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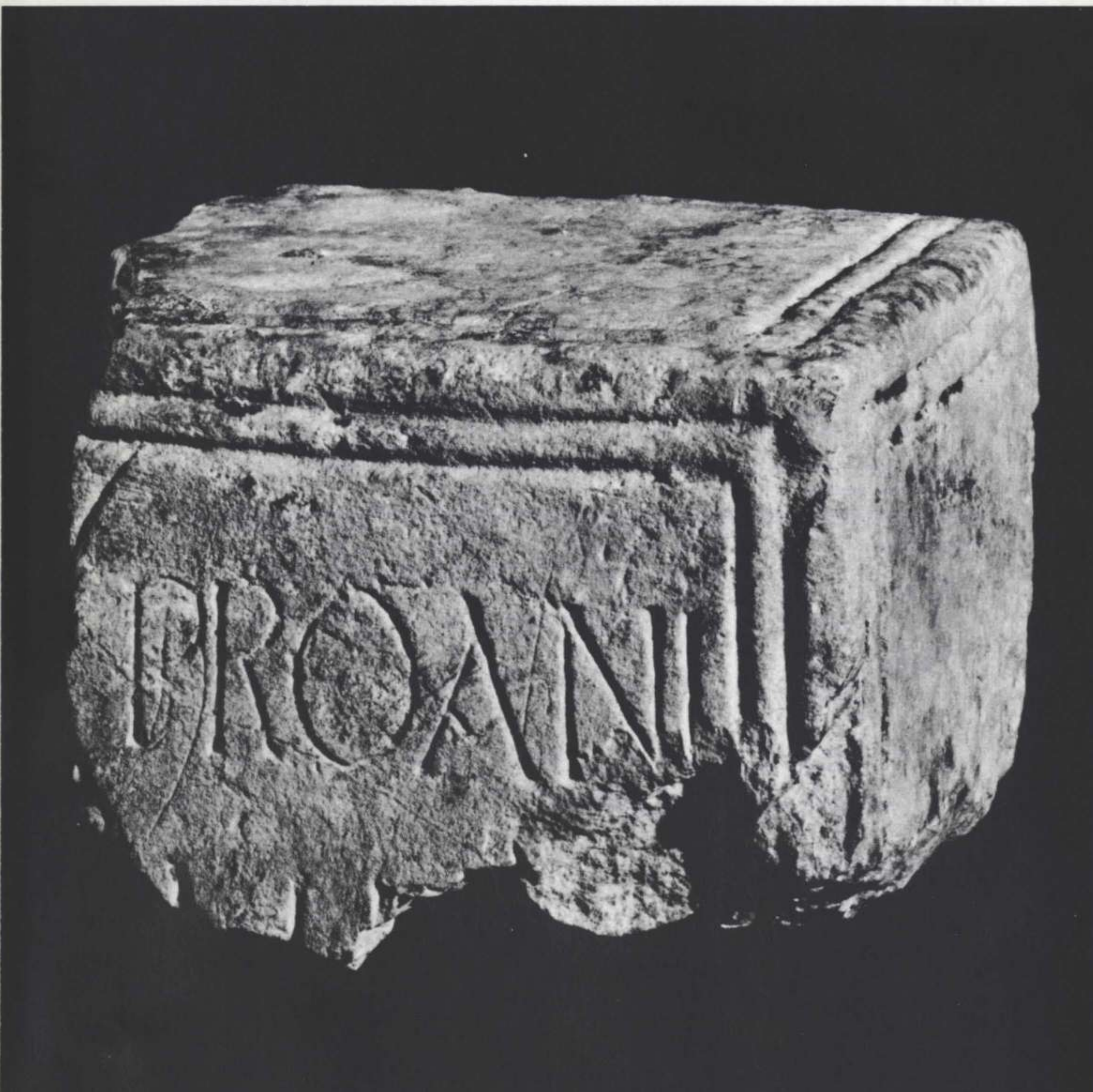

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Contents

York Minster by D. M. Mitchell Part 1-York 50

The use of model analysis in structural design by P. Beckmann 59

Model tests for the Sydney Opera House by J. C. Blanchard 60

Elastic model for 22-storey block of flats in Hong Kong by B. Wright 61

Model tests for Gateshead Viaduct by Srinivasan 64

The use of structural models by A. Stevens 65

Front and back covers: Saxon cross fragment re-used as rough masonry in the Norman foundations of York Minster.
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Editorial note: The papers on model analysis will be discussed at a Technical Staff Meeting in June Everyone, as usual, is welcome.

York Minster

David Mitchell

Part 1—York

The aim of this article is to provide a general historical background to our work in connection with the restoration of York Minster; a bold statement that disguises the immense difficulty of its achievement for there has been a building on the Minster site for nigh on two thousand years. The result is, therefore, a pot-pourri of facts and opinions of varying relevance.

Horace Walpole wrote: *'So incompetent has the generality of historians been for the province they have undertaken that it is almost a question, whether, if the dead of past ages could revive, they would be able to reconnoitre the events of their own times, as transmitted to us by ignorance and misrepresentation'.* (1)

However, it is said that, 'You can fool all of the people some of the time.'

Roman York

It is unlikely that the area of the north bank of the Ouse which formed the major part of the mediaeval city including the Minster was utilized before the first century A D. The only evidence for pre-Roman settlement is an Iron Age cemetery on the south side of the Ouse near the railway station, indicating the existence of a small community, and the Roman name for the city, Eboracum. This is a corruption of Eburacum derived from the Celtic which may mean 'the place of the yews' or 'the field of Eburos', a personal name derived from the place name. The substitution of the 'o' for the 'u' produces a Latin name meaning 'the place of the boar' (which became the emblem of the town). The succeeding Saxon and Old Norse names are direct translations, Eoforwick and Jorvick, the latter being corrupted to York.

In 43 A D Claudius landed in Kent with four legions and by 49 A D a northern frontier had been established on the line of the Severn and Trent with the IX Legion stationed at Lincoln. A treaty was arranged with Queen Cartimandua of the Brigantes, numerically the largest tribe in Britain, whose territory covered large areas of northern England.

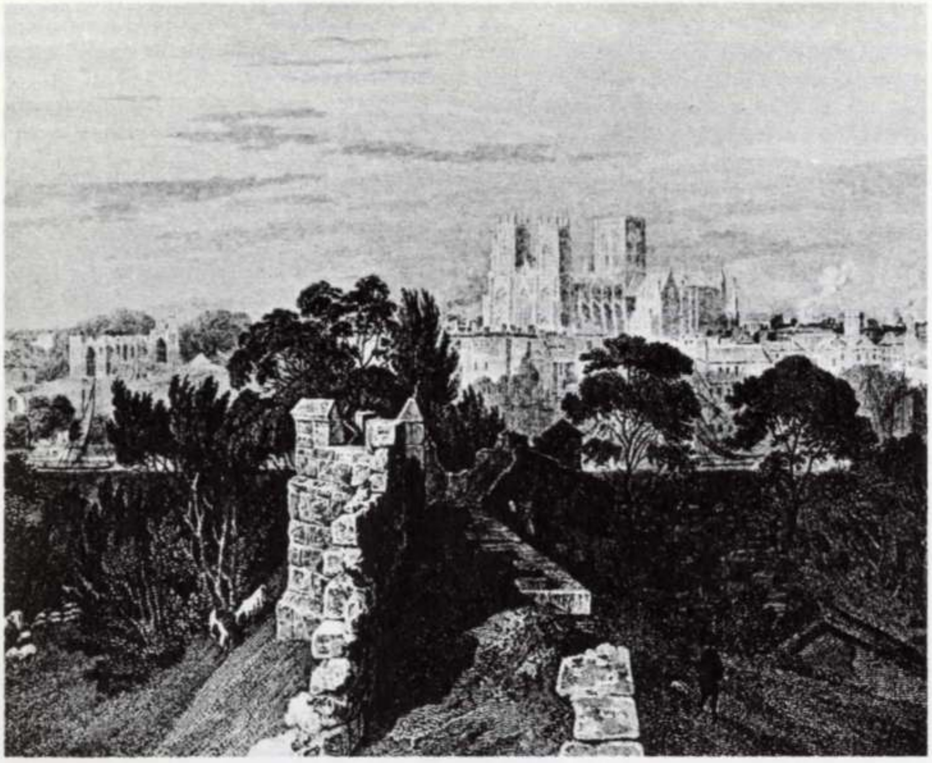
From the Roman viewpoint, the treaty was, theoretically at least, most useful as it secured the northern frontier enabling the High Command to tackle the problems of Wales.

However there were a number of local difficulties and in 71 A D an anti-Roman party gained control converting the Brigantes from a friendly buffer state into a hostile tribe. The reaction was a thrust by an army led by Petilius Cerealis using the natural land bridge of the Lincolnshire and Yorkshire Wolds through the territory of the Parisi. Cerealis advanced through Brough on the north bank of the Humber, later the tribal capital, to Malton, another important Parisian centre and finally to York, where a legionary fortress of standard size was built in 71-72 A D by the IX Legion, to act as winter quarters. This fortress was rapidly constructed with defences consisting of a 'corduroy' foundation of green boughs for a rampart of clay or sand with a turf front, with internal buildings of timber.

The reasons for the choice of this site were twofold; its great strategic importance being situated at the point where the Ouse cuts through the terminal glacial moraine which provides the natural route across the wide and marshy Vale of York and the existence of a navigable route to the sea for the ocean-going ships of the day.

Between 79 and 85 A D Agricola consolidated the gains of the earlier campaign completing the road and fort system planned by Cerealis, including a strengthening of the fortress at York. This included an earth rampart with a foundation of squared oak strapping, incorporating timber interval and angle towers.

In the first half of Trajan's reign the fortress was rebuilt in stone as part of a general reconstruc-



Note by Poul Beckmann

Our work at York Minister is not an intellectual tour-de-force nor will it be spectacular when it is finished, but it is nevertheless engineering. What makes it particularly interesting is that the problems are 4-dimensional. Time enters into the technical arguments very much and we cannot begin to understand what has happened to the structure without studying its history.

In studying the history of the successive churches which were superimposed on each other to form the present Minster one touches continuously on the general history of the city.

David Mitchell has been our foremost student of this backdrop to the long epic in which we made our entry a good year ago and he has from many varied sources compiled an account of the history of York which appears below as an introduction to a series of articles on our work in the Minster.

Fig. 1 View of York from the walls to the south of the Ouse showing the Minster dominating the City and the ruins of St. Mary's Abbey through the trees to the left.
(In: *Cathedral Antiquities*—John Britton—1836, Vol.1) Photo: Poul Beckmann.

tion programme of the three legionary fortresses in the island. At York the rebuilding is recorded by an inscription of A D 107-8.

The internal buildings, including presumably the principia or headquarters building, which partially covers the Minster's site, were also rebuilt in stone as well as the gates and towers and a stone curtain wall was added to the earlier rampart. The stone was magnesium limestone from quarries near Tadcaster which continued to be the major source throughout the mediaeval period. In soft patches beneath the rampart, short closely spaced timber piles were used.

It seems that soon after Trajan's death in 117 A D rebellion broke out in the north with heavy legionary casualties. Evidence for this is the issue of victory coins in 119 A D and the replacement by 122 A D of the IX by the VI Legion with its subsequent disappearance from the army lists. The legion must have been disbanded following an ignominious defeat. Despite the legends, it did not disappear into the 'Hieland mists' as some of its officers survived to serve in other legions. There are no reports of the circumstances or place of the trouble but the construction of Hadrian's Wall with its system of forts, mile castles and turrets suggests that the difficulties lay in south-west Scotland.

In 196 A D Clodius Albinus, Governor of Britain, transferred much of the army to the Continent in support of his claims to the Imperial title thus denuding the north of its garrisons. The news of his defeat by Severus was followed by the wasting of the north including the destruction of York by either the Maeatae of Strathmore and Strathern, who later became the southern part of the Pictish nation, or 'local wild men' from the north Yorkshire moors. Rebuilding started immediately and followed the same lines as the previous fortifications.

Another incursion of barbarians occurred in 296 A D upon a similar withdrawal of troops from the north necessitating yet again, the rebuilding of the fortress by Constantius I on a grander scale than ever before with polygonal towers being incorporated into the curtain wall facing the river.

From the first occupation of the site a civilian settlement would have existed to serve the needs of the legionary fortress and by the beginning of the third century Eboracum covered about 200 acres with a population of 10,000-15,000 (a legion's strength was 6,000) with the fortress and a civil settlement on the north bank of the river and a civil town to the south. This town, an important port and trading centre, became the capital of Britannia Inferior and received the title and privileges of a colonia, probably from Severus.

It is very difficult to evaluate the numbers or influence of Christians at any period as the evidence is so scanty. However, it is related in the *Acts of the Apostles* Chapter 13 that St. Paul converted Sergius Paulus, the Governor of Cyprus to the Christian faith. His daughter married Caristanius Fronto who became commander of the IX Legion at York in about 80 A D. Although Fronto could not have been a practising Christian, as part of his military duties engaged him in emperor worship, his wife may have been. It seems likely that this remained the pattern for some time, a small number of Christians mostly from the upper, (i.e. mobile) classes drawn particularly from among those who had served in the eastern Mediterranean.

It is next recorded, after Constantine the Great, who was acclaimed Caesar at York in 306 A D had secured toleration for Christianity in the Empire in 312 A D, that Eborius, Bishop of York, was one of the three British bishops who attended the Council of Arles in 314 A D.

There is no evidence as yet, of the site of a church which should be situated somewhere in the colonia. It is most unlikely to be on the Minster site as the principia would remain in use until the Roman withdrawal.

Saxon York

Throughout the fourth century the Roman machine began to disintegrate due to internal strife and external barbarian pressure. This was highlighted in 376 AD by the synchronised assault upon the province by Saxons, Picts and Scots. The Count of the Saxon Shore, who was head of coastal defence was killed, the Duke of Britain, the Commander-in-Chief of the inland forces, immobilised and the Wall and northern forts fell once again. Order was restored by reinforcements from the Continent but the settlements near the Wall never recovered and increasing use was made of mercenary troops to protect the frontier.

Evidence of their presence is found at York in the form of pagan cemeteries of Germanic mercenaries, Foederati, which could be as early as 375 A D although they are generally assigned to the early fifth century. There are no signs of integration with the Romano-British community, but their peaceful co-existence supports the belief that not every Saxon arrived as an invader.

The legions were finally withdrawn in 410 A D resulting in increasing economic chaos and the breakdown of the money economy to the more primitive system of barter.

The city's economy must have been seriously affected and severe winter flooding between about 450-550 A D must have partially, if not wholly, destroyed the port facilities upon which its prosperity largely depended. Evidence of this flooding is the silt layer which is up to 2 ft. thick over those areas of the city below the 35 OD Roman contour. Similar layers of silt in the Hatfield Chase area, which appear to be part of a general east coast phenomenon, have been dated by pollen analysis and carbon 14 tests to within this period.

With economic decline and political instability, York's population was drastically reduced and its magnificent civic and military buildings fell into disrepair. An eighth century Anglo-Saxon poet wrote of a similar city:

'Well-wrought this wall: Wierd broke it
The stronghold burst . . .

