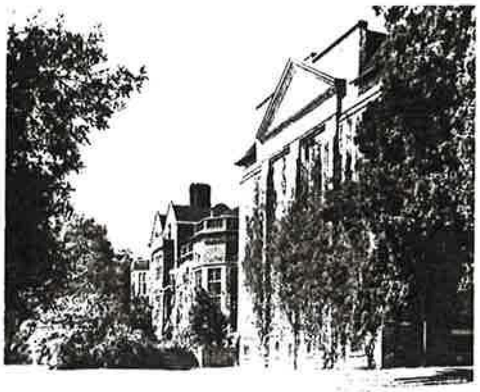
Engineering an opera house: the new Glyndebourne

Stas Brzeski Derek Sugden John Thornton John Turzynski



1. Glyndebourne in 1934: Organ Room (left), Theatre (right).

Introduction

The new Glyndebourne Opera House opened on 28 May 1994, the 60th anniversary of its predecessor, with the same opera, *The Marriage of Figaro*. The original building, constructed by Sir John Christie in the grounds of Glyndebourne House (Fig.1 above) near Lewes in East Sussex, was not only too small for current demand, but suffered from poor acoustics and sightlines, had inadequate ventilation, and sub-standard back stage facilities. By 1987 his son, Sir George Christie, had begun to plan a new Opera House; after approaching nine architects and asking two to develop proposals, he appointed Michael Hopkins & Partners early in 1989. Arups became involved in all aspects of the engineering and acoustics design apart from theatre equipment and production lighting.

The brief called for an increase in seats from 830 to 1150 and an improvement in technical standards. Sir George Christie was quite clear, however, that music, theatre, and an intimate atmosphere took precedence over technology. He did not want a building where the technology became an end in itself.

Clarity and integration

The design of an opera house is complicated. The problems of long spans over stage areas and the support of balconies and flytower are obvious, but there are many more: the form and detail of the auditorium must give good sightlines and create the required acoustic; the fabric must provide good acoustic isolation; and the ventilation system should be inaudible. Also, theatre and lighting equipment have very specific needs. (These are the technical criteria; the architectural planning, too, has its own demands).

Apart from the requirement that only one season should be lost during construction, Glyndebourne presented another challenge: how to relate to the House and gardens, and maintain those qualities which make 'Glyndebourne' unique.

The concept

Whatever success the design has stems from the simplicity and clarity of the overall concept of the building, which works for all disciplines at all levels. The diagram may seem obvious but a study of other theatres soon reveals that its clarity is exceptional. Such simplicity is not easily achieved and relies on the complete integration of architectural, engineering, and acoustic design. Instead of trying to reduce the impact of the new Opera House by fragmenting it, like Glyndebourne House itself, the Hopkins' chose to create a single compact building and then reduce its visual bulk, both by cutting into the hillside and through the detail of the design.

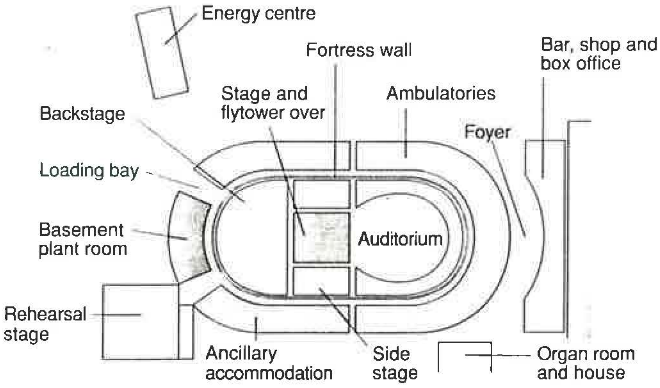
The design is a natural consequence of choosing a horseshoe-shaped auditorium for the intimate atmosphere it creates. The whole layout of the building is based on circular forms, which are used to soften its impact on the site. Recognizing that the auditorium and stage areas have the same requirement for acoustic isolation and generate similar widths, they are contained by an oval-shaped massive brick wall, the 'fortress wall'. At one end is the auditorium, at the other the back stage, and between lie the side and centre stages with the flytower above.

Around the fortress wall is wrapped the ancillary accommodation: dressing rooms, offices, and circulation space. Primary services distribution is located in this zone.

There is a basement. The area behind the proscenium contains plantrooms, stage equipment and dressing rooms, whilst in front there is a ventilation plenum beneath the auditorium, cloakrooms for the public, and plant rooms for the front-of-house areas. The back stage plantrooms supply air to the auditorium via two huge concrete ducts.

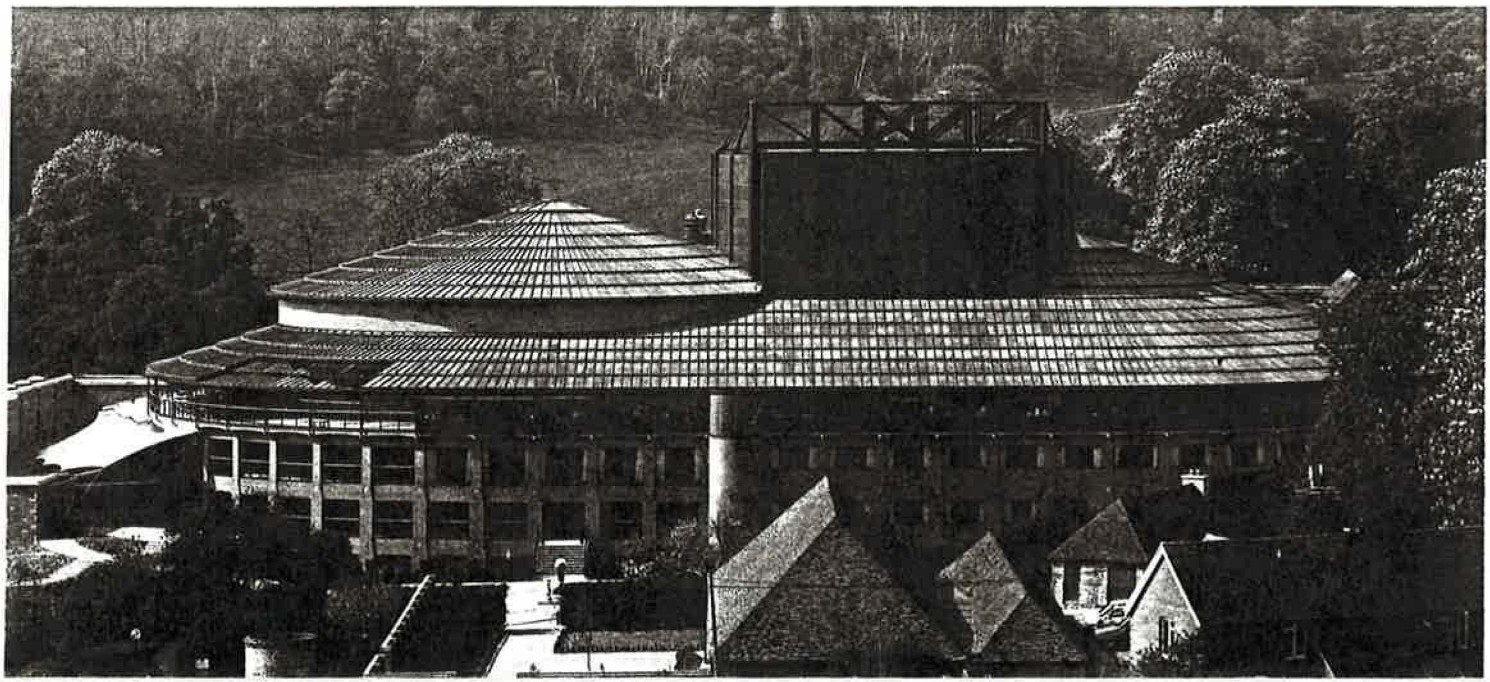
Noisier plant such as boilers and chillers are in a separate refurbished brick out-building.

