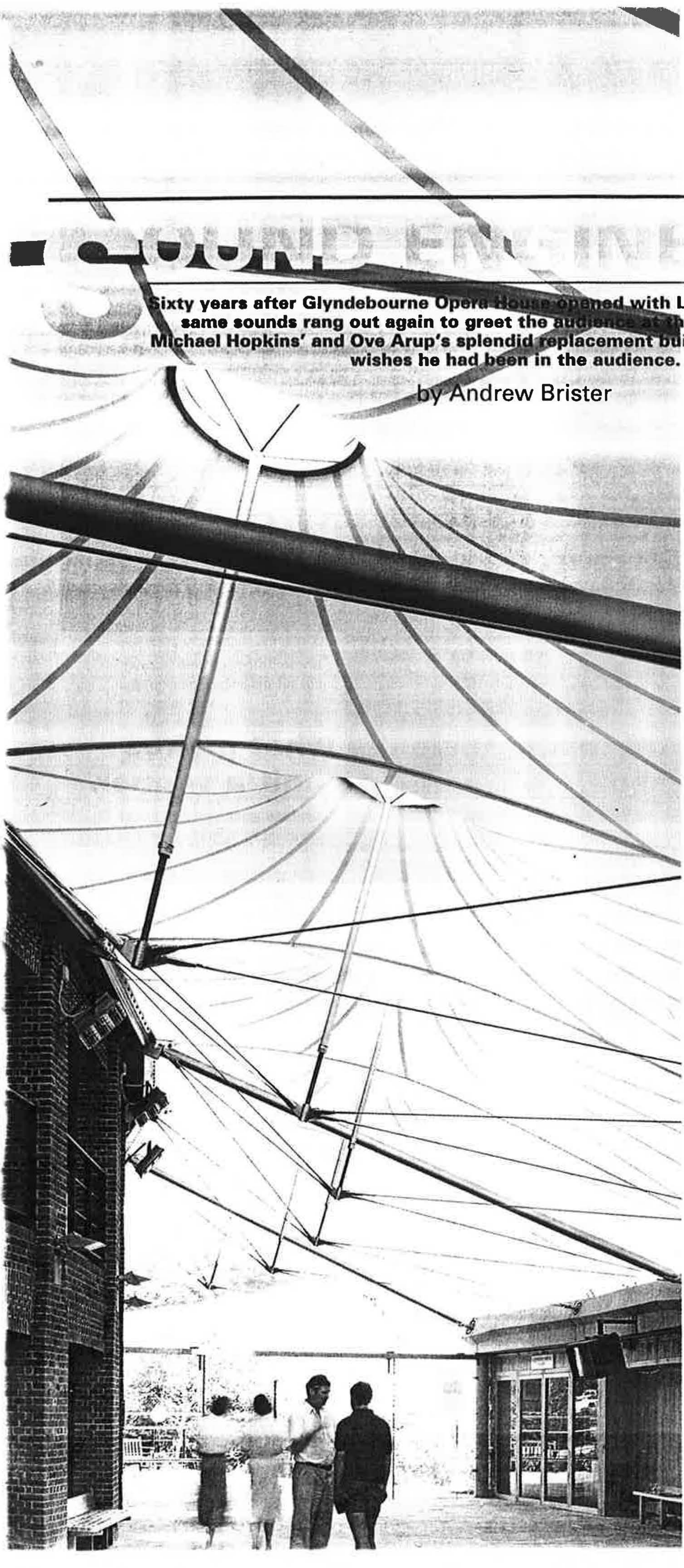
10430

SOUND ENGINEERING

Sixty years after Glyndebourne Opera House opened with Le Nozze di Figaro, the same sounds rang out again to greet the audience at the opening night of Michael Hopkins' and Ove Arup's splendid replacement building. Andrew Brister wishes he had been in the audience.

by Andrew Brister



Not many people can boast about having an opera house in their back garden. While some of us may stretch to a garden shed with in-house cassette recorder, the Christie residence near Lewes, Sussex is the proud home to £33 million worth of quality acoustics – Glyndebourne Opera House.

The new building is not the first opera house to grace the site. Sir John Christie first brought opera to Sussex back in 1934 and Glyndebourne has long been part of a social circuit that also takes in the likes of Royal Ascot and the Henley Regatta. For those lucky enough to have tickets, a picnic on the lawns during the interval at Glyndebourne is very much part of summer.

Part of the appeal at Glyndebourne has always been that it clearly isn't the Royal Opera House. The rustic charm of the location and the intimacy of the auditorium play an important part in this, but you can only take this sort of minimalism so far. The acoustics of the old building were poor by modern standards and the original 300-seater auditorium had become extended over the years so that 830 people were packed into its unventilated confines.