Snapped rooftrees, towers fallen
the work of the Giants, the stonesmiths, mouldereth.'*

The sixth and seventh centuries saw the establishment of two English (i.e. Anglo-Saxon) kingdoms between the Humber and the Forth, Deira and Bernicia, which were controlled at times by a single monarch and termed Northumbria. However, the assimilation of the Celtic population by the 'invader' was not rapid and at the beginning of the seventh century an independent British kingdom, Elmete existed not many miles to the west of York. This was conquered by Edwin, who gained control of Northumbria and arranged a political marriage with Ethelburga, a sister of the King of Kent, whose father had been converted to Christianity by St. Augustine. She was accompanied to the north by Bishop Paulinus and after two years Edwin was baptised.

Editorial note:
*The Anglo-Saxons usually referred to Roman ruins as the 'work of the Giants' (2).

Bede writes:

'So King Edwin, with all the nobility and a large number of humbler folk, accepted the faith and were washed in the cleansing waters of Baptism in the eleventh year of his reign, which was the year 627, and about one hundred and eighty years after the first arrival of the English in Britain. The King's Baptism took place at York on Easter Day, the 12th April, in the Church of Saint Peter the Apostle, which the King had built of timber during the time of his instruction and preparation for Baptism, and in this city he established the See of his teacher and Bishop Paulinus. Soon after his Baptism, at Paulinus' suggestion, he gave orders to build on the same site a larger and more noble basilica, which was to enclose his earlier little-oratory.' (3)

It is traditionally supposed that these churches were on the Minster site although no physical evidence has been found. It is also assumed that Paulinus brought masons from the Continent to construct the second, stone church as the vast majority of English buildings of this period were of timber.

The building of the Church indicates that York is to become the ecclesiastical focus of the Kingdom although there is little evidence of its civil status.

The early English kings did not possess a fixed capital but moved from royal palace (villa regalis) to royal palace. Edwin had other major centres at Yeavering and Bamburgh.

(Yeavering exhibits several examples of large and relatively sophisticated timber structures, including a remarkable timber amphitheatre).

The king and his household, i.e. the Government, led this perambulating existence for three basic reasons; to show the flag militarily and keep a check on the junketings of the nobles; to hold courts of law and to consume the produce of the royal manors on site rather than transport large quantities of food about the kingdom. Basically this remained the pattern of government until the thirteenth century when departments of state, still theoretically part of the royal household began to be centralised in London.

Towards the end of the seventh century St. Wilfrid became Bishop of York. He inherited a most difficult situation with the Northumbrian church split between those supporting the Celtic and the Roman churches. The Celtic church had developed in Ireland in isolation and comparative peace, while Europe was being overrun by the 'barbarian hordes'; consequently, differences with Rome had arisen in belief and practice. St. Columba founded a monastery on Iona in 563 A D and it was from here and later from Lindisfarne that missionaries were sent to the North of England and onto the Continent with resulting collisions with the Roman church, extending its missionary efforts northwards. In Northumbria the difficulties were discussed at the Synod of Whitby in 664 A D when St. Wilfrid presented the Roman case, which carried the day. How-

ever, disagreements and quarrels remained rife well into the next century.

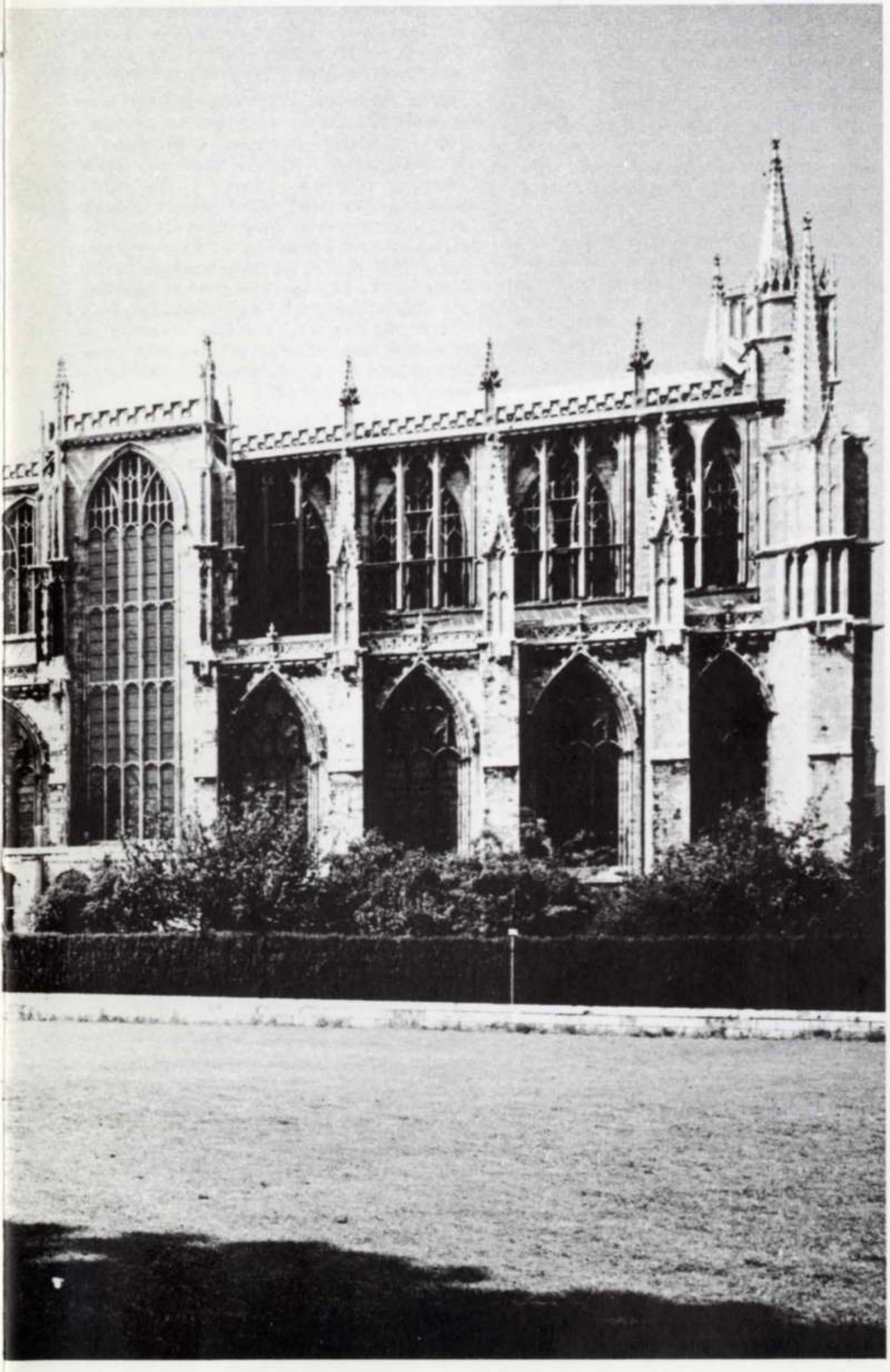
Although the results of the Synod would suggest qualities of statesmanship, Wilfrid appears to have been arrogant and quarrelsome, spending years and shoe leather chasing around Europe establishing his claim to the See and its independence of Canterbury, an issue to plague the English Church until the fourteenth century. However, it is recorded that he repaired the church on finding it in a serious state of neglect and endowed it with many lands. The dilapidated state of the church and the fact that the Synod was held at Whitby and not at York are perhaps signs of a temporary eclipse of Christianity at York.

During the eighth century the political history of Northumbria is frightening in its complexity and its successions of Kings, *'with P. G. Wodehouse names, Ugs and Berts and Threds and Walter Scott fates.'* (4)

In this context it seems amazing that this period is described as the 'Golden Age of Northumbria', with the establishment at York of a school under Alcuin, renowned for its library, scholarship and achievements in the arts. It is recorded in a poem by Alcuin that a new basilica was built during the time of Archbishop Aethelbert by his two pupils Eanbald and Alcuin which was consecrated about 780.

Scholars have disputed hotly whether this refers to the Minster or a different building. However, Symeon of Durham records that 'in the year 741 a monasterium in the City of York was burnt on Sunday IX Kal. May' and recent excavation has produced physical evidence of a Saxon building of this date on the Minster site.

During this period York slowly recovered as a trading centre and port to present an inviting target for Danish raids. In fact the city was captured by the Danes in 867 and only subjugated by the west Saxon Kings after a long struggle. The plains with their heavy marshy soils that lie immediately north and south of the York moraines were probably settled at this time by Anglo-Saxon colonists since all the present-day villages were there by *Domesday Book*. However, much of the vale was still marshy and relatively unproductive and Yorkshire's broad acres were yet to be dominated by crop yields and cricket. *Egil's Saga* refers to the city as 'York town, the dank demesne.'



Early Mediaeval York

After his victory at Hastings, William of Normandy pursued a policy of pacification, implemented largely by granting fiefs to his followers. To defend their lands the Norman and Breton nobles hastily constructed castles garrisoned by small numbers of knights and men-at-arms.

In 1069 a major rebellion broke out in Northumbria and a Danish fleet entered the Humber to be joined by an English army. The castle at York was besieged and the Norman defenders fired the houses in its vicinity to prevent their being pulled down and used as moat-filling material. The conflagration spread and the city, including the Minster and Alcuin's library, was destroyed. Despite the precautions, the castle was taken and its garrison massacred.

William crushed the rebellion ruthlessly and laid waste large tracts of the north. *'This scorched earth policy, which lay heavy on his conscience in later days, and even heavier on his reputation, fulfilled its political purpose* (5) breaking finally the will to resist in Northumbria.

York suffered economically and by 1086 its population had declined to about 5,000, approximately half of the 1066 total. Apart from the wasting of the north, another major factor in the city's decline was its isolation from its Scandinavian markets.

With the Norman conquest England changed its governors but not its system of government, for England under Edward the Confessor was a wealthy feudal monarchy with an advanced and unusually centralised financial system. William modified, disciplined and rationalised but made few major changes in the system. He did however, replace the majority of the tenants-in-chief of English or Danish blood, whether bishop or baron, with his own men.

As regards the church he was in a difficult position for he had received papal support for the invasion and was committed to ecclesiastical reform. However, his first priority was his own security and he vigorously maintained his right against strong pressure from Rome to nominate his own candidates for the major ecclesiastical posts. This royal policy produced bitter disputes between king, pope and clergy throughout the twelfth century.

However, one can sympathise with William for the prelates wielded, not only spiritual influence, but considerable political and military power, for they were temporal as well as spiritual lords with the estates, dues and services of great feudal nobles.

The following contemporary account of the behaviour of Bishop Alexander of Lincoln (1123-48) and Nigel of Ely should not be considered untypical:

'They were called Bishops but they were men given up to pomp and display; they so devoted themselves to a military life and the world's pomp that when they came to court all men marvelled at them for the crowd of men-at-arms who attended them' (*Gesta Stepheni*)

Fig. 2 The Minster from the north.
Photo: Shepherd Building Group Ltd.

An example of the 'jobs for the boys' policy was the appointment of Thomas of Bayeux to York on the death of Ealdred in 1069. Thomas was chaplain to Odo, Bishop of Bayeux and half-brother to William and was a son of a canon of Bayeux. The less charitable hinted that he owed his preferment to being a natural son of the conqueror.

He seems to have been a scholar, having studied extensively not only in France but also in Germany and Spain and in the light of his work at York, an organisation man par excellence. His vigorous prosecution of the eternal independence issue with Canterbury showed him to have considerable spirit and an admirable spleen.

On arrival in York, he found the Minster a blackened ruin and its clergy scattered. He repaired the building and set up an ecclesiastical organisation on the French model with a chapter of 36 canons, each endowed with a prebend; a church and its estates within the diocese. Included in this chapter were the four greater persons; the Dean, the Precentor who organised the Cathedral's worship, which at this time was its most important function, the Chancellor, who was responsible for the educational aspects of the Cathedral's life, and the Treasurer. This organisation remained basically the same until the Reformation with the exception of the development of Vicars-Choral (who were regularised by the foundation of a college of Vicars-Choral in 1252). They were deputies paid by the canons to sing services in their stead while they sat by the fire in the country or indulged in political chicanery at a nobleman's court or the king's court.

The Archbishop would only have resided in his palace at York for short periods, the majority of his life being spent in fairly constant movement either with the king or about his own 20 or more manors.

In about 1080 Thomas demolished the Saxon Minster and rebuilt the church from the foundations with nave, choir and transepts.

Thomas was succeeded in 1100 by Samson Gerard, Bishop of Hereford and then by Thomas II, son of Samson, the first Norman Bishop of Worcester, a brother of Thomas of Bayeux. They both continued the quarrel with Canterbury and were succeeded in 1114 by Thurstan, whose appointment was a reward for loyal service in the households of William II and Henry I.

During the eleventh century the control of the papacy had been assumed by a reform movement *'bent on bringing the church, and through it society closer to the idea of St. Augustine's City of God'* (6). In the next century the papacy, under the dominant influence of St. Bernard the puritanical founder of the Cistercian order, and finding inspiration in personal piety and asceticism, condemned the secular activities of the clergy and tried to disengage them from their dependence upon their lay lords. One of the results of this policy was the attempt by the papacy to interfere in appointments to bishoprics.

Thurstan was one of the leaders of the papal party in England and much admired in Europe. He was a personal friend of St. Bernard whose support he sought and received in furtherance of the argument with Canterbury. On his succession *'his great object seems to have been the reorganisation of the existing monastic orders and the bringing in of others who maintained a more ascetic discipline and sterner rule'* (7). Apart from his zeal as an evangelist he had other talents. In July 1139, during Stephen's troubled reign, King David of Scotland crossed the Tees with an army which included considerable numbers of pagan Pictish troops from Galloway. Thurstan assembled the barons of Yorkshire and persuaded them to fight. He ordered all men to defend the Church of Christ against the barbarians and commanded the victorious army in the ensuing Battle of the Standard.

In 1137 fire destroyed or damaged the whole of the city including the Minster and the adjoining Palace, St. Mary's Abbey and 39 other churches. The Archbishop immediately started collecting money for its reconstruction. However, the work was not started for another 20 years as his death in 1140 was followed by a disputed election. *'When he died, the Chapter of York (who were the official electors) wanted a successor who would remain firm against Canterbury, the King wanted to nominate a man who would be loyal against the Scots, and the monks of the province were determined to exercise their right (reaffirmed by the Lateran council of 1139) to assist in the electing and promote a monastic reformer'.* (8)

The Chapter with the king's approval elected William Fitzherbert, Stephen's nephew. However, the Cistercian interest, supported by the Archbishop of Canterbury and St. Bernard, arranged his deposition and replacement by Henry Murdac, the Abbot of the Cistercian house of Fountains. On Murdac's death in 1153, William was restored to be welcomed on his arrival in York by a great crowd. A wooden bridge over the Ouse collapsed, depositing the joyful throng in the drink, to emerge damp but unharmed due to William's intercessions. Thirty days later he died. It was popularly supposed that poison had been mixed with the wine in the chalice he used in the celebration of high mass.

