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The design and construction of timber hyperbolic paraboloid shell roofs in Britain: 1957–1975

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Introducing the timber shell roof

Early in 1957 the design of a spectacular roof for a new weaving shed at the Royal Carpet Factory in Wilton was completed by Hugh Tottenham of the Timber Development Association (TDA): this was the first timber hyperbolic paraboloid (hp) shell roof to be built with a boarded membrane in Britain (Fig.1)[1]. In 1975 the last known timber hp roof was built for a theatre at Blackpool: coincidentally, Tottenham, by then a partner of Hume, Tottenham and Bennett, was again the structural engineer. The eighteen years between these two projects were the era of the timber hp shell roof in Britain.

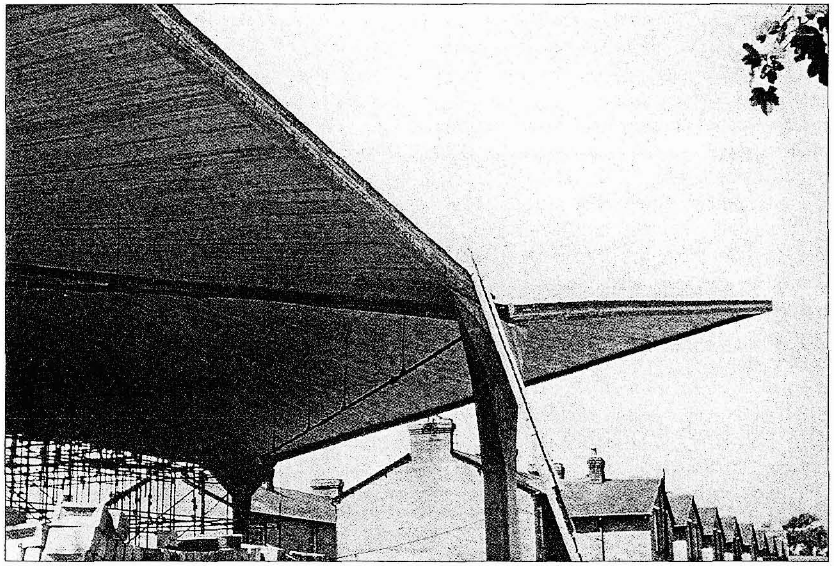


Fig.1 Royal Carpet Factory, Wilton (1957) during erection.

A shell roof covered a building with a thin membrane that derived its strength and stiffness from its shape. Thus a 3 inch thick membrane of timber with the shape of a doubly curved hp and with stiffened edges was capable of covering a 60 ft square without any internal supports. The membrane was usually formed from layers of boards; glued laminated timber members were usually needed to stiffen the edges. Outward thrusts at the supports were normally resisted by steel ties or sometimes by reinforced concrete buttresses. Roofs of buildings were formed from either a single unit or by combining units.

The late 1950s and the following decade were the most exciting years of timber engineering in the UK since the early years of the Victorian railways; timber shell roofs, particularly hps, epitomised that excitement. One hundred and forty buildings (excluding farm buildings) are known to have been covered with timber hp shell roofs. Much theoretical work that was independent of the material in the hp was undertaken by the trade associations and by the universities on the stress distribution in the membrane; a detailed assessment of that work is outside the scope of this paper. After some general remarks on the geometry and the methods of construction employed during the era of timber hp roofs, this paper examines some aspects of the roof that have not been fully discussed in the past: particularly the search for a simple design method, the standardisation of roofs by one company, the publicising of the roof by TDA and industry, and the failure to penetrate the industrial building market and the roof's subsequent demise.

Setting the scene: 1952-1955

Although this is a history of timber hp shell roofs, the earlier development of concrete shell roofs and their influence on the later development of timber shells must be mentioned. Reinforced concrete shell roofs were built on the Continent at the beginning of the twentieth century and the concept was well established in Europe by 1939. In contrast, there was little interest in this country pre-war; however by 1952, there were some 500 concrete shell roofs in Britain.

Interest in the immediate post-war period culminated in 1952 in the organization by the Cement and Concrete Association of a *Symposium on Concrete Shell Roof Construction*. The singly curved form, usually the circular cylinder, dominated the proceedings. No mention was made of doubly curved hyperbolic paraboloids (hp). However, architects were finding the cylinder restrictive and their interest was turning towards a number of doubly curved surfaces. The time was ripe for the hp, not just in concrete, but also in timber.

Two engineers were to play major parts in the application of timber to hp roofs: one provided the opportunity, the other brought the idea to fruition. The first was Phillip Reece. In 1952 Reece was the Director of the Timber Development Association (TDA) and in the first half of the decade he lead the transformation of TDA from the publicity body of the timber trade into a research and development organisation. When the TDA laboratories opened at Tylers Green in November 1955, it was with a programme of research formulated mainly by Reece and it was from a project on plywood farm silos that the work on cylindrical plywood shells, and later on boarded hp shells, evolved. The second engineer was Hugh Tottenham who at the time of the Symposium was a design engineer at 'Twisteel' Reinforcement. In February 1956 he joined TDA. Indeed, it can be argued that without his participation the development would not have followed the form it did and might never have taken place. Concrete had lead the way with the cylindrical shell, but thanks to Reece's foresight and Tottenham's expertise, it was timber that pioneered the hp roof.

Geometry and structural action of the hyperbolic paraboloid roof

Tottenham joined TDA in February 1956 and the initial emphasis of his work was on cylindrical roofs made from prefabricated panels. Research on the methods of design and construction proceeded during the summer of 1956 and a model was on display at the Association's Open Week in July. Also on display was a model of an hp grid roof made from prefabricated panels.

Although work was well advanced on the cylinders it was the hp that attracted more attention. As already mentioned, architects were turning their attention to the more exotic doubly curved surfaces. The time was ripe for the timber hp either in its grid or continuous membrane form.

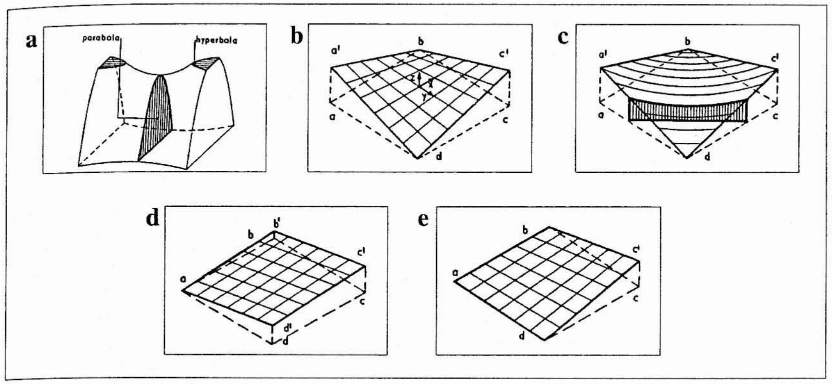


Fig.2 Geometry of the hyperbolic paraboloid.

When Robert Townsend was appointed architect for a new building for the Royal Wilton Carpet Factory near Salisbury in the autumn of 1956, TDA was appointed consultant for a structural design using an hp roof with a continuous membrane.

Before we describe the construction of the roof at Wilton we must define the geometry and structural action of the hp and then examine the state of the art of the timber shell when the design began in the autumn of 1956. The hyperbolic paraboloid is a three dimensional surface that belongs to the family of surfaces known as conicoids[2]. Better known examples are the sphere (a tennis ball), an ellipsoid (a rugby ball), an hyperboloid of revolution (a cooling tower), and the cone.

An hp is a saddle shaped surface which when cut reveals hyperbolas and parabolas.(figure 2a). Although the hp looks complicated it can easily be constructed. The four straight lines in Fig. 2b form the square abcd. Lift points a and c into new positions a′ and c′. To begin with place a′ and c′ at the same height above plane abcd. Now divide a′d and c′b into an equal number (say six) of equal portions and then join corresponding points. Similarly with a′b and c′d. The surface defined by these straight lines is part of a hyperbolic paraboloid.

Although straight lines exist on the surface this is a doubly curved surface and is known as a ruled surface. From Fig. 2b we see that all vertical cross sections of the surface parallel to the edges are straight lines while vertical cross sections parallel to the diagonals are parabolas (Fig. 2c).

Mathematically the surface may be expressed as: $z = kxy$ where the axes are shown in Fig. 2b. k is a constant and is a measure of the slope of the sides of the square. For example if k is small, the surface is shallow, whereas when k is large the slope of the edges is steep. The value of k is important since it determines the rise of the shell; for a symmetrical shell the rise is defined as half the difference in height of the high and low corners.

For simplicity in the above we placed a′ and c′ in Fig. 2b at the same height above plane abcd. In the general case all the points are at different levels (Fig. 2d) and the surface is still a hyperbolic paraboloid. An interesting special case of this is to raise (or lower) only one point (say c) (Fig. 2e).

Having defined the geometry, the stresses in the structure when subjected to load must now be calculated so that the size of the members may be determined. A complete analysis is extremely complicated but a simple model of the transmission of the load to the ground is available[3].

