations seem to have been constructed by simply digging a trench about 8 ft. deep and slightly wider than the proposed wall which was filled for about 5 ft. with rubble and mortar above which were roughly laid several courses of re-used Norman stone. At this stage of the investigations it certainly seems that although the superstructure shows a high standard of skill and workmanship, the foundations leave much to be desired.

The designer was probably the master mason William de Hoton. He conceived a choir, in the new style, of similar dimensions to the nave, with an almost identical horizontal and vertical grid although one bay longer and slightly narrower overall. (Figs. 25, 26) The vault is of wood and it is not clear whether provision was ever made for a stone vault, although pinnacles and stone springings were provided. An interesting structural device is the use of double mullions on the windows to take the wind loads on the large areas of clerestory glass. On Hoton's eastern bays the extra mullions and clerestory passage are on the exterior and are most awkward in detail whereas on the later work they are internal and elegantly treated. (Fig. 27) The dating is underlined by the tracery in the eastern bays retaining some curvilinear traces which are absent from the later work.

After a delay between 1372-80 these remaining bays were completed by about 1400 by Hugh de Hedon following the plan by William de Hoton including the backfilling of Roger's crypt and the construction of a small crypt under the fourth and fifth choir bays. To minimise the period when the choir could not be used it is likely that the aisle walls and buttresses were built on new foundations without disturbing Roger's choir. Similarly, that the construction of arcades was begun in the aisles of the existing choir, utilising its raft foundation, whilst it continued to be used. (Doubt is cast on this 'traditional' view of the construction sequence by the recent discovery of masonry of Roger's date in the foundations of the east wall including what could only have been part of an arch on a scale that would only have been found in the arcade of a major church.)

The east window was designed and built by Hugh de Hedon between 1400 and 1405, a contract being let in the latter year to John Thornton of Coventry for its glass. (Figs 28,

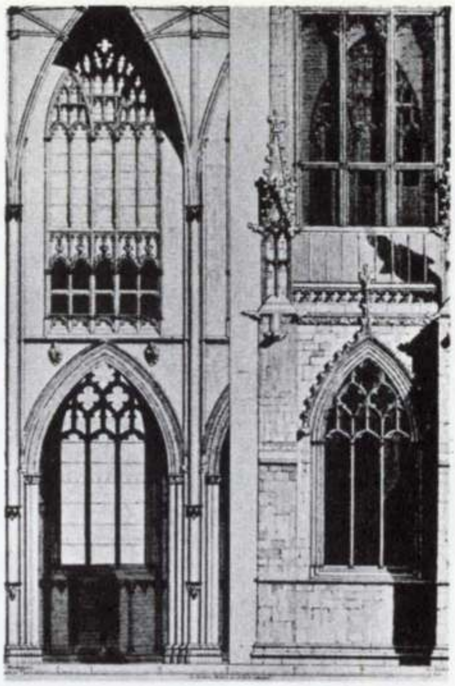


Fig. 26 above. Internal and external elevation of one of William de Hoton's eastern choir bays from a 19th century engraving from BRITTON'S *Cathedral Antiquities.* (Photograph by P. Beckmann from BRITTON, plate xxiv)

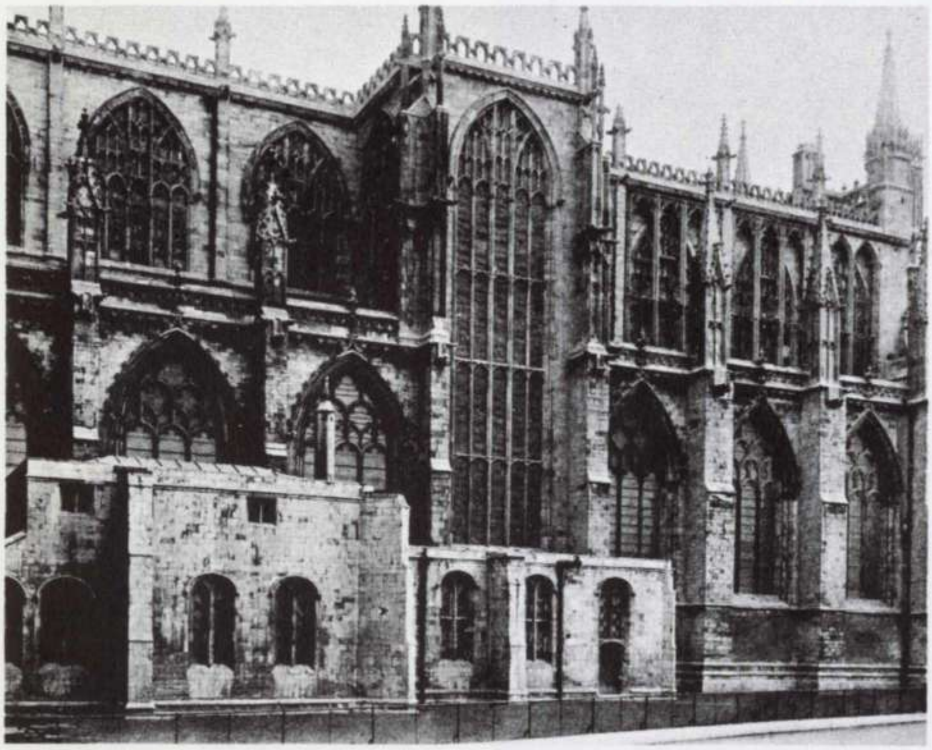


Fig. 27 The Perpendicular choir from the south with left to right two of Hedon's bays, the south choir transept and Hoton's eastern bays with their external double mullions and clerestory passage. Unlike the transepts (Fig. 18) the roof cannot be seen from this angle, hiding behind its pierced battlement. (Published with permission of Royal Commission on Historical Monuments (England). *Crown copyright*)

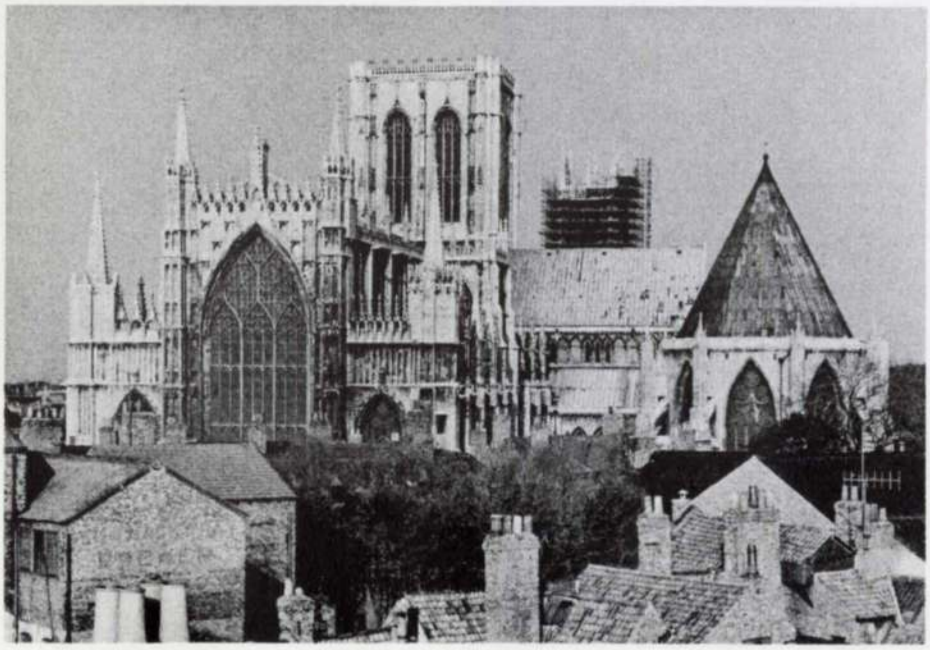


Fig. 28 The Minster from the east. (Published with permission of Royal Commission on Historical Monuments (England). *Crown copyright*)

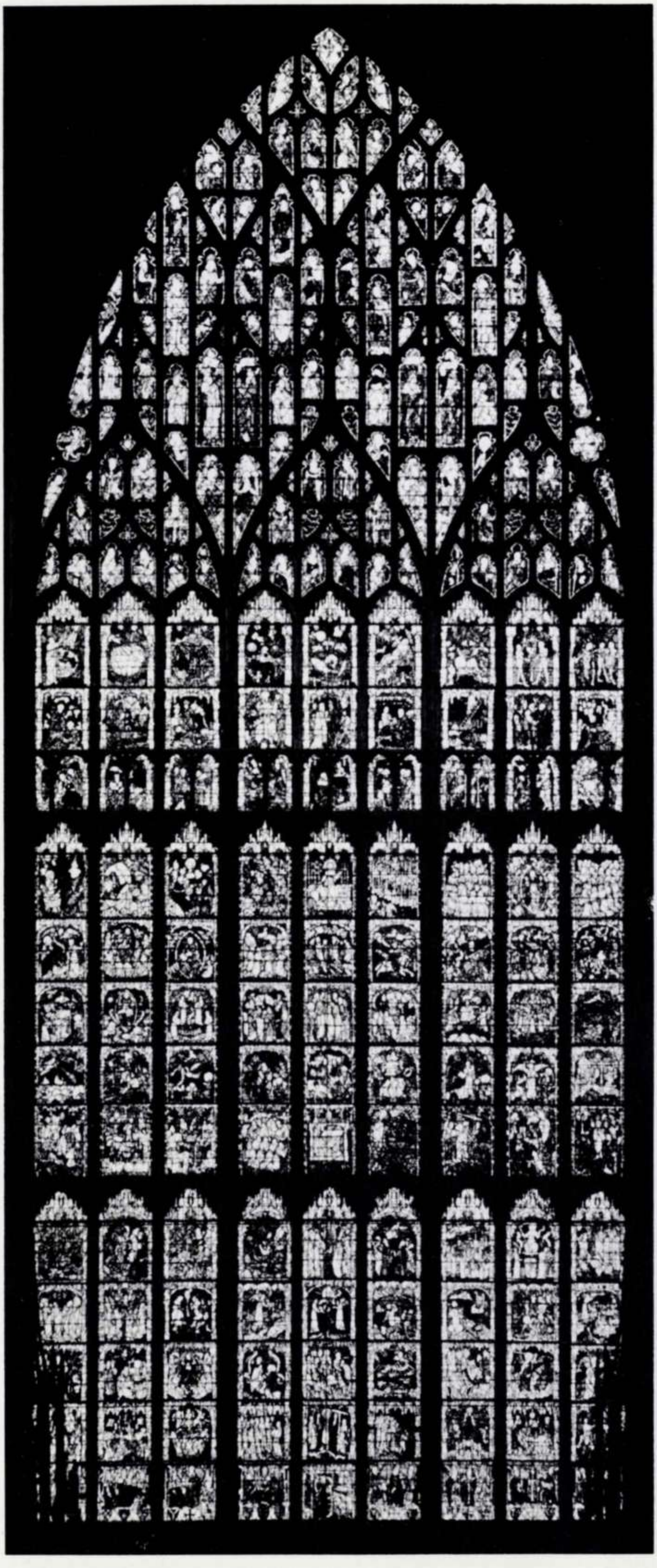


Fig. 29 The great East Window. (Published with permission of Royal Commission on Historical Monuments (England). *Crown copyright*)