The rehearsal stage too is outside the main envelope next to the loading bay, in which another stage can be built if necessary. The contours of the site are such that the rehearsal stage is almost completely underground, revealing its presence only by a low brick wall topped by a band of glazing and a lead roof.



2. Concept diagram.

3. The new Opera House looking westwards toward the South Downs.



Brickwork and the fortress wall

Glyndebourne House is a collection of mellow redbrick and stone buildings with gardens and lake, set in the Sussex Downs. The new Opera House not only had to relate to these physical characteristics, but also recreate the particular ambience which Glyndebourne has. In part this is created by the setting and the tradition of picnicking in evening dress in the gardens. It also lies, like the picnic, in the contradiction between sophistication and simplicity. In the old Opera House a complex art was performed at its highest level in a building which could best be likened to a large church hall. Some people were concerned that its acoustic qualities should not be lost but these in fact were poor with a dry sound and noise from aircraft using Gatwick.

Early in the design the architects considered using flint walling, a local material, but settled on brick as more appropriate. The hand-made bricks not only related its construction to the House, they also introduced a quality and scale of detailing which further reduced its impact and recreated the simplicity of the old building.

The fortress wall required mass to achieve its acoustic performance and, apart from under the flytower, the vertical loads are not particularly high, since above basement level the building consists of single-storey spaces with long-span roofs, or three-storey accommodation. This led to the idea of constructing the fortress wall out of load-bearing brickwork, double-skinned around the auditorium itself for acoustic isolation. It was then logical to add the enclosing accommodation as a dependent structure, in the way mediaeval cities built houses onto the outside of cathedrals and castles. This structural principle reinforces the architectural concept.

The Hopkins' work places great emphasis on the honest use of materials, but brickwork in large contemporary buildings is normally relegated to a cladding skin or a facing for precast units. This is betrayed in the bonding patterns, the use of the bricks in unlikely situations, and the location of mastic-filled movement joints. These are required by the expansion of brickwork and the lack of flexibility of modern cement mortars as much as by the need to absorb differential movements between frame and cladding. Nevertheless such joints would have undermined the visual integrity of the load-bearing structure and led to difficulties in detailing. They would also have been difficult to locate structurally and undesirable acoustically, so the older technology of lime putty mortar, which is more tolerant of movement, was adopted. The other distinguishing feature of modern brickwork, bonding patterns resulting from cavity construction, was avoided by building solid.

Auditorium, ancillary accommodation and roofs

Within the auditorium the balcony structures are of exposed precast concrete units stitched together by an in situ spine beam, balanced on a ring of columns, and restrained at the back by the fortress wall. (This follows the same structural principles as the Mound Stand and Compton and Edrich Stands at Lord's.)

The exposed thermal mass helps to smooth temperature fluctuations in the auditorium.

Outside the fortress wall, exposed precast slabs with an in situ topping are supported on precast beams which span between the fortress wall and brick piers. The outer ends of the beams appear through the walls and piers to make the construction legible and add detail to the brickwork. Brick spandrel panels span between the piers as flat arches carrying their self-weight. Precasting was chosen both for speed and for quality of finish; also, in the case of the accommodation structure, its form reflects the use of timber and cast iron in earlier brick buildings. The concrete mix was selected for its light colour and contained a mica-rich sand to give it sparkle. Precast panels were also used to form the ceiling over the auditorium and create the recessed lighting gallery. These elements play an essential role in the auditorium acoustics: apart from providing the mass necessary as part of the double-skinned acoustic enclosure, their sculpted form reflects and diffuses sound.

Above the precast units, the primary roof structure consists of radial steel trusses cantilevering into the centre from the perimeter where they are supported on the balcony columns and tied-down by the fortress wall. Above the trusses are double-skinned, lead-covered plywood panels. The mass of the lead and build-up of the panels is used for acoustic insulation. The trusses for the back stage are also radial, but in this case the centre of the system lies on the back wall of the flytower rather than over the space.

Continued on p.9

5. Main entrance (Organ Room in Glyndebourne House is on the left). ▶

Bricks and mortar

The bricks had to be similar to those used in Glyndebourne House, as well as satisfying engineering requirements, and their selection involved considerable research. The final choice was a Selborne hand-made, re-pressed brick, made from gault clay extracted from a deposit mined for many years. They are a modified imperial size, 220 x 106 x 60mm, to match those in the walls of the House. Compressive strength is 27.5N/mm^2 with an irreversible moisture movement of 0.37mm/m — classified as low by CERAM Building Technology. Water absorption is 14.3%.

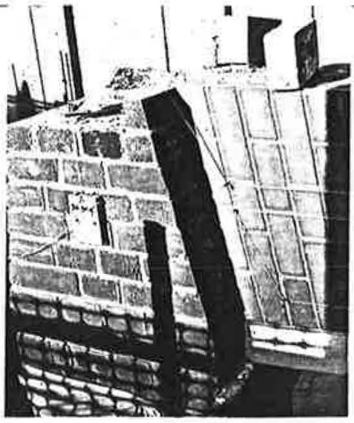
The facing bricks have a textured surface produced by coating with sand before firing. Both these and the common bricks are made of the same clay and have the same mechanical properties, thus avoiding problems of differential movement between facings and commons bonded together or in adjacent leaves of cavity walls.