The shell may be considered as a system of intersecting 'arches' (Fig. 3a) and 'suspension cables' (Fig. 3b), half the load being carried by the 'arches' and half by the 'suspension cables'.

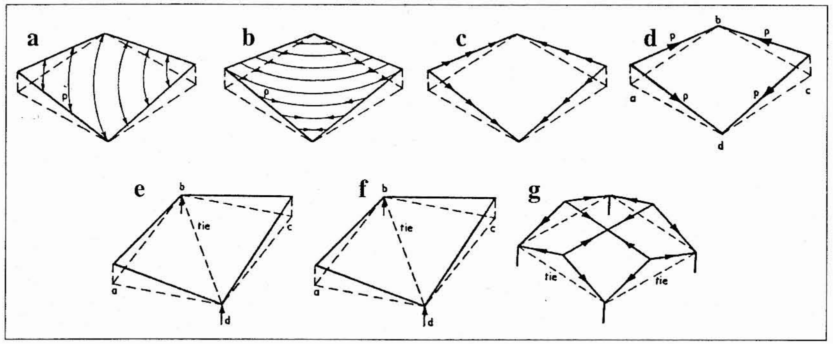


Fig.3 Structural action of the hyperbolic paraboloid.

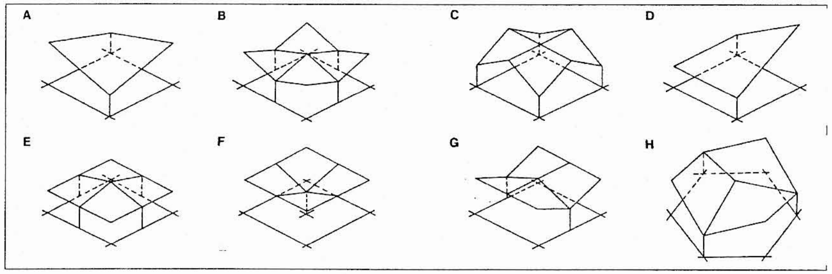


Fig.4 Hyperbolic paraboloid shell roof arrangements.

Thus the surface is in direct compression in directions parallel to the 'arches' and in direct tension in directions parallel to the 'cables'. Since the sections parallel to both diagonals lead to the same parabola, the force at some point on the edge due to the 'arch' is the same as the force applied by the 'cable'. Because they also act at equal angles to the edge and in opposite senses (one inwards, the other outwards), there is no component perpendicular to the edge. Hence this double system of forces can be resolved into a series of shear forces along the edge (Fig. 3c). These shear forces may be summed as a single force per edge (Fig. 3d) and an edge stiffening member, usually known as an edge beam, is required to carry this force.

The method of transmitting the edge forces to the ground depends on whether a single unit (e.g.Fig. 3f) is used or whether units are grouped together (e.g. Fig. 3g).

For a single unit, only two supports are required if the load is uniformly distributed. If the roof is supported by vertical columns at b and d (Fig. 3d) then the edge beams are in compression and the forces P to be taken at the supports may be resolved into a vertical downwards force V and a horizontal outward force H (Fig. 3e). The vertical force is transmitted directly down through the column to the ground. The outward horizontal force is usually resisted in one of two ways: the points b and d may be tied together (Fig. 3f) or the column can be designed as a buttress to resist the bending stresses caused by the horizontal force acting at its top. With multiple units it is often possible to use one unit to resist forces exerted by its neighbour. In Fig. 3g the forces along the ridge members balance each other, provided the units are equally loaded, and it is only necessary to restrain the four corners by the use of ties around the perimeter.

The units may be combined in numerous ways: the most common arrangements (designated A to H) are shown in Fig. 4.

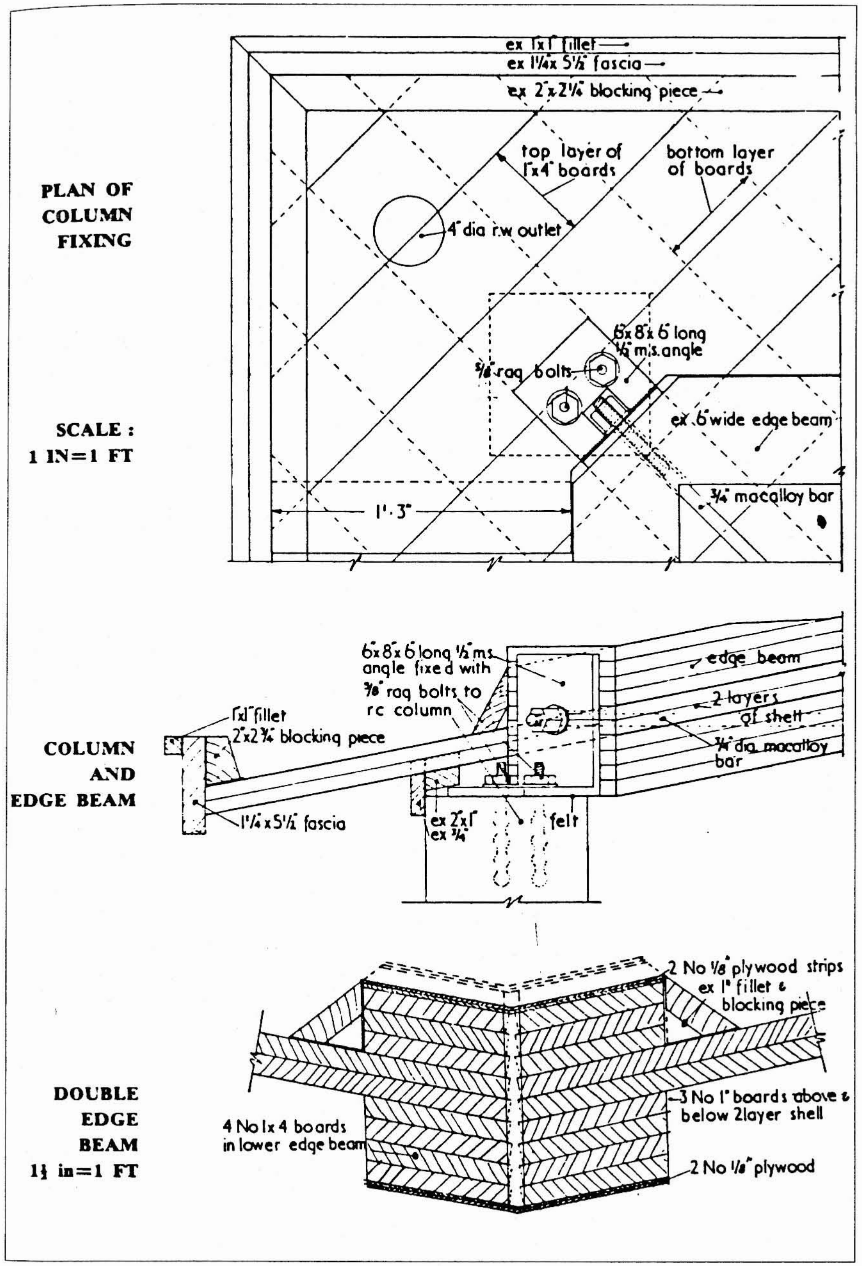


Fig.5 Typical details of shell construction at Chantry Primary School (from *Architect and Building News*, vol.216 no.2, 1959).

State of the art in autumn 1956

From the description of the structural action we see that designs were required for the membrane, the stiffening perimeter members of the membrane (subsequently known as edge beams), the membrane-to-edge beam connection and, finally, the edge beam-to-support system. When Tottenham began work on the design of the Wilton roof there were no precedents in the UK for any of these details and he had to rely on the little information obtained from the fabrication of some models in the TDA laboratories. Some typical details of the shells that evolved are shown in Fig. 5.[4] Within two years it was standard practice for the structure to consist of a membrane formed from a number of layers of boards laid at varying angles to each other and nailed-glued together, glued laminated timber edge beams, a bolted or coach screwed membrane-to-edge beam connection, and metal shoes at the 'low' ends of the edge beams acting in conjunction with diagonal metal ties to resist the outward thrust of the edge beams. All these details were devised by Tottenham for the Wilton project.

Although the boarded membrane was the most frequently used method, plywood was strongly advocated and used by Thomas Harley-Haddow, an Edinburgh based consulting engineer, in a few roofs in Scotland.[5]

Construction of timber hyperbolic paraboloid roofs

As the first of some 140 timber hp shell roofs, the Wilton roof (see Fig. 1 and Table 1) will be described in some detail.[6] The roof consisted of four units each 57 ft square and arranged with the supports at the middle of the four sides (arrangement B, Fig. 4).[7] The high corners were 12ft above the column heads.