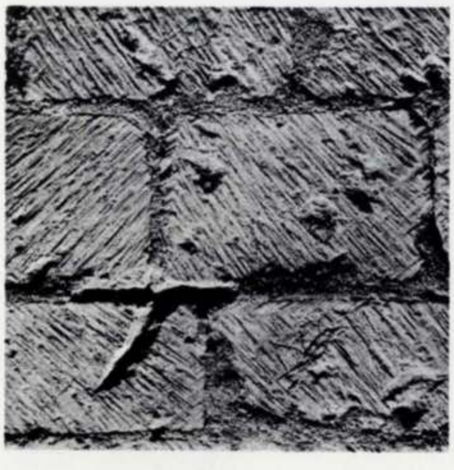
29). This beautiful window, 'the size of a tennis court' is most remarkable, although if teaching were one of the main functions of stained glass, then mediaeval eyesight was even more remarkable. Thornton designed similar windows for the choir transepts. These transepts were built on the foundation of Roger's eastern 'towers' and are simply three-storey structures in place of an aisle bay. (Fig. 27) Visually they serve a most useful purpose in effecting the transition between Hoton's and Hedon's tracery design. Another exterior feature is the ornate battlement, a decorative device which developed with the use of lead-covered roofs with shallow slopes.

Such men as William de Hoton and Hugh de Hedon were technically highly skilled, having spent several years learning the mysteries of their profession. These included—the various modules, series, methods of sub-division and empirical rules used in design; drawing; and the principles of Euclidean geometry used in setting out.

'By crafft of Ewclyde mason doth his cure,
To suwe hoes moodles ruyle, and his plumblyne' (*Lydgate*). (13)

Fig. 30 The tracing floor above the chapter house vestibule. Detail (about 12 in. x 18 in.) near to the west wall. (Published with permission of Royal Commission on Historical Monuments (England). *Crown copyright*)

Fig. 31 Norman masonry from the remains of the newel stair at triforium level by the south-east pier of the crossing. The blocks are newly quarried magnesian limestone with diagonal axed tooling and three mason's marks; five point stars. (Published with permission of Royal Commission on Historical Monuments (England). *Crown copyright*)



It seems that the design of plan and elevation was based upon many complicated geometrical systems which were passed from master to pupil and were probably closely guarded secrets. Structural design was determined not by theoretical analysis but by a set of empirical rules and good practice. This is illustrated by R. J. Mainstone in a recent article: *'All flying buttresses in the great northern churches prior to the second half of the twelfth century seem to have been added as casual expedients only after weaknesses had become apparent'*. (14) Obviously, design was also affected by material and economic considerations—the quality of the stone, the type of roofing material, the length of trees available, etc.

Drawings of several types were produced for a variety of purposes—sketches, working drawings and presentation drawing for the client. Very few drawings earlier than the fifteenth century survive in England but Europe has examples of all types. Amongst the earliest examples are those contained in the album of Villard de Honnecourt written around 1250. It contains notes and sketches of buildings, architectural details and machines which he admired on his travels through Europe. He was almost certainly a master mason, head of a cathedral (or abbey) lodge who compiled this album for the instruction of his pupils. There are additions at later dates suggesting a continuity of use for technical purposes.

'Molds' or 'patterns' of the mouldings to be used in the building were made of various materials including fir boards, canvas and lead. They were produced from a drawing either drawn on vellum or paper or incised in the surface of a plaster floor. In England such floors exist at Wells and at York on top of the masonry vault of the chapter house vestibule. (Fig. 30) The templates were either given or sent to the masons on site or at the quarry. 'Roughing out' was often done at the quarry as transport was so expensive. *'At York Minster the cost of carriage was particularly serious as all stone had to be carried by cart from the quarry to the river port (Tadcaster in the case of Thevesdale) thence by boat to York and finally by sled from the river to the Minster. In 1400 the wages paid to quarriers at Thevesdale amounted to £18 whilst the cost of carriage of stone to York amounted to £18.6.4.'* (15)

Two marks were often cut on the finished stone, one to identify the mason for administrative purposes and the other to designate its position. (Fig. 31) Similar position marks were often incised on the timbers of prefabricated roof trusses and there are many on the members of the chapter house roof.

Setting out was done with cords, measuring rods and large dividers, right angles being formed by three pegs and a cord to form a 3,4,5 triangle. There is some evidence that levelling instruments similar to those described by Vitruvius were also used. (It is known that copies of his work were in libraries at Bury, Ely, York and Canterbury.)

With the increasing use of scale drawings and improved technical knowledge there was a general improvement in standards of building throughout the thirteenth and fourteenth centuries.

Throughout the mediaeval period there was a revolution in machine design: *'the eleventh and twelfth centuries had applied the cam to a great variety of operations. The thirteenth century discovered the spring and treadle: the fourteenth century developed gearing to levels of incredible complexity; the fifteenth century, by elaborating crank, connecting-rod, and governor, vastly facilitated the conversion of reciprocating into continuous rotary motion'*. (16)

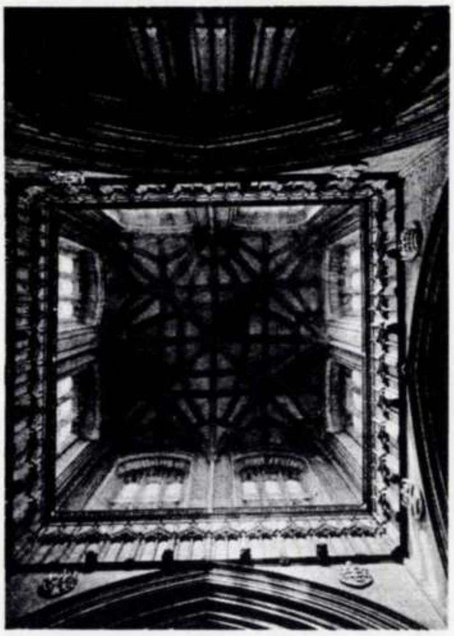


Fig. 32 William of Colchester's lantern from beneath. (Published with permission of Royal Commission on Historical Monuments (England). *Crown copyright*)

This obviously affected the building industry with larger and more efficient machines being used, demonstrated by the more widespread use of very large masonry blocks in later work. At York, the trend is illustrated by the gradation in size from the Norman to the Perpendicular work. (It is certain that the millstone grit blocks in the Norman staircase were lifted by mechanical means but the majority of the stones of this period could be manhandled, whereas most of the Perpendicular masonry must have been handled with a crane of some form.)

Perpendicular Towers

During the fifteenth century a new central tower and the two western towers were constructed. The new central tower was necessitated by the collapse of the Early English lantern in 1407. It is thought that this was due to a failure of the temporary underpinning then in use, while the crossing beneath was being revamped ('consistently decorated') in the Perpendicular style. However, it would not have been surprising if the collapse had been due to bad design or construction, for many of the great Norman towers had collapsed by this date, e.g., the central towers of Beverley, Ely, Winchester and Worcester and the western tower of Hereford. The Gothic towers were similarly inclined, the first tower at Lincoln falling in 1237 and extensive remedial works being necessary at Wells and Salisbury.

The functions of central towers were threefold—to give drama and a focal point to the exterior, to introduce light into the crossing and to give added vertical load to the crossing piers; to 'straighten' the lines of thrust from the 'unrestrained' arcade triforium and clerestory. Whether this last was ever a valid reason or merely incidental, central towers became a structural liability owing to an excess of weight. This gave rise to very large thrusts at the springing of the main tower arches which tended to distort the surrounding arms, particularly the transepts, which, as they are generally shorter and have fewer bays than the choir or nave, have less racking resistance. At Worcester, diagonal ribs were incorporated in the design of the fourteenth century nave and at Salisbury, strainer arches were inserted about 1400 on signs of distress.

The central tower was designed by William of Colchester and a substantial part was completed upon his death in 1420. After this, it seems that progress was slow, the tower being finally completed in the 1470's. It is the largest lantern of its type in England with a plan 52 ft. square (centre to centre of the crossing piers), an internal height of 180 ft., with 62 ft. to the capitals and 92 ft. to the apices of the crossing arches. (Fig. 32) Of course, it was almost inevitable that this lantern was built on such a grand scale, as the spans of the surrounding arms were also the largest in the Kingdom.

The Perpendicular central tower piers were more extensive than their predecessors, necessitating the alteration of the transept arcades as the nave aisle would otherwise be almost blocked by these piers. As the plan of the cathedral on completion of the Early English transepts is uncertain, the extent of Colchester's alterations is similarly undefined. However, it appears he rebuilt the arcade of the third bays of the transepts underpinning the triforium and clerestory, and inserted two arches, one of them much narrower than the other. (Fig. 16) This work was sympathetically done in the Early English style of the transepts, which is not particularly surprising, as William of Colchester was the pupil of Henry Yevele, who built the nave of Westminster Abbey in the thirteenth century style of the rest of the building. During the fifteenth century the narrow arch on the west side of the south transept was blocked up with masonry.