He became a venerated local figure and the Chapter tried to obtain his canonisation, as the only Saint buried in the Minster was a good Saxon lady, St. Everilda who does not seem to have inspired any popular veneration and thus little in the way of offerings. Owing to Cistercian power in Rome this was not granted until 1226 when the new transepts were being built. In a less cynical age Browne gives the reasons for the attempt to obtain his canonisation and refers to this reconstruction: *'The influence of the reputation of some illustrious saint was wanting to increase the zeal of the devout, to draw forth the liberal contributions of the wealthy and to render the recommendations and indulgences of the prelates in aid of the great work which the Archbishop was undertaking'.* (9)

In 1154 Roger de Pont l'Evêque, formerly Archdeacon of Canterbury became Archbishop. He was an able man and a great builder despite his deep involvement in the political affairs of his day, particularly in the quarrels between Henry II and Thomas à Beckett in which he supported the King. It is reported by Stubbs in the fourteenth century that *'the same Roger constructed anew the Choir of the Cathedral Church of St. Peter at York, with the crypt of the same, and the archiepiscopal Palace at York which is situated near the same Church. He founded also the Chapel of the Holy Sepulchre at the gate of the same Palace, on the north side of the Church of St. Peter'.* (10)

On Roger's death in 1181, the See remained vacant for 10 years, Henry II sweeping its great revenue into his needy coffers, an Angevin habit to cure an Angevin malaise. On his death Richard I appointed his half brother Geoffrey Plantagenet, the natural son of Henry II and the 'Fair Rosamund' Clifford, to the See. Geoffrey was a typical member of the 'Devil's Brood' with the great contradictions of character of his brothers Richard and John. He quarrelled with the Bishop of Durham, upset the Chapter by his hawking and hunting, his interference with appointments and by his efforts on his brother Richard's behalf to raise the ransom to release him from imprisonment in the Tyrol, after the third crusade. He had little difficulty in obtaining King John's displeasure and fled to his estates in Normandy where he died in 1212.

'In 1214 after he (John) had promised to allow free elections to bishoprics, he wrote to the Chapter of York forbidding them to nominate their dean as Archbishop, and adding 'if however you do elect him he can never hope to have our peace or love. This however, we wish to be kept secret'. (6) He had an able tutor in such missives in his father who wrote in 1172: *'Henry King of the English to his faithful monks of the church of Winchester, greeting. We order you to hold a free election, but neverless forbid you to elect anyone except Richard my clerk: the archdeacon of Poitiers'.* (6) Not surprisingly John's nominee, Walter de Grey was duly elected.

It was during de Grey's incumbency that the 'remarkable epidemic of building activity' took place in Yorkshire with the building of the presbyteries of Whitby Abbey (1220) Rievaulx Abbey (1230), Beverley Minster (1232) Kirkham Priory (about 1250) and the eastern arm of Fountains Abbey (1210-40) (11). The Minster's contribution was the building of transepts and lantern. The Archbishop financed the building of the east aisle of the south transept and issued an indulgence on behalf of the fabric in 1226. (A remarkable portrait of de Grey has recently been found on the coffin lid of his tomb in this aisle, see Fig. 3).

The north transept (1225 to about 1234) was financed by John Romanus who became subdean in 1228 and was *'the most avaricious and cantankerous of men and spent fifty years amassing enormous riches'* (12) The south transept was financed by the Dean and Chapter with a publicly subscribed fabric fund which seems to have made the period of construction longer than that of the north transept. At the same time a new crossing and lantern was being constructed which was finished by about 1250. This may also have been financed by Romanus. Little is known of this early English lantern save that it was famous for its beauty when it collapsed in 1407.

Archbishop de Grey was a political animal serving John as Chancellor and becoming one of the most trusted advisers of his son Henry III.

Henry was a most discerning and enthusiastic patron of the arts. The *Liberate* and *Close Rolls* contain many detailed briefs and instructions to the sheriffs and bailiffs of his many palaces and castles for structural alterations, new buildings and interior decorations.

'The justices of Ireland are directed to cause to be built in Dublin Castle a hall containing one hundred and twenty feet in length and eighty feet in width, with sufficient windows and glass casements, after the fashion of the hall at Canterbury; and they are to make in the gable over the dais a round window thirty feet in circumference; and also to paint over the same dais a King and Queen sitting with their baronage; and they are to build a great portal at the entry of the same hall. Bordeaux, April 24th' (13)

Apart from the King's energy and imagination these *Rolls* show the increasing sophistication and physical comfort of court life. There are references to the glazing of windows formerly fitted with wooden shutters, *'so that the chamber may not be so windy as it used to be'.* (13); to replacing central open hearths with chimneys; to wainscoting; the making of harbours; the installation of plumbing including baths and a conduit at Westminster which *'the King ordered to be made on account of the stink of dirty water* (from the kitchens) *which was carried through his halls'.* (13)

They also provide an indication of the organisation of the design and construction processes. It is of course a mistake to regard major mediaeval buildings as the chance results of the work of countless simple pious masons with mallets and leather aprons.

The client whether king, archbishop, or merchant would doubtless issue a brief similar to that for the hall at Dublin Castle either to an official with overall financial responsibility for

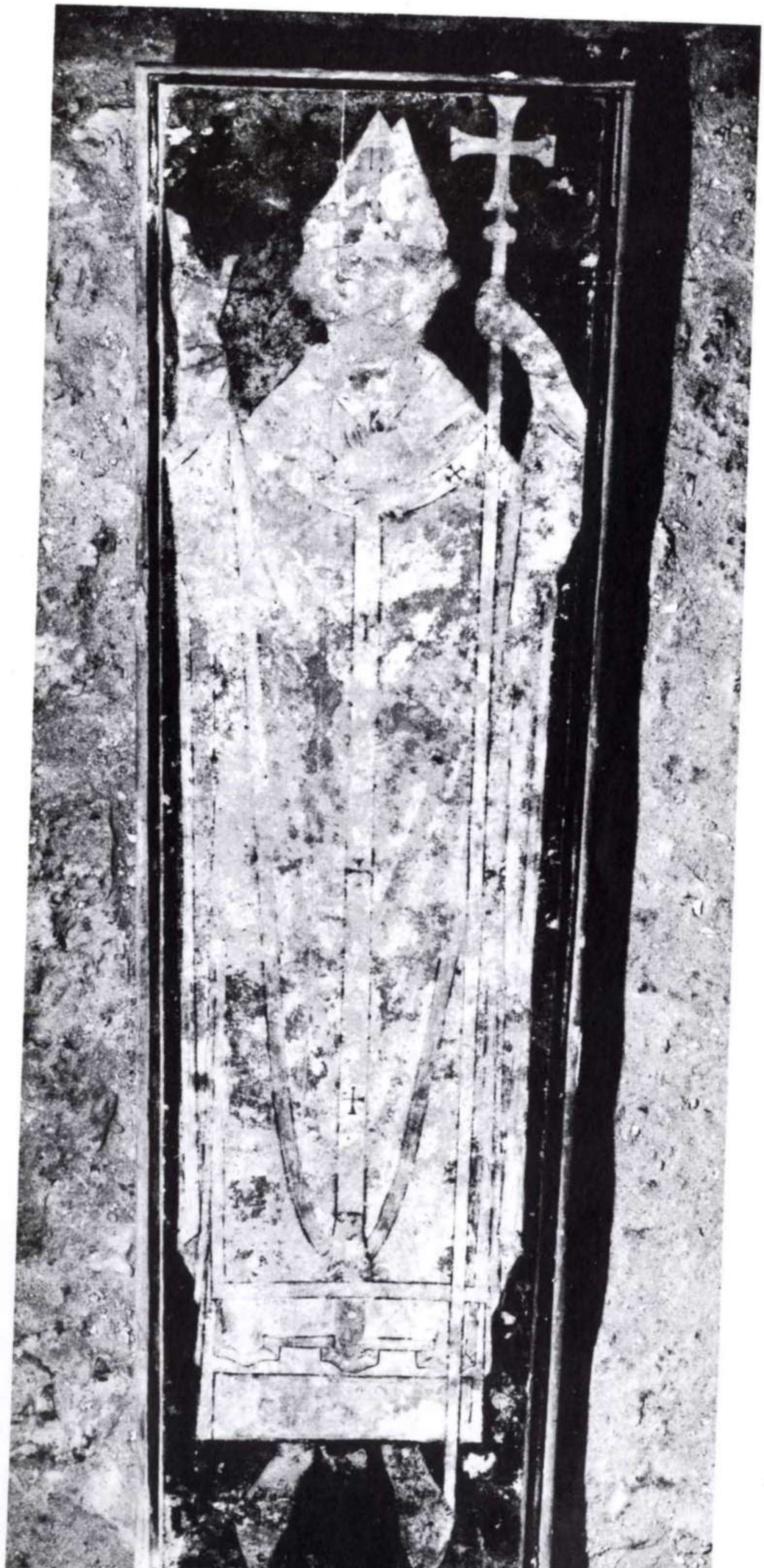


Fig. 3 'Portrait' of Archbishop Walter de Grey from the coffin lid of his tomb in the south transept.
Published with permission of: Royal Commission on Historical Monuments (England).

the works or directly to the master mason (or master carpenter depending upon the type of structure contemplated). The master mason would then not only design the building but also be responsible for the setting out and the organisation and direction of labour during the works.

He was invariably a layman and had attained his position after a trade training as a mason. Master masons working on a large project for the king or a cathedral were ranked as esquires and often provided with generous stipends, a house, an annual robe and a pension in the event of ill health or old age: *'know ye all that we, on account of the skillful industry and labour of William de Hoton, mason, son of Master William de Hoton, mason, employed and hereafter to be employed about the fabric of our Church of York, have given, granted and assigned to him ten pounds of silver as a yearly pension,* (*together with a dwelling within the close . . . which we assign to the aforesaid William provided only that he do not superintend any other works, whereby our work might be omitted, neglected, or in any wise delayed*) . . . 1351 (9).

In 1286 John Romanus, the nephew of the former Sub-Dean became Archbishop and it is recorded that in 1291 he laid the foundation stone of the new nave with great pomp and ceremony in the presence of the Dean and Canons. The nave took in the order of 50 years to complete, during which time an octagonal Chapter House was also constructed.

The designer was probably Master Simon the Mason. That he was a man of substance is demonstrated by the lay subsidy for the city of York in 1301 (a form of national taxation) when he paid the considerable sum of two marks (£1 6s 8d). The highest amounts paid by other masons were 16d and 11d respectively.

The sources of income for the fabric fund for the nave were several: offerings at St. William's shrine; bequests from wills; Penancers' accounts; parochial donations, etc. The Penancers were licensed officials who fixed and collected the fines which could be paid by offenders as a penance for their sins in lieu of fasting or mortification. With a suitable deduction for their services the money was then given to the Custodia Fabricae. Another source of income was from donations from the parishes of the See which were obtained by the issue of Briefs to be published by the parochial clergy in their churches; the bearers of these Briefs being duly authorised by a formal licence, with a cut for their pains.

These systems of raising money gave rise to great abuse in the fourteenth century. Magnificent examples of allied tradesmen are Chaucer's rogues, the Summoner and the Pardoner who

'Up-on a day he gat him more moneys
Than that the person (parson) *gat in monthes tweye'* (14)

The licensed bearer of Briefs has probably much in common with the Pardoner who describes his methods thus:

'Lordyings, quod he, in chirches whan I preche
I peyne me to have an hauteyn speche
And ryng it out, as Lowd as doth a belle,
For I can al by rote which that I telle
My teeme is always oon, and ever was;
Radix omnium malorum est cupiditas. (14)

Late Mediaeval York

During the fourteenth century York was a prosperous commercial city and port with goods from the Baltic to the Mediterranean arriving at its wharves after the journey up the Ouse from Hull. The main export was traditionally raw wool but from the middle of the fourteenth century the export of cloth was growing at its expense. Apart from the city's importance as a centre of trading it became the headquarters for military operations during the wars with Scotland. For short periods it was also the political centre of the realm. Edward I held a parliament here in 1298 and the courts of justice were removed from London and sat at York for seven years.

Most of the Archbishops of this period were statesmen, a typical example being William de la Zouche who was in the King's service in early life and had many preferments. He was elected as their Dean by the Canons of York in 1336, appointed Archbishop in 1340 and was constantly employed in various capacities by Edward III. In 1346 he was one of the wardens of the marches and commanded a division of the English army at the great battle of Neville's Cross. He was presented with an even deadlier foe by the Black Death in 1349 and the ensuing chaos and despair. On his death in 1352 he was succeeded by the Bishop of Worcester, a Yorkshireman John de Thoresby.

Unlike many of his predecessors Thoresby was a most capable and sincere pastor establishing proper provision for the instruction of the people in the principles of the Christian religion. He also closed the controversy with Canterbury, agreeing to sit on the King's left at parliaments and councils and for his cross-bearers to give precedence to Canterbury's in narrow alleys or gateways. The startling compromise was also reached whereby York was to be designated the Primate of England and Canterbury the Primate of All England.

During the fourteenth century, particularly after the Black Death which had decimated the skilled labour force, there was a general trend among masons towards tighter industrial organisation with greater standardisation of wages and formalised conditions and hours of work. Wycliffe states that *'men of sutel craft, as free masons and othere . . . conspiren togidere than no man of here craft schal take lesse on a day than thei setten'* (15)

These developments inevitably led to industrial disputes, evidenced by a report on the management of the work at the Minster in 1345. After evidence of errors of pay, bad workmanship, disputes between the various responsible officials and the misappropriation of materials; *'orders were given that no one shall interfere with the masons to appoint or remove them, except the master of the masons. Also that the master of the masons shall denounce to the Chapter those who are found disobedient or incorrigible. The said master shall take care that none of his masons receive more than he has earned by diligent work . . . No mason shall in future claim any right beyond the usual salary due to him.'* (16)

Owing to the perambulating nature of their work there were no craft guilds of masons, their corporate life being centred in the lodges on the site, whether cathedral or castle. Although there must always have been rules for the conduct of the lodge, the earliest set of ordinances to survive was drawn up in York in 1352. It was written in Latin and deals mainly with hours of work. A second set was issued about 1370 in English:

'Itte es ordayned by ye chapitre of ye kirk of Saint Petyr of York yat all ye masons sall wyrke till ye werkes of ye same kyrk of Saynte Petyr, sall fra Mighellmesse Day untill ye firste Sonday of Lentyn (i.e. the winter months), *be ilka day atte mome atte yare werke, in ye loge... als erly ale yai may see skilfully by day lygnte for till wyrke ; and yai sall stande yar trewly wyrkande atte yair werke all ye day aftyr, als lang as yai so skillfully wyrke, yft yt be alle werkday'.* (17) The documents continue with regulations for summer hours, holy days and breaks for meals; 'drynkyng' and 'slepyng tyme'.

'In 1361 a resolution was passed by the Archbishop and the Chapter declaring that every church ought to have its parts consistently decorated, and that the choir, which is destined for the offering of the sacrifice, should be more especially ornamented. The absence of a fitting place wherein the daily celebration of the mass of the Blessed Virgin Mary could take place, was also adverted to, and it was agreed to begin such a choir, and that the old choir, which, compared with the beauty of the nave, seems rude, should be taken down piecemeal, as it may seem expedient, and used for the completion of the new choir. It was agreed also that a decayed hall at Sherburn should be taken down and its materials applied towards the completion of the work'. (7)

The designer was probably William de Hoton, who conceived a choir in the Perpendicular style of similar dimensions to the nave.