Tubular steel scaffolding was erected to the level of the underside of the membrane. The membrane consisted of three layers of $\frac{5}{8}$ inch thick (finished) by 5 inch wide fifth quality tongued and grooved boarding. The top and bottom layers ran parallel to the edges of the units with the middle layer parallel to the diagonal joining the two low corners of each unit. The top and bottom boards were laid on the straight ruling lines, whereas the middle layer was easily bent to follow the parabolas. The bottom layer was placed on the tubular steel scaffolding; the second layer was occasionally nailed to the first layer and finally the top layer was fastened to the middle and bottom layers using 12 swg nails at 4inch centres. Random butt joints were allowed in each layer with the stipulation that joints in adjacent boards were not less than 3 ft apart. A 6ft zone was nailed-glued to increase the stiffness of the membrane adjacent to the edge beams.

The glued laminated edge beams consisted of two parts with the membrane sandwiched between them. Twelve laminations each 1 inch x 10 inch nominal size were used in each beam. The membrane was nailed-glued to the bottom halves of the edge beams; the top halves were then coach screwed to the membrane and the bottom halves of the beams. The outward thrusts of the edge beams were resisted by $2\frac{3}{4}$ inch diameter mild steel ties running diagonally between the concrete column heads.

Work on the Wilton roof began early in May 1957 and was completed at the end of June 1957. During the remainder of that year, outline schemes were prepared by Tottenham for a number of projects and firm design work began on two major buildings (Chantry Primary School and the Egg Packing Station). Further publicity arose from the shell roofs on the TDA stand at the London Building Exhibition at Olympia in November 1957.

Tottenham acted as structural engineer for five projects before he left TDA in February 1959 to become a Research Fellow at Southampton University and to begin his own practice in partnership with Charlotte Hume, formerly an architect with TDA. (They were later joined by J.D.Bennett to become Hume, Tottenham and Bennett.) Although all the construction details of

Table 1 Timber hyperbolic paraboloid shell roofs: first and early examples with notable features

Job Architect/Engineer/Contractor	Notable feature	Approx. date of erection	Size of units	Number of units	Total area	Config. of units ‡	Restraint T = tie B = buttress	Description reference ┐
			ft x ft		ft²			
1. Royal Wilton Carpet Factory, Wilton, Wiltshire Robert Townsend / Tottenham at TDA / Direct Labour †	First boarded membrane	1957	57 x 57	4	12 966	B	T	AJ: Sep57 CE: May59 Wood: Aug57 TTJ: Jul57 IASS: (7)60
2. Auchentoshan Special School, Glasgow Boswell, Mitchell & Johnston / Harley-Haddow / Kingston	First plywood membrane	1957	20 x 20	4	1 600	C	T	Int: May57 CE: May59
3. Building Exhibition Stand, Olympia, London; subsequently **Building Exhibition Stand, Manchester**: and subsequently **Laminating Laboratory, TDA, Tylers Green, High Wycombe** TDA / Tottenham at TDA / Jones	First diamond plan. Early prefab. units	1957 1958 1959	25 x 13* 25 x 13* 25 x 13*	3 3 4	490 490 650	D*(3) D*(3) D*(4)	T T T	IASS: (7)60
4. Scott Bader Conference Hall, Wollaston Brown & Henson / Booth / HNS	First with buttress. First HNS	1959	60 x 60	1	3 600	A	B	Wood: Sep59 CE: May59 ABN: Aug59
5. Giesen and Wolff Factory, Dallington, Northampton Brown & Henson / Booth / HNS	Largest initial area job	1959	48 x 48	16	38 864	D(16)	T	
6. Showroom, Odeon Cinema, Acton, London Druce / Booth / HNS †	Smallest area job	1960	15 x 15	1	225	A	T	
7. First Church of Christ, Scientist, Hendon G.B.A.Williams / HTB / RTE †	First by RTE	1960	38 x 27*	4	2 052	B*	B	
8. St. Patrick's Hall, Reading University Eastman & Robertson / Tottenham at TDA / Jones	Early double gable: config. C	1960	15 x 15	4	900	C	T	
9. Kobler House, East Grinstead, Sussex Katz & Vaughan / HTB / HNS	First private house	1960	40 x 40	1	1 600	A		
10. Calibrated Papers Factory, Petersfield, Hampshire Carter, Salaman, MacIver & Upfold / HTB / Gardner †	First hexagon	1960	76 x 44*	9	15 048	H(3)	B	AJ: Oct63 Wood: Apr61
11. NAFFI Shop, Aldershot War Office / HTB / Gardner	Largest single unit	1961	70 x 70	1	4 900	A	B	
12. St. Aldate's Church, Gloucester Potter & Hare / Gifford / GWE	Model test in TRADA New Lab	1962	82 x 72*	1	2 952	A*	B	
13. Crewe Railway Station, Cheshire British Railways / Harris & Sutherland / Tinker & Young †	Early umbrella	1963	18 x 8 22 x 8	16	5 120			Wood: Oct63
14. Chesterton Primary School, Battersea, London LCC / HTB / GWE	Most units	1964	43 x 43 15 x 15	2 56	16 298	A(2) E(14)	T	Wood: Feb65
15. ERNIE Theatre, Blackpool ? / HTB / RTE	Last hp roof	1975	105x 61*	1	3 202	A*		

* Diamond on plan
† Demolished
‡ See fig. 4 for arrangement of units
└ See abbreviations

Abbreviations
ABN = Architect & Building News
AJ = Architects Journal
CE = Civil Engineering
IASS = International Assoc Shell Structures
Inter = Interbuild
TTJ = Timber Trades Journal

the system had been established at Wilton, it is instructive to list the next few projects and to note the small differences.

The roof of TDA's Laminating Laboratory used four units that had previously been used at Olympia and so demonstrated the feasibility of prefabricating small units (see Table 1).[8]

Chantry Primary School, Ipswich was the second major project and in contrast with Wilton used many small units 25 ft square.[9] For such small units only two layers of 1 inch nominal thickness boards were required for the membrane: both layers of boards ran parallel to the diagonals. The ties were high tensile steel bars with a diameter of $\frac{3}{8}$ inch. The falsework consisted of a tubular birdcage up to a level approximately 2ft below the column heads. A boarded working platform was provided at this level and timber staging was used as the final supports for the laying of the membrane.

The Egg and Poultry Packing Station, Haughley Park, Suffolk was the third major project to be designed by Tottenham while at TDA.[10] There were two major differences compared with Wilton. High tensile steel bars were used and were supported from the membrane by V shaped hangers. The construction procedure was improved by building a tubular birdcage to about column head level and then using scaffold boards to provide a working platform. The membrane was then laid on demountable timber falsework which was moved from shell to shell. Finally, the membrane was pierced with 1½ ft square openings to provide some natural light and 4 ft x 1¼ ft openings for ventilators.

Scott Bader Conference Hall, Wollaston, Northamptonshire completed the opening phase when in the spring of 1959 H.Newsum & Sons built their first shell roof with L.G.Booth acting as their structural engineering consultant. Booth had joined TDA in November 1955. Although his doctoral thesis had been concerned with concrete shells, his work for TDA was on other topics. In May 1959, he became a Research Fellow in Civil Engineering at Southampton University and revived his interest in shell structures when he became Newsum's structural engineering consultant. The Scott Bader Hall (see Fig. 6 and Table 1), which followed the form of construction established at Wilton, consisted of one unit 60 ft square (the largest built at that time) and differed from previous shells by the use of reinforced concrete buttresses at the two low points instead of the usual steel tie bars.[11]

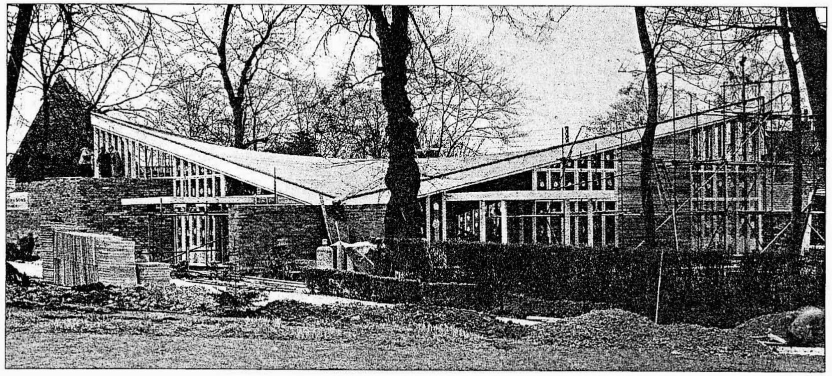


Fig.6 Scott Bader Conference Hall, Woolaston (1959).

State of the art in summer 1959 and changes to come

By the end of the summer of 1959, seven projects had been completed using timber hp shell roofs. Of these seven, four (Wilton, Chantry School, Haughley Park, Scott Bader) were typical of the future use of shells. The projects, all with boarded membranes, used most of the construction features that were to recur in the next 15 years. The details devised for Wilton had proved to be satisfactory and few immediate changes were needed.

Site experience suggested that three layers of boards were required for shells with sides greater than 30 ft and two layers for 25 ft and less. For 30 ft, the boards needed to be ⅝ inch thick increasing to ⅞ inch thick at 60 ft (thicker than at Wilton): for 25 ft, ⅞ inch boards were appropriate. Ringed shank improved nails were preferred to ordinary round wire nails.