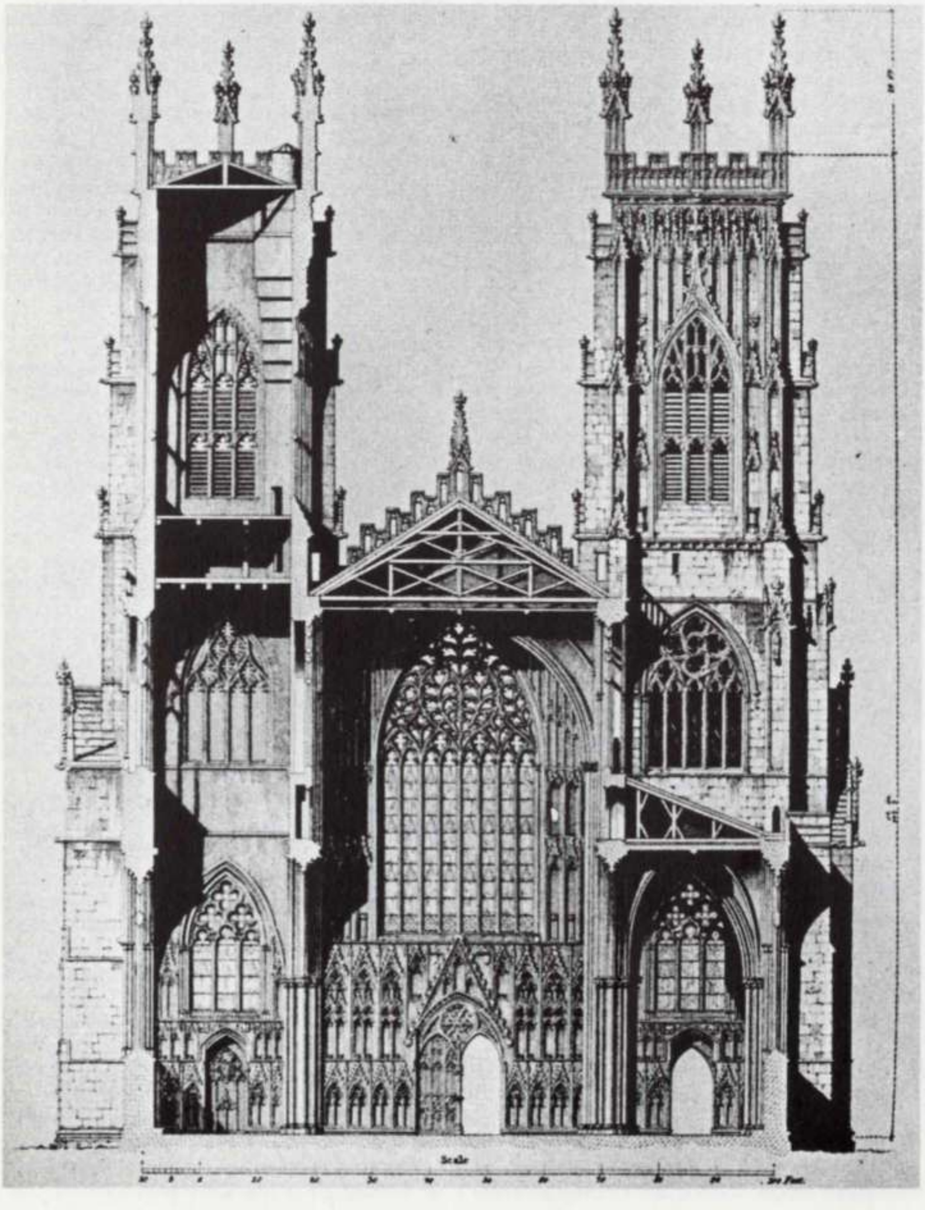
The remaining parts of the Minster to be completed to give the entity visible today, were the two western towers, the south-west (1432-56) by Thomas Pak and the north-west (1470-74) by William Hyndeley, who also designed and built the central tower vault (in wood once again), and the Rood screen (1475-1500). (Fig. 33)

Since completion the Minster has been repaired on many occasions, the major restorations being noted in the first article. The most significant of these, structurally, appear to be Lord Burlington's in the 1730's and Sir Robert Smirke's after the fires of 1829 and 1842.

Burlington strengthened the central tower and blocked up the three remaining narrow arches in the transepts. He was presumably concerned with the distinct racking of these transepts, apparently due to thrust from the central tower (the narrow arch in the south-west arcade had been blocked up during the fifteenth century).

Smirke restored the roofs, vaults and damaged masonry. This included re-facing parts of the choir and nave piers, replacing many of the mediaeval stones with veneers of magnesian limestone. He also reinstated Roger's crypt after Browne's excavation, supporting the choir floor on brick vaults.

Fig. 33 The 15th century western towers from a 19th century engraving from JOHN BRITTON'S *Cathedral Antiquities*. (Photograph by P. Beckmann from BRITTON, plate xxix)



Acknowledgements

I would like to thank Herman Ramm, Eric Gee and John Harvey of the Royal Commission on Historical Monuments for their kindness and patience and their invaluable help in the preparation of the two articles.

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Corrigenda

There were some errors in Part 1 of this article (*The Arup Journal*, May 1968).

1. Fig. 2 page 53 should read 'The Minster from the south'.
2. Para. 7, third column, page 54, line 9, 'harbours' should read 'arbours'.
3. Para. 7, second column, page 56, line 6, 'mome' should read 'morne'.
4. **References** third column, page 58. Eliminate references 2, 7 and 20, number references consecutively and then they are correct.

Editorial note: This ends part 2.
The final articles have not been thought of yet but it should be published in due course.

The rebuilding of the London Stock Exchange: Founding the tower

J. N. Martin and P. J. Thompson

First, it should be explained why a tower is wanted at all, when the Stock Exchange is basically a market, its business being done like any traditional market in a large clear space with stalls specialising in the sale of different kinds of stocks and shares. For the Stock Exchange already had a large enough market space—the Floor of the House as it is called—and antiquated though arrangements seem to be, particularly their system of communications, nevertheless things apparently run very efficiently. There is a lot to be said for the directness of just shouting when you want somebody, and if further refinement be needed, why look for anything more sophisticated than a system of illuminated numbers to be switched on to summon an elusive broker.

The main reason for pulling down the old building is basically that the higgledy-piggledy collection of fairly low office buildings, together with the House itself which they surrounded, were a very wasteful use of one of the most valuable sites in London. Firms of stockbrokers and jobbers have to be accommodated in offices right away from the Stock Exchange. Admittedly, stockbrokers have their boxes at the Stock Exchange from which they maintain a vital telephone link with their base, but conditions are not ideal for them however smoothly business may go in the market itself.

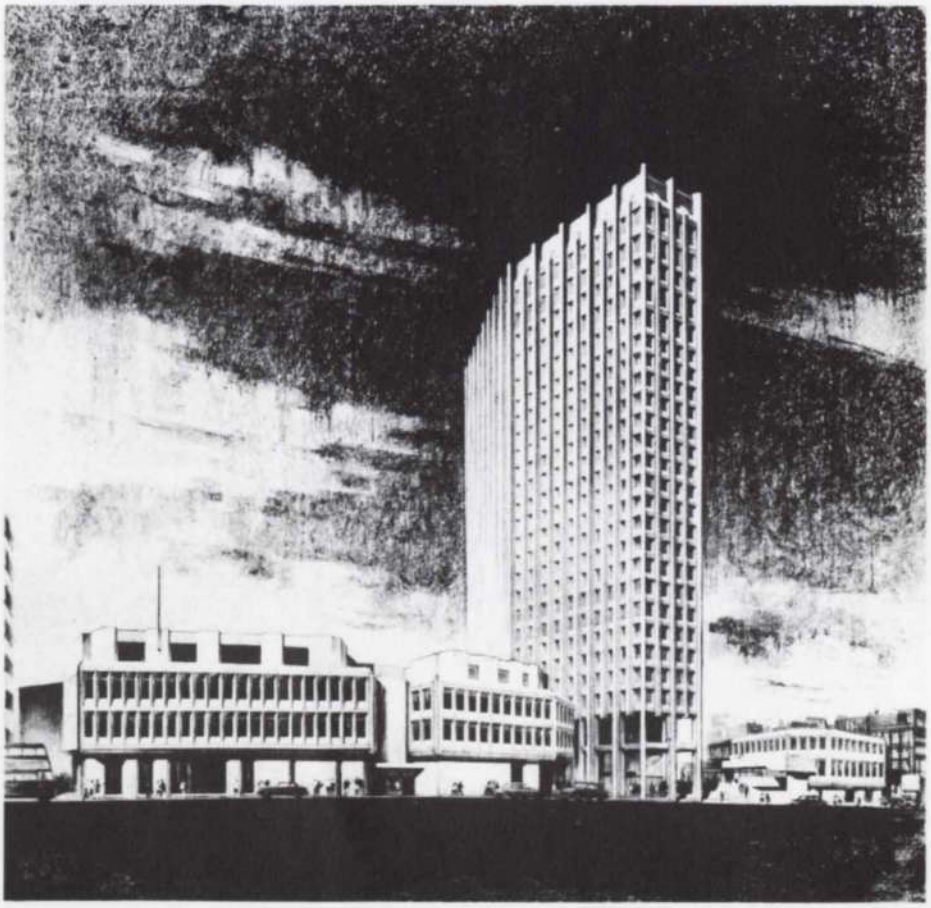
Thus the aim of the reconstruction is both to provide as many offices on the site as possible, and also to give the market better ancillary accommodation. The offices will belong to the Stock Exchange and be let only to member firms of the Stock Exchange and although the new market will be about the same size as before, there will be room for more and better boxes. There will also be a new post office, some private offices, and a cinema and public viewing gallery.

Once the accommodation requirements and planning limitations were established, the form and arrangement of the new Stock Exchange were fairly well fixed. There was no possibility of moving the Market to another site during the rebuilding and it has been necessary to squeeze it up a bit to one half of the site, whilst Trollope & Colls build the office tower, the post office and the public concourse areas in between. Once this stage is over, a temporary market is built in structural steel and precast concrete planks, using some of the lower floors in the tower together with the post office roof and by filling in the four-storey gap over the concourse between the tower and the post office. Everyone now changes sides and the other half is built. This broadly consists of the new Market, car park and service floors under a small block of offices including a merchant bank, and the public parts of the Stock Exchange.

The office tower is 26 storeys and 325 ft. high and has a rather irregular coffin-like shape on plan. The shape resulted from the planning limitations of the site and is not so wilfully odd as might appear. So far work on the tower

Fig. 1 The Stock Exchange before reconstruction, aerial view. (Photo: Fairey Surveys Ltd.)