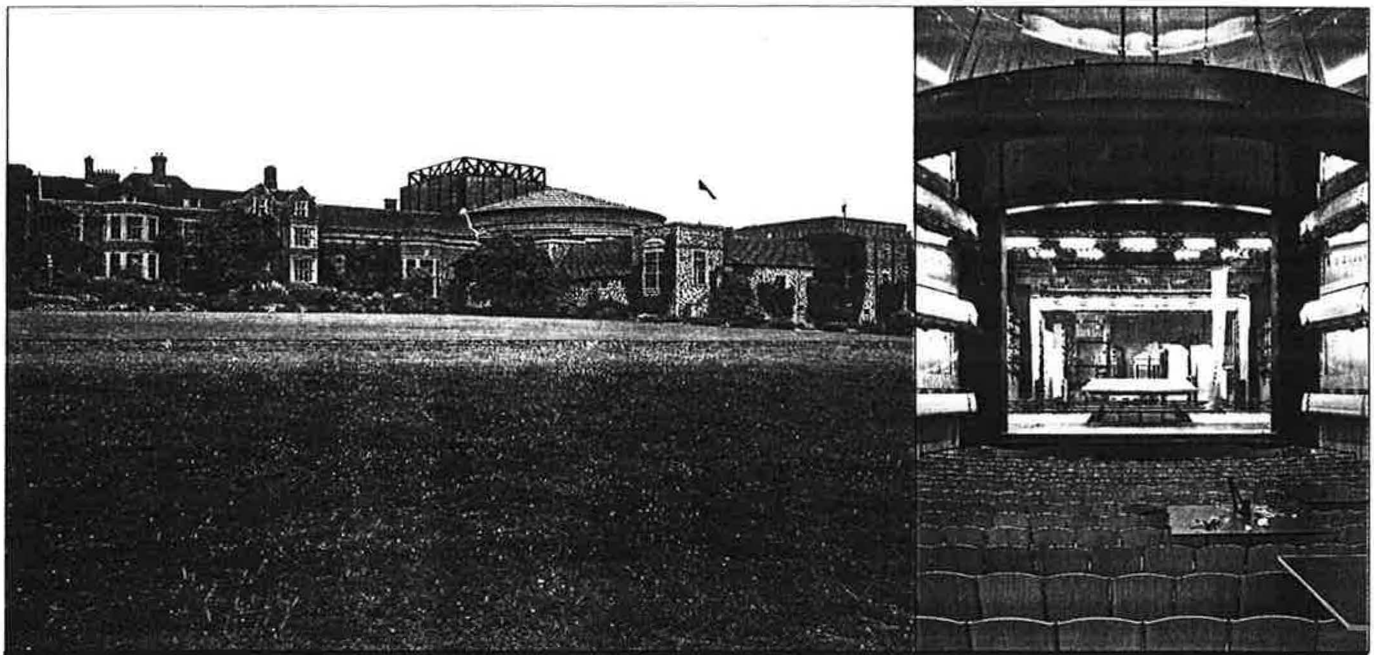
Something had to be done and Michael Hopkins' glorious structure is the end result of present incumbent Sir George Christie's ambitious plan to replace the sprawling array of buildings at the old site with a purpose-built opera house.

So as the curtain fell at the end of the 1992 season, the demolition men were waiting in the wings to make room for the new scheme, due to be ready in time for the 1994 season – a build programme of just 17 months.

A number of architects had been approached for proposals before the list of possibles was whittled down to James Stirling and Michael Hopkins to prepare preliminary schemes. Hopkins' plan won the day, not least because his compact scheme retains the scale and intimacy of the old Glyndebourne and essentially reuses the original footprint.

Layout

A look at the site (figure 1) explains the Hopkins masterplan. The original building was linked to the manor house via the organ room, which lead directly into the backstage area. The front of house was away from the popular picnic spots of the gardens below the house. The new building effectively turns the whole site around, providing a far more logical layout. Now the foyer and front of house areas lead into the gardens, keeping the backstage and loading



Left: The apparent bulk of the new auditorium is reduced by setting it into the gentle hillside which forms the site. The building should age gracefully as the brick and lead weathers-in.
Right: Much of the stage lighting is unobtrusively housed in a circular bridge.

bay areas tucked out of the way around the back. The apparent bulk of the building is reduced by virtue of it being set into the gentle hillside which forms the site.

Traditional materials were always likely to be the order of the day at Glyndebourne. What was not so certain was the return to long-forgotten construction techniques, especially given the fast track programme. The oval-shaped perimeter boasts load-bearing brickwork, traditionally laid using lime mortar without the need for expansion joints, the roof is covered in fine leadwork and, once inside the auditorium, expertly-joined reclaimed pitched pine takes over managing to exude quality without the fuss of velvets and so on.

The fly tower which houses the extensive production equipment has a steel-frame only because there wasn't enough time for Hopkins' original load-bearing brick design.

What is astonishing is the way that this level of craftsmanship has been achieved in just 17 months. As well as the quality, there is a clarity and logic about the scheme which belies the compact schedule.

Basically, the double width wall surrounding the auditorium itself forms an oval which defines the acoustic envelope (the noise criteria for the auditorium is a tough PNC 15, just on the threshold of audibility). A second wall forms an outer skin, allowing the space between the two to be filled by offices and dressing rooms back of house and the foyer and box office areas front of house.

Of course it takes a lot of thought to make things look effortless and much credit must go to the design team for that. Michael Hopkins was joined by Ove Arup and Partners as both structural and building services engineer, who was also responsible for co-ordinating the works of specialist theatre consultants. Construction management was carried out by Bovis Construction.

Services strategy

Cooling and ventilation did not figure strongly at the old Glyndebourne. The new 1250-seat ventilated auditorium will therefore be something of an improvement on the conditions experienced during past summer seasons. On the whole, though, ventilation and cooling is only provided where absolutely necessary. Offices and the like are naturally ventilated with simple perimeter heating.

