Proceedings of the Institute of Acoustics

THE INFLUENCE OF HEIGHT/WIDTH RATIO AND SIDE WALL BOXES ON ROOM ACOUSTICS MEASUREMENTS

John O'Keefe Aercoustics Engineering Ltd., Toronto, Canada

1 INTRODUCTION

The Queen Elizabeth Theatre in Vancouver, Canada opened in 1959 with a seating capacity of 2900[1]. The building design was commissioned in 1956 and now, in 1999, is ready for a major renovation. Much of the renovation will be driven by acoustical concerns and, as such, the room presents a good opportunity to compare our mid-century understanding of acoustical design with the formidable revelations of the last forty years.

For most of this century the Reverberation Time (RT) has been the predominant quantifier of sound in a room. One reason for this is that it can be easily calculated. With Sabine's formula, RT can be determined from two simple pieces of information: the enclosed volume and the amount of acoustical absorption. Of course, it is now clear the subjective significance of RT is not as important as was thought in 1956. In 1965 Atal et al.[2] demonstrated that the early part of the decaying sound correlates much better with the subjective assessment of reverberation. In many rooms, the so-called Early Decay Time (EDT) is shorter than the RT and, in this sense, the Queen Elizabeth Theatre is no different than any other. It was during an effort to improve EDT in this room that the concept of this paper developed: the influence of simple geometric parameters on modern acoustical measurements. In particular, the Height to Width ratio in a simple six sided box and the presence and geometry of balconies or side wall boxes.

2 HYPOTHESIS

One possible explanation for the difference between EDT and RT was suggested by Hodgson[3] during a series of scale model experiments for the Queen Elizabeth Theatre. The Queen Elizabeth Theatre is typical of its age in that it has a relatively low ceiling. Traditional 18th and 19th century performance venues are high and narrow. The Queen Elizabeth Theatre is flat and wide. When this was pointed out, Hodgson suggested that it might be the reason for its low EDT/RT ratio.

The hypothesis can be explained as follows:

1. A theatre or concert hall, in its simplest form, can be thought of as a six sided box with acoustical absorption on only one of the six sides, i.e. the floor.
2. One might expect the early reflected sound (and hence the EDT) to be influenced by the sides of the box that are closest to each other. In a narrow shoe box shaped room, this would be the two non-absorbent side walls.
3. In a flat and wide room like the Queen Elizabeth Theatre, the closest pair of sides is the ceiling and the floor. The latter, of course, is the only acoustically absorbent surface in the "box".

3 PROCEDURE

A number of experiments were performed using computer models of six sided shoe box and fan shaped rooms. In all cases, except one, the acoustical absorption was limited to the floor. The rooms were 40 m in length and the height was varied from 1/8th of the width to twice the width, increasing in a 1/3 octave sequence, i.e. 0.125W, 0.160W, 0.200W, etc. Three room widths were tested: 10 m, 20 m and 40 m. For the narrower rooms, source and receiver elevations were higher than 1/8W, which limited the range of ratios, e.g. from ¼W to 2W. The angles of the fan shaped rooms were 8.5° and 16.7° for the 20 m and 40 m rooms respectively. Schematic representations of the six sided boxes are shown in Figure 1.

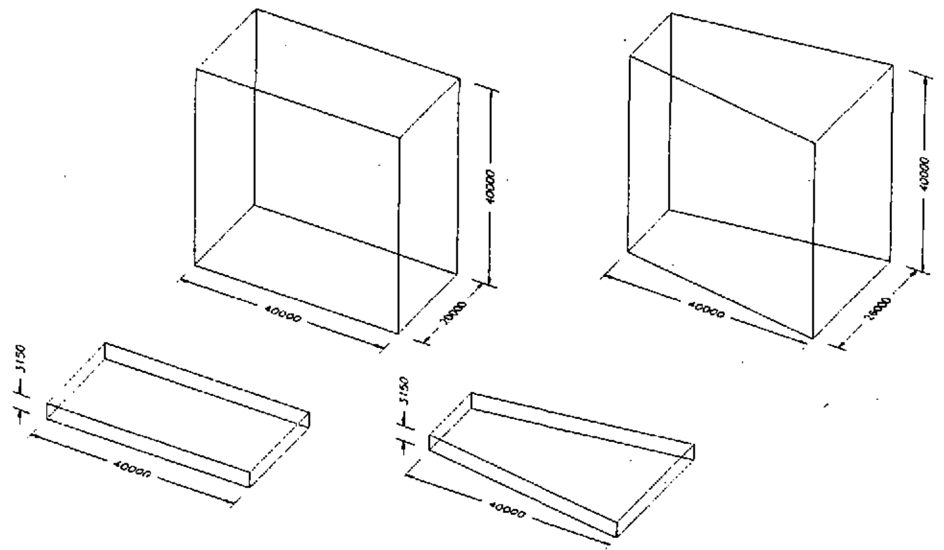

Figure 1 Schematic representations of the six sided boxes used in the initial computer model experiments

