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THE ACOUSTICS OF GLASGOW ROYAL CONCERT HALL

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INTRODUCTION

The Glasgow Royal Concert Hall opened in October 1990. It seats an audience of 2195 plus 263 choir. This makes it comparable in capacity with the Free Trade Hall, Manchester, and the Royal Concert Hall, Nottingham, but larger than Symphony Hall, Birmingham. The internal volume of the hall is 28,700 m^3 with the furthest seat at 37 m from the stage front. As well as the normal concert arrangement with raked stalls seating, the first eleven rows of stalls seating can be removed by being hovered on air-castors. This, together with the fact that all stage sections are on lifts, allows the creation of an extensive flat floor area and the staging of arena format productions. As well as flexibility in the auditorium, additional facilities are provided in the building for conferences, functions and exhibitions.

BRIEF HISTORY

Britain's only classical rectangular concert hall with a good acoustic reputation, St Andrew's Hall of 1877, tragically burnt down in 1962 (see Beranek [1] for discussion of the hall). Design of an arts complex including not only a replacement concert hall but also a drama theatre and accommodation for the Royal Scottish Academy of Music and Drama was begun in 1968 by Sir Leslie Martin [2,3]. Early schemes included a large space suitable for concerts with a flytower over the stage for dramatic performance. However, no solid commitment to actually build it was made until the mid-1980s. In the meantime, Scottish Opera had moved into the renovated Glasgow Theatre Royal and the Royal Scottish Academy had commissioned purpose-built headquarters.

But, despite changes in the brief, the site for the development had remained constant. A design for a large concert hall was produced in 1984 which in its general form was in the tradition of galleried halls like the old St Andrew's Hall but the plan form and section improved all the sight lines as well as offering acoustic advantages. In 1985 this design was tested as an acoustic scale model at 1:50 scale. This and subsequent designs had seating at two basic levels with two levels of access. The 1985 plan was an elongated hexagon with a single balcony running around all six sides. Around the stage the balcony served as choir seating. The basic symmetry of the plan provided for both an orchestral stage and central arena performance.

The elongated hexagonal plan was then modified for reasons both of performance and acoustics to be parallel-sided at the stage end with a reverse-fan plan towards the rear. Serious progress towards realisation of the scheme occurred in early 1987 when Glasgow learnt that it had succeeded in its nomination as the European City of Culture for 1990. Design now proceeded in earnest with responsibility for the architecture passing from Sir Leslie Martin to RMJM (Scotland), who completed the design and acted as executive architects. Sandy Brown Associates were appointed at that time as acoustic consultants for the entire project with Dr M Barron remaining jointly responsible for the auditorium.

In both the elongated hexagon plan and its successor, structural support of the roof consisted of open-truss beams within the hall. Developments involved alternative methods for visual screening this structure. Some ventilation ducting was also included within the auditorium volume. As the width of the hall was very substantial at the highest level, reflectors were introduced around the sides to enhance early reflections to the balcony seating. The design both of the reflectors and the hall as a whole was tested in two further acoustic scale models in 1987 and 1988.

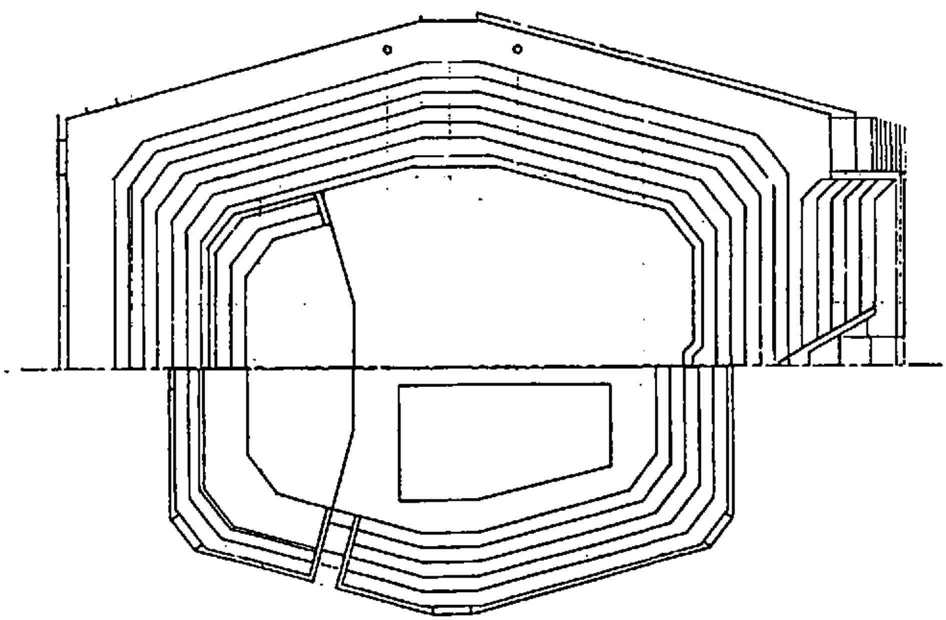

Figure 1 Plan of the 1984/85 design of the Glasgow hall.