Fig 2 The new Stock Exchange. (the architects' perspective)



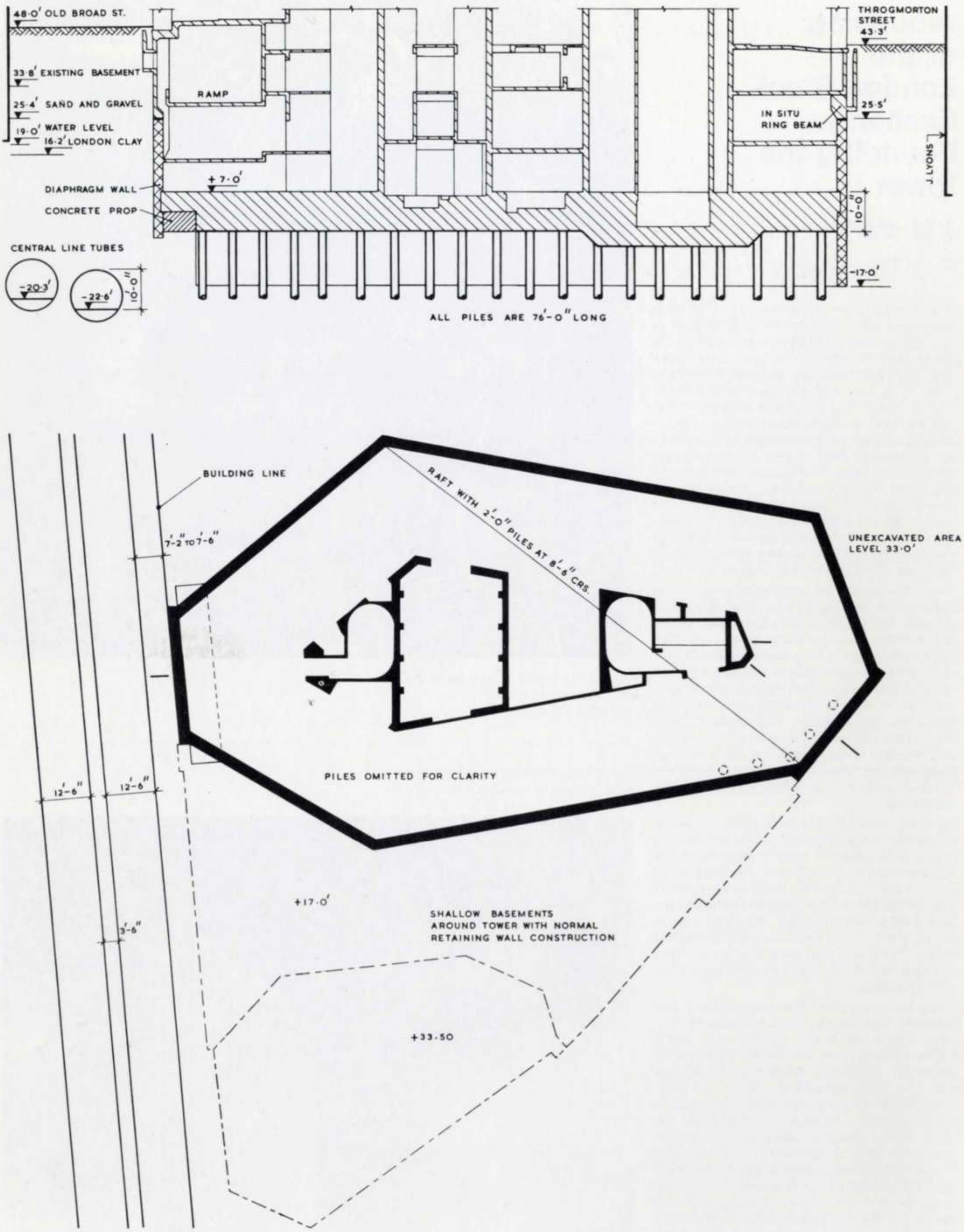


Fig 3 The tower block and the Central Line tubes. (Illustrator: Margaret Woodward)

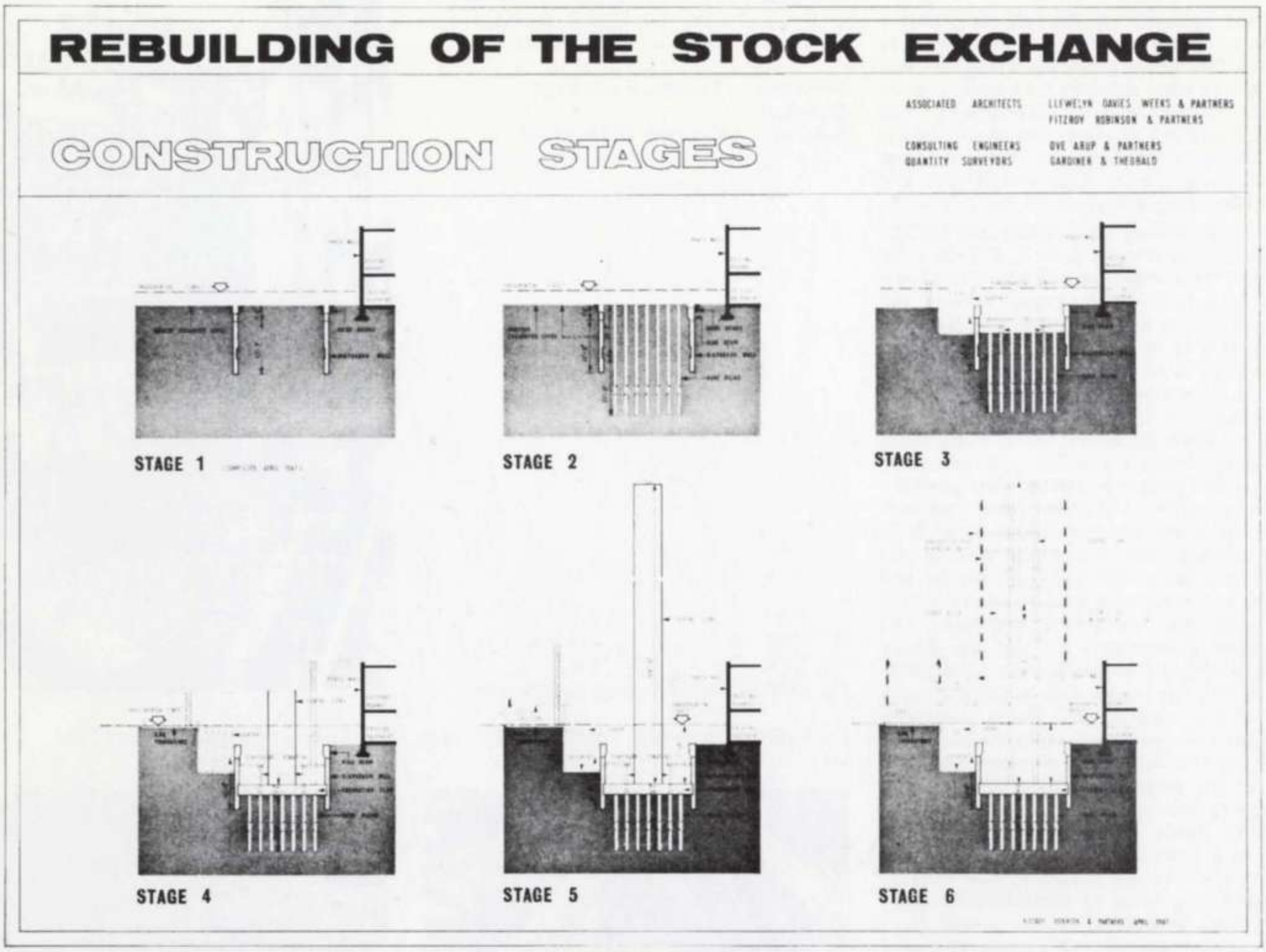


Fig 4 Stages in the construction of the tower foundations.

has just got to the point where the sub-structure is complete and the core has been cast to the top by slip-forming. This article is concerned with the problems of the foundations and the sub-structure which, at times in the design stage, were threatening to get quite out of hand.

In general, the whole of the site presently being worked on already had a basement of one storey and, above that, fairly heavy buildings of three or four storeys. In the middle, the House itself had one lofty storey with a domed and vaulted roof. Under the site, there is gravel to about 16 ft. down, then 100 ft. of London Clay above the Woolwich and Reading beds. In the new scheme there are basements generally extending down 23 ft. below the original level, but under the tower is a different story.

In the early days of the design it looked as if at least a 60 ft. depth of basement would be needed. We knew that the two tubes of the Central Line underground from the Bank to Liverpool Street Station passed by the site under Broad Street, and since that street is only about 40 ft. wide, the tunnels would be very close to it and also at about the same level. A visit to the offices of London Transport's Chief Civil Engineer did not encourage us. Their immediate reaction was to be extremely worried about the whole thing. We were even asked if we could find another site for our building. There were no records showing precisely how the position of the tubes would relate to the street above, and this would have to be established by a survey. One thing seemed to be quite clear, however. These tubes of cast iron rings which had been put in before 1930 were considered to be in a somewhat fragile state already, and the L T E were not happy to contemplate anything which might make matters even the smallest degree worse. It seems that the tubes had already been subjected to strain due to a realignment which had been carried out some time ago.

It is usually a statutory requirement that any building works carried out within a certain stated distance of L T E tubes must be subject to the engineering approval of London Transport. This is not necessarily the case however, and would normally depend upon the particular Act of Parliament relating to that section of tube. It was not clear whether we were under any such obligation but the question was really quite academic. It would, of course, have been foolhardy, even if permissible, to carry on with our scheme without discussing it with the London Transport engineers. The prospect of dislocating services on the Central Line was not to be contemplated.

A long period of study, research and meeting ensued. The tunnels were surveyed and the east-bound tube was found to pass within 5 ft. 3 in. of our building line, apparently well outside the limits of deviation prescribed for the construction of this tube, not that this fact was of very much help. Fortunately, during the years which passed, trying to reach some satisfactory and acceptable solution to the problem of constructing the basements and particularly the deep basement under the tower without causing excessive movement in the tubes, the architect began to find less need for such a deep basement and our difficulties began to diminish. The final picture is shown on the cross-section in this article. This was a great improvement on the position from which we started, but the L T E were still very unhappy about it.

A diaphragm wall was constructed with the use of bentonite, which would probably have been the natural solution to the retaining wall problem even without the tubes. In general, these walls are taken down some 24 ft. below the floor level of the lowest basement, but this was not acceptable on the side next to the tubes. It was thought that to take any kind of excavation down to that level so close to the tubes would risk movement of the tunnel sections, thus on that side the diaphragm wall is cut off 1 ft. 6 in. below the level of the base slab and is propped by a prestressed beam which later forms part of the main slab and which was constructed in heading before the main basement excavation was carried out.

This propping beam was inspired by an idea of Dr. Ward's of the Building Research Station, and its purpose is to minimise earth movement vertically or horizontally in the immediate vicinity of the tubes.

It would have been possible to have designed a simple raft foundation for the tower, but since settlement and heave during excavation were our main problems so far as the tubes were concerned, we had to find a way of keeping both as small as we could afford to. This was facilitated by piling the site before excavation. These piles were taken down to a level only 10 ft. above the Woolwich and Reading beds where heave movement would be quite small. The idea was that by linking the upper and lower levels of the London Clay with piles at quite close centres, the tendency to heave would to some degree be restricted, the piles of course going into tension. The piles also limit the settlement by allowing a substantially lower effective raft level to be used in the design. Fortunately the L T E were prepared to let us continue and they planned to take frequent check measurements in the tunnels to look for early signs of movement of distress. The sequence of construction went like this.

After the demolition of the first half side the existing massive concrete sub-structure was cut out. One of the problems of this job was that the original building had been put up to last for ever and the specification had obviously been that everything should be the best of its respective kind. The huge steel columns were clad in thick marble slabs and there were concrete bases up to 17 ft. thick.