Knowledge about the manufacture, use and behaviour of lime mortar, chosen to avoid the need for movement joints, is not widespread, and an investigation was carried out, including a visit to The Lime Centre in Hampshire to gain practical experience. Lime for mortar is produced by burning chalk or limestone (calcium carbonate) in a kiln at about 900°C to produce calcium oxide. Two types of lime are used for mortar: lime putty or dry hydrate. The former was employed at Glyndebourne for its good water-retention properties, workability and availability. It is produced by hydrating or slaking the lime (calcium oxide) with water to produce calcium hydroxide. The reaction is exothermic, vigorous and potentially dangerous. The putty is stored under water, the longer the better, for increased plasticity and bonding properties.

Modern cementitious mortars (which incorporate unhydrated dry lime) set by the action of hydration with water. The mortar sets throughout the depth of the joint and, like most cement-based compounds, is accompanied by shrinkage.

In contrast, true lime mortars set by the action of carbonation at the exposed surfaces of a joint. Atmospheric carbon dioxide is absorbed into the mortar and the calcium hydroxide present is converted back to calcium carbonate in a lengthy process known as induration. The depth of setting is relatively shallow, and the core of a mortar joint remains plastic. It is this softness that permits the masonry to absorb stresses caused by movement. Any cracking that does occur is small and distributed along and across a wall. In effect, movement joints are created at every bed and perpend joint.

The lime putty was delivered in tubs, and the mortar mixed on site using gauging boxes and mortar mixers: the proportions were 1:2:9 (white PC : lime putty : sand).



◀ 4. Brickwork detail on arch.

Bricklaying commenced with the construction of sample panels for the approval of bricks, joint profile, blending and colour. This was a useful testing ground to establish working procedures for the main building.

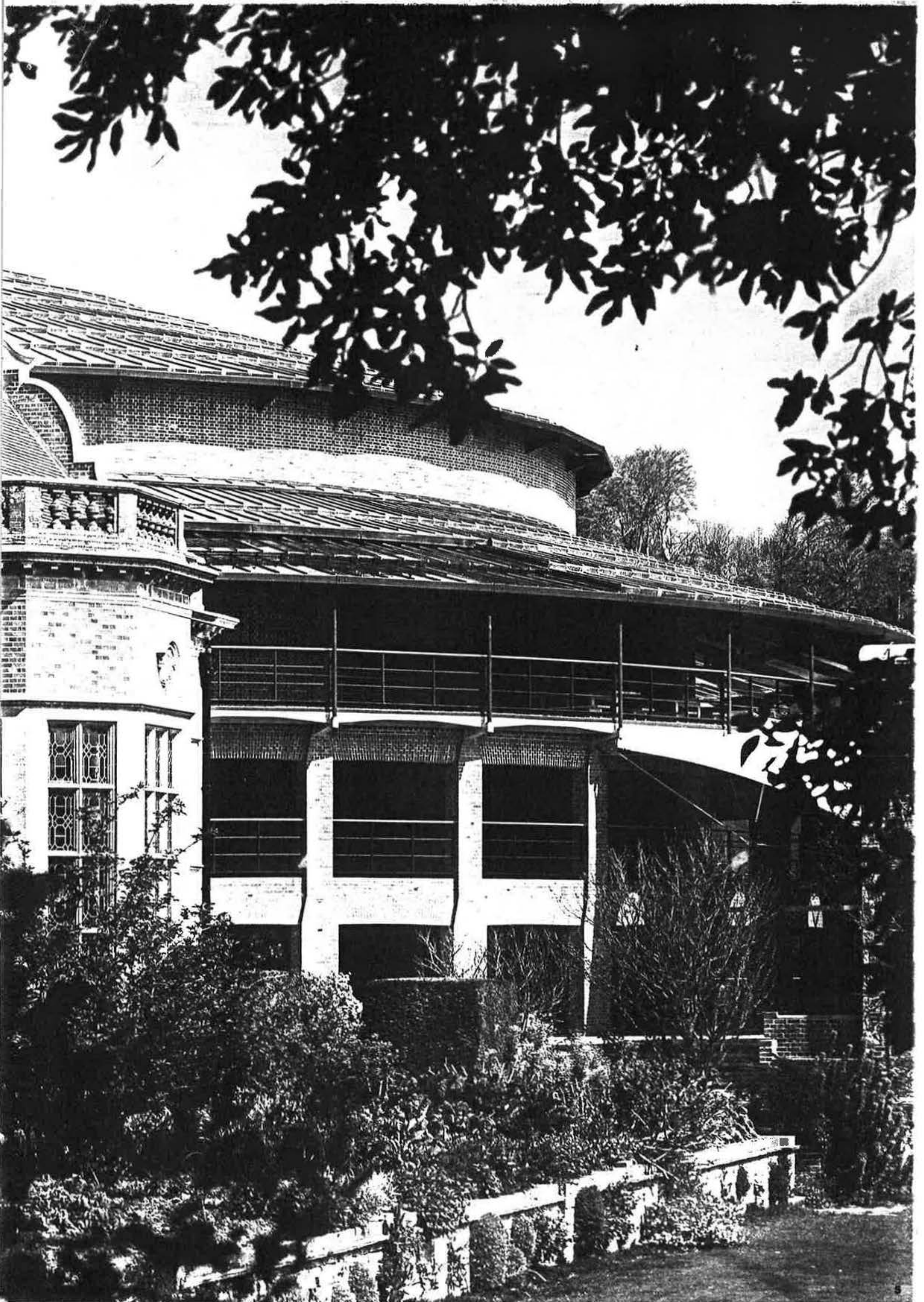
The cross-bonded flat brick arches span up to 2.9m between skew-backs built into the piers. They are 334mm thick and 536mm high, are unreinforced, and incorporate a rise of 25mm. They support their own weight and a brick spandrel panel above. The bricks for each arch were made from a single column of clay. Each brick had a unique number, and complete arches were delivered on a single pallet.

Although the arches are relatively lightly stressed there was concern that they might be prone to movement and, with negligible tensile strength, exhibit unwanted cracking. A load test was carried out, both to answer this question and to assess the comparatively weak mortar.