It seems that Thoresby himself was the driving force behind this new building project and on his death 12 years later the four eastern bays were completed.

After Thoresby's death in 1373 there was a delay in building operations. However, work started again in about 1380 and proceeded slowly for the next 20 years. *'Complaint was made at a visitation of the Archbishop in 1390 that the work was delayed and that the rents and income devoted to the fabric were diverted from their proper purpose'* (9) Some of the delay may have been for political reasons as Richard II was deposed by Henry Bolingbroke after a period of political instability.

These remaining bays were completed by Hugh de Hedon, following the plan by William de Hoton. Hugh de Hedon also designed and built the east window between 1400 and 1405, a contract being let in the latter year to John Thornton of Coventry for its remarkable glass.

With the completion of the choir the crossing was revamped in the same Perpendicular style. This entailed underpinning Romanus's Early English lantern which collapsed during the progress of the work in 1407.

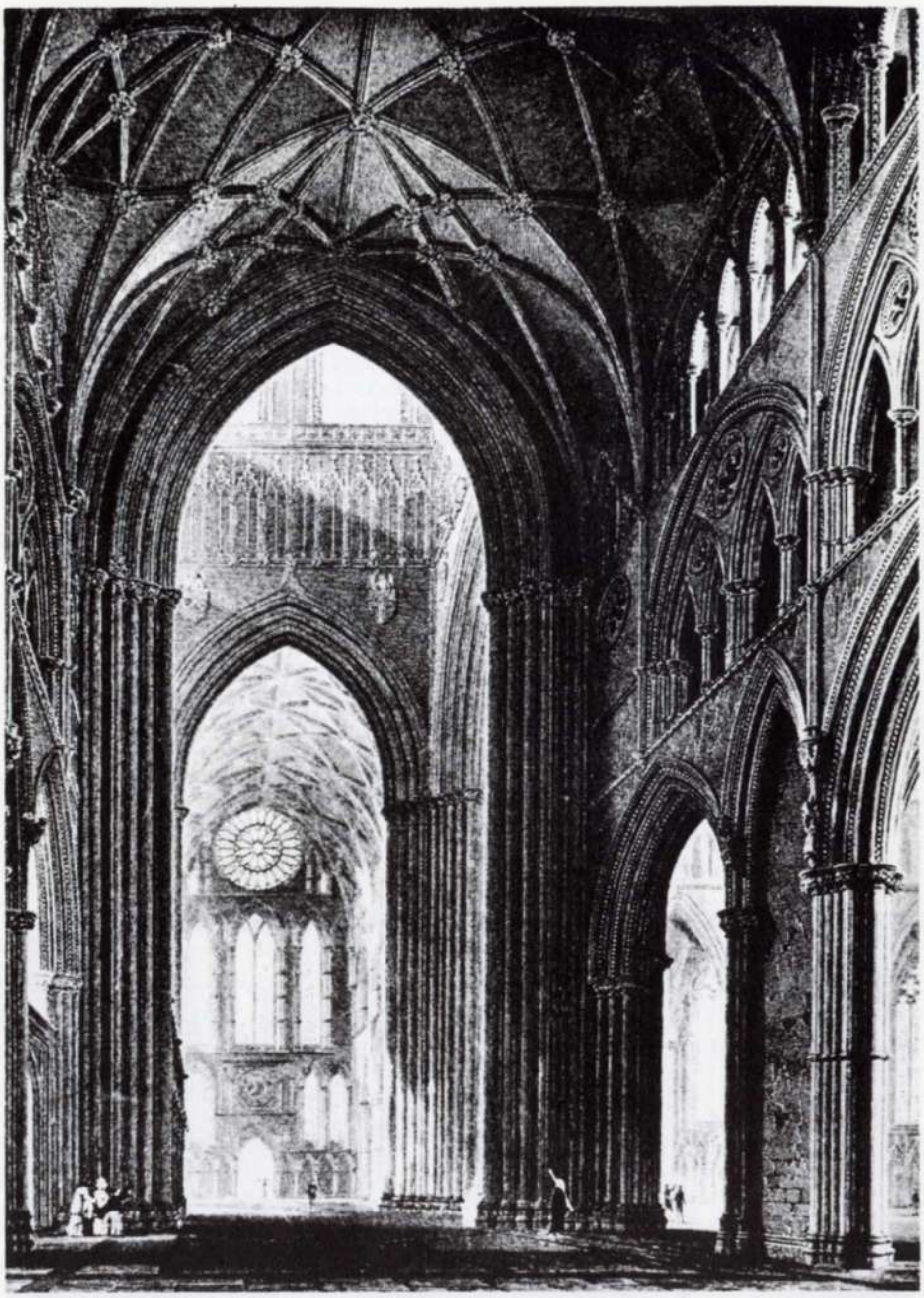
Following the collapse William of Colchester was sent to York in 1407 by Henry IV to design a new lantern. He received a most unpleasant reception owing to jealousy among the York masons and to popular resentment resulting from the King's execution of Archbishop Richard le Scrope two years previously following an abortive northern rebellion. This did not endear him to Yorkshire folk as the Archbishop was a popular figure and a Scrope of Masham, a leading sword-swinging Yorkshire family. The Archbishop was buried in the Minster and thousands flocked to his tomb to make their prayers and offerings as at the shrine of a saint and martyr. The King tried to stop these demonstrations of affection to a treasonable subject with little success.

William of Colchester's movements are not exactly clear but he was probably in York until 1410 when his charter was revoked by the Chapter. Doubtless he was pleased to go as he had been severely injured in an affray with local masons. However, it seems he returned to the City in 1415 where he was in charge although not in permanent residence until his death in 1420. Before his work in York he directed the rebuilding of the nave of Westminster Abbey in 1395. He was appointed King's mason in 1418.

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 and the Rood screen (1475-1510).

By the end of the century the Renaissance began to impinge upon English life affecting not merely the arts but also political and theological thought. Scholars such as Colet and Erasmus were expressing views which partially led to the English Reformation. Intellectual life was also stimulated by the printing press introduced into England by Caxton in 1474. By 1500 a press was operating in York.

Fig. 4 Interior view from the north to the south transept.
(In: *Cathedral Antiquities*—John Britton—1836, Vol. 1). Photo: Poul Beckmann.



An expression of the malaise within the Church was the appointment of Wolsey to York in 1514. He was already Bishop of Worcester and Tournai and by 1528 had acquired the Sees and of course the incomes of Bath and Wells (1518), Durham (1523) and Winchester (1528). Perhaps it is not surprising that he never visited York during the whole period he was Archbishop.

Post-Reformation York

Apart from the foment within the Church, the Reformation brought widespread political and social unrest particularly in the towns. York had examples of the typical disturbances and persecution of the period although the sympathy of the population remained largely with the old religion for some years. Sir Ralph Sadler writes, in 1569, that '*there be not in all this country* (Yorkshire) *ten gentilmen that do favour and allowe of her Majestie's proceedings in the cause of religion*' ([6]).

Economically York was in decline due to keener competition from London which had become the administrative and commercial centre of the realm and due to the increasing size of merchant ships. The latter severely limited the use of its port facilities owing to the journey up the Ouse from Hull.

This decline in the City's relative prosperity and commerical importance is reflected in both tax yields and population figures. For example in 1334 York was the third richest city of the realm after London and Bristol with a population of 11,000. By 1523-7 York was fifteenth in the list of tax yields, the richest cities being London, Norwich and Bristol. The population had declined to 8,000 in 1520 but increased to 10,000 by 1700. During the same period London's population shot from 60,000 to 420,000 and by the latter date both Norwich and Bristol had populations of 30,000. By 1801 York had 16,000 inhabitants. Thus from the Conquest to the Industrial Revolution the city's population was either below or at the same level as that of Roman York, whilst other cities were growing rapidly.

However, York retained certain political and military importance owing to its geographical position and the threat of Scottish invasion and was the headquarters of the Council of the North from 1482-1641.

During the Civil War a Royal Army under the Marquis of Newcastle was shut up in York by the Scottish Army and an English force under the Earl of Manchester. After a siege of 18 weeks Prince Rupert relieved the city, joined forces with the Marquis and battle with the Earl on Marston Moor (1644).

After the engagement the Parliamentarians held the field and Prince Rupert retreated towards Chester and the Marquis towards Scarborough where he took ship for Hamburg. '*York was left to the discretion of the governor thereof, to do with it as he thought fit: being in a condition only to deliver it up with more decency, not to defend it against an enemy that would require it.*' ([18])

Fig. 5 Interior view showing the fourteenth century Perpendicular choir and the remains of Archbishop Roger's twelfth century crypt which was excavated by John Browne after the fire of 1829.
(In: *The history of the metropolitan church of St. Peter's York*—John Browne—1847).
Photo: Poul Beckmann.

One of the conditions of the surrender was that neither churches nor other buildings be defaced, which saved the Minster's magnificent stained glass and statuary.

With the Restoration life became more settled and, for the upper classes, at least, more comfortable. For example, towards the end of the Stuart period there was a post office in Lendal, a Turkish bath or bagnio off Coney Street, annual races and the first waterworks. York was saved because of the importance of its geographical location for the coaching routes and it became the hub of fashionable life in the north. Throughout the eighteenth century there were assemblies, routs, balls, coffee houses and a theatre. Drake, an antiquary who published a book on York and the Minster writes: *'There is no place out of London so polite and elegant to live in as the City of York.* ([19])

In the 1730's Lord Burlington and his assistant William Kent repaved and repaired parts of the Minster. Following this renovation William Shout restored the West Front (1802-11) during the Napoleonic wars.

In 1829 a fanatic, Jonathan Martin, set fire to the choir, and a careless workman's forgotten lamp, the nave in 1840. The damage in both cases was very extensive with the roofs and vaults destroyed, serious damage to the stonework and the destruction of the fine mediaeval stalls in the choir. The only 'good thing' to emerge from the flames was the discovery of Roger's crypt and its subsequent excavation by John Browne.

The repairs were carried out by Sir Robert Smirke, designer of the British Museum and a leading architect of the day who was appointed surveyor to the Fabric after the first fire in 1829.

In 1875-80 the south wall of the south transept was restored by G. E. Street, scion of the Victorian Society and architect of the Law Courts in the Strand. Further restoration was carried out by G. F. Bodley at the turn of the century.

During the nineteenth century York's commercial development was closely linked with George Hudson, the railway king, who established York as a major railway centre.

Apart from the great fires of the nineteenth century the building has been constantly washed by the tides of history including of course flood, fire, hurricane, drought and earthquake.

'During Lent there occurred throughout the whole of England an earthquake so great that the monks of Melsa (Yorkshire), *while at vespers, were thrown so violently from their stalls that they all lay prostrate on the ground'* (1349): *'An earthquake not far from York which in some places shook the very stones out of buildings and made the Bells in Churches to jangle'* (1581, beginning of April about 6.00 p.m.) ([20])

'a terrible hurricane was experienced in York in 1763 . . . so powerful was the wind, that the weathercock and part of the battlement at the West end of the cathedral were blown down' ([21])

In a more recent time an east end pinnacle performed notable conversions of both a new Ford and clerical garden.

Fig. 6 Mediaeval building methods from a late fifteenth century *Book of Hours.* (British Museum Add Ms. 35313, fol. 34) Reproduced with permission of the Trustees of the British Museum.

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Editorial note: We hope to publish part 2 of this article in the July issue of *The Arup Journal.*

The use of model analysis in structural design

Poul Beckmann

If you want to produce a new model of a piece of mechanical hardware your design process will probably run as follows: First a design is produced on paper. Then a mock-up will be made, to see what it really looks like, and critical parts will be stress analysed. As a result of this analysis, the shape of some parts may be modified and a prototype will now be made to test. As a result of the test, more modifications may be made to the design, before production starts. In due course feed-back from the use of the production model may lead to further modifications. Eventually the sum total of all the experiences gained on this model will be considered when the next model is being designed.

Most structures are of such a size that a prototype test is not practicable (the mind boggles at the thought of Sydney Opera House being load tested to destruction). In most cases we must therefore test structures by analysis. This is not such a contradiction as it sounds because what you use in analysis is a mathematical model and the test is carried out by simulating the effects of loading and consequently internal forces by calculation.

There are two drawbacks to this procedure. Firstly that in order to make the calculations practicable, the mathematical model must be crude in respect of geometrical similarity and material properties and secondly, that even then, there are many cases where the volume of arithmetic gets out of hand.

The computer can deal with the second complaint, but even with the help of the computer it is difficult to approximate the real behaviour of the structural materials by anything better than Hooke's Law and this will in many cases produce ridiculous answers as infinite stresses at re-entrant sharp corners. We therefore resort to model tests.

Materials and methods

We have at present at our disposal different materials and methods that can be employed in model tests. Broadly speaking they fall in two catagories: Elastic models, which are generally used by measuring deflections and strains. These measurements can be used in two ways; either to check calculated deflections or strains and thus confirm analyses based on hopeful assumptions, or to derive internal forces from the elastic relationship which exists between these and the deformations. The second type of model is a miniature prototype in which the actual material properties for the real structure are reproduced as far as possible in the model so that the mode of failure is realistically simulated and ultimate strength can be established fairly accurately.

Elastic models

Elastic models are usually made of a synthetic resin material. For most applications their low Young's modulus is useful but as most tests take a considerable time, creep should be as low as possible.

A favourite material at present is *Perspex* and similar acrylic resins. Models are built up of sheets cut to shape and glued together or in the case of intricate shapes by machining out of solid blocks.

If it is desired to measure deflections, this can be done either by simple dial gauges or by electrical transducers. Strains are measured by strain gauges and the fashionable thing today is to have all deflection transducers, load cells and strain gauges, wired up to a black box which automatically scans up to 50 devices at the push of a button, and punches a paper tape. When this is fed to a suitably primed computer, it will print out all the loads and deformations.

A special variation of the elastic model is the photoelastic in which the strains show themselves as coloured fringes in polarized light; for three dimensional problems this does not work directly and in this case the following technique is used: The model which is now usually of *Araldite*, is loaded after being slightly heated, this means that the strains are frozen in when the model is allowed to cool whilst still loaded. It can now be cut up in thin slices and these will exhibit fringes proportionate to the strains in the plane of the slice.

An allied technique is the one of brittle lacquers which crack at a certain known tensile strain. Being of a colour contrasting with that of the model they will for each load show the zones in the models at the critical strain as areas of fresh cracks perpendicular to the tension.

When the strains have been measured they must be translated into stresses in order that they can be related to the loading of the model. This involves the use of Young's modulus and Poisson's ratio for the model material. These have to be measured by testing on suitable specimens.

At the end of the exercise we therefore have stresses in the model under a certain loading and these can be translated into stresses in the real structure, under a certain specified load always assuming that the real structure behaves elastically.

Miniature prototypes

We do not necessarily know from an elastic model test where and in which way the structure will fail and what its ultimate load is and in testing a miniature prototype we try to overcome this difficulty by simulating not only the geometry of the real structure, but also the properties of its material. To give full simulation of the behaviour the grain size of the model material should be of a similar magnitude in relation to the dimensions of the model as is the case for the real structure.