Diaphragm walling was carried out by Soil Mechanics-Soletanche Ltd. It is 2 ft. 8 in. (80 cm) thick and cast in bays alternatively 11 ft. and 16 ft. wide centred beneath the perimeter tower columns. The total depth of wall cast is 42 ft. 6 in. and the reinforcement cages were fabricated in one length without laps to eliminate any possible bond slip occurring. The cages also had the block-outs fixed to them necessary to form receiving chases for the raft and the slabs above it. These were found to be remarkably accurately positioned when the slabs were cast into them. They are arranged generally at 8 ft. 6 in. centres over the entire area of the tower, this dimension being critical for soil heave, and they were cast in empty boring down to the foundation raft level and reinforced parabolically to suit the heave tensions. While this was going on the propping beam was made. This entailed sinking two shafts outside the tower perimeter adjacent to Broad Street. From the bottom of the shafts a tunnel was driven along the inside face of the diaphragm wall. This was big enough to form an 8 ft. wide and 5 ft. high concrete beam. This beam was filled in sections and dry packed at the top to make a tight fit and then it was post-tensioned using a prestressing force of approximately 3000 /kips. The basement was excavated to a depth of approximately 10 ft. and a temporary ring truss put in to prop the diaphragm walls. This truss was supported by hangers at the wall face and by steel columns placed in convenient pile bore-holes at approximately 20 ft. centres along the inner boom of the truss. The gap between the wall and the truss was dry-packed so that we could be reasonably sure of the truss taking load before any significant movement occurred. The depth and profile of truss were determined from the requirement for clear space in the centre of the tower area to allow the core to be slid.

After truss installation the excavation continued under the truss to a total depth of 32 ft. The site was covered with 1 ft. of blinding concrete which in combination with the remaining earth above the toe was considered to strut the diaphragm wall at this level.

The 10 ft. thick base slab was then cast in two layers, one of 6 ft. the other of 4 ft. and in bays of 25 ft. width. The maximum continuous pour between day joints was in the order of 300 cu. yds. and the minimum of 150 cu. yds. Once the base slab was complete the core was slid in two sections for the full height of the building. This was a very successful operation but we will save up the details for another occasion. Now the floors and an access ramp are being cast between the core and the diaphragm wall. As soon as these are complete the steel truss will be removed.

So far as waterproofing is concerned, we are using cavity construction, with an inner brick skin to line the diaphragm walling. In fact, very little seepage of water has occurred.

Heave points were put in right at the start of the job and so far as work has permitted, levels have been taken on them ever since. Also the Central Line tubes have been checked for line and level on several occasions since we started work. The movements observed so far have all been so small that no clear pattern of behaviour can be traced and certainly nothing has been observed which has given cause for alarm.

Acknowledgements

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Quantity Surveyor:	Gardiner & Theobald

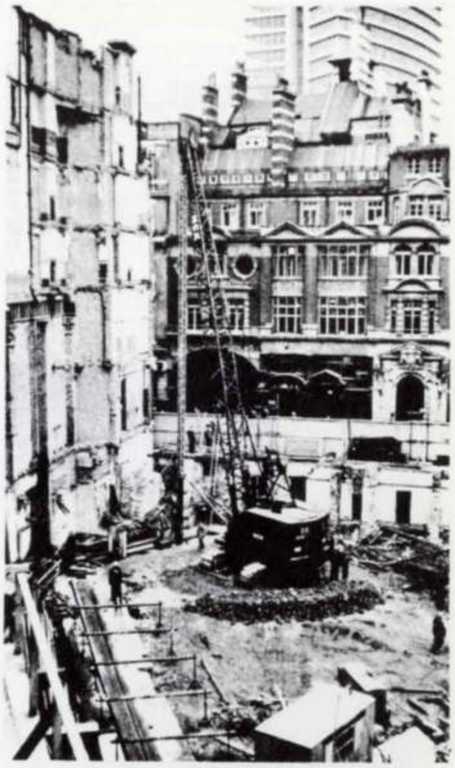

Fig 5 right Diaphragm wall construction.

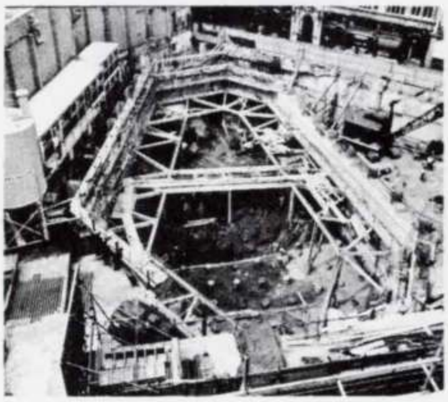

Fig 6 below. Excavation inside the diaphragm wall. (Photo: S. W. Newbery)

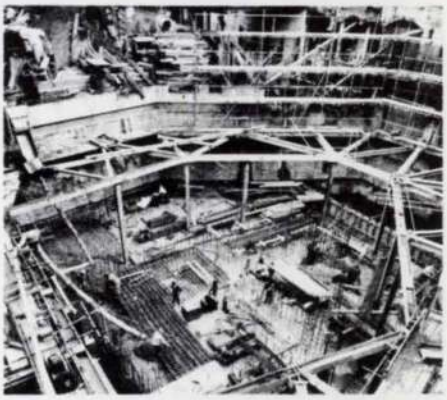

Fig 7 below. Casting the base slab. (Photo: S. W. Newbery)

A new theory of adhesion

A. G. Callegari

One aspect of recent developments in adhesion theory was discussed at a recent conference in London which will have far-reaching effects for the adhesives field. Since widespread use is already made of adhesive materials in various building operations it is important that we should be aware of its implications.

This article is concerned with one implication of the theory and how it is helping in the attempt which is being made to find a solution to one major problem in building operations.

The problem

There are various building operations in which adhesives are directly involved and, although there is a multifarious range of adhesives commercially available, only two of these have found widespread use. These are either epoxy resin or polyvinylacetate (PVA) polymer emulsion adhesives which form the basis of those products which are most frequently used. Although epoxy resins are very effective, there are a number of disadvantages inherent in their use (apart from their relatively high cost) so that PVA has found widespread use. Unfortunately, it is becoming increasingly apparent that PVA lacks the durability required for many purposes. Failures have occurred in situations where moist conditions have prevailed. In looking for a satisfactory replacement for PVA, there is little in the way of guide-lines by which one can be certain of choosing a material which will not deteriorate unreasonably with long-term exposure. Manufacturers' claims may not be substantiated in practice because these are often based on accelerated test methods, which invariably fail to give a satisfactory prediction of long-term properties.

This year's conference was attended with this problem in mind and in the hope that a solution to the problem might be suggested. If the surface-free energy theory of adhesion (originally formulated at Bell Telephone Laboratories, USA) is not the complete answer, it is showing itself to be of considerable assistance.

The Sixth Annual Conference on Adhesion and Adhesives

For the sixth year running, the chemistry department of The City University held a conference on the subject of adhesion and adhesives. This year's attendance of nearly 200 delegates was a considerable increase on that of last year. Representatives from most of the more enterprising adhesive manufacturing concerns were present although, somewhat surprisingly not from some of those companies in whose products we are most interested.

It was intended that, this year, greater emphasis would be laid on theoretical aspects of adhesion than had hitherto been the case, yet few contributions were in fact given in this vein. The most notable exception was in the introductory paper on surface energy by Alner, who is the head of Chemistry at City University. This article is mainly concerned with some of the results presented in the lecture (see section: **Surface-Free Energy).**

Some of the other contributions were of cursory interest particularly those in which some reference was made to the manner in which research and development is, and should be, carried out in the adhesives field. For example, Pitkethly (BP Research Centre and visiting lecturer at City University) called for immediate efforts to close the excessive gap which exists between theoretical studies and development work and mentioned the example at BP Research where efforts are made to combat this problem by holding regular bridging discussion groups. Such comment shows that there is an increasing awareness of the alienation which exists between academic and development workers. There is no doubt that this derives from the aversion which the former show for sullying their hands with development work and the stigma they attach to it. The latter suffer from the financial considerations of industry where the directive is given to pursue the pragmatic approach (which, unfortunately, all too often tends to be highly subjective). Yet it should be in the area where these two extremes coalesce that the most valuable developments would arise. Unfortunately this is where least effort is directed, and in many cases restricted, from both sides. One was therefore encouraged by hearing that The City University is committed to expanding its research endeavours in the academically unglamourous field of adhesion and its various aspects. Having a UK based school in this topic provides backing and will undoubtedly assist us in the future. The lead which has already been given is the main point of this article.

Alner's lecture was stimulating for its concise presentation and objectivity. It showed quite effectively that there is the ability to control the balance which should be maintained between pure and applied studies of adhesion. The lecture was concerned to show the importance of surface-free energy in adhesion where previously it had been largely ignored.

Previous theories of adhesion

The theoretical interpretation of adhesion has not been ignored in the past (1). An excellent introduction to adhesion and adhesives for the non-specialist is given by Parker and Taylor (2) in which a discussion is given (3) on the controversy which exists over the polar group criterion for adhesion. The new theory and the way in which it contradicts existing theories is discussed (4) somewhat briefly, so that this article is an extension of the discussion to a sufficient degree to enable it to apply to the problem as defined above.

Surface-free energy

Most of us are familiar with the phenomenon of surface tension. It will manifest itself at the surface of any material because the attractive force field surrounding molecules in the surface is much less symmetrical than that operating in the bulk of the material. The result of this is that the surface molecules are pulled into the bulk phase until the stress is relieved. One can see quite readily that adhesive materials aspire to make use of this 'attractive' phenomenon. In practice, however, the strength of an adhesive joint falls considerably short of that which is theoretically calculated on the above basis.

Physical chemists define surface tension (γ) in terms of the thermodynamic concept of free energy (hence the term surface free energy) according to the equation.

$$\gamma = \frac{\triangle G}{\triangle A} \qquad \text{dyne. cm}^{-1}$$

where ($\triangle$ G) is the free energy change at the surface for a surface area change of $\triangle$ A caused by the effect at the surface. The advantages of using this approach are associated with the methods which have been developed for determining free energies to a high degree of accuracy.

A sufficient amount of data was presented to enable one to conclude that the interfacial tension between two phases, A and B, can be represented empirically by

$$\gamma_{AB} = \gamma_A + \gamma_B - 2\,(\gamma_A{}^d\,\gamma_B{}^d)^{\frac{1}{2}}$$

where γ_A, γ_B are absolute surface tensions of phases A and B, $\gamma_A{}^d$, $\gamma_B{}^d$ are the corresponding values when the two phases are in contact and dispersion (London) forces are operating (prefix d signifies dispersion only; it is not a power).

Since γ_{AB}, γ_A and γ_B can be determined experimentally and independently, the value of the geometric mean factor $(\gamma_A{}^d\,\gamma_B{}^d)_{\frac{1}{2}}$ can be evaluated by virtue of the difference. For several compounds in contact with water (a polar compound), the difference was found to be quite small and insignificant. It lends a considerable amount of support for using equation (2) and for concluding that, in these cases, ONLY dispersion forces are operating at the interface. By contrast, several compounds gave differences which were extremely large. In this category, were such materials as butyronitrile, cyclohexanol and octanoic acid. These exhibit the tendency to form hydrogen bonds via their function groups i.e., the nitrile, alcoholic (ol) and acid groups in the above three compounds.