Changes were likely as the number of engineers and contractors involved increased considerably in 1959-61 (see Tables 2 and 3). Three particular topics generated different opinions: the gluing of the membrane, the direction of the boards in the membrane and the need for specialists.

Table 2 Timber hyperbolic shell roofs: number of jobs and areas by engineers and years of creation

Table 2. Timber hyperbolic paraboloid shell roofs: number of jobs and areas by engineers and years of erection

Year	Engineer*																		Totals	
	Tottenham						Booth				Harley-Haddow		Gifford		Kay		Others †			
	TDA		RTE		Various		HNS		NTE											
	No	Area ft²	No	Area ft²	No	Area ft²	No	Area ft²	No	Area ft²	No	Area ft²	No	Area ft²	No	Area ft²	No	Area ft²	No	Area ft²
1957	1	12 996									1	1 600							2	14 596
1958	1	2 052																	1	2 052
1959	3	55 900			2	4 440	3	43 024			1	1 600							9	104 964
1960			1	2 052	4	18 628	4	7 019									5	53 456	14	81 245
1961			1	1 600	4	10 596	6	17 916					1	5 016	1	1 296	3	39 772	16	76 196
1962					2	2 000	10	35 307			1	3 600	1	2 952			4	31 708	18	75 567
1963			2	4 709			2	3 944	6	29 049	1	3 600			1	1 764	4	39 284	16	82 350
1964					2	20 523			8	22 767	2	7 200			2	2 665	2	5 800	16	58 955
1965			1	1 444	2	5 904			1	3 249			2	4 800	3	4 869	6	28 294	15	48 560
1966			1	900					3	8 100					2	5 648	2	5 416	8	20 064
1967			3	4 162	1	1 225			4	6 462									8	11 849
1968			2	4 021	1	1 600			2	4 964							1	1 600	6	12 185
1969			4	4 185					1	1 296									5	5 481
1970			1	2 178															1	2 178
1971			2	2 078															2	2 078
1972																	1	1 600	1	1 600
1973																				
1974			1	784															1	784
1975			1	3 202															1	3 202
Total	5	70 948	20	31 315	18	64 916	25	107300	25	75 887										
Total	43			167 179			50		183 187		6	17 600	4	12 768	9	16 242	28	206930	140	603 906

* Engineers who designed four or more jobs
† See table 3

Table 3 Timber hyperbolic shell roofs: number of jobs by engineers and contractors

Engineer *	Contractor											Totals	
	HNS	NTE	RTE	Kay	GWE	Wheeler	Tyson	BBH	Beves	Holme	Others ‡		
H.Tottenham: TDA						2		1			2	5	43
H.Tottenham: HTB	2		20		3	1	1		2		9	38	
L.G.Booth: HNS	25											25	50
L.G.Booth: NTE		25										25	
T.Harley-Haddow	1										5		6
E.W.H.Gifford					4								4
W.Kay				9									9
O.Arup											3		3
C.V.Blumfield				1			2				1		4
E.C.Ozelton										3			3
Others †			4		1	2	1	2	1		6		18
Totals	28	25	24	10	8	5	4	3	3	3	27		140

* Engineers who designed three or more jobs.

† Others who were engineers for one or two jobs included Bolton Hennessey, W.G.Curtin, M.R.Devon, Wallace Evans, A.M.Gear, A.Grant, Harris & Sutherland, R.Hobin, Leonard & Grant, J.G.L.Poulson, D.H.Robinson, Structural Timbers, B.Vogt.

‡ Others who were contractors for one or more jobs included Bawtry, Bland, Gardner, Jones, Kingston, Pochin, Structural Timbers, Tinker & Young.

In the early shells it had been thought that to resist the bending stresses adjacent to the edge beams it was sufficient to nail-glue an edge zone. However, the membrane remained very flexible and when tests on panels showed that gluing increased the stiffness by a factor of four it became standard practice to nail-glue all the membrane with ringed shank nails.

In the early days it was thought that the ruling lines of the hp were a great advantage in that the top and bottom layers of boards in the membrane need not be bent. However, it was found in practice that the middle layer could be bent easily to the parabolic diagonal: this led to a reassessment and by the end of 1961 it was generally agreed that there were merits in running all three layers parallel to the diagonals, with the centre layer on the tension diagonal and the top and bottom layers on the compression diagonal. Rainham Timber Engineering began to use factory finger jointed boards in the bottom layer, a technique that eliminated the occasional springing of butt joints in tension boards.

Mixed views were expressed at the International Conference on Timber Engineering at

Southampton in September 1961 on the need for the specialist engineer and contractor.[12] (The discussion is a particularly useful source for current thinking on many topics.) The general view seemed to be that good quality control was needed (particularly with glue) and the required standard would be more likely to be achieved by the specialist. The specialist versus the non-specialist debate continued with both having their eyes on the potentially lucrative indusrial building market. However, penetration was disappointing and the non-specialist contractor began to lose interest and the specialist usually won the day. Of the 98 jobs built in the period 1962-75, 59 were built by H.Newsum and Sons (HNS), Newsum Timber Engineers (NTE) and Rainham Timber Engineering (RTE).

Timber hyperbolic paraboloid roofs: early examples and some with notable features

Before we discuss the design methods that evolved for timber hp roofs it is appropriate to look at the structures that emerged using the construction methods we have just described.

When the opening phase was completed at the end of the summer of 1959, all the basic techniques required to build timber hp roofs had been established and were working satisfactorily. During the years 1957-75, 140 hp shell roofs were built. The following details of all the jobs have been tabulated elsewhere: approximate date of erection, the size and number of units and their configuration, total area, the method of restraining the edge forces (ties or buttresses), the names of the engineers, contractors and architects.[13] Some of the data are summarised in Tables 2 and 3. Table 2 gives the number of jobs designed by engineers who designed four or more in 1957-75, and Table 3 distributes these jobs among the engineers and the contractors. Table 2 also shows the areas of the jobs designed by the engineers in each of the years.

It is clearly not feasible to comment here on all these jobs; however, details are given in Table 1 of 15 notable jobs. They have been chosen as the first, or early, examples of their kind, or because they had some interesting feature.

The era of the hp may be conveniently divided into four phases: opening, consolidation, peak and final. The opening phase (already described) ran from 1957 to summer 1959, consolidation from autumn 1959 to autumn 1961, peak from 1962 to 1965, and the final phase from 1966 to 1975.

After the opening phase, progress was rapid and by the end of 1959 twelve projects had been completed or were under way (see Table 2). During the period of consolidation Table 2 shows that in 1960 and 1961, fourteen and sixteen projects were erected. Hume and Tottenham had designed ten and Newsum/Booth the same number: the other ten projects had been designed by nine different engineers. Of the new names only Gifford, Kay (a manufacturer), Ove Arup and Cyril Blumfield were to design any more hp roofs.

Notable jobs during consolidation (see Table 1) were a factory at Northampton (Giesen and Wolff) that had the largest initial area (some jobs were finally larger but were built in stages), a show room (Odeon Cinema, Acton) that had the smallest area, a church at Hendon (First Church of Christ, Scientist) that was the first of many roofs built by Rainham Timber Engineering (RTE), a dining hall (Reading University) that used the double gable configuration with perimeter metal ties, a private house (several public houses were to follow!), a factory at Petersfield that had hexagonal units formed from three diamond shaped hp units (see Fig. 7) and finally a shop (NAAFI, Aldershot) that had the largest single unit (70 ft x 70 ft). Also of interest were the concrete buttresses on the dining hall at King Alfred's College, Winchester (see Fig. 8).

By the end of 1961, forty two jobs had been completed, thirty of them in the last two years. New engineers included Alan Grant, E.C.Ozelton and D.H.Robinson. During the peak (1962-65), 65 jobs were erected.

Of the eighteen jobs erected in 1962, St. Aldate's, Gloucester was notable as the first large

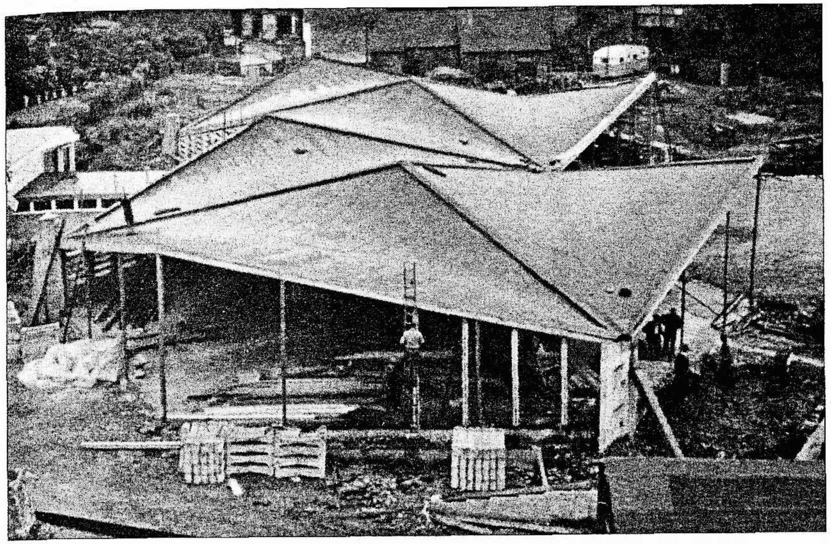


Fig.7 Calibrated Papers Factory, Petersfield during erection (from *Wood*, vol. 26, April 1961).