This strategy is aided enormously by the mass of the building. The extensive brickwork and exposed concrete provide a good deal of thermal storage and act as a buffer – Glyndebourne's season lasts from the end of May through to August, experiencing the best of Britain's summer.

One of the concerns on such a site is not to let the services intrude too much, both visually and aurally. So the energy centre (figure 2) is housed in a converted outbuilding which is easy to mistake for the gardener's potting shed. While plant may seem a long way from where heating or cooling is needed, this is because of the need to keep plant-based noise away from the auditorium.

The energy centre houses the main chiller and boiler plant alongside the primary lv switchboard and standby generator. Low noise air-cooled condensing equipment is similarly out of sight, positioned in a compound below the hedgeline around the back of one of one the restaurant buildings. A trench runs from the energy centre through to basement plant areas in the opera house, generally located between the two brick skins for acoustic isolation. Incidentally, all major plant is supported on springs as are the piped services in the trench.

Electrical services

● It is somewhat unusual to have an Opera House in such an isolated part of the countryside, and when it came to the electrical provision the client was nervous about the risk of power failure.

So, untypically, the energy centre houses two completely independent transfomers fed by different incoming lines. The transformers feed the switchboard with automatic changeover in the event of a failure of either one.

In the unlikely event of both power sources going down there is a standby generator just big enough to serve the statutory emergency loads (sprinkler pumps, emergency lighting and smoke extract fans).

Electrical risers are housed in the stair wells of the new building (as are the hot water pipes for office perimeter heating). Electrical services then come out into the corridor into a raised floor which runs throughout the back of house areas before simply branching into office areas as required.

Arup was responsible for co-ordinating the electrical services with the works supplied by theatre equipment specialists and installers – no easy task since there are miles of trunking in the flytower alone. Co-ordination of the sound cabling was made tricky by the need to separate the low, medium and high frequency cabling by prescribed distances (interference from mains cabling is picked up by low frequency cabling, which is also sensitive to the medium and high frequency routes).

TV production facilities have also been provided with their own wiring routes through to the auditorium to avoid trailing cables during filming.

Auditorium lighting

When it comes to lighting, it is the racks of stage lighting that are all important but Glyndebourne boasts some nicely understated house lighting based on different scenes.

As the audience arrives, the uplighters and downlighters set into the pre-cast concrete draw them in – tungsten halogen lamps create a warm interior, ideal for brick and timber and picking up the shimmering concrete. As they leave, wallwashers take over, giving lower light levels and accentuating the curves of the horseshoe interior. Also, custom-made fittings, the 'twinklies', pick out the balconies.

Designed Architectural Lighting supplied the bulk of the auditorium lighting, including the recessed fittings specially designed to fit the holes in the pre-cast concrete – quite an achievement since coffers are of different length and radius throughout. To minimise the noise impact of low voltage lighting transformers, they are carefully sited outside the acoustic isolation wall.

American lighting consultant George Sexton advised the design team on the auditorium scenesetting, and Strand Lighting was responsible for the stage lighting. Responsibility for co-ordination into the rest of the works fell on Arup's shoulders.

As much as possible of the old stage lighting has been retained, suspended on a circular bridge below the auditorium dome. Four rooms of dimmers are housed in the flytower with both stage and auditorium lighting controlled from a booth in the auditorium.

Of primary interest as far as the services are concerned is the auditorium ventilation strategy – how do you get sufficient air volumes for 1250 people into the space, distribute it evenly and meet the PNC 15 noise criterion? While supply from the ceiling, beneath the seats or the sides of the auditorium are all possible, Arup's director John Berry describes the underseat approach as intuitive for large volume spaces: "We made that decision very early on. But you do have to make sure that you are going to have the necessary space for plena underneath the seating."

This certainly seems the most logical approach. By supplying air from under the seats on the displacement ventilation principle (with extract at high level), you can avoid recirculating all the heat gains and so work with higher supply temperatures, maximising the amount of free cooling.

Diffuser selection

After deciding on displacement ventilation the correct diffuser selection becomes all important. Arup assessed various generic unit types: a flush-to-the-floor unit and two protruding units, the mushroom and pedestal types, the latter integrating with the seat.

In addition to the obvious criteria of air distribution and acoustic performance there were a few unusual things to bear in mind on this project. At Glyndebourne, the tradition has been to roll up coats and place them under the seats, so there was a danger that air flow would be blocked off with the flat unit. On the other hand, should Glyndebourne ever want to put on a prom, the flush type would have no projection above the floor and would be better suited to a standing audience.