Implications of this theory

Although there is no exacting theroretical justification for using equation (2), it would appear to provide an excellent method for differentiating between cases where only dispersion or dispersion and polar interaction forces are operating.

Although extension of this criterion to non-ideal systems (such as are represented by the case of bonding two surfaces together using the conventional type of adhesive) is as yet virgin field, the criterion should still hold true. It must therefore, be inferred that it is NOT a prerequisite for satisfactory adhesive performance that polar interactions must necessarily operate. Dispersion forces are more than sufficient in themselves. Yet it is often due to the fact that adhesive materials contain polar groups (previously considered to be essential) that troubles arise.

Polyvinylacetate contains the acetate functional group which, when subjected to hydrolysis, forms acetic acid. The acid can react, not only with cement paste (which is an alkali), but also with reinforcing steel causing severe corrosion. The latter problem arose in some of the tile lids which were repaired on the Sydney Opera House using a PVA based adhesive.

Where such problems arise with PVA, it is usual to fall back on the use of epoxy adhesive. Various research investigations (not in the UK) have tended to suggest that there may be a number of possible alternatives to using either PVA or epoxy. However, little is known at present concerning their long-term durability. The comparative shortness of most research studies does not readily allow scaling up to allow long-term predictions to be made unless some exceptional qualities are showing up in the short term. Two materials exhibiting vastly superior short-term qualities over those of PVA are styrene-butadiene (SBR) and acrylonitrile-butadiene (ABR) co-polymer emulsions. The basic cost of these materials is not high; SBR is comparable with that of PVA whereas ABR is about one and a half times the cost of SBR, although still less than that of epoxy. The overall cost, however, depends on the mode of application and in this respect the above order could easily be reversed (see Section: **Proposed Trials**).

It is interesting that these findings, in the case of SBR, are in keeping with the new criterion (i.e., functional groups are not a prerequisite for satisfactory adhesion) in that SBR lacks functional groups.

The ABR is anomalous in this respect although attempts have already been made to explain anomalous behaviour of acrylonitrile in other circumstances (4).

Proposed trials

As little use has been made of SBR so far, proposals have been drawn up for running comparative trials between epoxy, PVA and SBR adhesives which should illustrate the relative merits of handling and short-term properties. A report on these trials will appear in due course.

Recent applications

It is fortunate that some of the suggested replacements for PVA and epoxy adhesives had already been used on sites. Although few in number and only of recent application, a careful watch may be kept on this in the future to enable assessments of durability under actual conditions to be made.

One disadvantage which manifested itself was the unusually long setting time of an SBR modified mortar screed flooring used for a car park in Edinburgh. It should not be difficult to overcome such a problem. A similar composition used to add cover to a projecting nib on another job (Maynard Road, Bermondsey) had shown no signs of deterioration after six months' exposure to predominantly winter conditions whereas a similar application using an acrylate modified mortar produced crazing soon after application. Acrylates are one of the materials which manufacturers claim to exhibit improved water resistance. The claim would not appear to be substantiated, therefore, in this case, whereas the new criterion holds good—acrylates contain the ester functional group.

Conclusion

One may criticise this article for the degree of subjectivity which has been introduced but find justification for attempting to take a lead, in view of paucity of effort which has been made in this field. However, the comment is based mainly on the assessment which has been made of various research studies of a range of adhesive polymers, a review of which will appear in due course in the form of one of our *Technical Papers*.

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(3) ibid, p.13.

(4) ibid, p.19.

Rough boardmarked white concrete

Ralph Stephenson

Introduction

In the Manchester office, we have now done three jobs involving boardmarked finishes to white concrete, the architects for all three are Cruickshank & Seward. Our specifications for this finish have become much more comprehensive as we have gained our own experience and have benefited from that of others, in particular I am thinking of Tony Powell's article in the July 1966 *Arup Journal* which should be compulsory reading for anybody concerned with this type of work, and more recently of the Cement & Concrete Association's publication on the production of quality finishes.

The three jobs are described in the order in which they were done. The description of the University of Manchester Institute of Science & Technology job includes several things that have come to light during the course of the site work that might well be included in future specifications.

Manchester University. Economics and social sciences building. 1965

This is a six-storey load-bearing brick building, 150 ft. x 40 ft. in plan. Because of the lack of interest in the shape of the building and the fact that it is in a very drab area, the architect wanted to have as exciting an elevation as his budget would allow. Several cladding schemes were drawn up, and the boardmarked precast panels shown in Fig. 1 were finally chosen.

The dished panels of white concrete are 10 ft. x 8 ft. wide x 4 in. thick, the 2 ft. dish forming a wide window-sill cum working area. They are vertically boardmarked. A detail of part of one of these units is shown in Fig. 2. Two small samples were made, one with limestone aggregate and one with calcined flint. *Snowcrete* cement was used in both samples. As there was no difference in colour the mix made with the cheaper limestone was chosen.

The horizontally boardmarked infill panels are of dark grey concrete made from high alumina cement and grey river sand and gravel. No additives were used. Fig. 3 shows the type of finish achieved on these small units.

The panels were made by Evans Bros. of Derby, a firm with a reputation for producing good quality though often expensive work. They were cast against 8 in. wide Douglas Fir boards of the same thickness and free from saw markings. The natural variations in the thickness of the boards produced the lines on the panels. After assembly the boards were given several coats of an epoxy barrier paint. Although the slope forming the dish is shallow, a double mould was used. The units were cast outside face down. After the concrete in the horizontal section, including the window opening, had been placed and tamped, the inner mould was clamped to the outer and the remaining concrete placed. External vibrators were used.

After each use the moulds were thoroughly cleaned and then inspected by a joiner, after every third use they were stripped down and rebuilt. 150 panels were produced from three moulds and it is no exaggeration to say that the last unit produced was as good as the first.

The total cost of the panels was £11,000. The cost of a dished panel was £56. The general contractor was Pochin (Contractors) Ltd.

The concrete strength specified was 4,500 lb/sq. in. and we gave the outer reinforcement $1\frac{1}{4}$ in. cover. At our request Evans quoted an extra for galvanized reinforcement, at £1,000. It would have meant too big an increase in the cost of the units to be acceptable.

Sealing was by Bostik M.R. polysulphide and a polystyrene insulation was stuck on to the internal faces.

Manchester University. Arts building —phase III. 1966-67

This is a five-storey in situ concrete building, the external walls of which are in white concrete. The finish specification for the walls was changed from smooth vertically grooved to horizontally boardmarked after the bill had been priced. No doubt this gave the quantity surveyor and the contractor more headaches than the building of the walls.

2 in. nominal thickness x 8 in. wide Hemlock boards were used, their thicknesses varying by 1/16 in.—$\frac{1}{8}$ in. to produce offsets. They were grooved and had loose tongues and were fixed via studding to a steel framework. The boards were cut to size in the contractor's workshop and the shutters assembled and painted on the site. The mould oil was Duckham's *Zedcreme* 200. Fig. 4 shows a part of the finish produced by a mixture of boards-band sawn, circular sawn and naturally weathered.

Derbyshire limestone aggregate, *Taylor Frith* coarse and *Hopton Wood* fine, and *Snowcrete* were used in the mix which had an aggregate : cement ratio of 6:1 with 33% fines, and a water : cement ratio of 0.5. No additives were used. The specified strength of the concrete was 4,500 lb/sq. in. and $1\frac{1}{2}$ in. cover was given to the external reinforcement.

In general the appearance of the finished walls is satisfactory. The offsets at the board edges are crisp and the grain marking is consistently good but several faults showed themselves during the course of the job.

No special precautions were taken to prevent leaks at the horizontal construction joints. Some touching up had to be done in these areas and at close quarters it is easy to see where they are.

Fig. 5 shows:

1. The result of using supposedly better than normal cardboard tubes for the shutter ties. The leakage of water through them leaves a sandy textured discoloured area. Cardboard tubes should never be used in exposed concrete.
2. Discolouration from incorrectly applied mould oil. The contractor sloshed it on with a mop, consequently some areas were uncovered and some inundated. Nothing we said would persuade him to do otherwise even though it was obvious that if he sprayed it on his consumption of the stuff would drop considerably. The build-up on the offsets produced discoloured lines on the finished surface as the excess oil was absorbed into the concrete. This does not seem to disappear with time.

We also had trouble caused by incorrectly applied shutter barrier paint. Towards the end of the job the repetitive work finished and some new shutters were brought on to the site. The paint was not applied under the right conditions, nor was it allowed to cure properly. Consequently large areas of it stuck to the concrete surface when the shutters were stripped.

The only complaint that the contractor had was that the mix was unworkable. However, he easily overcame his difficulties and there are very few signs in the finished work that one could attribute to unworkable concrete.

Fig. 6 shows the fire escape. This is in a prominent position and its construction was made difficult by the fact that the architect did not want to see any construction joints. The vertically boardmarked column was cast in two halves, each half being taken up progressively to the soffit line of the stair flight on one

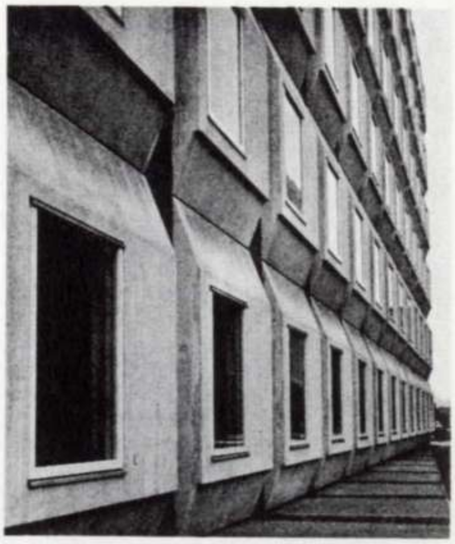

Fig. 1 University of Manchester Economics building.
Photo: G. Howarth.

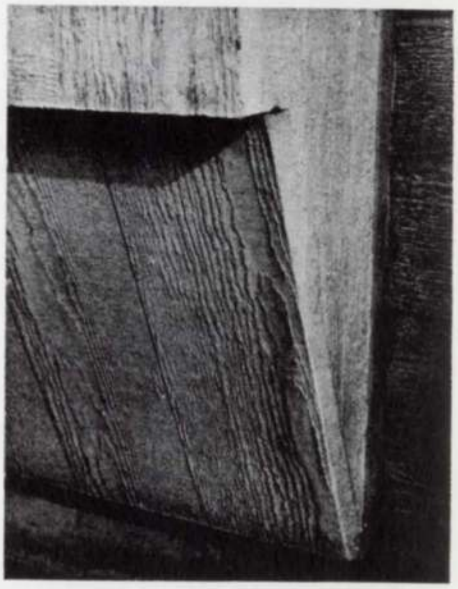

Fig. 2 University of Manchester Economics building. Detail at the bottom of a dished unit.
Photo: Ralph Stephenson.