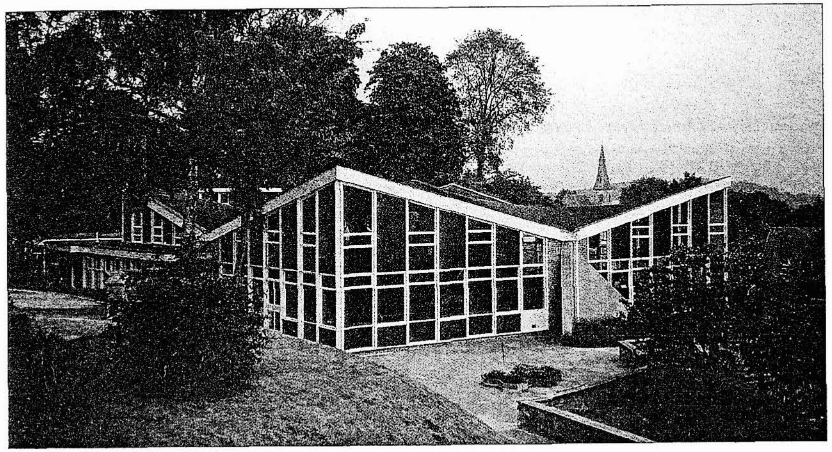


Fig.8 King Alfred's College, Winchester

scale model to be tested by TRADA (as TDA had become early in 1962) in its new Shell Testing Laboratory,[14] Crewe Railway Station was given an unusual umbrella roof (Fig. 11) and the most units (56) were used at Chesterton Primary School (Fig. 12)). Typical small multiple shells were used on a school hall (Fig. 9) and a printing works (Fig. 10).

No central records were kept at the time but the general feeling among the timber engineering firms was still one of cautious optimism. The numbers were steady, but sadly there were very few industrial buildings, the main output being in the education (see Fig. 13) and ecclesiastic sectors. Only HNS, and their successors NTE, could look at their output and see real progress

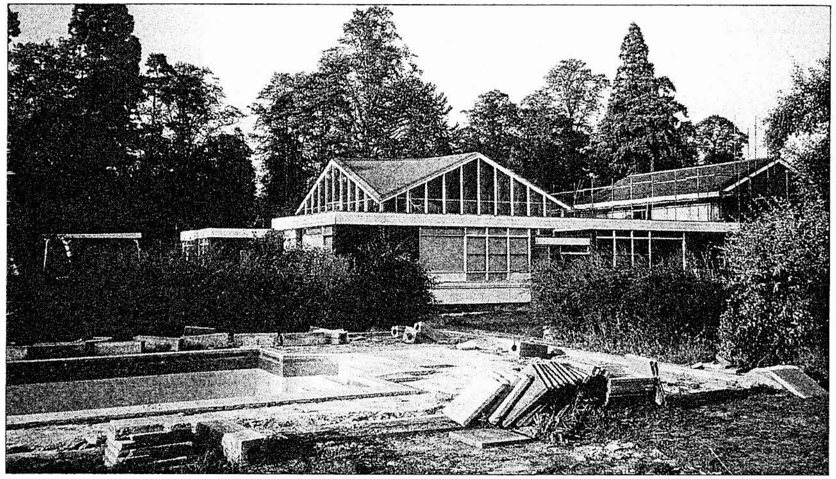


Fig.9 RNID School, Stoke Poges, Buckinghamshire.

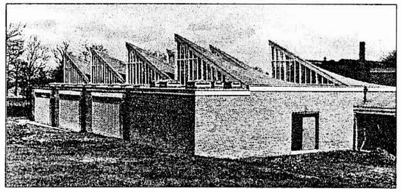


Fig.10 Preston Brothers' Printing Works, Huddersfield.

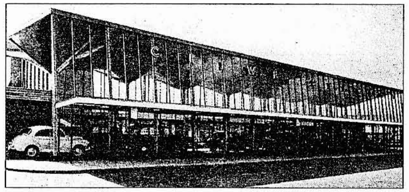


Fig.11 British Rail Station, Crewe (1963).

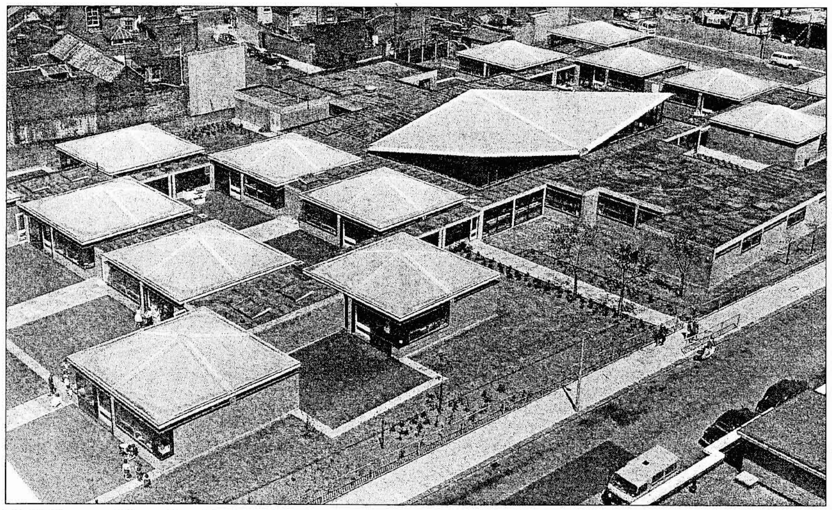


Fig.12 Chesterton Primary School, Battersea, London (from *Wood*, vol. 30, February 1965).

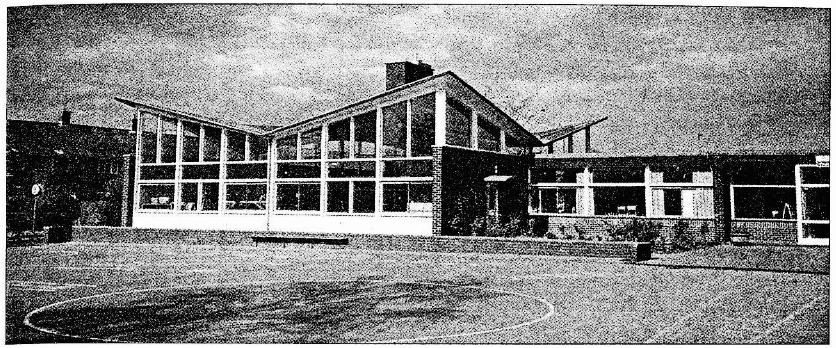


Fig.13 Woodside Infants School, Norwich.

with twenty seven buildings erected, compared with thirteen in the previous three years. In fact, 1962 turned out to be the peak year (18 jobs) in the peak period. (See Table 2.)

By the beginning of the final decade the specialist industry had settled down; firms had their own techniques and created structurally adequate shells: no important changes were required or made. There were only 33 jobs in the final decade of which a mere eleven were erected in the last seven years (see Table 2). There were no industrial buildings but schools, libraries and churches continued to use hp roofs.

It was a disappointing end to the era. Interest had turned to trussed rafters and timber framed wall panels: both generated more money than hps but they failed to provide the excitement of the timber shell roof.

Design of timber hyperbolic paraboloid roofs

We have described the method of construction of timber hps (particularly the first at Wilton) and looked at some notable examples (see Table 1) built during the era 1957 to 1975, but we have said nothing about the method(s) used to design Wilton and its successors.

A discussion of the actual theoretical and experimental research is beyond the scope of this paper which concentrates on design methods available to engineers from 1957.

The stress distribution away from the edges of the hyperbolic paraboloid membrane when subjected to a uniformly distributed load was well known and the shape had been exploited in concrete by Candela in Mexico. For concrete hp roofs, relatively simple methods of structural analysis based on the membrane solution had been published in North America (e.g. Candela[15]). However, it was generally accepted that significant bending stresses existed near the perimeter and the shell would need stiffening near the edges to carry the edge forces to the supporting structure; this aspect of the behaviour was not well understood.

The use of prototype testing was provided for in the current British Standard Code of Practice CP 112 *The Structural Use of Timber in Buildings* and the work at TDA had borne this provision in mind during the load testing of a quarter scale model of a Wilton shell to validate a theory and to establish a design method. Although the investigation was in its early stages, Tottenham considered that sufficient information was available and he undertook the design in the winter of 1956. Work on site began in the spring of 1957 and the roof was completed in the late summer that year.