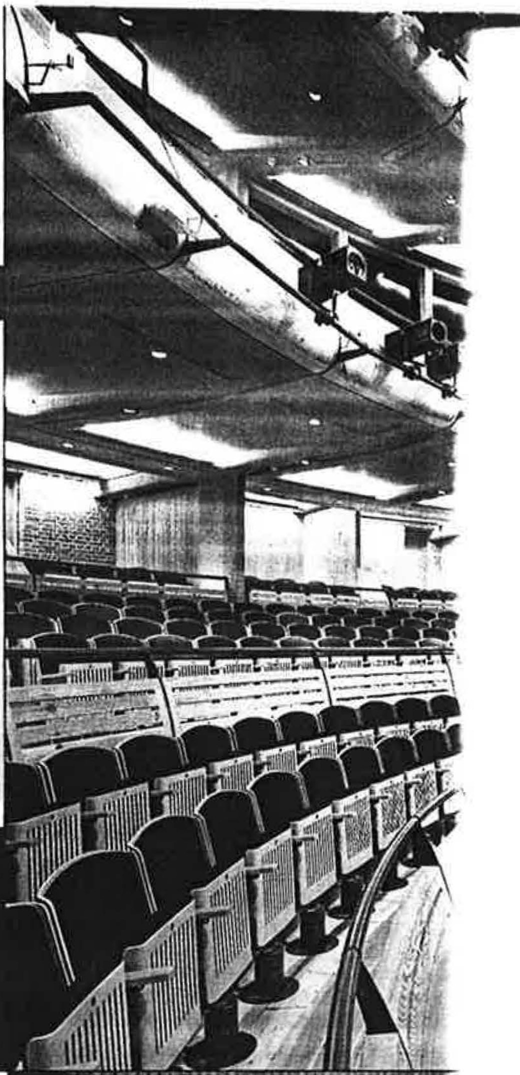
Pressures are also important. For system balancing a higher pressure is desirable but for leakage and noise a lower pressure is best. At the end of the day, the pedestal type was chosen because the lower system pressure (10 Pa) was less of a leakage risk than either the flat [illegible]room units (30 Pa). Arup felt that 20 Pa [illegible] absolute maximum. Krantz won [illegible] rivals because its terminal had the best air performance at low velocities and achieves the closest to pure displacement flow.

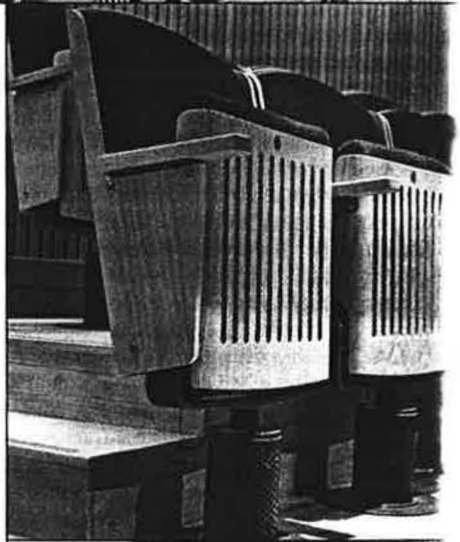
Its one thing satisfying yourself that the diffuser will perform okay, but you have to make sure that the air reaches them in the first place – no mean feat when you are relying on pressurised plena and distributing air over long distances. Air leaves the air handling plant room (figure 2) and travels in 2 m by 2 m builderswork ducts under the basement slab until it reaches the auditorium where distribution returns to sheet metal again. An inspection role was critical for Arup's resident engineers because of the extensive use of builderswork ducts.

"We could have sat back and given a performance specification," explains John Berry, "but we took an interest in ensuring that the plenum construction was sound. The pressure tests vindicated that, and our decision to limit the system pressure to 10 Pa."

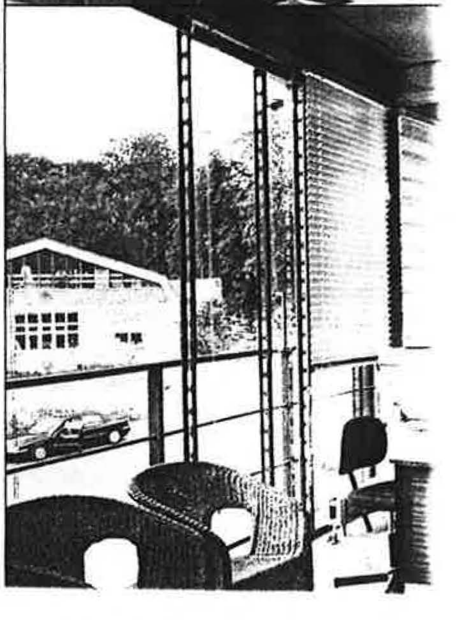
While the bulk of the seats have their own diffuser, they are not to be thought of as a personal air supply – the strategy is to treat the auditorium as a whole. As Arup's Stas Brzeski explains: "In some upper level locations we don't have active diffusers simply because the balcony depth dictated by the sight lines is such that there is no way you can get air through the plenum. You can allow for this by treating the auditorium as a whole and our tests (see box 'A model performance') shows that conditions in these areas don't vary substantially from others."

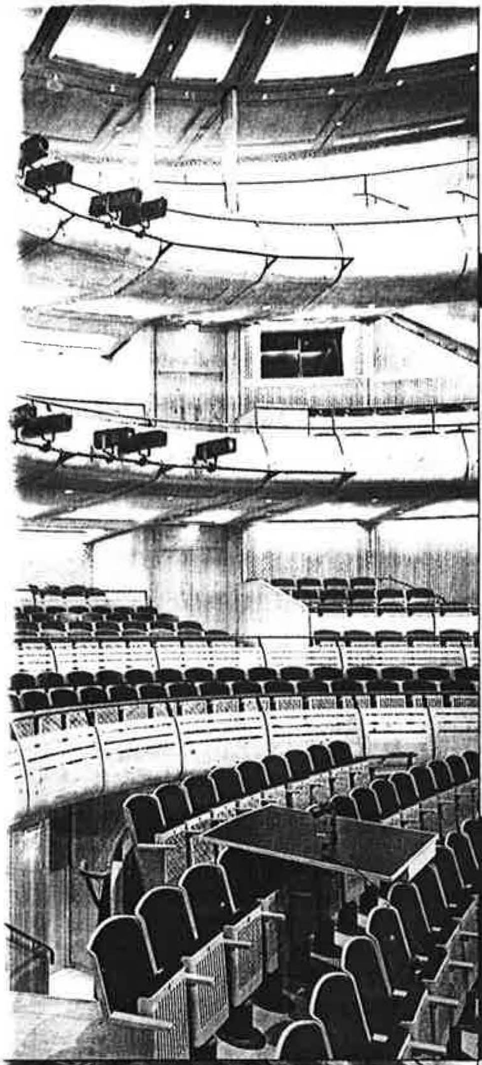
The design aims for a fresh air supply of 10 litres/s/person which equates to 11 litres/s from the majority of diffusers since around 10% of the seating is not active. Slightly larger