DEVELOPMENT OF THE DESIGN

The design of an auditorium is shaped by a multitude of factors, of which the acoustics is but one. The following discusses developments as seen from an acoustic perspective. The basic acoustic concern in the early design stages was to ensure that there were sufficient exposed surfaces to provide early reflections at each seating level.

The elongated hexagonal plan of 1985 is shown in Figure 1. The form has a persuasive logic about it. The need for a narrow stage generates a fan shape plan, but the fan shape has attained a poor acoustic reputation, especially for conditions towards the rear of the auditorium. The use of a reverse-splay plan for the rear half of the hall introduces a virtuous acoustic form, noted for its dense provision of lateral reflections. A famous example of the elongated hexagonal plan is the De Doelen concert hall of Rotterdam (1966). Virtually all room surfaces in that hall have been rendered acoustically diffusing. There are no overhangs in the hall, but the subdivision of the stalls seating is of particular interest [4].

In the 1985 design of the Glasgow hall, the stalls seating was on a flat central floor surrounded by raked seating overhung by the balcony. The maximum widths were about 32 m at stalls level and 44 m at balcony level. These widths have remained substantially constant with 31 m and 42 m in the final design. The side walls at high level just below the ceiling in the 1985 design were tilted down from the vertical, providing an external appearance for the hall reminiscent of a box for an egg.

Model tests showed reasonable uniformity in response except for an unforeseen problem of 'focusing' by plane surfaces. It was found that at least six surfaces were tangential to an ellipsoid with one focus near the source position. An excess number of reflections arrived in the region of the other focus; with delays of between 160 and 180 ms they would have been perceived as an echo. At this receiver position there was also a lack of early sound.

There were several ways in which these problems could have been resolved. It was decided for performance as much as acoustic reasons to replace the fan-shaped element of the plan with a parallel-sided one. The bounding walls at the upper level also became continuous, vertical and parallel with the main axis of the hall. The early reflection situation in the rear central stalls was improved by raking the stalls floor, tilting the balcony fronts to direct reflections down onto the stalls and tilting down from the vertical the side walls bounding the stalls. With regards to the wall below the balcony opposite the stage, this tilting of the bounding wall had the effect of suppressing a possible echo back to the stage. Model tests had also shown a lack of early reflections in some side areas of the balcony. It was proposed to remedy the situation by introducing freely suspended reflectors in the ceiling area.

The seating arrangement described above remained virtually unchanged from 1987 to the completed building, Figure 2. The width at ceiling level became 44.5 m and a technical gallery was installed along the sides above a promenade behind balcony seating. With a tight design and construction schedule, changes were mainly limited to the upper levels of the hall. In the 1987 model, visual