After the success at Wilton, the hp received considerable publicity and the Association was inundated with requests for design data. The Association was reluctant to publish a firm design method until the research was complete but something had to be provided. The outcome was Advisory Service Leaflet No. 5 (ASL 5), entitled *The hyperbolic paraboloid*.[16]

The leaflet, which consisted of five foolscap size pages of typescript and three pages of diagrams, covered five topics: geometrical form, necessary curvature, structural behaviour, forces in the membrane and edge beams, and construction. The structural behaviour was explained in terms of the 'arches and suspension cables' model. The restraint of the edge beam forces by either metal ties or buttresses was discussed. The limiting values for the ratio of the rise divided by the side were given. A numerical example for a 30 ft square unit was given. The tension and compression forces in the shell were calculated using the well known membrane solution. The compression forces in the edge beams were calculated but suitable cross sections were not given. No details of a tie were given. The leaflet emphasised that the specimen calculations were for estimating purposes only.

When the leaflet was combined with the details and photographs in the technical press, an architect interested in this form of construction had adequate information to prepare an outline design. The engineer was less well advised. There is no doubt that this cautious approach was sensible bearing in mind the limited amount of research that had been completed on the behaviour of timber hp shells: before the Association could publish firm design methods much better understanding of the deflection of the membrane and edge beams was required.

Tottenham's theoretical work on design methods continued at Southampton University and as a result a design method was proposed.[17] The solution, which required a non-linear analysis or a bending analysis or both, was "very lengthy" and was beyond the computational capabilities of most designers. The theoretical work extended the understanding of the behaviour of shells but the lack of a universally accepted simple design method was considered by TDA's R&D Committee as a brake on progress and it decided to give priority to the building of a new laboratory to test large scale models.[18]

Not all shells behaved satisfactorily. TRADA remained confident that, when in the hands of specialists, the construction was safe. It responded to adverse criticism by undertaking a survey in 1964-6 of 12 roofs designed by its personnel in 1957-62.[19] Apart from repeated concern about the springiness of Wilton, all was well. The current use of ⅞ inch boards (rather than ⅝ inch) and total area nail-gluing (instead of edge zone) was the recommended solution to this problem.

TRADA also acknowledged that it had some responsibility to ensure that design methods were available for the Association's Approved Manufacturers and for consulting engineers. ASL 5 was still in circulation but its design method was still limited to estimating purposes. It was suspected that it had been used for final designs in some cases and it clearly needed to be revised, but TRADA's Engineering Advisory Panel was divided on its contents and it was not until June 1966 that agreement was reached.

Progress had been made in that the leaflet had been expanded to cover many shapes of shell, not just the hp. On the negative side was the absence of any method of calculating sizes; even the approximate method previously restricted to estimating was missing. The restriction, which was implied in the new title (*Architect's guide to softwood timber shell roofs and their specification*), was emphasised in the Introduction:

> "*the architect should employ an engineer with specialist knowledge of timber technology and the analysis of shell roofs, and ... the construction work [should] be carried out by a specialist contractor...*"[20]

TRADA still saw the way forward through model testing in the new laboratory and in the autumn of 1962 L.O.Keresztesy was appointed to revive the programme. Like Tottenham, he concluded that a simple design was impossible. However, he proposed a design method for the edge beams that used a set of nomograms. This method was published in 1965 but it came too late to revive a system that was already in decline[21]. The publication of Keresztesy's reports in 1965 signalled the end of TRADA's work on shells. Reece, Tottenham, Lee and Booth had all moved on; the trade could not see the hoped-for penetration of the industrial market, whereas timber frame housing showed great promise.

No report on the Wilton model tests was ever published by TDA and no calculations or typical design details issued. Despite this lack of detailed information some 130 more timber hp shell roofs were built in 1960-75. There is no doubt that the ASL had a strong influence on those designs. Although the majority were designed by Newsum/Booth (50) and Tottenham (43), other engineers were involved in the next 15 years (see Tables 2 and 3).

Newsum standard HP shell roofs

It is appropriate to note the way in which a manufacturer such as H.Newsum and Sons (HNS) operated. Its sales representatives visited architects and offered a design/manufacture/erect service for a particular job (say the roofs of various buildings at a new school). If the company won the tender, it became a nominated supplier and the successful quotation was incorporated in the bills of quantities as a prime cost item.

During the Southampton Conference, R.A.Newsum announced that his company had recently been investigating the standardisation of hp roofs.[22] It was logical for the company to think along these lines when it is remembered that most of their production consisted of standard roof components such as Trofdek and Girdalinc. These timber-plywood beams were available in standard depths and lengths, and were used with standard curtain walling panels: standard details were available and it was therefore possible for the company's drawing office staff to prepare drawings rapidly to meet the architect's requirements and to submit a price for the scheme. In the case of hp roofs, more work was required: the company needed manufacturing drawings for the glued laminated edge beams and the metal shoes and ties, and erection drawings for the membrane (number, arrangement and thickness of the boards), the edge beam-to-membrane connection and the support details. In a competitive market, the manufacturer who could persuade the architect to think from the start in terms of a standard shell was the most likely one to win the job (and any flat roof areas) when it was put out for tender (see for example Fig. 13).

The Newsum *Standard Hyperbolic Paraboloid Roof* was launched in a leaflet in December 1961.[23] The standard shell was square and the two high corners were each at a height above the low points equal to one fifth of the side of the shell. The minimum size was 15 ft square rising in 5 ft increments to a maximum size of 70 ft square. The leaflet contained the width of the beams and the overall depth of the fascia but in a competitive market the number and thicknesses of the boards in the membrane were not given: these values for the membrane had been found by site experience and were withheld from competitors. The leaflet also tabulated the loads on the columns (vertical and horizontal) for the architect's consulting engineer; the prices included erection but were exclusive of tie bars and metal shoes at the column heads. The felting, or similar covering, was not included in the price.

Although the emphasis was on standard shells the company policy did not exclude non-standard units such as double gable roofs (arrangement C, Fig. 4) and single diamonds (arrangement A*). The company simply reserved the right to restrict their designs to well-tried arrangements and sizes. During the next few years, until it was taken over by Dexion and relaunched as Newsum Timber Engineers (NTE), the company (HNS) constructed twenty two jobs of which only four were non-standard. The restriction to standard sizes and arrangements was not just determined by the wish to reduce design costs but also bore in mind the uncertainty surrounding design methods.

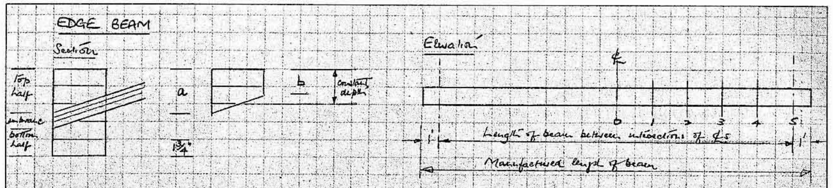
In the early years of hp roofs at Newsums the standard details evolved as the company and

Booth gained experience together. Changes were made quite frequently and no one document contained all the shell details. When HNS was succeeded by NTE, there were major changes in the personnel and the new management rationalised some of the procedures that had evolved during 1959-63. The emphasis on standard designs, rather than one-off designs, increased.

In the case of the hp roofs, the system was standardised in a report by Booth for the company entitled *Standard hyperbolic paraboloids: dimensions for working drawings*.[24] Standard dimensions and details were given for edge beams (see Fig. 14), membranes (number and thickness of boards and nailing patterns) (see Fig. 15), membrane-to-edge beam connections (extract in Fig. 16) and tie bars (see Fig. 17). This information was confidential and local authorities were generally happy to rely on Newsum's extensive experience in lieu of calculations.

In the standard range, single shells (arrangement A) with metal ties were limited to 45 ft square and those with buttresses to 70 ft square: the perimeter curtain walling was made load bearing. The units in arrangement B (as at Wilton) were limited to 45 ft square: perimeter curtain walling was made load bearing and the central edge beams were fastened together to increase their torsional rigidity. Units combined to give double gables (arrangement C) were limited to 25 ft square. Other arrangements and sizes were treated as non-standard and one-off designs were undertaken only if they were thought to be in the long-term interest of the company.

From previous parts of this account it is clear that no completely satisfactory method of structural analysis was available. It is not known what procedures were adopted by other designers; so far as is known, no designer has published a design method and a complete set of calculations for a job. The basis of the designs by Newsum/Booth, which has not previously been published, was a combination of the following: the sizes determined from the membrane analysis, the behaviour of the TDA model of the Wilton shells, supplementary tests on panels carried out at the company factory in Gainsborough, theoretical research at Imperial College on boundary effects, the adoption of a limited number of arrangements, support conditions and sizes of units and, most important, the site experience obtained from twenty three jobs completed in the period 1959-62.