An arch was constructed at CERAM's laboratories using the chosen bricks and lime putty mortar in the agreed bonding pattern. The arch was buttressed in a similar manner to those on the building, and was loaded in a predetermined sequence. Strains and movements were monitored at relevant points such as springing point, extrados centreline and intrados centreline. The arch withstood the applied load without undue distress and with displacements close to predicted values.

The maximum length of continuous brickwork on the building is just under 100m around the front of the Opera House. In other areas, perforations in walls for doors or other openings reduced this length. The potential long term irreversible moisture expansion of the bricks has been estimated as about 24mm, which does not account for moisture movement which occurred over the months the bricks were stockpiled in the open. This strain was considered acceptable, taking into account the restraint that was provided by the floor slabs and beams.

The use of load-bearing brickwork with lime putty mortar on a building of this scale has not been seen for many years. The investigations, tests, and trials were an essential part of developing the design and understanding the techniques required for construction. In the end, though, the design depends on engineering judgement.



The acoustic

The brief

Sir George Christie's brief was simple and direct, but very difficult to achieve: he asked for a sound which combined the clarity of the old house with a 'resonance' that would flatter the orchestra and singers. Like many acoustic briefs it illuminated two fundamental criteria which are virtually mutually exclusive. Throughout the history of opera there has been an argument about whether words or music are of primary importance; the French with their literary tradition favoured the words, whilst the Italians were more concerned with melody, harmony and timbre.

This dichotomy is still with us today and its resolution, achieving that delicate balance between words and music, was the starting point for the geometry of the Opera House as a response to Sir George's brief.

Setting the standards

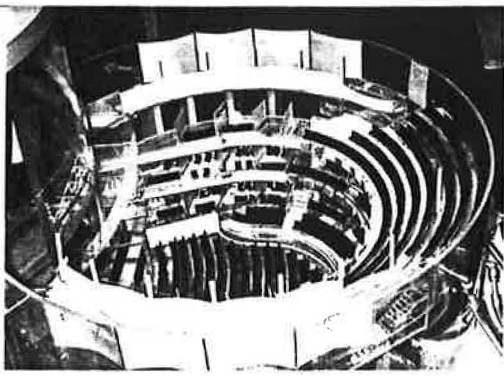
At the earliest stage, after the Hopkins' appointment but before that of the theatre consultant, some discussions took place whilst the auditorium still had the vestigial fan-shaped form of the John Bury brief*.

This did not inhibit the setting of geometrical standards to achieve the preferred acoustic. Auditoria for music, whether concert halls or opera houses, invariably fall short of the volume per seat necessary to achieve the appropriate reverberation time (RT); defined as the time taken for a sound to decay through 60dB, RT is still considered the prime criterion for measuring the quality of sound within an enclosed space. Its value at different frequencies is also very important to the quality of the sound. It is directly proportional to volume and inversely proportional to the absorption of all the surfaces.

Volume decreases as the architectural concept is developed and detailed. In addition, clients and architects find ways of increasing seat numbers as the design and sight-line analysis develops.

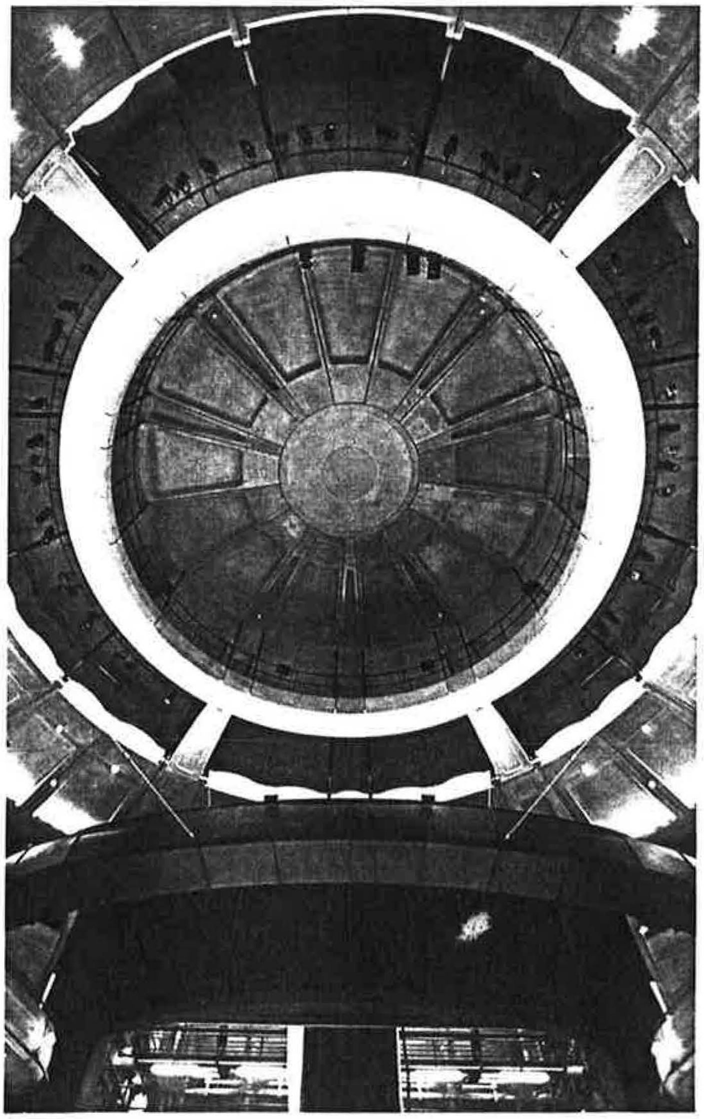
Initially, 8m^3 per seat was the volume fixed to achieve the preferred RT; for clarity, a maximum 17-18m between balconies was set to ensure strong early side reflections; whilst for acoustic and visual intimacy, the furthest seat was to be a maximum of 30m from the stage riser.

The quality of any acoustic is immeasurably enhanced by a quiet background. To achieve this a double skin wall and roof construction of sufficient mass with the appropriate cavity was specified, together with an air-conditioning strategy that would ensure a background noise level of PNC15 — approximating to the threshold of hearing.



6. Acoustic scale model showing convex reflectors installed for impulse testing.

7. Auditorium roof showing use of structural ribs for sound diffusion and 'jelly-mould' sound diffusing form of vertical precast sections.