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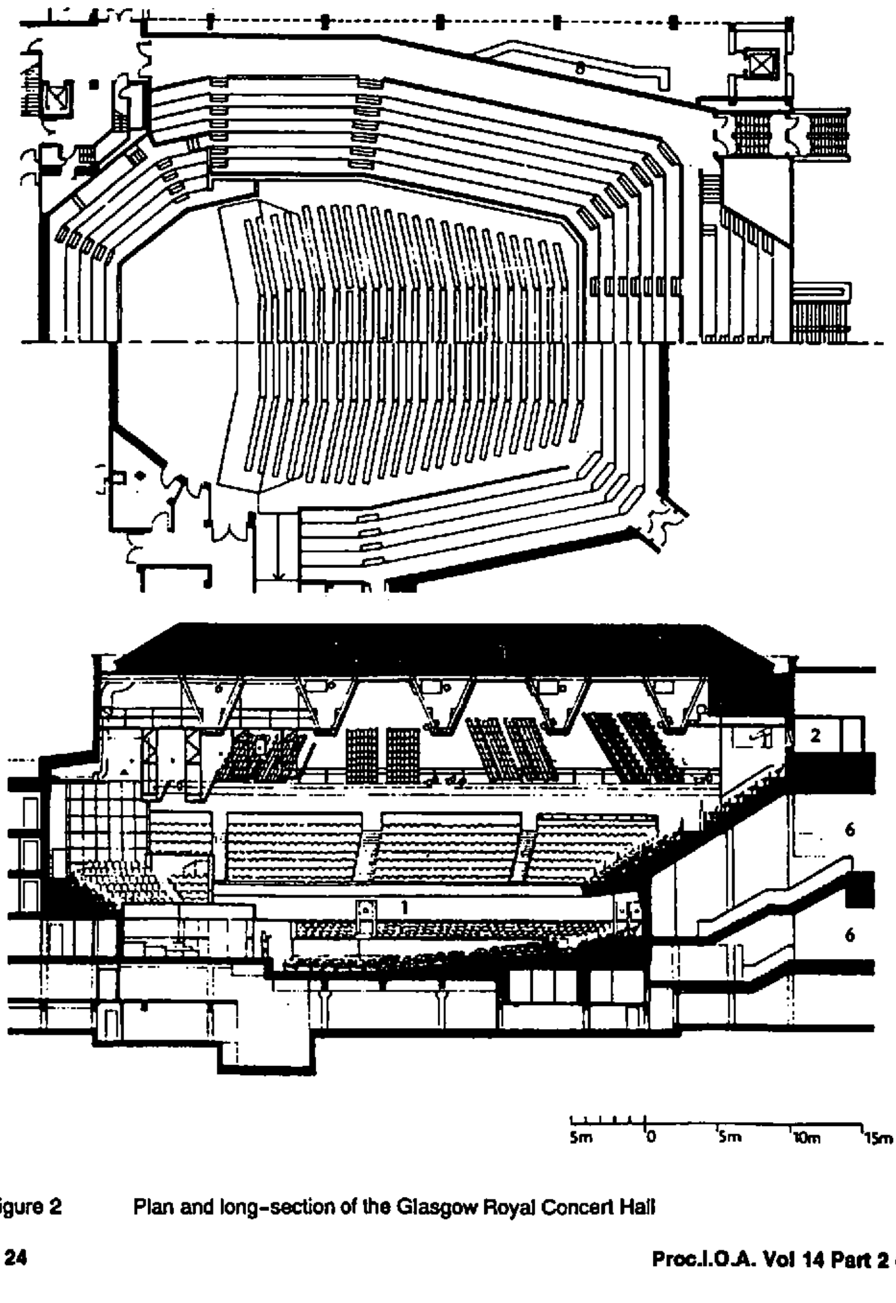

Figure 2 Plan and long-section of the Glasgow Royal Concert Hall

screening of the structure was achieved by a suspended horizontal egg–crate. A model measurement of transmissibility through the screen showed that at high frequencies it was worse than one predicts from geometrical considerations of the fraction of area obscured, Figure 3. This would have the effect that, rather than energy being reflected off a horizontal ceiling towards the rear of the hall, a lot of energy would be reflected back towards the stage end. As a solution to visual screening, it appears to carry acoustic risks.

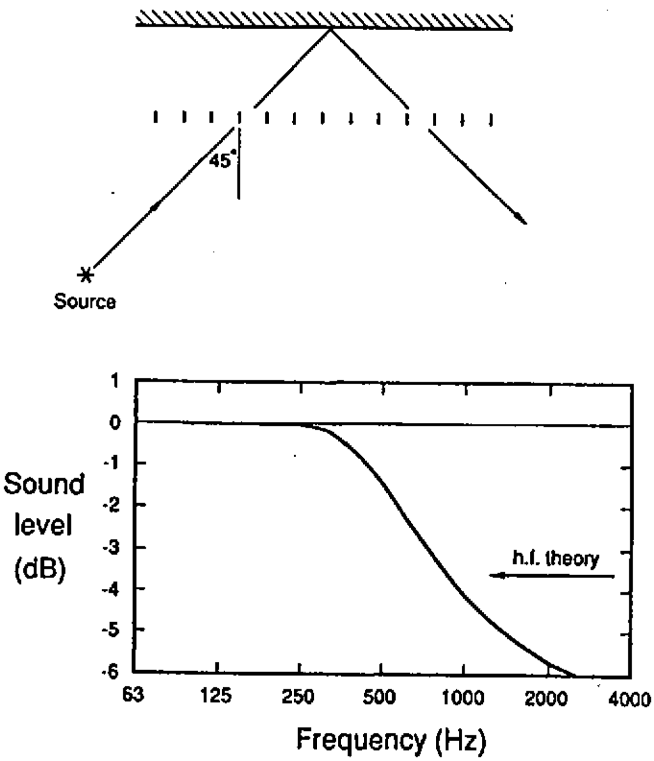

Figure 3 Sound level reduction for sound passing through regular slats, 280 mm high spaced 900 mm apart, with reflection off a hard ceiling