Side of shell (ft)	Manufacturing dimensions of half beam: Nominal width (in)	Number of laminations	Depth (in)	Cross section dimensions after shaping (half beam): Width (in)	Constant depth (in)	Section 0 a	Section 0 b	Section 1 a	Section 1 b	Section 2 a	Section 2 b	Section 3 a	Section 3 b	Section 4 a	Section 4 b	Section 5 a	Section 5 b
15	4	2	3 1/2	3 1/2	3 5/32	3 5/32	3 5/32	3 7/32	3 3/32	3 9/32	3	3 13/32	2 30/32	3 14/32	2 28/32	3 16/32	2 26/32
20	4	2	3 1/2	3 1/2	3 5/32	3 5/	3 5/	3 7/	3 3/	3 9/	3	3 13/	2 30/	3 14/	2 28/	3 16/	2 26/
25	4	3	5 1/4	3 1/2	4 29/32	4 29/	4 29/	4 31/	4 27/	5 1/	4 24/	5 4/	4 22/	5 6/	4 20/	5 8/	4 18/
30	5	3	5 1/4	4 1/2	4 26/32	4 26/	4 26/	4 28/	4 23/	4 31/	4 20/	5 2/	4 17/	5 5/	4 14/	5 8/	4 11/
35	5	4	7	4 1/2	6 18/32	6 18/	6 18/	6 20/	6 15/	6 23/	6 12/	6 26/	6 9/	6 29/	6 6/	7	6 4/
40	6	4	7	5 1/2	6 14/	6 14/	6 14/	6 18/	6 11/	6 21/	6 7/	6 25/	6 4/	6 28/	6 1/	7	5 29/
45	6	5	8 3/4	5 1/2	8 6/	8 6/	8 6/	8 10/	8 3/	8 13/	7 31/	8 17/	7 28/	8 20/	7 25/	8 24/	7 21/
50	7	5	8 3/4	6 1/2	8 3/	8 3/	8 3/	8 7/	7 31/	8 12/	7 27/	8 16/	7 23/	8 20/	7 19/	8 24/	7 15/
55	7	6	10 1/2	6 1/2	9 27/	9 27/	9 27/	9 31/	9 23/	10 4/	9 19/	10 8/	9 15/	10 12/	9 11/	10 16/	9 7/
60	9	6	10 1/2	8 1/2	9 21/	9 21/	9 21/	9 26/	9 15/	9 31/	9 10/	10 5/	9 5/	10 10/	9	10 16/	8 26/
65	10	6	10 1/2	9 1/2	9 18/	9 18/	9 18/	9 24/	9 12/	9 30/	9 6/	10 4/	9	10 10/	8 26/	10 16/	8 20/
70	10	7	12 1/4	9 1/2	11 10/	11 10/	11 10/	11 16/	11 4/	11 22/	10 30/	11 28/	10 24/	12 2/	10 18/	12 8/	10 12/

Fig.14 Newsum Standard hyperbolic paraboloid shell roof: edge beam dimensions (Booth, 1963).

MEMBRANE

Side of shell (ft)	Nominal width of boards (in)	Finished thickness of boards (in)	Number of layers	Thickness of membrane (in)	Gauge of nails	Length of nails: 2nd to 1st layer	3rd to 2nd layer (in)	4th to 3rd layer (in)
15	4	5/8	2	1 1/4	10	1		
20	4	3/4	2	1 1/2	10	1 1/4		
25	4	7/8	2	1 3/4	10	1 1/2		
30	5	5/8	3	1 7/8	10	1	1 1/2	
35	5	3/4	3	2 1/4	10	1 1/4	2	
40	5	3/4	3	2 1/4	10	1 1/4	2	
45	5	7/8	3	2 5/8	10	1 1/2	2 1/4	
50	5	7/8	3	2 5/8	10	1 1/2	2 1/4	
55	5	7/8	3	2 5/8	10	1 1/2	2 1/4	
60	5	7/8	3	2 5/8	10	1 1/2	2 1/4	
65	5	3/4	4	3	10	1 1/4	2	2 3/4
70	5	7/8	4	3 1/2	10	1 1/2	2 1/4	3

NAILING PATTERNS

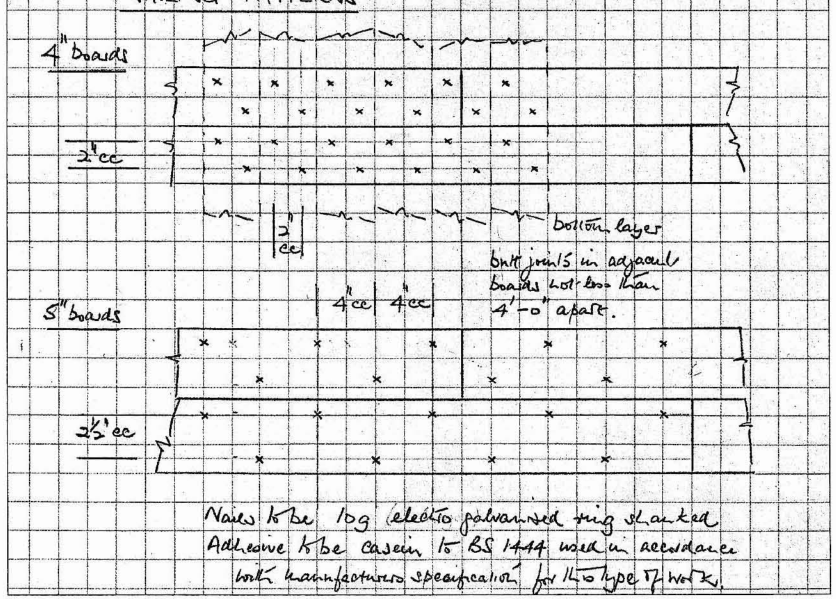
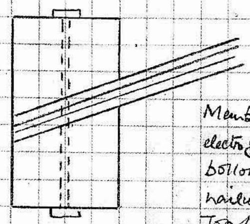


Fig.15 Newsum Standard hyperbolic paraboloid shell roof: membrane dimensions and nailing patterns (Booth, 1963).

EDGE BEAM to MEMBRANE CONNECTION



Membrane is nailed with 10g (or larger) electro galv. ring shanked nails & casein glued to bottom half of edge beam. For nailing pattern see below.
Top half of edge beam is bolted with ½" bolts at 2' centres + glued to top layer.

Side of shell	1st layer to beam		2nd layer to beam		3rd layer to beam		4th layer to beam	
	Nailing pattern	Length of nail	Nailing pattern	Length of nail	Nailing pattern	Length of nail	Nailing pattern	Length of nail
15'	A	2½"	A	3"				
20	A	2½	A	3				
25	A	2½	A	3				
30	B or D	2½	C	3	D or B	4"		
35	B or D	2½	C	3	D or B	4		
40	B or D	2½	C	3	D or B	4		
45	B or D	2½	C	3	D or B	4		
50	B or D	2½	C	3	D or B	4		
55	B or D	2½	C	3	D or B	4		
60	E or G	2½	F	3	G or E	4		
65	E or G	2½	F	3	F	4	G or E	4"
70	E or G	2½	F	3	F	4	G or E	4

Nailing Pattern A : Shells 15, 20 & 25' : Edge beams 3½" wide

Boards at 45° to beam

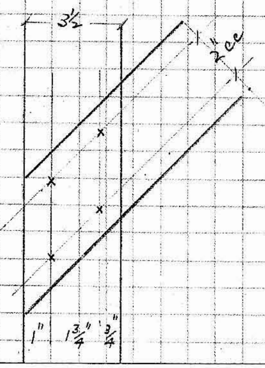


Fig.16 Newsum Standard hyperbolic paraboloid shell roof: edge beam to membrane connection (Booth, 1963).

TIE BAR of mild steel

Side of shell ft.	Tie force lb.	Tie area sq. in.	Nett diameter in.	Extension Dead in.	Extension Live in.	Extension Total in.	
15	10 000	0.44	0.75	0.08	0.11	0.19	
20	17 700	0.79	1.00	0.10	0.15	0.25	
25	27 600	1.23	1.25	0.13	0.19	0.32	
30	39 800	1.77	1.50	0.15	0.23	0.38	
35	54 200	2.41	1.75	0.18	0.26	0.44	
40	70 700	3.15	2.00	0.20	0.31	0.51	
45	89 400	3.99	2.25	0.23	0.34	0.57	
50	111 000	4.42	2.50	0.26	0.38	0.64	
55	134 000	5.96	2.75	0.28	0.42	0.70	
60	159 000	7.09	3.00	0.31	0.45	0.76	†
65	187 000	8.32	3.25	0.33	0.50	0.83	†
70	217 000	9.65	3.50	0.36	0.53	0.89	†

Notes

1. Tie force is computed on a total load of 25 lb/sq.ft.
2. Diameter given is nett and allowance must be made for the thread by either increasing the diameter or upsetting the ends
3. Extensions are calculated on a dead load of 10 lb/sq.ft. and a live load of 15 lb/sq.ft. These extensions have been calculated on the nett diameter and it should be noted that with increased diameters to compensate for the thread the values will be slightly less.
4. † For shells larger than 60' side the extension of the tie is excessive, the diameter and self weight of the tie make for difficult handling, appearance is poor and for these reasons the use of buttresses is suggested. †

Fig.17 Newsum Standard hyperbolic paraboloid shell roof: tie bar forces, dimensions and extensions (Booth, 1963).