This is not usually a problem with metal structures but in the case of concrete a model to 1/24 full size would demand a maximum aggregate size of 1/32 in. to correspond to the normal ¾ in. size. In other words the model would have to be made of reinforced mortar or as it is more glamorously called, micro-concrete.

These models give very good results. They have, however, to be built as the real structure but with extra difficulties in making and removing miniature formwork and they have to be cured, so that in addition to being generally very expensive they take a very long time to make. Because of this expense, the tendency is to make and test only one model, which therefore wants to be as near as possible to the final design and is made relatively late in the design process. If the model takes much longer to make than envisaged, one might get into an embarrassing situation of having spent (the clients') money on a model test, and yet be unable to adjust the design in the light of the test in time to vary the tender documents.

A model material with many of the advantages of micro-concrete, but which is easier to pour and much quicker curing is gypsum plaster, similar to that used for dental casts. When wet, its consistency is slightly thicker than cream, it sets under very slight expansion and achieves strengths up to 5000/6000 psi, in the course of hours. The strength increases as it dries out and in order to eliminate variations of strength due to different rates of drying, the model is coated with shellac after such a time that the correct strength and E-value are obtained.

As the mix can be poured and no mechanical compaction is necessary, it is in most cases possible to re-use moulds. These usually have a timber skeleton and are faced with glass fibre reinforced epoxy resin. Hollows are formed by cores of expanded plastic which are removed with a solvent after the model is completed.

The final model material differs from the concrete in the following respects; the E-value for a given strength is lower than for concrete; the tensile strength for a given compressive strength is higher than for concrete, but the bond to steel is lower. Where the test is mainly to investigate the ultimate load determined by concrete compression failure the first two differences are of little importance. The bond problem is usually overcome by using thin screwed rod reinforcement in beams and columns, and welded mesh for slabs and walls.

Because of the ease of making and speed of curing it is quite feasible to produce modified models when the results of the first test show this to be desirable. Member sizes can be reduced by blocking out the moulds and reinforcement details can be altered to suit and in this way model testing becomes an active design tool rather than merely a verification procedure.

It should be mentioned for completeness that a special demountable electric strain gauge has been developed by Professor Brock of Loughborough University of Technology for use with these plaster models and it is possible to test the models in the elastic range initially. To get good results from this the models should be loaded and unloaded half a dozen times beforehand, to allow bedding in.

Model tests we have done

With the exception of photoelastic and brittle lacquer techniques, we have used all these methods on model testing in the past. Some notable examples are the micro-concrete model of the Smithfield dome, where the test mainly served to confirm the buckling load.

This is described in detail in the *Proceedings of the Institution of Civil Engineers*, Vol. 30, January, 1965, pp. 109-130, written by L. L. Jones and G. D. Base.

The tests on the *Perspex* model of the Sydney Opera House shell scheme are described by John Blanchard. Bryan Wright then reports on tests on a *Perspex* model of the structure for a tall building which, however, was never built. As regards plaster models, our work on these has been carried out by Professor Brock of Loughborough University. We have, in this issue, Tony Stevens' description of the test on a *Perspex* model and finally what amount to tests on the production model, i.e., the proposal to instrument the final structure.

Model tests for the Sydney Opera House

J. Blanchard

The year is 1960. Income tax is 7s 9d in the pound and electronic computers are used chiefly for playing noughts and crosses. The roof over each hall of the Sydney Opera House is to be constructed as a group of shells with parabolic geometries. Each shell will have two skins, 6 ft. apart and connected by thin webs in two directions. The shells will be supported at their edges either on adjacent shells or on the louvre walls which close off the ends of the larger shells. These louvre walls are themselves supported by the next shells so that all 16 double shells act together as one very complex structure.

Several methods of analysis have been devised but they are not entirely consistent. Furthermore, they all make heavy simplifying assumptions and give little information about the stresses in certain critical areas. It is obviously too important a structure to be designed in this way, so a structural model of the complete roof over the larger hall has been made and tested to confirm and augment the theoretical values of stresses, deformations and support reactions.

The model was made of *Perspex* to a scale of 1/5 in. to 1 ft. The outer skins of the shells had already been made in Denmark by pressing warmed white *Perspex* sheets into timber moulds. The webs and louvre walls were made in London from clear *Perspex* and cemented to the outer skins. The inner skins were simulated, for simplicity, by flanges cemented to the underside of the webs. The complete model was assembled and tested at Southampton University by, amongst others, Clinton Tang and Bob Emmerson, under the supervision of Peter Rice and with advice from Dr. Booth who was then with the University.

Dead and wind loadings were represented by weights attached to the shells by strings and placed on X platforms which could be lowered hydraulically. In this way, if the strings were suitably adjusted, loads could be applied simultaneously either to individual shells or to the whole model.

Horizontal reactions at the supports were measured by proving rings fitted with electrical resistance strain gauges. Vertical reactions were measured by electrical resistance strain gauges fitted to the simply supported aluminium beams carrying the shells. Sophisticated bearings were required to ensure that the whole reaction was transmitted through the measuring device and in the right direction. Rotations at the supports (which were fully hinged) were measured by deflecting beams of light from mirrors attached to the shells.

Strain measurements on the shell, webs and louvre walls were made using over 1,000 electrical resistance strain gauges which could be switched in or out of two 50 channel strain-gauge recorders. The readings were recorded manually on prepared forms and sent direct to London for interpretation. This meant that a foolproof notation had to be devised for describing unambiguously the position and orientation of all the gauges. Two types of strain gauge were used: Tinsley gauges made from fine wire on a paper base protected by felt and Saunders-Roe gauges made from etched metal foil on an epoxy resin base unprotected. The former were attached satisfactorily using *Durofix* but some difficulty was experienced with the latter. Eventually a glue was found (Eastman 910 @ 70/- per ounce) that worked quite well except that it set on contact, so that you had to be right with your first attempt to position the gauge. The whole test rig was surrounded by polythene sheeting to exclude draughts and to limit humidity changes to which the unprotected Saunders-Roe gauges were very sensitive.

It was not found easy to obtain accurate strain readings. If light loading was applied to the structure then the galvanometer movements were too small to read with precision. With heavier loads the galvanometer readings were satisfactory but creep became important. It is doubtful whether, even on a good day, strains could be measured to an accuracy of 15%. The inaccuracies in the full-scale stresses were of course very much larger than this, especially as the model was not exactly similar even to the idealised full-scale structure.

Nevertheless, it was felt that significance could be attached to the results. These confirmed recent theoretical predictions of unacceptably high bending stresses in the larger shells. They also indicated very high shears between louvre walls and shells showing that the load was not being transferred to the supports in the way that the analysts had expected. No doubt Arups could have redesigned the shells to reduce the stresses and no doubt a theoretical proof of the shear distribution could have been devised; but we were not to have the opportunity.

The architect, Jørn Utzon, had begun to express his dissatisfaction with certain aspects of the shape of the roof, with its internal appearance and, above all, with the louvre walls which he had never really liked. Nor were Arups completely happy about the construction problems involved. A new scheme with the shells formed by fan-like ribs was therefore investigated and found to be workable so the original scheme was dropped. As for the model it lingered on for a few years, circulating slowly round the offices at 13, Fitzroy Street until it finally disappeared.

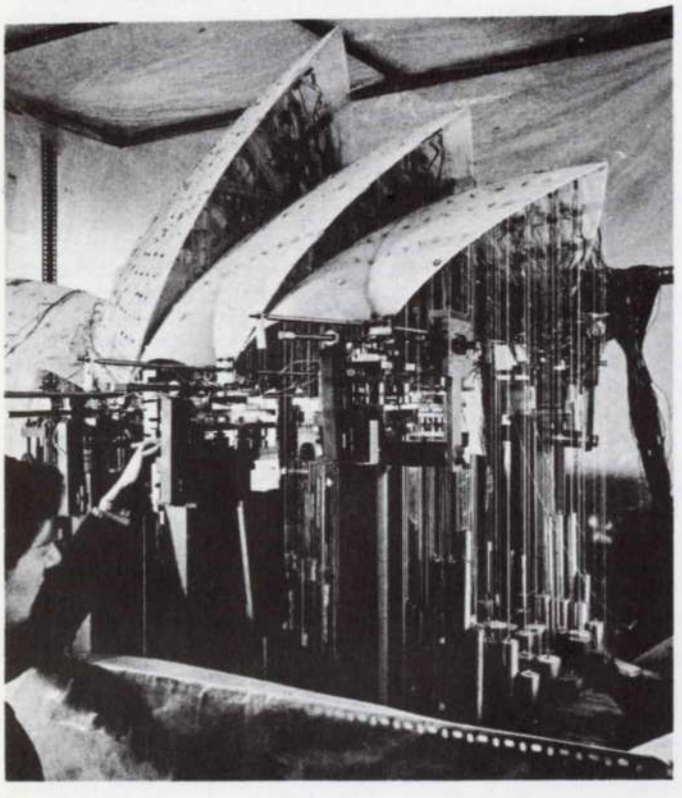


Fig. 1 General view of model in test rig

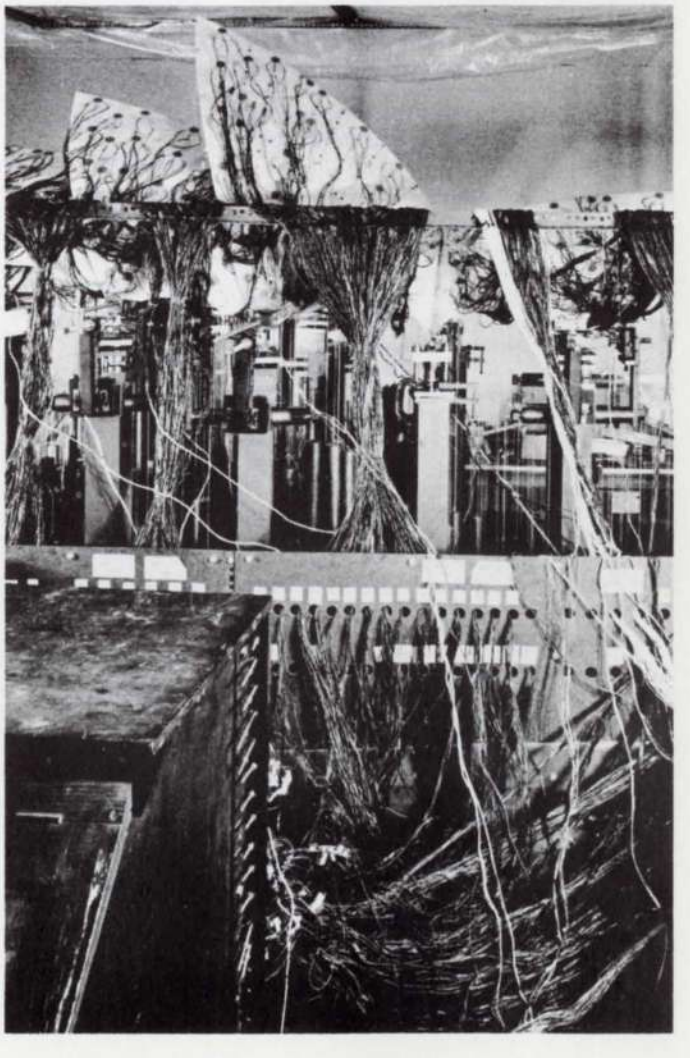


Fig. 2 Bolognese

Elastic model for 22-storey block of flats at Hong Kong

Bryan Wright

The site was at Repulse Bay, Hong Kong, sloping at an angle of 38°, swept by winds of up to 150 mph. Two blocks of flats each over 22 storeys high were required by Hong Kong and Shanghai Hotels Ltd. Messrs. Marmorek and Womersley, architects, Hong Kong, invited us to participate in the design in 1964.

A typical floor plan is shown in Fig. 1. The structural system was dictated by the planning of the dwellings and the architectural concepts. The main structural problem was to resist horizontal wind forces which could produce a moment of 180,000 kip ft. and a shear of 140,000 kips at the foundations.

Five vertical cantilevers or shear walls in reinforced concrete provide this resistance. These are the amah tower, the lift well, the stair well, the east bathroom tower and the west bathroom tower. Vertical loads are carried by these five units plus the four slab columns. Unfortunately the system is ill-conditioned in that the slab columns which have little resistance to horizontal loading, are obliged to carry a high proportion of the vertical loading.

Hand calculations

1. *Wind on north-south axis*

It was assumed that the five towers would resist the total wind load acting as vertical cantilevers tied together at each floor level by the slabs. Because of the high ratio of the stiffness of the towers to the stiffness of the floor slabs (in the order of 1,000:1) it was assumed that no frame action would occur. The slabs would be capable of some rotation at their ends. Since each of the five towers varied in cross section and were founded at considerably different levels, yet were constrained to deflect together, an iterative process was used to calculate the moments in each tower, and the axial (shear in the case of bathroom tower connections) forces in the floor slabs. Torsional effects on the buildings were neglected since it is virtually symmetrical about the N-S axis.

2. *Wind on east-west axis*

The same assumptions were made but the calculation was complicated by the torsional effects, the rotation centre of the building being calculated to be at approximately the quarter point of the width.

Computer calculations

The central part of the building, i.e. amah, lift, stairs, and connecting slabs, was analysed as a two-bay wide column frame on a program which had just been developed by Mr. I. MacLeod at Glasgow University. The results suggested that there was much interaction between the towers, and that these, acting together, were much stiffer than assumed.

The model

Calculations made for the wind on the N-S axis were considered to be a little conservative as far as predicting moments in the towers was concerned. The validity of the computer analysis was doubted because it was difficult to assess how much of the floor slab was effective as a connecting beam. Many doubts existed as to the validity of the calculations for torsion with the wind on the E-W axis. When Glasgow University offered to construct an elastic model, and to provide the facilities for testing, their offer was gratefully accepted.

Material

The most important criterion for a model material is that it should maintain a constant creep characteristic up to a reasonable stress level, and that it can be bonded to withstand stresses up to this level. Thermoplastic models can undergo wide ranges of deformation and their low elastic stiffnesses reduce the magnitude of loads necessary. *Vybak* is probably the best thermoplastic material available for the construction of elastic models, since it possesses excellent dimensional stability, is free from humidity effects, and is available in most 0.01 in. increments of thickness from 0.01 in. to 0.25 in.

Perspex was chosen in this instance mainly because it was more readily available especially in thicknesses greater than 0.25 in. Unfortunately it was not available in small increments of thickness, which introduced some scaling problems.

Tension tests were conducted on samples of the *Perspex* in the model testing laboratory to determine the E value at the same temperature and humidity to which the model would be subjected. E was found to be about 4.0×10^5 at 5 minutes. Fig. 2 shows the variation of E with time. The behaviour is linear for stresses up to 2,800 lb/sq. in.

Using the available electronic strain gauge recorder, it was possible to read the gauges at the rate of about 60 per minute. Using a load application time of five minutes, it was felt that the effects of creep would be insignificant. The model is shown in Fig. 3. The scale of 1/48 resulted in an overall height of approximately 4 ft. 6 in.