Right: The magnificent auditorium. The pitched pine is 150 years old and has been reclaimed mostly from warehouses in the north of England. Note the extensive use of exposed concrete which provides a substantial thermal store. Below right: The Krantz displacement ventilation supply terminals have been neatly integrated with the auditorium seating by Audience Systems.





Acoustics

One of the problems at the old Glyndebourne was the 'dry' acoustics with a reverberation time of only 0·8 s. Arup Acoustics was given the task of ensuring the Hopkins plan improved on that.

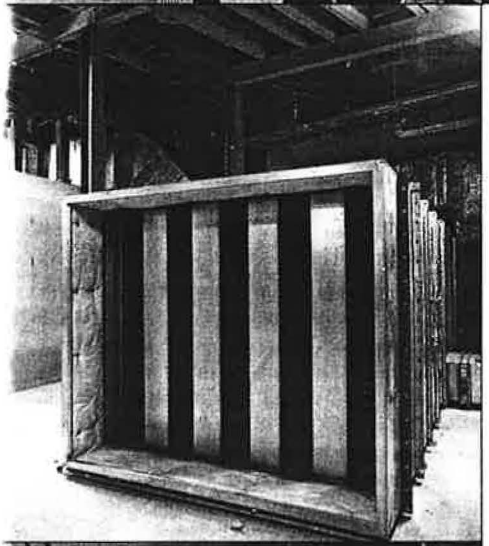
The auditorium volume is now much greater with a reverberation time of 1·3 s when full. Intimacy has been retained, however, since the horseshoe interior allows back seats at the new auditorium to be closer to the stage than before.

The shape of the auditorium is also very important to avoid any focusing of sound. Arup payed a lot of attention to the shape of the balconies to provide the right reflection – hence some fronts are slatted while others are solid timber.

Other problem areas where reflections are concerned are the concrete walls (where convex timber panels are placed against the concave wall to break up reflections) and the concrete coffer (where sculpting avoids flat surfaces).

While there are no reactive systems to vary the acoustic environment for different performances, there is a choice of a solid or slatted front rail to the front of the orchestra pit.

The balance between the orchestra and the singers is now much improved. At the old Glyndebourne, the extended stage created a slot-like aperture for the pit and the orchestra had to really crank up the volume to compete with the vocal performers.



Below left: The air supply plenum for the stalls displacement terminal units. Ductwork branches off to take air to upper seating levels.

Bottom: Office areas rely on natural ventilation but the exposed concrete is an excellent buffer against the English summer.

outlets appear in the boxes (18 litres/s) to cope with the extra loose seating. This is a compromise since the larger the volume from the outlet, the more difficult it is to avoid the cold feet syndrome – the specification also called for velocities of 0·15 m/s at a distance of 500 mm from the terminal.

The design aims for temperatures of 23±2°C – the 2 K variation being less of a control band and more of a reflection of the variation you can expect around the auditorium due to the varying height of the seating levels. The supply air temperature required to meet this is 20°C, so even in the summertime there are periods of free cooling.

The original modelling work had estimated that 19°C would be the right supply temperature, but Arup has found that the slow response of the thermal mass allows it to be raised to 20°C. This stability means that there is no need to pre-cool the auditorium prior to a performance – the only thing that is going to raise temperatures significantly is a large load such as the audience. Care does have to be taken that the lighting is not left on for long periods, particularly uplighters near to the concrete soffit, which could warm up the structure and create problems.

While Glyndebourne does not put on performances during the winter, heating plant has been sized for winter loads. "The auditorium ventilation plant is capable of full fresh air in winter. We took the view that it was a small cost to include it now, but a large cost to have to add it on later," argues Stas Brzeski.

If winter performances do become established, then pre-warming of the auditorium may be necessary with the air plant going into full recirculation. Heat recovery has been included between supply and extract so that the winter heating load would be minimised.

The system is manually controlled via a simple central heating type controller – ventilation is either on, off or on timer. There is also 0-100% occupancy control – at 100% occupancy the system gives full fresh air, at 50% the system would give half fresh air and half recirculated air. This gives the opportunity to run the system economically, but really with full fresh air based on 10 litres/s/person you wouldn't want to see the dial being turned too far towards recirculation.

The orchestra pit is worthy of a mention. Here, displacement air just spills out from a grille running across the back of the pit and fresh air moves across the orchestra. Air volumes here, though, are higher (15-20 litres/s/person depending on the size of the orchestra) than for the auditorium, since you need lower temperatures for comfort – design point is 21±2°C. The displacement strategy suits the particular design consideration of the effect of air movement over the string sections. If the air supply is a lot cooler than room conditions, it can put instruments out of tune.