The advantages of the standard shells were threefold. Firstly, architects knew the final sizes at the time of their preliminary designs (see Table 4 for extract from NTE leaflet[25]) and secondly, the final drawings could be rapidly prepared by Newsums. Thirdly, there were unlikely to be any structural problems during erection or in the short and long-term behaviour of the shells.

Publicity and promotional literature

The completion of the roof at Wilton in July 1957 was the start of a campaign in the timber trade press and in architectural and engineering journals extolling the merits of timber hp shells.

The *Timber Trades Journal* led the way with two pages devoted to technical details and photographs under the head line "*Unique timber structure: the first multiple hyperbolic paraboloid timber roof in the world*".[26] The completion of the roof was also noted frequently in the next two months in a wide range of trade journals. The architectural magazines *Architect and Building News* (*ABN*) and *Architects' Journal* (*AJ*) devoted little space to the roof: they were to correct this brevity with longer pieces when the method had become established by 1959. In August 1959 the *ABN* devoted fourteen pages to the Scott Bader Conference Hall, Chantry Primary School, the Egg Packing Station at Haughley Park and an introductory article by Booth.[27]

Several handsome booklets extolling the advantages of timber engineering were published in the late 1950s and mid 1960s: these booklets dealt with all forms of timber engineering components and usually contained photographs of shell roofs. TDA's *Design in timber* (c. 1959)[28], which contained photographs and line drawings that had previously appeared in the magazine *Wood*, included details of Wilton. *Timber Engineering* (by British Woodwork Manufacturers' Association, 1963)[29] and *Design for progress with Timber Engineering* (by Timber Trade Federation, c. 1964)[30] included a photograph of a chapel at Woolton. TTF's *The new world of Timber Engineering* (c. 1965)[31] contained photographs of three shell roofs. These four publications, aimed at clients and their architects, were dominated by photographs interspersed with paragraphs of technical sales information.

By far the most elaborate publication by TRADA that was devoted entirely to shell roofs was *Timber shell roofed factories* (c. 1962).[32] The target for this twelve page publication was the factory owner: it contained some remarks on the advantages of timber shell roofs followed by "technical information for your factory consultant" and concluded with graphs and sketches prepared by Hume and Tottenham giving the economic ranges and practical sizes of various geometries. A copy of ASL 5 was loosely inserted. Sadly it did not lead to a major inroad of hp shell roofs into the factory market: 1962-75 saw 98 projects covered with hp shell roofs, of which there were only three factories and two fire stations.

Whereas the booklets mentioned above were of little help to structural engineers, the articles on various timber engineering structures and components that appeared regularly in the monthly magazine *Wood* contained photographs and working drawings of details that were particularly helpful to engineers. Between August 1957 and April 1969, *Wood* contained articles on eighteen hp shell roofs.[33] The typical article consisted of three pages of photographs and text, and one or two pages of drawings. The only other journal to show a consistent interest in timber engineering was *Civil Engineering and Public Works Review*, which published timber supplements for three years in the late 1950s.

It is not possible to say how effective the glossy booklets were in attracting business for the timber engineering firms. Certainly the booklet on shell roofs for factories failed in its objectives.

H. Newsum & Sons' (HNS) technical data sheets usually consisted of four pages of sketches of typical details, load-span tables and prices. The first data sheet (November 1959) introduced hp, ep, cylindrical and conoid shapes and gave an indication of the limiting geometrical ratios.[34] *Standard Hyperbolic Paraboloid Roofs* followed in December 1961.[35]

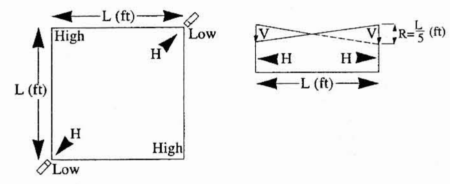
Table 4 Newsum Timber Engineers Standard Hyperbolic Paraboloid Roofs (from NTE, 1966)

Plan area
HP shells can be square only.
Minimum size is 15 feet x 15 feet.
Maximum size is 70 feet x 70 feet (this is for a single shell; greater sizes can be obtained by grouping the shells).

Rise
When a shell has two high points and two low points, the edge frames are straight on elevation and rise at a slope of 1 in 5.

When a shell has one high point and three low points at the same height, two edge frames are straight and horizontal and the other two are straight and rise at a slope of 1 in 2.5.

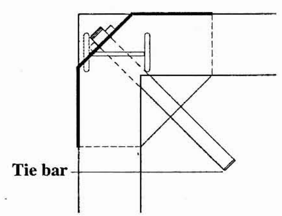
Loading table
The table below gives the vertical and horizontal forces to enable an approximate design to be made for the buttresses. The given forces are for estimating purposes only and the figures for final design must be confirmed with Newsum Timber Engineers.



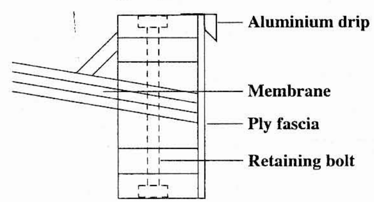
Plan **Elevation**

Size of Roof Floor Plan area L' x L'	Rise L/5 in feet	Width of edge beam in inches	Depth of fascia in inches	Vertical load on column V in pounds	Horizontal thrust at column head H in pounds
20 x 20	4	3½	8⁹⁄₁₆	5500	19500
30 x 30	6	4½	12¼	12300	43800
40 x 40	8	7½	12⅝	22000	77700
50 x 50	10	8½	16⅞	34300	122000
60 x 60	12	9½	19¼	49500	175000
70 x 70	14	9½	27⅞	67300	239000

Corner detail with tie bar



Section through edge beam



Newsum Timber Engineers' (NTE) first data sheet, which was also entitled *Standard hyperbolic paraboloid roofs*, was issued in November 1963.[36]

Second to HNS and NTE in the number of shells constructed was Rainham Timber Engineering (RTE). The company issued a twelve page coloured brochure (entitled *Shell roofs*) that contained photographs of completed jobs and drawings of construction details.[37] There was no attempt to standardize the product and no sizes of the constituent parts of the hp shell were given.

Although RTE had their own experienced engineers and draughtsmen, they called on Hume, Tottenham and Bennett to prepare calculations and drawings for hp shell roofs. The targets for the brochure were clients and their architects, and the high quality of the publication must have impressed them. From Table 2 it can be seen that during the six years prior to 1966, RTE constructed nine hp shells; in 1966-68 the figure fell to six jobs, in 1969-72 the figure rose to seven jobs, but in 1972-75 only two jobs were constructed. Looking at these totals it can be argued that the first two issues of the brochure (June 1966 and July 1969) were successful but that the final 1972 issue was extolling a product that was no longer wanted.

In comparison with Newsums and RTE, who built fifty three and twenty four hp roofs respectively, the other contractors were small and none of them devoted complete leaflets or booklets to shell roofs. No one gave a design method.

It is always difficult to determine the effectiveness of promotional literature but TRADA's booklet clearly failed to achieve penetration of the industrial market. At least it can be said that the Newsum approach of giving more technical data in their leaflets and standardising the product (see Table 4) resulted in their building more shell roofs than any other company (38 percent of the total).

Conclusion

When the scene was set at the beginning of this account, the birth of the thin shell roof was attributed indirectly to government restrictions on building materials that had been endured by architects in the immediate post-war era. Anchor, in a recent review of concrete shell roofs in 1945-65, has attributed the popularity of concrete shell roof construction to the shortage of steel and to the advantage that a concrete shell used less steel than its alternative steel truss.[38]

Anchor also thought that "*Fashion also played a part in design, and no self-respecting architect at this time would be without a shell roof job.*" He considered that concrete shell roof construction ceased on any scale around 1965 when structural steel had become more readily available and "*architectural fashion had moved on.*"[39] No doubt fashion also played an important part in the demise of the timber hp shell.[40]

So we may summarise: favourable economics created the cylindrical concrete shell roof, frustration amongst architects led to the doubly curved concrete hp, Reece's foresight and Tottenham's expertise gave timber the lead, but the vast amounts of government subsidy for the steel industry more than restored the competitiveness of steel and in so doing swung the fashion away from the concrete shell and its competitor timber. Thus timber's real competitor has been steel, not concrete. Whoever the enemy, the timber hp reached its peak in 1965, hung on for another ten years and then it too died.

This time there was no Reece, now a leader in the trussed rafter industry, and no Tottenham, now a Professor at Southampton Universty with no longer a hundred percent commitment to timber. This time there was no magic carpet for timber to jump on. Fashion prevailed and the timber hp roof was rolled up. But fashion is a cyclical mistress. Perhaps the hp, or another shape in timber, will one day return.

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Finally we must all acknowledge the major contribution made by Hugh Tottenham to the era of the timber hp: without his expertise and enthusiasm many years ago there would never have been such extensive use of timber shell roofs in general and hyperbolic paraboloids in particular, nor would there have been a history to recall.

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