8. Derek Sugden firing a .38 revolver during initial acoustic tests in December 1993.

Design and analysis: the 1:50 scale model

As the design developed, it became clear that Hopkins' auditorium would not include any 'carpets and curtains' and a minimum of absorbent secondary fixings, so the volume per seat could be relaxed a little. However, the 8m^3 per seat did decrease to just below 7m^3 per seat as expected, indicating a mid-frequency reverberation time of 1.4 secs. Anthony Whitworth-Jones, the General Director of Glyndebourne, placed great emphasis on clarity. He considered the Coliseum in London and the Bayreuth Festspielhaus with RTs of 1.5-1.6 secs to be too reverberant. Both these auditoria, but particularly the Coliseum, lack short powerful side reflections. With the short powerful side reflection, an RT of 1.4 secs - still somewhat more reverberant than most opera houses — was considered to be appropriate.

With the geometry and seating finalized, a 1:50 scale model was constructed in Arups' Model Shop, with the first roof and ceiling scheme.

Four were tested before the architects were convinced about a design, which incorporated a 'flat dome', a common feature of many opera houses. Sound waves focus in a similar way to light, and this design avoided the focusing problems associated with many earlier schemes. The model was also essential in exposing focusing from the drum at high level. This was corrected by the introduction of convex panels. Slotted lift-off panels were also introduced to allow the inclusion of small areas of absorption to deal with certain focusing and to allow for a limited degree of fine tuning.

Extensive work was carried out in the model to define the final geometry of the balcony fronts — fundamental in achieving, after the direct sound, the strong early reflections which provide intimacy, clarity and envelopment. The detailed geometry was resolved in the model to achieve this without focusing effects. The profiles reflect sound down into the stalls at the sides, with a subtle change in profile towards the back of the auditorium, and are slotted to provide acoustic transparency where focusing would occur.

To ensure an orchestral sound of some richness and warmth, a 20-25% increase in RT at low frequencies is needed. This is quite uncommon in most opera houses, where orchestras sound dry and rather 'boxy'. It was most rewarding that Hopkins' design of the auditorium without an architecture of second and third fixings was fundamental to achieving this aim. The soffits are of exposed concrete, the main floor is a stiff composite layer with a minimum thickness of 40mm, and all the balcony fronts are of very rigid solid pine, with a geometry that adds to their structural stiffness and so ensures a minimum of bass-absorbing resonance. This was a most important aspect of the acoustic design.

There was extensive acoustic input into the seat design in addition to the close work with the mechanical engineers to achieve the specified noise attenuation. The seats were tested in a laboratory with and without auditors. Following the first test, adjustments were made to certain aspects of their construction to achieve the specified absorption coefficients. These modifications were confirmed in a final test.

Predictions and measurements

Measurements in the model predicted a mid-frequency RT of 1.4 secs, with 1.7 secs at 125Hz. A test concert with full audience was held on 28 March 1994, where measurements gave an average mid-frequency reverberation time of 1.25 secs with 1.65 secs at 125Hz. The clarity index was high throughout the auditorium and the impulse traces were of 'text book' shape.

The orchestra pit

One of the central problems for an acoustician in the design of an opera house is the balance between pit and stage sound. The orchestra pit of a modern opera house must be able to house and adapt to a wide repertoire, from the orchestras of the Renaissance operas of Monteverdi and Cavalli, through Haydn and Mozart, to Verdi, Wagner and Richard Strauss, and on to Birtwistle and beyond.

In the last 200 years the orchestra has changed out of all recognition and the instruments have become enormously powerful. Conductors have a love affair with that great lush sound favoured by many recording engineers and producers. The power of the human voice may have increased somewhat, but there is no comparison with the size and power of a modern orchestra.

The brief for the orchestra pit was not precise about the maximum number of players. There is a tradition at Glyndebourne which encourages young singers, and to achieve the delicate balance between stage sound and pit sound with a large modern orchestra, a maximum distance of 3.6m between the orchestra rail and the stage riser was agreed. It was always the intention to place the more powerful instruments of a modern orchestra on descending rostra under a limited cantilever section of the stage. The final structural scheme, together with the abandonment of a proposal for sliding proscenium boxes and subsequent change in geometry of the sliding bridges — part of the original John Bury brief — resulted in a decrease to the overall length of the pit. To compensate for this, the distance between the orchestra rail and stage riser was increased to 4m.

Following the test concert, the London Philharmonic Orchestra, with c.75 players on modern instruments, tested various configurations of the orchestra for *Figaro* and *Peter Grimes*, under conductors Bernard Haitink and Andrew Davis. The rostra geometry, particularly at the back of the pit, was resolved both for sight lines and comfortable seating.

The other Glyndebourne band is the Orchestra of the Age of Enlightenment, about 50-strong, who play on 'original, and thus less powerful, instruments. In view of this, it was desirable that all their players should sit forward of the stage riser, but with the growing demand of orchestral players for increased space and the presence of the safety net this was not possible. However, with the adjustable pit lift slightly below the preferred stalls level the OAE can be accommodated with the brass and woodwind placed under the safety net or edge of the cantilever.