The stage and flytower area has no ventilation supply but the high production lighting load means heat build-up could occur, particularly if the curtain is down for any length of time. The flytower's smoke extract fans can be run during intervals to disperse any heat but primarily the strategy is more preventative than remedial, with avoidance of heat build-up in the first place being the objective.

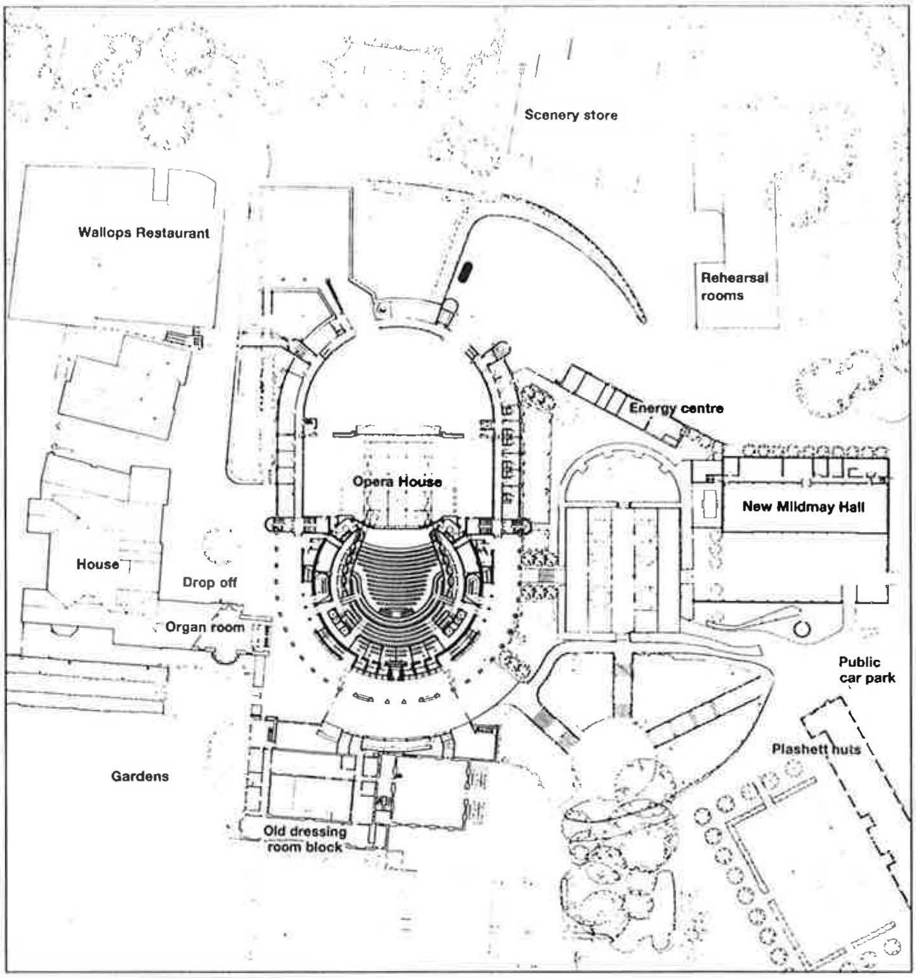
Front and back of house areas

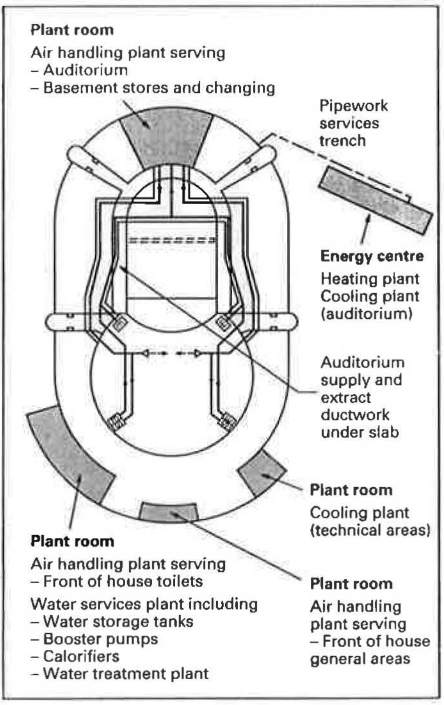
Back of house areas are often spartan, especially in comparison with the lavish materials on show in most auditoria. At Glyndebourne, though, there is much less of a divide.

The back of house recreates the brickwork, exposed concrete and recessed lighting with the same attention to detail. Offices are positioned around the perimeter and so benefit from natural light and openable windows for ventilation. Blinds were advised by Ove Ar

Right, figure 1: The new scheme vastly improves on the old Glyndebourne by making access to the gardens much easier via the front of house. New plant has little impact on the ambience of the gardens.

Below, figure 2: Services have been laid out to minimise plant-based noise. The energy centre is some 30 m from the building, and plant areas are outside of an acoustic isolation wall.





but it has been left up to Glyndebourne as to whether or not they are fitted.

Circulation space runs between the offices and the acoustic wall of the auditorium and backstage areas. The top section of inner office walls is glazed to get at least some natural light into the corridors. However, there is also artificial lighting in special fittings suspended from the concrete panels.