Fig. 3 University of Manchester Economics building. Finish of infill panel.
Photo: Ralph Stephenson.

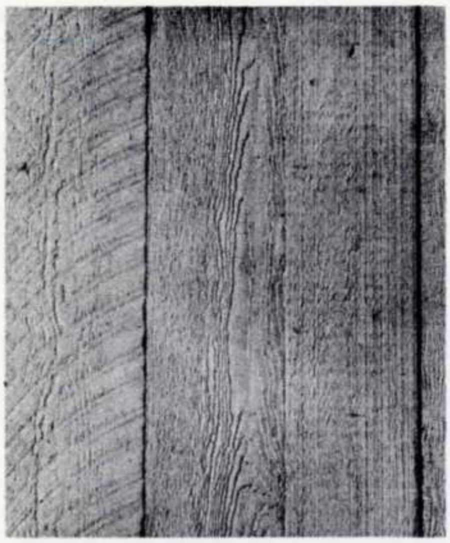

Fig. 4 University of Manchester Arts Building. Finish produced from a variety of board textures.
Photo: G. Howarth.

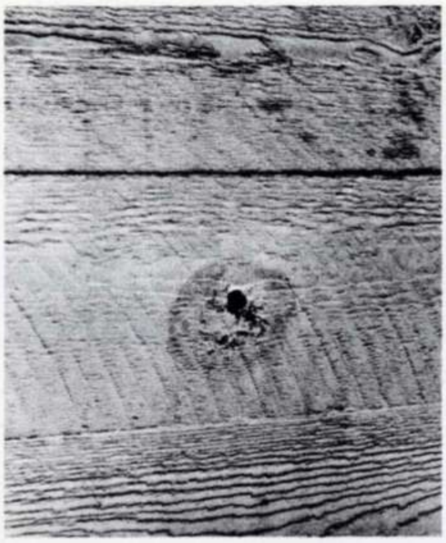

Fig. 5 University of Manchester Arts Building. Surface blemishes caused by a leaking shutter tie tube and by excess mould oil being absorbed into the surface of the concrete.
Photo: G. Howarth.

Fig. 6 University of Manchester Arts Building. South wing fire escape staircase.
Photo: Ralph Stephenson.

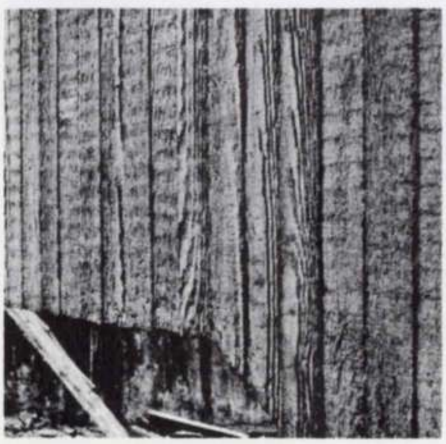

Fig. 7 University of Manchester Arts Building. External finish to balustrade to fire escape stair.
Photo: Ralph Stephenson.

side or the other. The stairs and landings which are boardmarked on their soffits cantilever off the column. The balustrades were cast on to and over the edge of the flights so that the vertical boardmarking was not interrupted by a construction joint at the flight level. The soffits were slightly discoloured by rust from the reinforcement which had dropped on to the shuttering. Fortunately this was easily brushed off. In small units like this staircase, this can be prevented by suspending the reinforcement from above and covering the soffit shutters with polythene sheet, the sheet being removed just before concreting.

The cost of white concrete in 9 in. thick walls was 51/2d. per sq. yd. The cost of boardmarked shuttering eventually agreed was 75/- to 125/- per sq. yd. depending upon the amount of repetition. The contractor was Fram Russell Construction.

University of Manchester Institute of Science and Technology. Mathematics and electrical engineering buildings. 1967-68

This is a group of buildings for the Institute of Technology (see Figs. 8 and 9.) The site is a prominent one at the junction of two of the city's main traffic routes. The south elevation of the Mathematics Building is heavily modelled and the architect has used horizontally boardmarked white concrete for the external walls and spandrel beams of all four buildings. The appearance of the large areas of unbroken wall in the lecture theatre and high voltage laboratories depends almost entirely on the quality of this finish.

Some of the walls are over 100 ft. in length so our first task was to agree with the architect and contractor a pattern of construction joints. As the boardmarking is horizontal the shutters had, wherever possible, to be continuous between the construction joints to prevent the appearance of vertical marks at the junction of the individual pieces of shuttering. Fortunately the agreed joints were around 30 ft. apart and the contractor made his shutters to suit. On the Mathematics Building we have a 42 ft. long wall which, after much heart searching, the contractor agreed to cast in a continuous shutter. At the same time a pattern of shutter ties was agreed and the contractor produced a plastic *Rawlcone* to replace the normal timber cone of the tie. These have proved very successful—see Fig. 10.

We next visited the contractor's timber yard and were shown many boards with different grain textures and saw markings. Fortunately the architect had definite ideas about what he wanted and he went to great pains to select board with not too prominent grain, with saw marks subdued by weathering and as free as possible from knots and wain. As one would expect, boards to match this specification were in short supply so we had to mix Hemlock and Douglas Fir to get them. Unless a barrier paint is being used this is not good practice because the different timber absorbencies affect the colour of the finished concrete.

The chosen boards which were 4 in. wide and of three thicknesses to produce a planned system of offsets were then planed on back and edges and lightly sanded on the rough front side to remove all loose whiskers but not the grain marking. They were also slightly chamfered at the offsets to ease stripping. After this they were given two coats of paint all round, including the end grain and the inside of bolt holes. The paint specified was supplied by Charles Turner of Croydon. It is a two-part paint, an epoxide primer (EP/LA) and a catalyst (A81). It must be applied in dry conditions at temperatures above 50°F and be given 7 days to harden before concrete is cast against it. Barrier painted shutters have many advantages; variations in timber absorbency are no longer a problem. They are easier to strip because the grain is sealed and

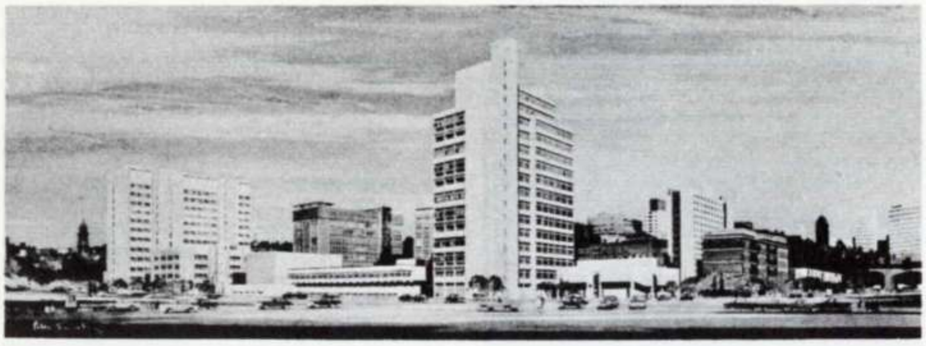

Fig. 8 University of Manchester Institute of Science and Technology. View from the south-east at the junction of the A6 and the Mancunian Way. The Mathematics Building is in the centre with the Lecture Theatres to the right and the Electrical Engineering Buildings to the left.
Photo by Elsam, Mann & Cooper from a drawing by Peter Sainsbury. Drawing commissioned by Cruickshank & Seward.

Fig. 9 Plan showing the Mathematics Tower and its related buildings imposed on an ordnance map of the area as it was before development. Other Cruickshank & Seward/ Ove Arup buildings on the Manchester University Institute of Science & Technology campus are the Reynold Building and Chandos Hall.
Photo : Stan Parkinson.

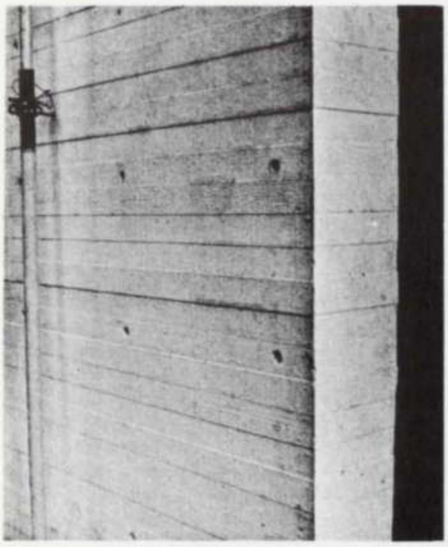

Fig. 10 Manchester University Institute of Science and Technology Mathematics Building—end of north gable wall showing holes produced by plastic *Rawlcones*. The holes will eventually be filled.
Photo : Stan Parkinson.

does not get locked into the concrete. They are easier to clean down and the grain texture is preserved. They are also much less susceptible to distortion caused by moisture movement. The manufacturers of the paint claim that timber shutters treated in this way have lasted for up to 200 uses. Whilst this may be an exaggeration the finish obtained from the shutters of the Economics Building panels (150 panels from 3 shutters) was consistently good.

A normal type of shutter consisting of 4 in. x 3 in. timbers and standard size $\frac{3}{4}$ in. ply sheets was bolted to a steel channel framework. The boards were then glued and back-screwed to the ply and given a third coat of paint to improve their resistance to wear from scouring by the concrete. The shutter for the 42 ft. wall which is 15 storeys high is split at mid-storey height to ease the handling problems. All the other shutters are storey-height. At horizontal joints the shutters overlap the kickers by one board width. A 3 in. wide strip of white foamed polyurethane is stapled to this board and it is then clamped to the kicker by the bottom ties. We found that off-white foam stained the concrete.

At vertical joints the shutters are butted up and clamped together with a foam strip between. The pattern of the board offsets is the same on each side of the joint. Vertical joints in horizontally marked walls cannot be made so indistinct that they do not affect the appearance of the wall. In our case the architect accepted this but decided not to emphasize the joint by grooving or by introducing vertical boards at the vertical joints. The great thing is to prevent the loss of water from the mix at the joint; the end grain of the boards must be sealed and the shutter edges protected from damage so that the close fit on clamping is maintained.

Fig. 11 shows the shutter detail at an 'external' corner and Fig. 12 shows the corner produced from that detail. It worked very well.

A thin film of *Noxcrete*, which is a clear chemical release agent, was sprayed onto the shutters. This dries off after about 3 hours and the shutters do not appear to have been treated. However, it is fairly long-lasting, does not get washed off unless exposed for long periods and does not pick up as much dirt as the cream type mould oils. If shutters have to be exposed after the application of mould oil for any length of time, then a sheet of polythene should be hung between the shutter and the reinforcement to prevent their picking up grime, wind blown rust off the the reinforcement, etc., and imparting it to the concrete surface.