The final design for the structure which supports the roof consists of five V-shaped trusses. These have been screened on both faces by acoustically transparent perforated boards. Compared to the egg-crate screen there is evidence that the revised ceiling scheme provides more reflected energy. In the open stalls area, for instance, model measurements suggest that the ceiling is responsible for 20-30% of early energy (within 80 ms of the direct sound).

Increased reflection from the ceiling inspired a re-assessment of the situation in the open stalls. Since the original design in which inadequate reflections reached the stalls seating, design changes to remedy this and changes made for other reasons had led to an excess of early reflections in these seats. The side walls bounding the stalls were therefore made vertical again, as opposed to being tilted down.

REFLECTOR DESIGN

Concert halls of the capacity of the Glasgow hall confront what can be called the 'large concert hall problem': that, by incorporating an enclosed volume sufficiently large to achieve a long enough reverberation time, the room surfaces become too remote from seating areas to supply sufficiently strong early reflections. A solution to this problem has been termed the 'directed reflection sequence hall' by Marshall. The first of these, the Christchurch Town Hall in New Zealand of 1972 [5], spawned two further derived halls: the Michael Fowler Centre, Wellington, New Zealand of 1983 [6], and the Hong Kong Cultural Centre of 1989. All these halls use freely suspended reflectors to enhance early reflections to the balcony seating. Plane reflectors were used in Christchurch, but were found to produce two minor undesirable effects of false localisation and tone colouration. To avoid these problems, plane reflectors were replaced by Quadratic Residue Diffuseres (QRDs) in the two later halls.

For the Glasgow Royal Concert Hall, suitable orientation of a series of plane reflectors was calculated that gave good geometrical reflection coverage to the side balcony areas. This reflection arrangement was then tested in the model and found to give satisfactory objective behaviour. Plane reflectors were replaced by QRDs at the same locations and subjected to further model tests. The final reflector scheme consists on each side of the auditorium of four pairs of single element QRDs; all QRDs have the same profile based on prime number 7. One series of model tests looked at the options of having either a plane reflective panel in the space between a pair of QRDs or of having a void in the gap. It was anticipated that a linking panel would cause greater reflection at low frequencies but that with the panel there might be excessive screening of the balcony seats from later reverberant sound. Both these effects were observed in the model but on balance a void between the QRDs was judged to be the preferred option.

In addition, overstage reflectors have been provided to assist the orchestra with hearing themselves and one another; these reflectors also mask lighting grids.

REVERBERANT CONDITIONS

Orchestral excellence having been stressed in the brief, it was our intention to supplement the lateral reflections with adequate reverberation. The large volume - 28,700 m^3 for an audience of 2,455 providing 11.7 m^3 per seat - was expected to give a mid-frequency reverberation time (T_{60}) in excess of two seconds.

As the design developed, the widespread use of timber panelling as the preferred finish gave us some concern. All the timber finish was selected to be heavy, ranging from 19 mm dense chipboard with a Melamine facing to 12 mm plywood. The timber materials were tested in a reverberation room and the calculated T_{60} using these results still looked adequate. However, in practice, an excessive amount of untreated (rear) surface was exposed and in some cases edge sealing of panelling was not included. As a result the reverberation time was lower than calculated and the mid-frequency T_{60} in the fully occupied auditorium was measured at 1.75 seconds. The measured values with and without an audience are compared in Figure 4.

The results show a rise to 125 Hz which adds warmth to the sound. The reduction in reverberation time with the audience present is greater than expected, particularly at low frequencies; some of this difference will be explained by the inherent inaccuracies of measuring RTs from gunshot recordings.