Front of house, the thought is to recreate the feel of the old Glyndebourne with an open-ended but covered entranceway. The fabric canopy, a Hopkins trademark, is the link between the new and existing buildings.

The fair-faced finishes undoubtedly look great but working this way does impose a discipline, not least on the services profession. As Stas Brzeski points out: "It does mean that things such as the lighting design have to be solved in principle very early on because the contract for the pre-cast concrete had to be placed. While the exact angle of recess can be left until the final details are required, at tender stage you do have to know how many holes you've got, roughly how big they are and what sort of fitting you want to put into them."

There is no doubt that the effort has been worth it – the building really is as hand crafted as a Jermyn Street suit. Those of you thinking of putting up an opera house in your back garden could do worse than appoint the same design and construction team.

A model performance

At each stage in the development of the auditorium ventilation system testing played an important role, *writes Stas Brzeski*. The successful outcome confirms the importance of testing in situations where attention to detail is vital in achieving the end result.

The decision to use a displacement ventilation system was put to the test using saline modelling. A 1:25 scale perspex model of the auditorium and flytower was inverted in a water bath, and coloured saline solutions were used to represent heat flux and air flow. Several key aspects of the design were examined:

☐ the depth and stability of the stratified hot layer at the top of the auditorium;

☐ the need to provide extract ventilation at high points to the rear of the balconies to avoid local hot spots;

☐ the possible influence of warm air from the stalls on the front rows of the balconies;

☐ the requirement for a neutral pressure across the interface of the stage and auditorium.

The studies showed the depth of the hot layer to be closely related to the volume of air extracted at roof level and confirmed that air should be extracted from the rear of the balconies to prevent local hot spots. Extract design would have to achieve a balance between the requirements of the roof and balconies.

Buoyancy forces driving hot air up from the stalls were found to be sufficiently strong to carry the airstream past the balcony fronts without adversely affecting the front row seats.

Analysis of pressure differences across the proscenium was prompted by the need for an air flow balance between the auditorium and stage to avoid dust rising as the curtain lifts, which could affect performers' throats.

The saline study showed that a temperature difference of just 3°C between auditorium and stage resulted in air flows of about 60 m^3/s in and out of the flytower. Any pressurisation introduced using a ventilation plant of approximately 15 m^3/s would have little effect. The solution was to ensure (by careful management) that large temperature differences between auditorium and stage did not occur before curtain up.

Many factors were considered in the choice of the air outlet. Each outlet was tested in its standard form at the manufacturer's works to determine velocity and temperature distributions as well as acoustic performance. The air flow characteristics that were sought were those of a true displacement device: low velocity and no mixing.

Further tests followed the appointment of the supplier, Krantz, this time at an acoustic

GLYNDEBOURNE OPERA HOUSE, GLYNDEBOURNE, LEWES, EAST SUSSEX

Client
Glyndebourne Productions
Client's project manager
Eric Gabriel
Architect
Michael Hopkins & Partners
M&E and structural engineer
Ove Arup & Partners
Acoustic consultants
Arup Acoustics
Fire engineering
Arup Fire
Theatre consultant
Theatre Projects Consultants
Quantity surveyor
Gardiner & Theobald, Gardiner & Theobald Engineering Services
Construction manager
Bovis Construction
M&E and public health contractor
Matthew Hall

Main suppliers
Boilers: Fröling
Boiler flues: Selkirk
Burners: Weishaupt (UK)
Chillers (R22): Trane (UK)
Sprinklers: Matthew Hall Merrol
Pressurisation and boosters: GC Pillinger & Co
Pumps: Wilo Salmson, Grundfos, New Haden (sump pumps)
AHUs: Redbro Manufacturing
Fans: Redbro Manufacturing
Motor control centres: Lloret Electrical Systems
Commissioning: Byrne Engineering
Fan coil units: Energy Technique
Ductwork: Hotchkiss
Toilet extract: NuAire
Smoke extract: Woods of Colchester
Grilles and diffusers: Waterloo Ozonair
Auditorium seating: Audience Systems
Lifts: Otis Elevators (good passenger)
Gantree Engineering (vehicle)
Stage equipment: Telestage Associates (UK)
Sound and communications: Shuttlesound
Security: General Security
Auditorium ventilation supply terminal: Krantz
Raised floors: various suppliers
Strainers: Hattersley
Coils (duct-mounted): Energy Technique
LV switchgear: Square D
Controls: Lloret Electrical Systems
Louvres: various suppliers
Lights/luminaires: DAL, Hyco, Thorn, Trilux, Reggiani, Marlin, Existalite, Bega, Rada, Erco, Moorlite, Philips, Strand, Concorde
Stage lighting: Strand Lighting
Dampers: Zest, Actionair, Advanced Air
Sound attenuation (including anti-vibration equipment): Sound Attenuators
Valves: Hattersley
Calorifiers: IMI Rycroft
Water heaters: IMI Rycroft
Water storage: AC Plastics
Water conditioning: Liff Industries
Water treatment: Aquastat
Water filtration: Carter
Fire protection: Wormauld Britannia (fire alarms)
Standby generation: Dale Electric
Electrical accessories: MK, Britmac
Radiators: Arbonia (Bisque), Runtalrad, Stelrad
Electric heaters: Ambi-Rad, Infrared Internationale, Dimplex
Buffer tanks: Rother Boiler Co
Expansion joints (and deaeration equipment): Engineering Appliances
Trace heating: Jimi-Heat
TRVs: Tour & Andersson
O&M: Watson & Sole Associates