Constants

S_L (scale factor) $= 48$

$E_{perspex} = 4.0 \times 10^5$

$E_{concrete} = 3.0 \times 10^6$

Sf (stress scale factor) $= \dfrac{Ep}{Em} = \dfrac{3.0 \times 10^6}{4.0 \times 10^5} = 7.5$

Force = stress x area

$P_p = \sigma_p A_p = Sf.\ \sigma m\ S_L^2\ Am$

$Pm = \sigma m\ Am$

then $\dfrac{P_p}{Pm} = Sf\,S_L^2 = 17{,}280$

$\dfrac{Mp}{Mm} = SfS_L^3 = 829 \times 10^3$

Poisson's ratio concrete 0.15

perspex 0.36

Shear stress scale factor $= \dfrac{Gp}{Gm} = 8.9$

It is a similitude requirement that Poisson's ratio for model and prototype should be equal. This requirement is not important if the model is subjected to tensions and compressions only but there may be considerable inaccuracies when shear deformations are significant.

Dial gauges were used to measure deflections, while linear foil resistance gauges 1 in. long were bonded to the *Perspex* using epoxy resin adhesive. Horizontal loads were applied by connecting to the model wires which passed over pulleys on a fixed frame and attaching weights to the free ends.

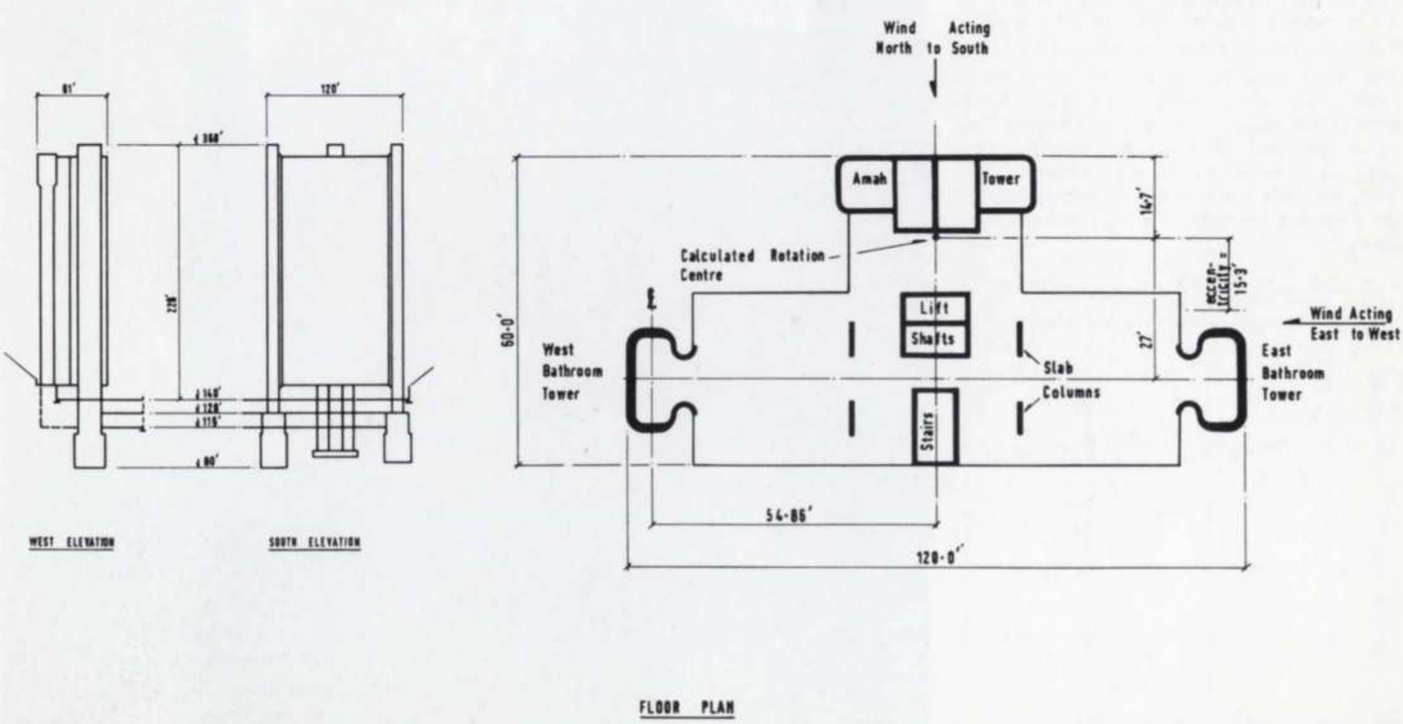


Fig. 1 Plan & elevations of prototype.

The first test : wind on N-S axis

Three point loads were applied at every fourth floor to simulate the wind loading. Dial gauges were placed on the amah and bathroom towers at floors 2, 6, 9, 11, 14, 16, 19 and roof. A total of 62 strain gauges at foundations, first floor, and floor 11 were read. The loads at each point were applied in increments of 0.5 lb. from 1 lb. up to a maximum of 14 lb. then decreased to 1 lb., readings on dial gauges and strain gauges being taken at each increment. Fig. 4 shows readings from a typical strain gauge.

The dial gauges indicated that the deflected form of the model was akin to that of a frame, with a point of contraflexure at floor 11. Strain gauges at this level indicated that the stress was too small to be measured, thus corroborating the deflected form.

Although contraflecting, the bathroom towers assumed a different deflected form from that of the three central towers, suggesting that considerable distortion of the floor slabs was occurring. Total deflection at roof level was about 60% of that calculated.

Stresses in all vertical units were much less than calculated. The slab columns to the south were in compression, while those to the north were not stressed.

It was evident that the moments and shears induced in the connecting floor slabs must be high. An attempt to measure these was made using $\frac{1}{4}$ in. strain gauges. This failed due to the long length of gauge compared with the length of the connecting members, and due to the low accuracy of a $\frac{1}{4}$ in. gauge. However, an assessment of these forces was made by calculating the rotations and displacements of the ends of the slabs from the measured deflections. It was found that the slabs were loaded to about 80% capacity.

Stress distributions for hand, computer and model analyses are shown in Fig. 5. Hand calculations indicated that the bathroom towers each resisted 30% of the total wind moment, while the model analysis indicated 10%. In the computer analysis, the frame was loaded with 80% of the total wind loading, i.e. the same proportion taken by the equivalent part of the model.

The second test : wind on E-W axis

First the rotation centre of the model was ascertained by loading at different positions and measuring deflections at the extremities. The centre was found to be at a distance of 17 ft. from the north face—a difference of 2.3 ft. from the calculated position of 14.7 ft.

The model was then loaded at the centre of rotation and a test similar to the first one was conducted. Again the results indicated that the model was behaving like a frame, with large axial forces in the slab columns. Deflections were much less than calculated, but the deflected forms of all the towers were identical.

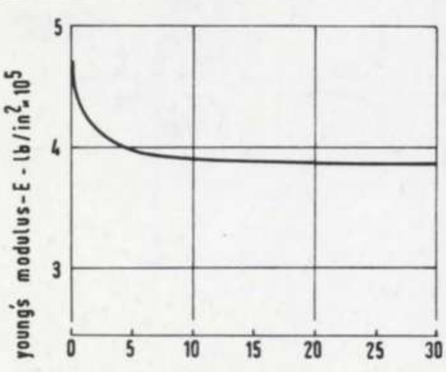


Fig. 2 Young's modulus for *Perspex*.

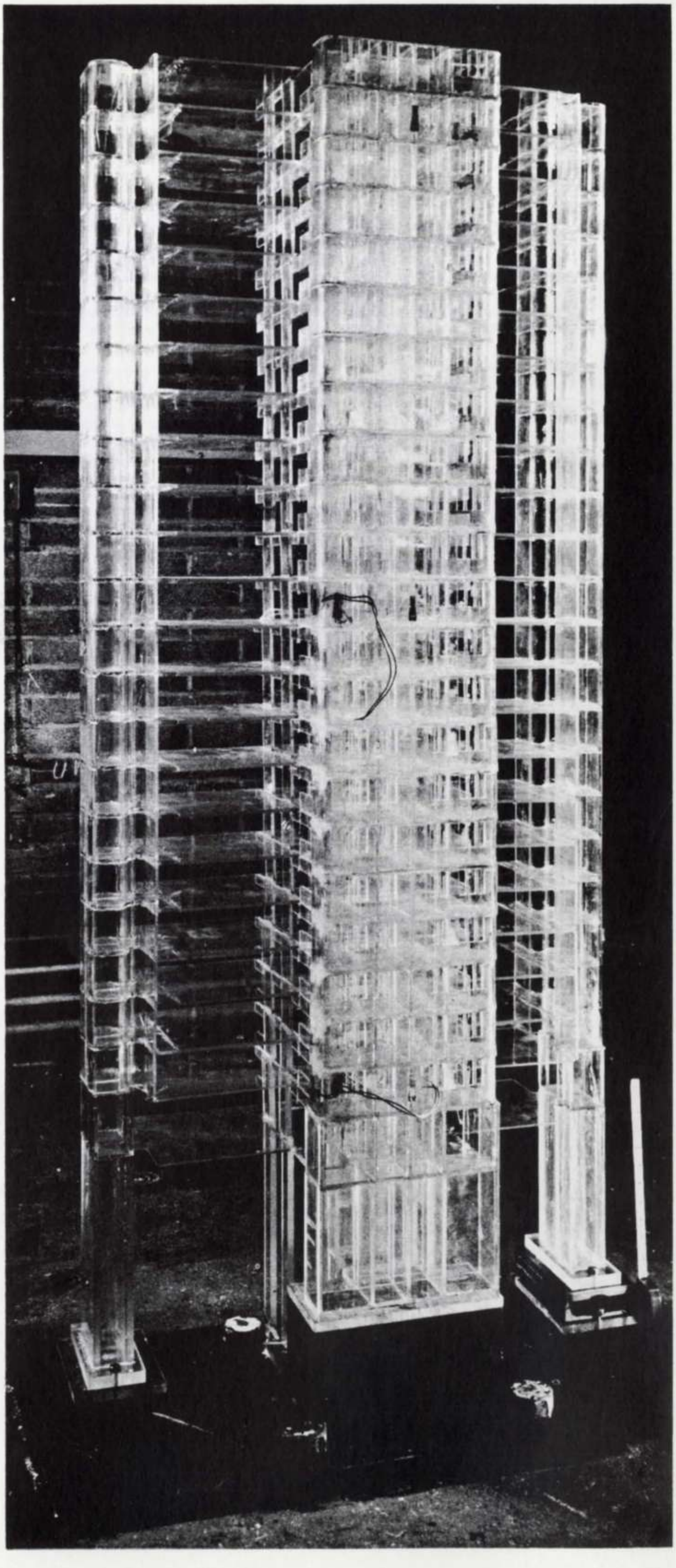


Fig. 3 right. Model (Photo : Studio Swain)

The test was repeated with loads applied at the centre of wind pressure, dial gauges being positioned to effect measurement of the rotation at various levels. These were found to be considerably less than calculated levels. It was not possible to measure the shear stresses due to torsion in the towers, but the small rotations seemed to indicate that the torsional rigidities were much greater than calculated, probably due to the stiffening effect of the floor slab diaphragms, which were neglected in the calculations for torsional rigidity. It is probable that the dissimilitude in Poisson's ratio for model and prototype also affected rotations.

Conclusions

The ultimate load factor would have been similar whether the load calculations or the model analysis had been followed for wind on the N-S axis. However, hand calculations would have grossly over reinforced the towers, while considerable cracking in the floor slabs would have occurred before the ultimate state was reached.

The computer analysis of the three central towers showed greater interaction than did the model test which was probably due to :

1. Inaccuracies in computer input
2. Neglect of local deformation at the tower-slab junctions in the program

In considering model test results for the wind on the E-W axis, it was evident that the lift, stair, and slab columns acting together as a frame, possessed enough stiffness to cause the whole model to deflect as a frame. The results allowed this stiffness to be accurately assessed, with a consequent change in the position of the calculated rotation centre to 15.8 ft. from the north face.

Fresh calculations assuming no torque were in close agreement with the model test results when loaded without torque. However a comparison of the 'with torque' results showed poor agreement, probably due to :

1. Dissimilitude in Poisson's ratio
2. Inaccurate assessment of torsional rigidities in the calculations

There is no doubt that the model analysis enabled a much more accurate assessment of the behaviour of the prototype to be made, as well as providing academic interest. The time required to fix the strain gauges and conduct the testing was very great, but had the model been used as a direct design aid, dispensing with tedious hand calculations, it would have been economically viable. Unfortunately the job was postponed in 1965.

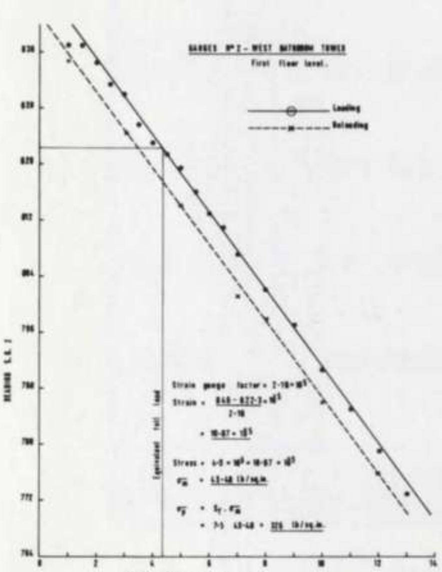


Fig. 4 Plot of typical strain gauge readings

Looking back, the main weakness of the model was over-complication. We were attempting to solve too many structural problems simultaneously. To be tractable, calculations for I and J values of the towers had to be inaccurate, due to the irregular shapes and the presence of many door and window openings. A better approach would have been to test the various component parts of the model separately, before fitting together. Separate tests for bending and torsion would have been made, using the appropriate stress scale factor and rosette gauges to measure shear strains.

We are indebted to Mr. H. Nelson of the Department of Civil Engineering, Glasgow University, who organised the construction of the model, made available the testing facilities, and advised on the testing.

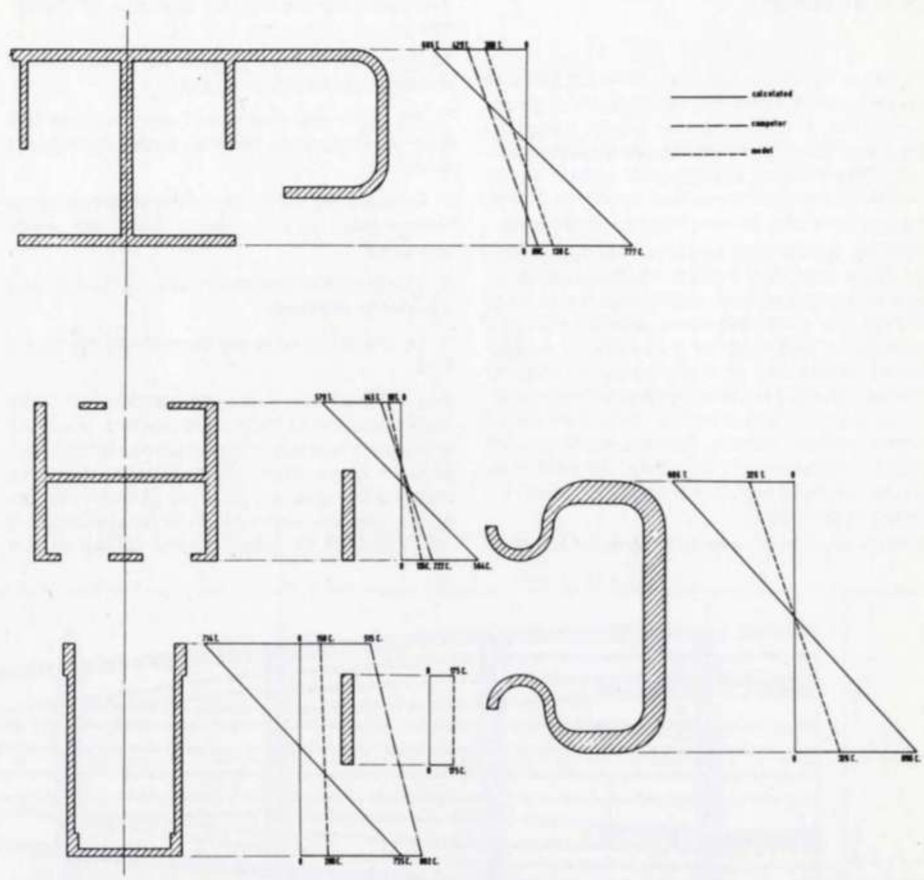


Fig. 5 Stress diagram showing comparison of calculated, computer and model results

Fig. 6 Architect's model. (Photo: John Maltby Ltd.)