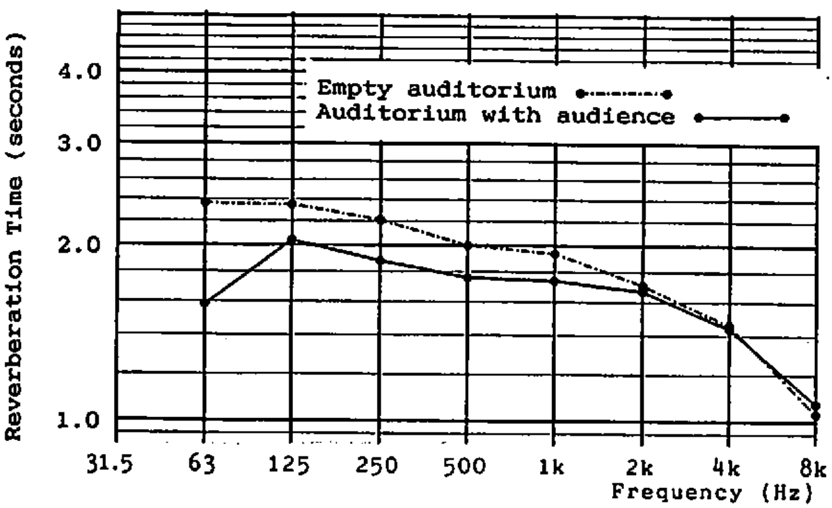

Figure 4 Comparison of reverberation times in occupied and unoccupied auditorium

Impulse response measurements in the completed hall have shown the following. The mean early decay time (EDT) at mid-frequencies is 88% of the measured reverberation time. The ratio of EDT to RT is slightly lower in the Stalls than the Circle, in line with subjective responses. Calculation of the 88% figure does not include overhung seats which traditionally have low EDT values. Values of the mid-frequency Clarity Index (ratio of early-to-late energy) are in the range of -1 dB to 3 dB for seats that are not overhung. The fraction of early lateral energy is one of the highest measured in British halls, with no seats having deficient values. This indicates the effectiveness of the tapered plan forms and the reflectors around and above the Circle. The total sound level is above criterion at all seats except those in the Upper Circle opposite the stage, but no complaints of quiet sound have been received from this seating area.

NOISE CONTROL

The concert hall site was selected and maintained over many years because, in planning terms, it was a prime site on the axis of two of the major streets of central Glasgow (Sauchiehall Street and Buchanan Street). However, acoustically it was a challenging site with heavy traffic on two sides - one of the roads rising to traffic lights on the corner - and the underground train passing immediately beneath the auditorium at the stage end; aircraft noise did not contribute to the overall noise climate.

The airborne traffic noise was eliminated by the usual design expedient of wrapping foyers and rear-of-house accommodation around the auditorium; foyer noise levels are compatible with their proposed use. Traffic noise is barely audible in the auditorium even at stage left, where a wide passage with three sets of doors having removable central stiles provide access.

Underground train noise was predicted to be intrusive on the basis of site measurements carried out on test piles and the decision was taken to float the auditorium and its surrounding accommodation on elastomeric pads. On the south side of the site, the break could be achieved beneath the first floor (auditorium) slab and over shops, the elastomeric pads being sited on the expanded pile caps to allow easy access and examination and minimise the bridging that can occur when the isolation is in the ground; however, the road level rises sufficiently across the site for the separation to fall below ground level for the external walls at the north side of the building. The achievable separation, taking into account the need for weatherproofing on the outside skin, shear keys at lift shafts for wind stability and screw jacks deep into the ground for stage lifts, was less than had been predicted and in the unoccupied auditorium trains are just audible.

The audibility of the underground train noise in the quiet auditorium has been exaggerated by the extremely quiet building services. The design background noise level of MNR 20 (low frequency weighted NR 20) was bettered and ventilation noise is so low (approximately NR 10) that noise from auditorium house lights has had to be further attenuated. The main plantroom is sited at roof level in the second, unisolated part of the building - containing function room, exhibition hall, restaurant, etc - and the distance and isolation of the auditorium have contributed to the low noise level; these quiet conditions have been a source of favourable comment to the extent that we are inhibited from raising the noise level.

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ACOUSTIC CHARACTERISTICS OF THE COMPLETED HALL

Only an incomplete study of the subjective behaviour of the hall has been made. Minor differences in sound quality within the hall were observed but these constituted differences of character rather than matters of consistent preference. There was no obvious preference for one seating area compared to another. To the perceptive listener, the character of sound in the Stalls is more immediate and in the Circle is more reverberant. The difference is however quite subtle.

Overall the sound is clear, intimate, enveloping and sufficiently loud. The sense of reverberance is sufficient but not as high as in some halls. The hall can offer very exciting listening conditions with a high degree of perceived musical detail against a background of room sound. There have been no complaints of undesirable acoustic effects associated with the QRD reflectors.

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