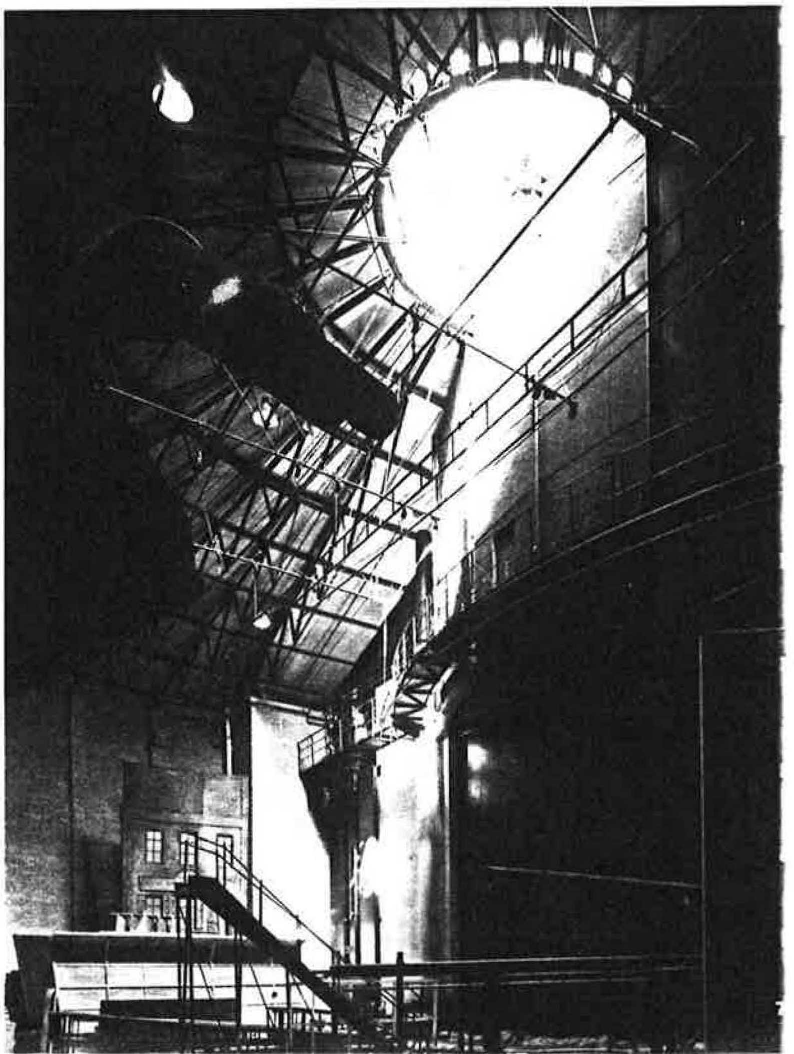
Coda — art or science

Acoustics is often referred to as a 'black art', but it is no more nor less an 'art' than any other branch of engineering. Engineers, like architects, work from precedent, but primarily from intuition, using calculations as a guide to what they want to do, and with detailed analysis as a supporting tool. Acoustics does perhaps differ, in that the choice of an acoustic is highly subjective, whereas the overall stability of a structure is not a matter of taste or opinion. A quiet background, however — one of the most important qualities of a great acoustic — is not a matter of opinion, although even on this subject we can argue how quiet we should make an auditorium. This aspect of acoustics, the setting and achievement of sound insulation and sound attenuation, was one of the great success stories at Glyndebourne. Rob Harris of Arup Acoustics observed that it was the first auditorium we have measured that achieved PNC15 at the first test with no modifications or 'tinkering' necessary.

* John Bury was the theatre designer and consultant who prepared the drawings for the competition brief. He had designed a series of Glyndebourne productions for Peter Hall, including *Figaro*, *Fidelio*, and *Carmen*, and had been auditorium consultant to the original Edinburgh Opera House.

9. The auditorium.

10. Semi-circular backstage area.



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The trusses span from the fortress wall to a semicircular torsion beam hung from the flytower roof, the semicircle being used to create a skylight. The side stage roof trusses simply span from flytower to fortress wall.

In these areas the acoustic requirements are less than over the auditorium so the ply and lead roof is the only skin, thus allowing the steelwork to be seen from below. The roof of the rehearsal stage also consists of exposed steelwork with lead/ply panels. Like other parts of the design the steelwork continues the contrast of simplicity and sophistication, the design being based on simple back-to-back angles and tie rods. The sophistication lies in the organization and the refinement of the details. The roof over the accommodation uses timber and steel flitch beams to introduce a more domestic scale.

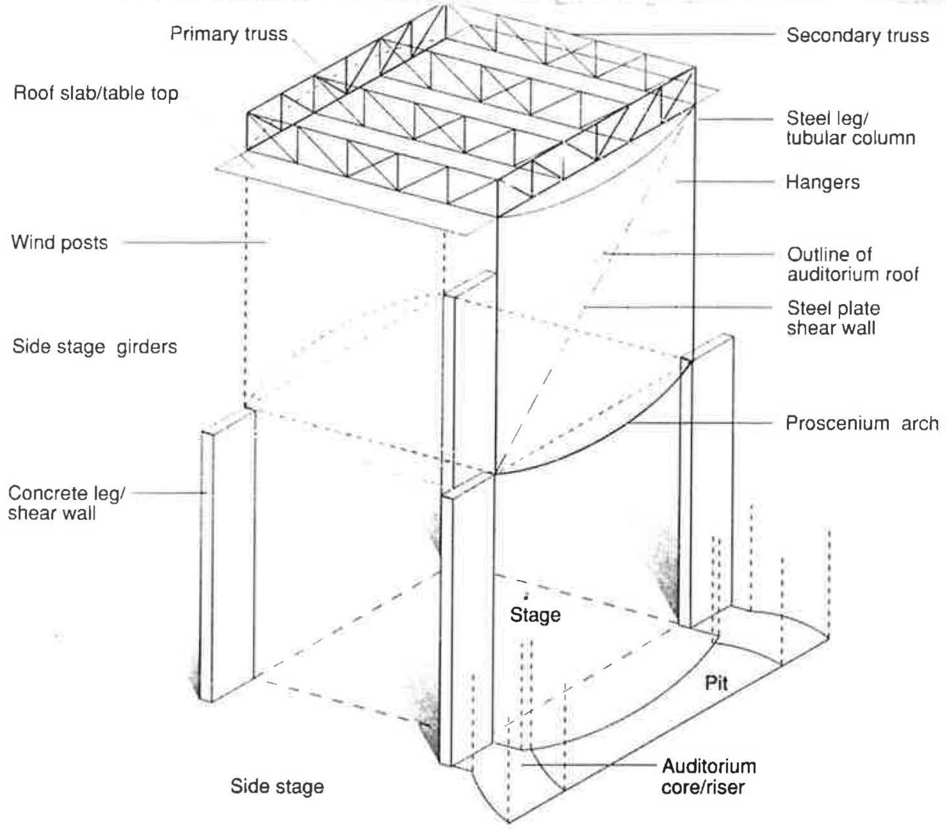
The exposed brick, the finely detailed precast concrete, the reclaimed pitch pine balcony fronts and panelling, and the bare timber floors have a tactile quality which creates a particularly restful atmosphere in the auditorium. This is enhanced by the apparent absence of services, not easily achieved in a building without applied finishes. Air is supplied through perforated seat pedestals, lighting is recessed into the precast concrete, and conduits are cast-in. The back-of-house areas were detailed with the same attention; great care was taken over the co-ordination of services, brickwork and concrete, conduits were cast-in wherever possible and final routing was simple. A fairly robust approach was adopted for the actual detailing and selection of fittings.