Calculations were performed at five receiver locations in each of the four computer models. A single source location was used, situated at the front of the room, stage left of the centre line. The computer program employed for the experiments was CATT Acoustic Version 7. The method of images algorithm was set to 5th order with a truncation time of 300 ms and diffuse reflections commencing after the 1st order. The ray tracing algorithm was set to 12,000 rays and a truncation time of 6000 ms.

Later, in an effort to verify the computer modelling, some of the experiments were repeated in a 1:25 scale model. Two sets of verification tests were performed on a 10 m wide room[4] using the MIDAS system[5] and, more recently, the WinMLS system.[6]

The six sided box experiments produced some very interesting results so the concept was extended to include side wall boxes and end wall balconies. Two levels of balconies and side wall boxes were introduced into the 40 x 20 x 20 m (l-w-h) six sided fan and shoebox shaped rooms.

1. In the first experiment, the vertical distances between the two balconies was varied from 3 to 7 m.
2. Next, the importance of the fascia height was examined. For two balconies (separated vertically by 5m) the height of fascia was varied from 0 m (i.e. no fascia) to 4.5 m.
3. In the third set of tests, the depth of the balcony overhang was investigated. Experiments were performed in both the 20 m and 40 m wide fan and shoebox shaped rooms. In both cases, the rooms were 20 m high and 40 m long. The depth of the overhang ranged from 1 to 8 m in the 20 m wide room and 2 to 16 m in the 40 m wide room.

4 EARLY DECAY TIMES

Results from the initial experiments are shown in Figure 2. EDT/RT ratios are seen to decrease as a function of the Height to Width ratio. For Height to Width ratios greater than 1.0, the EDT/RT ratio is perfectly efficient, i.e. there is no compromise in Early Decay Time for a given Reverberation Time. If the Height to Width ratio is less than 1.0 there is a degradation of the Early Decay Time and hence the perceived reverberance in the room. The effect seems to be independent of the shape in plan, i.e. fan or shoebox. Likewise, the nominal width of the room, 20 or 40 m, was found to have little effect on the EDT/RT ratio.

The ideal RT for a concert hall is in the range of 2.0 s. The difference limen for Reverberance are thought to

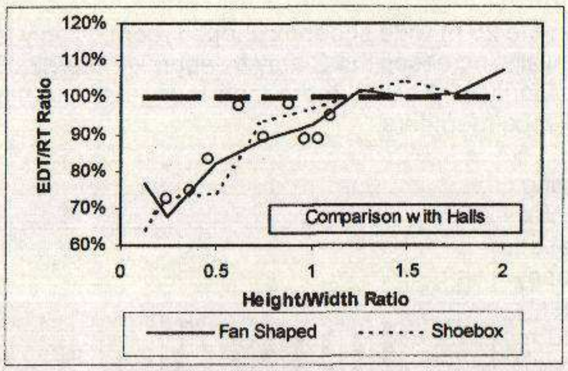

Figure 2 EDT/RT Ratio vs. Height/Width Ratio. Computer models indicated by dashed and solid lines, selected halls by circles.

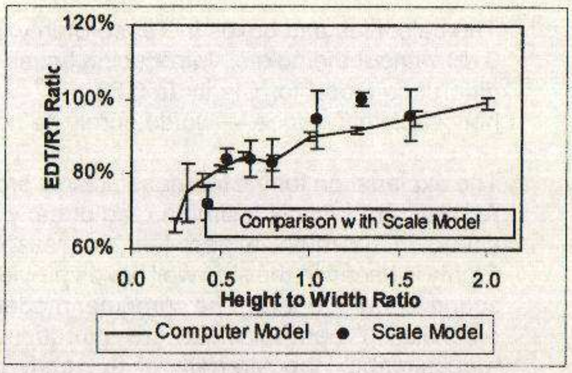

Figure 3 Comparison of a 10 m wide shoebox shaped scale model (dots) and 10 m wide computer model predictions (line).

be in the range of 0.1 seconds[7]. The results shown in Figure 2 suggest that the EDT can be as much as 0.4 seconds shorter than the RT in a low ceiling concert hall, i.e. four times the difference limen. The difference between RT and EDT, under these circumstances, would be clearly audible to both casual and expert listeners.