Model tests for Gateshead Viaduct

Srinivasan

There are fundamentally two different kinds of models used for carrying out analysis of structures. One is the analytical model based on structural theory and investigated mathematically. The other is the physical model which directly simulates the actual structure. These models have their relative merits and demerits.

With the growth of computers structural analysis, using analytical models, has been developed into a sophisticated technique. A model of this type for a slab structure could consist of a network of beams or of a number of regular panels connected at their nodes. A shell of arbitrary shape can, for example, be represented by a space framework or by a number of panels joined in space. These models do not exactly represent the structure. At best they can be made to simulate a structure based on elastic hypothesis.

Analytical models which require to be constructed for unconventional and complex structures have to be evolved with the aid of physical models. For a thorough appreciation of the behaviour of a complex structure, a study of both types of models is necessary with, if possible, similar studies on the prototype.

The Gateshead Viaduct is a multi-cellular structure in prestressed concrete, being designed by Ove Arup & Partners Consulting Engineers for the County Borough of Gateshead.

Model tests for this project are being carried out for the following reasons:

1. To verify the method of analysis that has been developed to suit this particular type of structure.

2. To study the behaviour of the structure at the intersection of the ramp with the main structure.

3. To obtain the dispersion of longitudinal and transverse prestress.

4. To check the ultimate strength of the structure.

The Cement and Concrete Association were commissioned to carry out a model test of part of the structure which includes the ramp intersection. Micro-concrete as a material for the model was ruled out because of lack of space for a big model such as this. As an alternative it was decided to make a 1/48 model of the structure in *Perspex*. (Fig. 1) The model is about 10 ft. long and represents five spans of the actual structure. There are over 150 SR-4 strain gauges installed on the model. The strains will be recorded automatically by electronic logging equipment. As it is not possible to simulate self weight of the structure, this model can only be used to study the effects of arbitrary loads and to obtain influence surfaces. This physical model will represent a perfectly elastic structure and the results from this test will be compared with those of the analytical model.

Another series of model tests is being undertaken at Loughborough University of Technology under Professor Brock. The material used in this case is plaster which is considered to have characteristics similar to that of concrete. The purpose of these tests is to examine the ultimate load capacity of the structure. The section of the Viaduct subject to test in this case was a straight span. (Fig. 2) The effects of continuity were simulated on the model by providing a cantilever on either side of the span.

The model was made to a scale of 1/24 and reinforced with thin gauge wires and mesh to conform to the reinforcements in the actual structure. The prestressing cables were replaced with unstressed steel of equivalent area. The loading was applied to the model by means of springs of the same stiffness. The distribution of springs depends on the configuration of load to be applied. One end of the spring passes

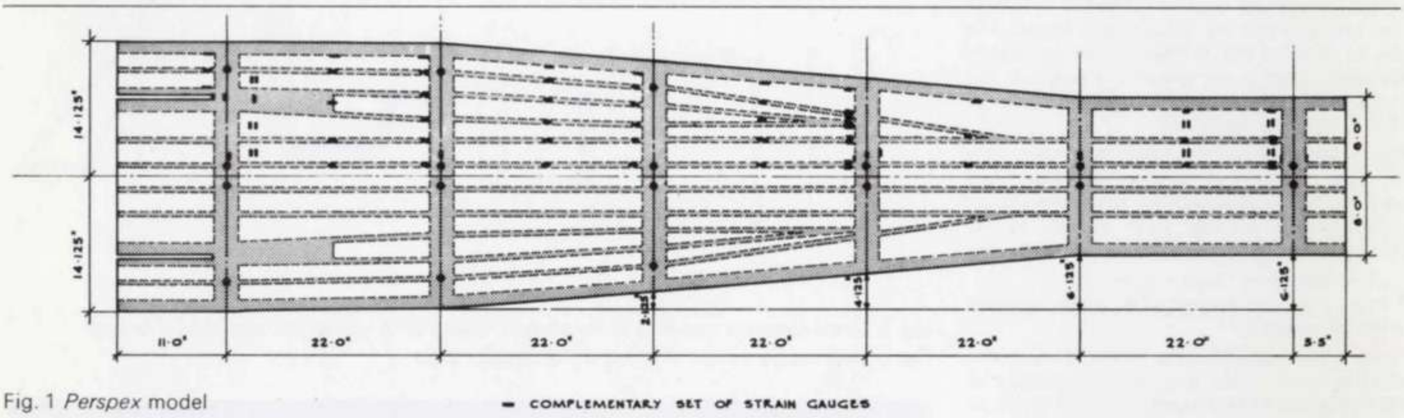


Fig. 1 *Perspex* model

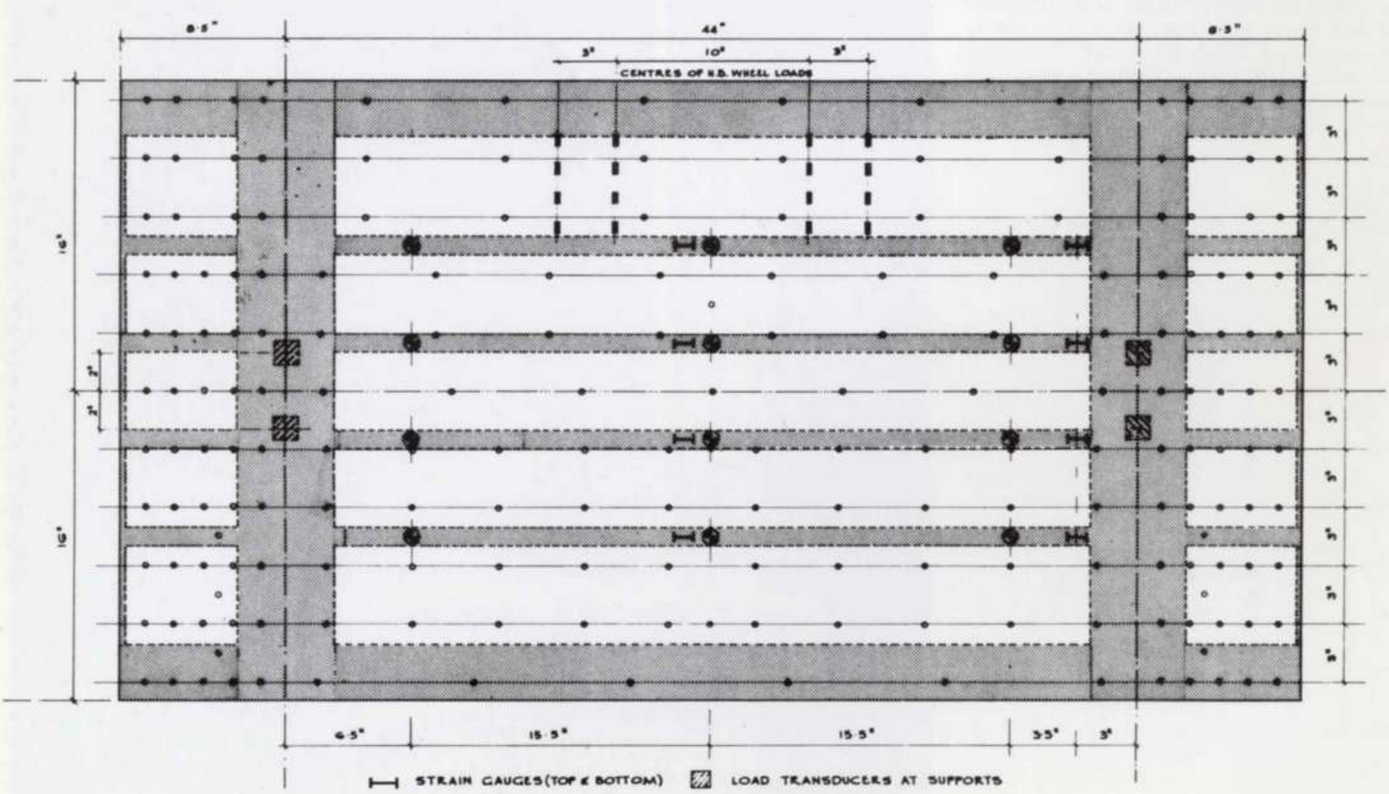


Fig. 2 Plaster model

through the model and is fixed at the top of the model while the other end is connected to rods at the base of the test rig. (Fig. 3) A pull is applied at the centre of gravity of the springs by a hydraulic jack. The self weight and uniform live loads were applied by means of springs while the abnormal HB load was applied by a special rig on the top of the model. Strain gauges (Fig. 4) were installed on the top and bottom on the model along the ribs at mid-span and at third points of the span and load cells at the supports. The loads were applied in stages of $\frac{1}{4}$ design load (i.e. self weight plus live load). The model behaved elastically for load cycles up to about $\frac{3}{4}$ design load. The strain recordings were made after every increment of load. The model collapsed at just over twice design load by ribs failing in shear. The results obtained from these tests showed reasonable agreement with analysis.

Finally, it is intended to instrument sections of the structure on the same lines as the model using acoustic strain gauges which will be cast in concrete. The results of these tests should enable us to assess further the accuracy of the analysis.

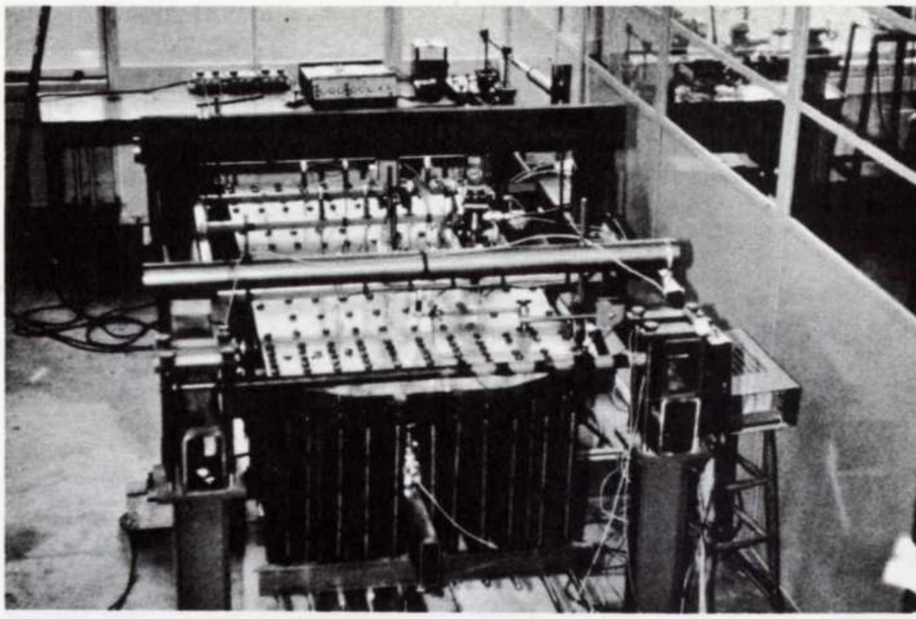


Fig. 3 Test rig (Photo: Srinivasan).

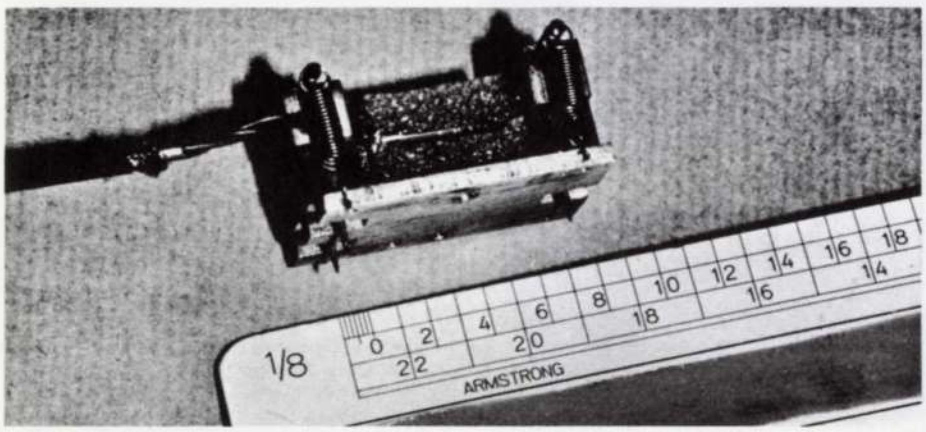


Fig. 4 Strain gauge for plaster model test (Photo: Srinivasan).

The use of structural models

A. Stevens

I have been involved with three model testing programmes over the last seven years. On the last two of these occasions after investigation we decided to do what we did in the first instance, that is to make and test a number of reinforced plaster models. My experience in model testing is therefore confined to one type of model and in fact to working with one man, Dr. later Professor Geoffrey Brock now of Loughborough University.

The principles involved in scale model testing have been described elsewhere([1]) by Professor Brock. Suffice it to say here that with gypsum plaster representing the concrete and threaded rod the reinforcement accurate scale models of reinforced concrete elements can be made and test loaded.

My model testing experience is in some respects rather dated now. Loading rigs and measuring equipment have developed considerably since my time. However the principles of the technique proper are the same as ever.

Beam

The first model we made in 1961 was of a beam which was to be incorporated in fairly large numbers in the Biology Building at Birmingham University. The beam spanned 40 ft. and was riddled with holes to allow the passage of services through the web. (Fig. 1). We had designed the beam around the holes on an approximate Vierendeel basis([2]). Originally we curtailed the reinforcement in accordance with the parabolic bending moment diagram.

A programme of seven 1/10 scale model tests was carried out (Fig. 2). The tests showed that the beam would develop its full strength with the reinforcement we had designed provided that the main steel was not abruptly curtailed but was bent up in curves normally associated with prestressing tendons. The scaled-up ultimate carrying capacity of the beam determined from the model tests was 94 tons uniformly distributed. In this instance we did test a full-scale prototype which developed about 115 tons. There were thought to be various reasons for the difference in carrying capacity but I think the co-relation was not too bad.([3])

L-shaped wall

In 1963 we were faced with the design of an L-shaped wall (plan dimensions approximately 10 ft. x 19 ft.) which was supported only at one point in the longer leg. The plan position of the support was not coincident with the centroid of the vertical loads. Further, as you will see from Fig. 3 the wall was punctured with door openings creating a difficult stress flow problem. We thought we could estimate the stresses fairly closely but that experimental verification was desirable.