Flytower

The largest single piece of structure and the most conspicuous element of the building is the flytower, its size following inevitably from that of the stage and the height of the proscenium. Originally it was to be elliptical and of brick construction, but as the design developed the shape changed to a rectangle with curved front and back walls. As well as softening the shape, the curves create spaces for the curtains, a staircase, smoke extract plant, and dimmer rooms. However, the curved torsion beams required to support these walls were very large and would have been an unacceptable intrusion into the auditorium above the proscenium. The design was changed so that the walls were suspended from roof top trusses, which also helped speed construction. A grillage of exposed steel trusses is carried by four steel columns supported on concrete shear walls, two of which form the proscenium. The grid floor and stage equipment are suspended from the grillage as well as the front and rear walls which are formed of lead-clad timber panels and precast concrete units; similar side walls are supported by storey high trusses.

The House in the garden

Part of the attraction of Glyndebourne is strolling around the grounds before the performance and during the intervals, one of which is long enough for people to eat in the restaurants or picnic in the grounds. This, and the fact that the season takes place in the summer, creates opportunities which a more conventional situation cannot. The dining room is in a separate simple brick building, while outside the auditorium the walls of the circulation areas consist only of the piers with balustrades between. This helps reduce the solidity of the façade as it looks out to the House and gardens. Another softening device is the PVC-coated polyester canopy (left: Fig.13) which links the building with the bar, shop and box office attached to the original dressing room block which was retained. This creates additional circulation space sheltered from the English summer.



14. Flytower structure.

Construction

Construction started in March 1991 with an enabling works contract to divert existing site services. After the close of the 1991 season work began in earnest with the demolition of as much as possible of the existing building without affecting the operation of the main part of the opera house in the 1992 season. Work then proceeded on the structure behind the proscenium until after the 1993 season when the rest of the old opera house was demolished.

Before work started there had been concern over the problem of removing 33 370m^3 of excavated chalk through the narrow country lanes. This was solved by a slight modification to the topography of one of the adjacent fields. The Christies seemed to delight in the 10m deep hole, literally outside their back door, as a sign that their project was under way, but it cannot have been easy for them to live with a large, complicated, fast construction project in their garden.

The choice of load-bearing brickwork for a project to be built in a very short time might seem perverse when speed is normally associated with steel frames. However as a simple labour-intensive activity it is well suited to working in many areas at the same time. Moreover, the extensive use of precast concrete helped speed the work. Other key factors were the simplicity of the ventilation system and the fact that almost all structural components were self-finished, which minimized the fitting-out time.

Glyndebourne is a special building both in the quality of its design and the feeling that it will be there for a long time. Many people have remarked on the enthusiasm of those who worked on its construction. Perhaps it was these things which generated the enthusiasm or perhaps it was just that men could see the skill of their hands in the finished building, something increasingly rare as construction becomes an assembly process and finished surfaces are machine-made.

Timetable

Architectural appointment:	February 1989
Scheme design approval:	December 1990
Start on site (Phase 1A):	27 July 1991
Start on site (Phase 1B):	5 August 1992
Completion and handover:	31 December 1993
First night:	28 May 1994

Credits

Client:
Glyndebourne Productions Ltd.
Architect:
Michael Hopkins & Partners
Consulting engineers:
Ove Arup and Partners Jeremy Brasington, Pat Clowry, Barney Jordan, Rob Kinch, Clare Murphy, Steve Peet, Caroline Ray, Mervyn Rodrigues, David D Smith, John Thornton, John Turzynski (structural)
John Berry, Stas Brzeski, Martin Greenblat, Carolyn Gallehawke, Nigel Tonks, Graeme Walker (mechanical)
Joe Patel, Alex Perkins, Chris Taylor, Andy Worsick (electrical)
Bob Bassan, David Carroll, Tony Minchinton (public health)
Bob Cather, Chris Murgatroyd (AR&D), Nicos Peonides (Controls)
Chris Barber (Arup Fire), Adam Chodorowski (Arup Geotechnics)
Vaughan Sutton (Transportation)
Acoustic consultant:
Arup Acoustics Derek Sugden, Rob Harris, Raf Orlowski, Helen Thornton
Theatre consultant:
Theatre Projects Consultants
Cost consultant:
Gardiner and Theobald
Construction manager:
Bovis Construction Ltd.
Illustrations:
1, 15: Courtesy Glyndebourne Archive
2, 12, 14: Dennis Kirtley
3, 5, 9-11, 13: Martin Charles
4, 6: Peter Mackinven
7: Ove Arup and Partners
8: Richard Davies

15 1994 programme

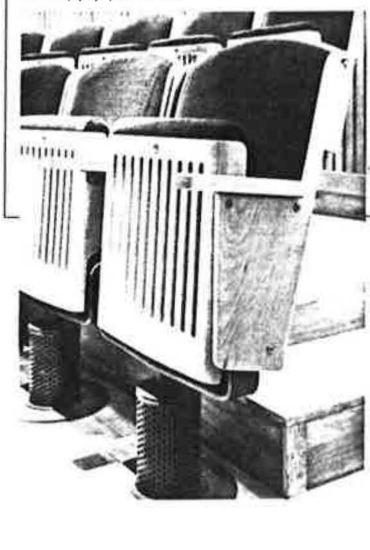
Auditorium ventilation system

Choice of system

The design of the ventilation system for an auditorium is distinguished by two key features: the large concentration of occupants within a relatively small proportion of the overall volume, and the absolute importance of the system's acoustic performance.

The decision to ventilate the auditorium by a displacement system supplying air at low level under the seats and extracting at high level was natural and intuitive. Systems supplying air from above must overcome the natural upward airflow resulting from buoyancy forces generated by the heat of the audience. Falling fresh air becomes mixed with rising hot air so that heat and odours are recirculated to the occupants. In contrast, displacement ventilation complements the natural air flow pattern. Cooler, fresh air supplied from below replaces stale rising air so that the occupied zone is constantly purged with conditioned air and local recycling is eliminated. There is no need for higher air velocities to overcome the natural air movement, so there is less likelihood that noise will result. A benefit of the resulting increased cooling efficiency is that air is supplied at higher temperatures than required for ceiling supply systems, so refrigeration running costs are reduced.