We were conscious of the fact that consistency of colour was an important factor in walls of the size we were dealing with. Above second storey our type of grain marks cannot be distinguished and above fourth it is difficult to pick out individual boards. We specified that the cement and aggregates should come from the same sources throughout the course of the job and that if additives were used they should be used thoughout. In future we will add that the shutters must be stripped at a constant age of concrete and that easing the shutters so that odd areas dry out at different rates will not be allowed. It is also a good idea to cover the aggregate piles if you are building in a dirty atmosphere such as ours.

Several methods were tried to prevent rust staining, grout washing of starters, polythene sleeves over starters and covering the wall tops with an absorbent material to stop rust-laden water running down. In the majority of cases these methods were satisfactory. Where they were not we found that *Deox* supplied by National Chemsearch got rid of the stains without damaging the concrete surface. With the help of a strong arm and a scrubbing brush it also shifted young grout runs and paint.

Derbyshire Limestone, Tern Hill coarse and Hopton Wood fine, with *Snowcrete* cement were used to produce the white concrete. The aggregate cement ratio was 5.2 to 1, with 36% fines and the water cement ratio was 0.49. The contractor was not too pleased about the workability of this mix for the walls—normal storey height 12 ft. 5 in. so *Febflow* plasticiser was added. Even with the plasticiser the contractor had difficulty in getting the concrete out of the skip. We considered that the mix was workable enough and came to the conclusion that the design of the skip was at fault.

Our resident engineer paid more than usual attention to the placing and compaction of the concrete. It seemed to us that concrete was normally under-vibrated, so with the contractor's co-operation he laid down a few guide lines to put this situation right. The concreting programme was arranged so that as far as could be foreseen no delays occurred once pouring of a wall had started, and the rate of placing was controlled so as to inundate the vibrating gang. Concrete was placed in no more than 18 in. deep layers. The first layer above a kicker was 12 in., and it was brought up evenly along the length of the wall by the skip, and not pushed along by the pokers. CCL $2\frac{5}{8}$ in. poker vibrators working at 14,000 cycles per minute were inserted vertically at 18 in. centres deep enough to ensure that newly placed concrete was vibrated with the layer immediately below it. All this is normal good practice and what we expect but do not always get. It paid dividends and with the combination of Turner's paint and *Noxcrete* produced a dense lime-free surface with a faithful representation of the shutter boards.

The cost of the white concrete in the 9 in. wall was 34/9d. per sq. yd. The cost of boardmarked shuttering was 31/6d. per sq. yd. The contractor was Pochin (Contractors) Ltd.

The above rates are very low, and since getting first-hand experience of this type of work the contractor has left us in no doubt that we will have to pay very much more next time. It is to his credit that he has not let the standard of the finish suffer and has maintained his reputation for producing first-class joinery work in the shape of the wall shutters.

Some further thoughts

Have we come to the end of the boardmarked white concrete era? Now that we have two successful jobs behind us and a third well on the way, we hope not. We may well have to pay more for it next time as contractors become aware of the difficulties involved in producing the necessary top quality shutters but this upward trend in cost can be counteracted by careful architectural and structural detailing to ease the problems.

It is essential for the architect, engineer and clerk of works to agree among themselves what sort of boardmarked finish is being aimed at and what will and will not be acceptable on the job. Confusion will reign and the job will suffer if the contractor is given conflicting opinions and instructions. The standard required will largely depend upon how the building is detailed architecturally, but personal likes and dislikes also enter into it. To illustrate this point we can consider the infill panels of the Economics Building and the fire escape of the Arts Building, both of which were specially detailed for a boardmarked finish.

The small precast infill panels are, apart from a few pin holes, faultless, the grain marking is very pronounced and individual boards can be picked out with ease, the quality is uniform throughout. The shuttering expert of a local contractor swears that they were cast against fibreglass and not timber. To some, this finish looks like petrified timber rather than concrete and to them it is not acceptable. We think that for this size of unit it is ideal and are sure that the majority share our views.

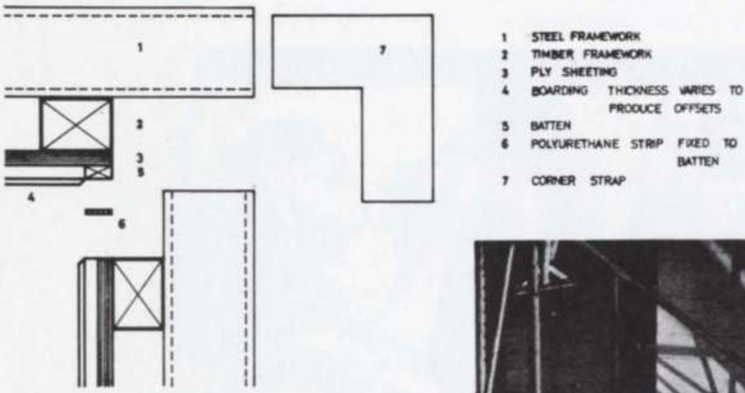

Fig. 11 Detail at the corner junction of wall shutters.

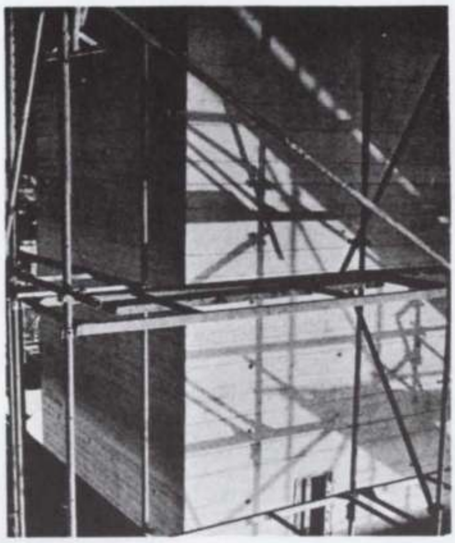

Fig. 12 University of Manchester Institute of Science and Technology Mathematics Building. Walls to north staircase.
Photo: Stan Parkinson.

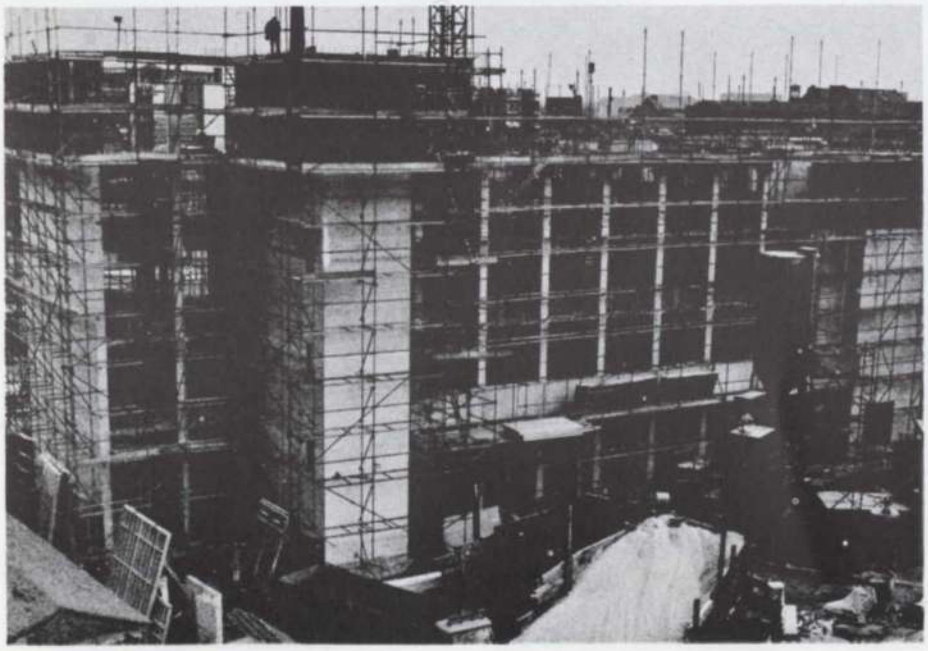

Fig. 13 University of Manchester Institute of Science and Technology. Mathematics Building—general view. Fourth floor under construction, the spandrel beams following on three floors behind the frame.
Photo: Stan Parkinson.

The fire escape staircase is very bold, well detailed and constructed. The surface finish has been criticized. It has blow holes, bits of honeycombing in odd areas and the offsets at the board edges have in many cases been plucked off on stripping the shutters. To the critics the staircase is 'rough' but to those who view it as a whole it is a very good piece of work.

What is acceptable can cover a very wide range but two things must be achieved whatever the quality of the surface. These are consistency of colour and good detailing architectural, structural and shuttering.

Realistic rates in the bill for the shuttering and concrete are a great help. In future specifications we hope, with the help of photographs and better descriptions of what is wanted, to go further towards achieving this. It may be that the method of describing the bill items is at fault. In the time available when he is preparing his tender the contractor very often cannot sort out repetitive and non-repetitive work, nor can he plan his construction procedure, so the effort put into producing labour and material saving details is not always reflected in his rates.

The shuttering and the methods that the contractor proposes for assembling it and the concrete mixes must be proved by a properly organized programme of testing. The sooner this is done the better. If necessary to avoid delays the first samples can be made on another of the contractor's sites leaving the final sample that is to be used as a standard until the contractor has access to your site. This final sample should be of storey-height set in a prominent position. It must include horizontal and vertical joints, internal and external corners, in fact, everything that will affect the appearance of the finish. To ensure that this programme is carried out in a businesslike manner, the samples required must be measured in the bill or a sum provided for them.

Finally our specification for rough sawn boarded formwork might well start: 'The use of the word rough in this specification refers to the texture and not the quality of the formwork.'

This article was written before *The Architects' Journal* of February 14, 1968 was published. This issue of *The Architects' Journal* includes a techical study of in situ exposed concrete finishes by Michael Gage of the Training Division, Cement and Concrete Association. Also included are information sheets on surface defects, formwork linings and surface finishes and a bibliography.

Referring to site conditions and labour, Mr. Gage says 'No matter how carefully a concrete finish is designed and specified the quality of the result is always dependent on site organization and the training and enthusiasm of the operatives.'

This is, of course, very true. From the earliest possible stage the contractor's interest must be aroused and his determination to produce good quality results stimulated by discussion, visits to other buildings that have the desired standard of finish and by the production of the sample panels. Whenever possible, the tradesmen should be included in these preliminaries and their opinions should certainly be sought during the course of the job.

Contrary to popular belief we have found that joiners, steelfixers and concretors are interested in what they are doing and in what the finished job will look like, provided, of course, that somebody takes the trouble to explain to them what is wanted and to discuss problems with them if they arise.