In the building the L-shaped wall was prevented from overturning by restraining forces developed in the floors which in turn were held back by lift shafts and etc. The models which were made had to be similarly restrained and we wanted to measure these restraining forces. We had some difficulties developing the loading rig which were eventually overcome. The scale of the model was dictated by the reinforcement we wanted to put into the prototype and we found we could only make a model of the lower three storeys although the building had more than twice that number. Since we were interested mainly in the stresses close to the column support we decided this curtailment would be acceptable.

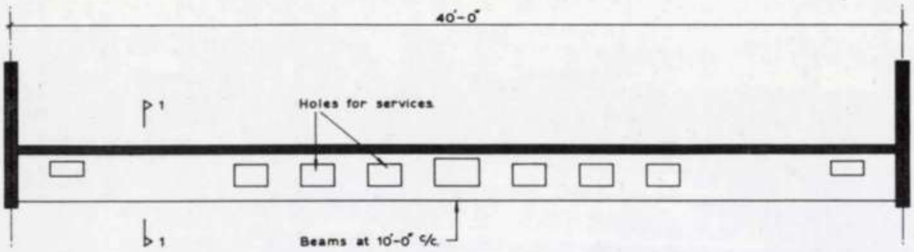
Six models were made, not all of which were entirely satisfactory from the point of view of the model making. Test loading of the successful models, however, showed that a load factor of 2 would develop. Failure occurred just above the column (Figs. 4 and 5).

We tried to measure the stresses in the walls but at that time Professor Brock used *Demec* gauges and the results were not very satisfactory. I mean that the stresses we measured did not seem to tally very well with any theory that we could think of and that the gauges were large compared with the model. We had hoped also that the model would give some indication of the cracking which could be expected. This aspect of the programme was never very successful, I now think understandably so.

We have since built two of these walls on the Barbican and they seem to be behaving quite satisfactorily. We have four more to build.

Columns

Later in 1964 we ran into a problem with the column design of the Tower Blocks on Barbican which I believe could only have been solved by a plaster or micro-concrete model. In the lower levels of the Tower Blocks twin rectangular perimeter columns bear on to one 4 ft. diameter circular column. At one stage we had this junction designed as indicated in Fig. 6a but had very serious doubts about whether the



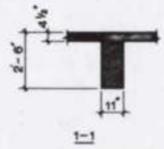


Fig. 1. Typical floor beam, Birmingham University Biology Building.

Fig. 2 Collapse of Beam 7, University of Birmingham Biology Building, reproduced with the permission of Professor Brock.

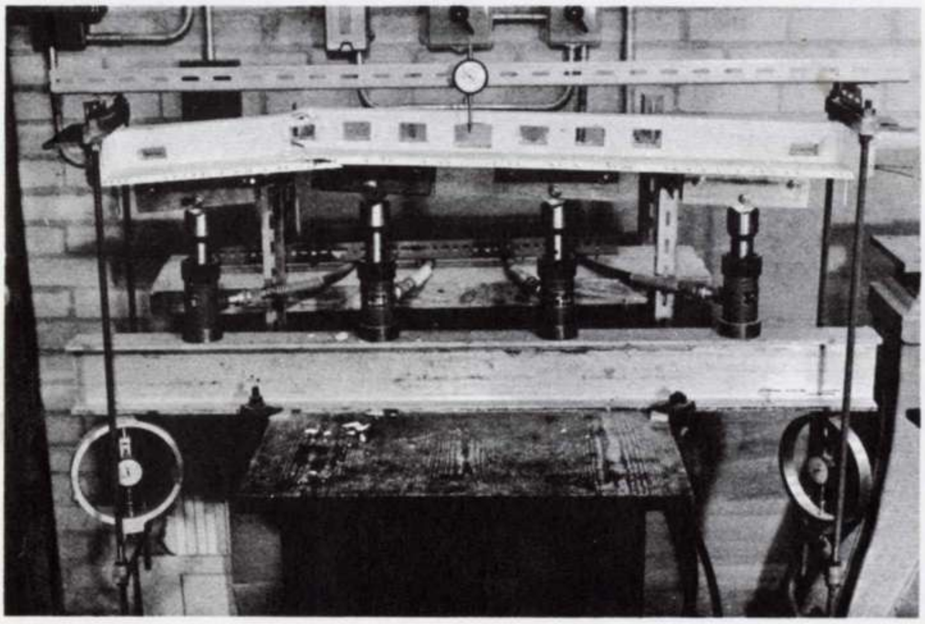


Fig. 3 Diagram of L-walls.

reinforcement in the junction would work in anchoring the forces developed. A plaster model was made (Fig. 7) which failed at the junction and in the column at a load factor of approximately 1.1.

As a consequence we modified the design to the current outline (Fig. 6b) and amended the reinforcement accordingly. The theory showed that the flow of forces would be much less severe and this was eventually confirmed by the behaviour of the revised model which gave a load factor of 2 (Fig. 8).

Conclusions

The three models I have described—a standard element with unusual details, a plane stress and a three-dimensional stress problem—give a good idea of the range of the technique. The reports of the test programmes are in the Library (3) (4) (5). The limitations seem to be only the ability to make the model but I have found that the way in which the loads are actually applied can affect the result quite seriously. First of all it is essential that the model be loaded in precisely the same way as the prototype. This sounds obvious but sometimes the restraint system in the prototype is quite complicated and the point easily missed. Secondly it seems quite easy to produce bursting forces and the like in the model which will not be typical of the prototype. These factors can always be overcome but it is a good idea to look out for them from the start.

The choice of scale and the accuracy with which the model is made is of course vital to success. If you are interested in a particular detail in the behaviour of the model then the scale will have to be chosen to make it possible to form this detail accurately.

Professor Brock was never very happy about our approach to his type of model test programme. We always went to him with preconceived ideas of what was going to happen asking him only for confirmation. His view was that the technique should be used to design the reinforcement by repeatedly loading the model and adding reinforcement at points of failure until a satisfactory load factor is achieved.

I have always been disappointed that we have never been able to draw any general theoretical conclusions about the behaviour of models that were made and tested. This is rather illogical since model testing is usually employed when no manageable theory will cover the situation. However the technique is a powerful and useful tool and I have been very glad on more than one occasion to have it available.

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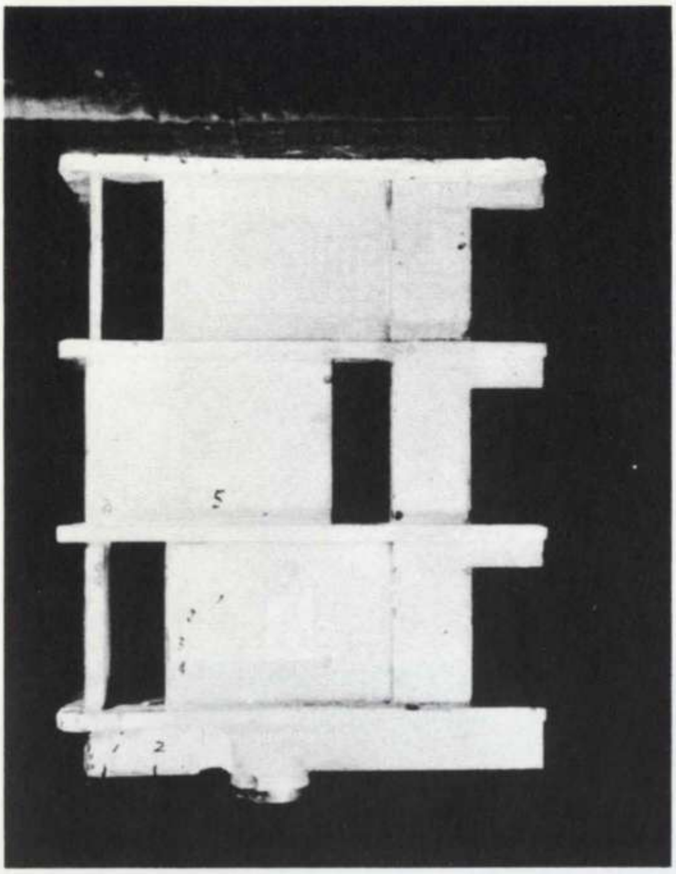
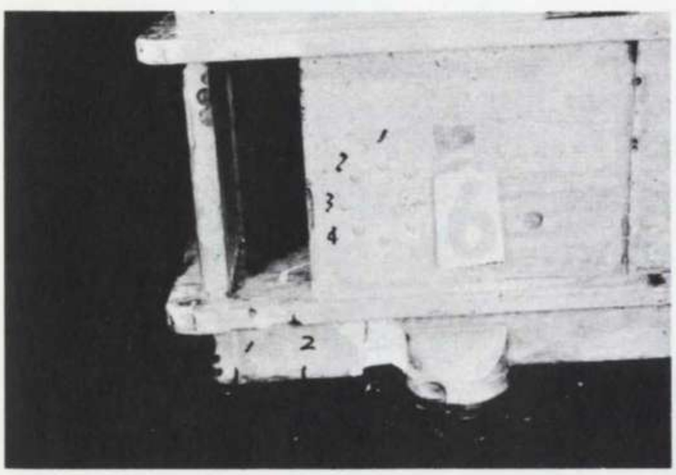


Fig. 4 Collapse of Model 6—Barbican Redevelopment Scheme—reproduced by permission of Professor Brock.

Fig. 5 Collapse of Model 6—Barbican Redevelopment Scheme: failure of beam—reproduced by permission of Professor Brock.



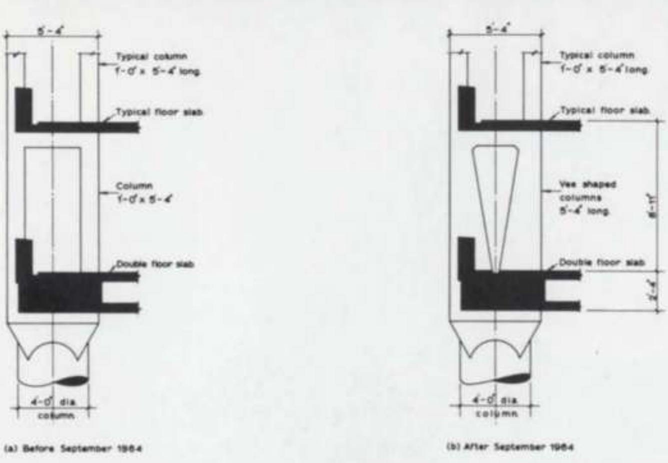


Fig. 6 Barbican Tower Block column junction
(a) Before September 1964. (b) After September 1964.

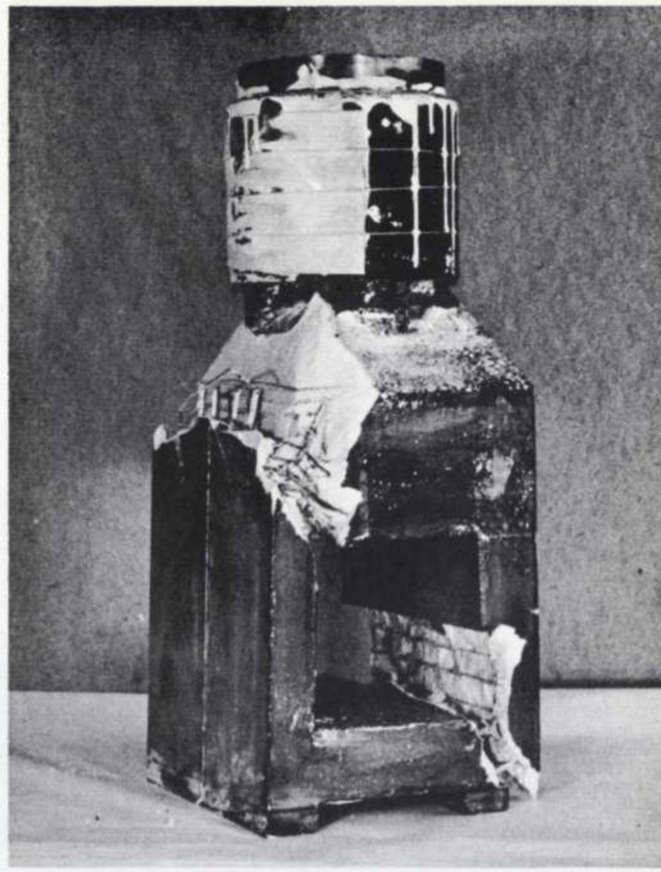
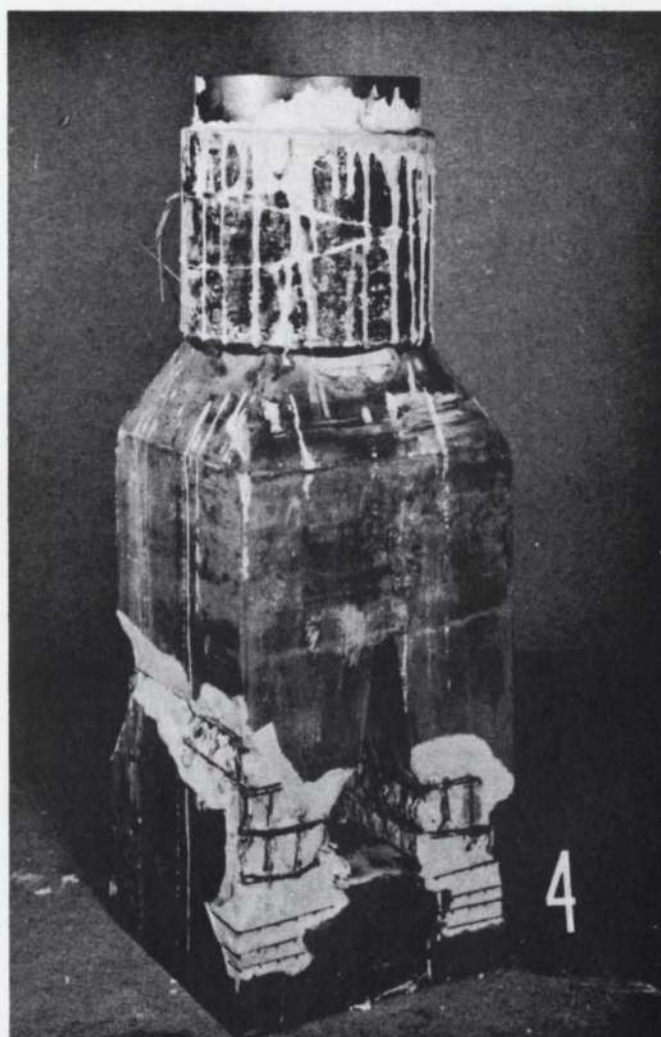


Fig. 7 Collapse of Model 1—Barbican Redevelopment Scheme—reproduced by permission of Professor Brock.

Fig. 8 Collapse of Model 4, Barbican Redevelopment Scheme—reproduced by permission of Professor Brock.



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