11. Seating with acoustic absorbent base, mounted on integrated air supply pedestal.



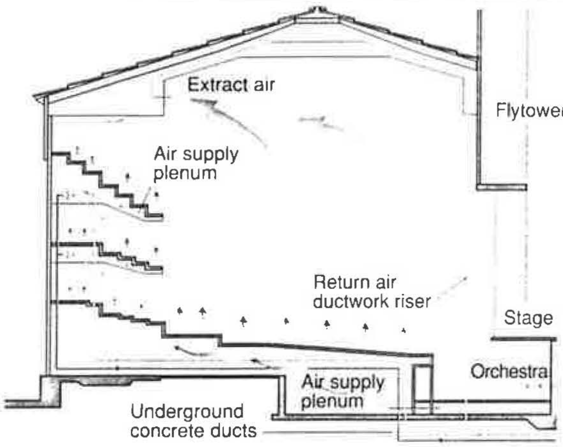
Early on, modelling studies were carried out in conjunction with Cambridge University's Department of Theoretical Physics and Applied Mathematics. A 1:25 perspex model of the auditorium, stage and flytower was inverted in a water bath, with coloured saline solutions of various densities used to represent hot air movement. The choice of a displacement ventilation system was confirmed and important data obtained for subsequent use in the design.

System design

To meet the PNC 15 noise limit, plant is located at a distance from the auditorium and, in addition to extensive attenuation, very low air velocities have been used in all distribution systems to avoid noise generation. The ventilation system is integrated with the building fabric wherever possible. Four 50m long, 2m x 2m concrete ducts buried in the ground beneath the backstage areas connect the ventilation plant to the auditorium. Air is injected into large plena beneath the floors of the stalls and each of the circles, and enters the auditorium through air supply outlets integrated with the seating support pedestal. The orchestra pit is similarly supplied, but with a flat grille served by a separate plenum connected to a branch of the main system. The exposed structural concrete within the auditorium provides a substantial thermal cooling store which smooths temperature swings by absorbing and releasing heat energy.

Choice of air outlet

Various auditorium air outlet types were considered, both integrated with the seat support and separate. Each outlet was tested to prove its air flow and acoustic characteristics and examined to ensure that it could be accommodated within the space available. More unusually, two further criteria peculiar to Glyndebourne were imposed : the ability to allow seats to be removed to locate cameras for video broadcasts, and the resilience of the performance of the outlet to the Glyndebourne tradition of placing coats under seats.



12. Auditorium ventilation principles.

On completion of the tests and studies, the integrated seat pedestal air outlet was chosen. A detailed simulated load test at an acoustic laboratory followed. A block of 24 seats with air supply pedestals was built above a plenum pressurized by a fan. A lamp bulb was placed on each seat to represent the heat generated by the audience, and detailed air temperature and velocity measurements were taken, as well as further acoustic measurements.

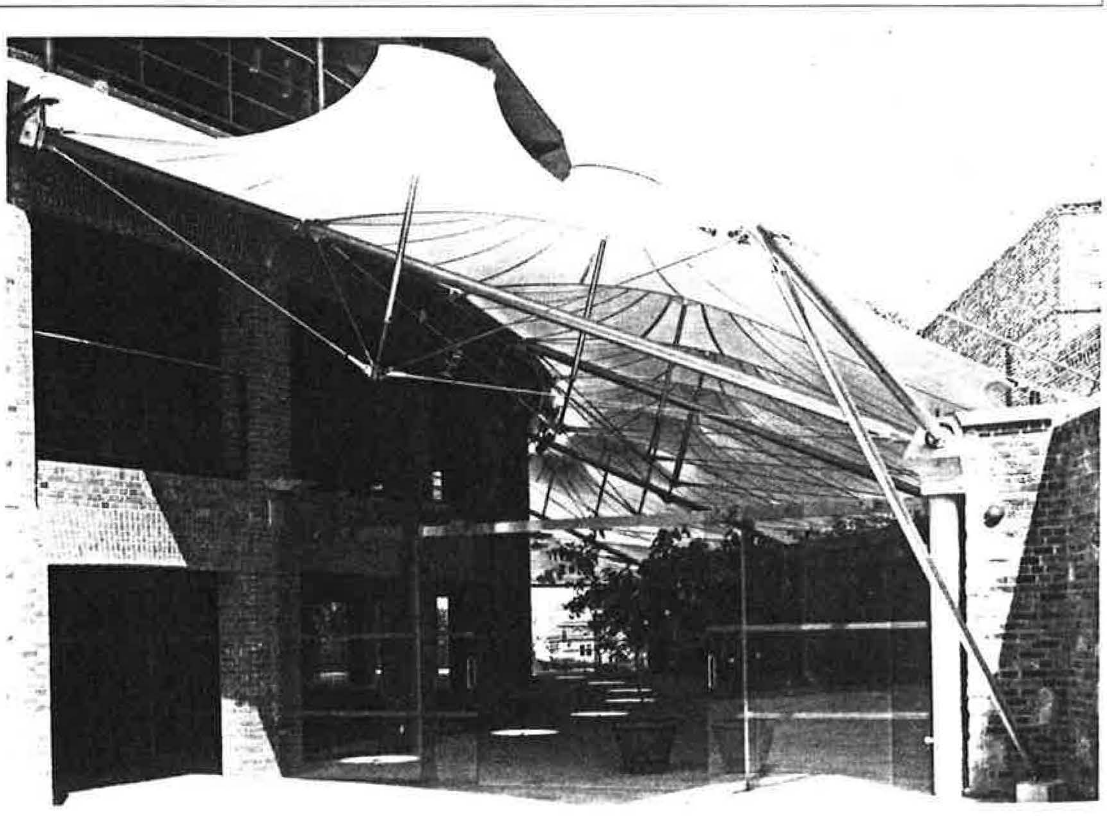
System tests

The heat load test was repeated on site at full scale during commissioning trials. Lamp bulbs and convector heaters were distributed throughout the auditorium to simulate the heat generated by a full house — equivalent to about 1250 domestic 100W lamps. Sufficient theatrical lights were rigged and operational to represent the heat given off by production lighting during a performance. Temperatures were recorded at various locations and tracing smoke used to examine the flow of air throughout the auditorium and stage area. The results showed an acceptable correlation with the predictions of the earlier scale model test.

The real proof came with the first use of the auditorium for a public performance, at the 28 March 1994 test concert, which lasted approximately 90 mins. Temperature measurements compared favourably with the design predictions and reports from members of the audience and orchestra were positive. The acoustic performance of the system has been confirmed both by measurement and by its inaudibility to the human ear.

Conclusion

Testing at successive stages in the design, construction, and commissioning process underpinned initial design assumptions, confirmed detail design parameters and, finally, proved satisfactory system performance. The successful outcome confirms the importance of testing in situations where attention to detail is paramount in achieving the end result.



13. Fabric canopy, designed by Arups, over the foyer entrance.