Engineering data
Total area (gross): 13 500 m² (approx)
Plant rooms: 670 m²

U-values (W/m²K)
Walls: 1·2-1·7
Floor: 0·35
Roof: 0·45
Glazing: 5·70

External design conditions
Winter: -4°C db, -4°C wb
Summer: 28°C db, 19°C wb

Internal design conditions
Auditorium: 23±2°C db
Broadcast and control rooms: 21±2°C db
Principal's dressing room: 23°C min db
Offices: 21°C min db

Installed loads
Installed boiler capacity: 1400 kW
Installed chiller capacity: 350 kW (auditorium cooling)
50 kW (technical area cooling)

Distribution circuits
LTHW: 80°C flow, 70°C return
DHWS: 65°C flow, 55°C return
Chilled water:
6°C flow, 12°C return (auditorium cooling)
7°C flow, 11°C return (technical area cooling)

Primary air volumes
Auditorium ventilation: 12·5 m³/s
Technical areas: 0·5 m³/s
Basement stores, changing rooms: 4·9 m³/s
Toilets: 2·4 m³/s
Green room: 0·7 m³/s

Ventilation (auditorium)
Scheduled supply air temperature: 20°C
Room temperature: 23±2°C
Fresh air: up to 100% (user-adjustable)
Maximum recirculation: user-adjustable
Filtration EU category: 7

Noise levels
Auditorium: PNC15
Broadcast and control rooms: NR25

Occupancy
Total auditorium occupancy: 1250 approx (audience); up to 80 (orchestra)
Staffing numbers vary (minimum 150, maximum 650 in peak periods)

Electrical supply
415 V/3 ph/50 Hz supply
2 x 1000 kVA transformers
1 x 100 kVA standby power generator

Lighting
Types: fluorescent, compact fluorescent (rear of house); low voltage, tungsten (auditorium and public areas)
Lighting load: 95 kW (general)
285 kW (production loads)
Lux levels (maintained)
Auditorium: feature 150-200 (varies)
Public foyers: feature 150-200 (varies)
Rehearsal stage: 150-300 (variable)
Offices, workrooms: 300 plus task lighting
Toilets, changing rooms: 200
Circulation areas: 50-100 (varies)

Lifts
1 x 10 person lift (public areas)
1 x 1000 kg lift (rear of house)
1 x 1600 kg lift (loading bay/basement)
1 x 40 tonne vehicle lift, dock leveller

Costs
Total cost (inc landscaping, etc): £33 million
Total construction cost: £23.6 million
Total net cost: £1750/m²

---

aboratory. Detailed air temperature and velocity measurements were taken together with further acoustic measurements on a block of 24 seats with lamps to generate audience heat outputs. The test gave added assurance that he design criteria would be achieved.

The heat load test was repeated on site at ull-scale during commissioning trials. 100 W amps were used to simulate the audience on each seat in areas where temperatures were to be measured and, for reasons of economy, distributed 2 kW heaters elsewhere. Theatrical ights represented production lighting gain.

Early attempts to carry out these tests had o be aborted, partly as a result of excessive prewarming of the building fabric. The auditorium lighting, some 90 kW of load, had been on virtually continuously for several weeks to alow contractors to work around the clock to complete the fitting-out. Slab temperatures had been as high as 27°C.

Testing restarted when slab temperatures eturned to normal. With a displacement supply air temperature of 19°C, space temperaures were found to lie in the range 21-24°C with peak temperatures in the boxes. Tracing smoke tests showed air flow was in accordance with the results of the saline modelling.

The real proof of the system came when a test concert was held before an invited full house shortly after the building was handed over to Glyndebourne.

Temperature measurements showed a distribution within the acceptable range of 21-23°C with the radiant temperature measured at a single point approximating to the average space temperature. Air temperatures in the boxes were found to be much closer to the general temperatures on the open balconies than was predicted by the earlier performance trials. Reports from the audience and orchestra were positive.

Two key points emerged from analysis of the test data. First, the saline test provided a good representation of air flows, but tended to overestimate temperatures. Second, the performance trials overestimated temperatures within the boxes, but gave good predictions of temperatures elsewhere. The clue to these variations lies in the size of the convective and radiant components of the heat load.

At the stage that the early model tests were carried out, the final architectural form of the auditorium was not fully evolved. Lightweight finishes were assumed to give a conservative model with a higher resultant convective component. The exposed structural concrete of the final design provides a substantial thermal store and therefore has a significant effect on temperatures (space temperatures were 1-2°C higher when slab temperatures reached 27°C).

The 100 W lamps provided an acceptable approximation to the convective heat output from a person, but the radiant component was greater than reality. This was not considered important due to the substantial thermal mass available to absorb the hot radiation, which proved correct in the open stalls and balcony areas.

However, the boxes are enclosed by timber panelling which greatly reduces the effective thermal response time. Therefore the radiant component of the modelling load became significant and higher temperatures resulted during the performance trial.

These tests illustrate the importance of modelling the radiant/convective balance correctly to suit the anticipated room response. If assumptions are to be made it is important that these are conservative and the opportunity is taken to repeat the tests as soon as a true representation of the load and room is available. At Glyndebourne this allowed final adjustments to be made to the control settings before the opening night.

Stas Brzeski is an associate with Ove Arup & Partners consulting engineers.