Recognising that computer models can be misinterpreted, a number of attempts were made to validate the results. In the first, a comparison was made with measurements taken in a number of existing halls.[8] A random sample of 50 halls produced little or no correlation with the computer model results. When the sample was limited to rooms that matched the very simple geometry of the model, correlation was much better. Please see Figure 2. A second comparison between the computer model and a 1:25 (physical) scale model is shown in Figure 3. Once again the correlation is good. Note however that the seat to seat variation, indicated by the standard deviation bars, is higher in the scale model than in the computer model. Thus it appears that the EDT/RT phenomenon exists in the scale model but, in this experiment at least, the relationship is less consistent than the computer model might suggest.

Other attempts to challenge the hypothesis were made through a series of changes to the computer model parameters. Seat absorption coefficients were varied from 0.5 to 0.99, EDT/RT results did not change appreciably. Seat diffusion coefficients were changed from 30 to 80%, again no difference was found. Changing the absorption coefficient of the entire room did however effect EDT/RT ratios. Absorption coefficients of the seats, floor, walls and ceiling were varied from 0.5 to 0.99. In Figure 4 the EDT/RT ratio is shown to be proportional to the Height to Width ratio and inversely proportional to average room absorption.

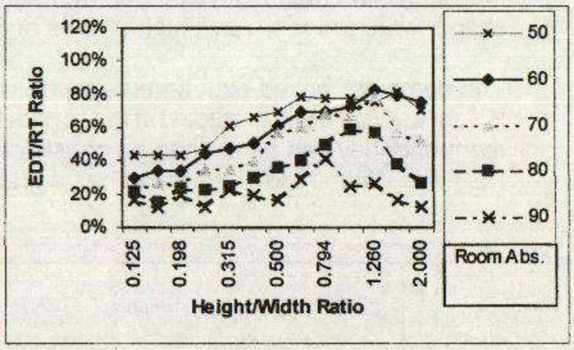

Figure 4 EDT/RT vs. Height/Width Ratios calculated for a range of room absorption coefficients.

Turning to the study of balconies and side wall boxes: as expected, the EDT/RT ratio is reduced significantly as the overhang is increased. Even shallow, 3 m deep balconies reduced the EDT/RT ratio by almost 30%. The effects were evident in both the shoebox and fan shaped models.

Fascia height may have a marginal effect on the EDT/RT ratio. In the 20 m wide shoebox, the EDT/RT ratio is in the range of 65% for fascia heights less than 1.0 m. A larger fascia, for example 2 m or higher, results in a ratio of 70% to 74%, an improvement of almost ten percent. For a 2s RT this is the equivalent of two difference limen. Changing the vertical separation between side wall balconies had no effect on EDT/RT ratios.

5 CLARITY

The balconies and boxes increase Clarity quite a bit. In the 20 m wide shoebox shaped room, Clarity is about 0 dB without the boxes. Introducing boxes on the side walls increases the Clarity by approximately 3 dB. The difference limen for Clarity is 0.67 dB.[9] A change in Clarity of 3 dB — more than four times the minimum noticeable difference — would surely be heard by audience members.

The explanation for the increased clarity proves interesting. Acoustical Clarity is a simple ratio of early to late reflected sound. One might expect that the reason for increased Clarity is because the side wall boxes provide stronger early sound to the listeners. The computer model study suggests otherwise. When balconies are introduced into the 40 m wide shoebox the strength of the early reflected sound (G80) remains essentially the same. In a 20 m wide room, shown in Figure 5, the early energy goes up slightly, by about 1.0 dB. However, in both rooms, the late reflected energy (Glate) is reduced by approximately 3 dB when the balconies are added. In other words, contrary to expectations, Clarity is increased not by stronger early reflected sound but by weaker late reflected sound. (It is worth noting however that the fascia were perpendicular to the floor, i.e. no effort was made to direct the sound back down towards the seating plane.)

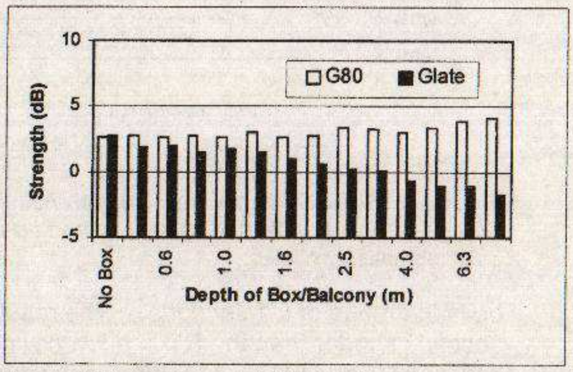

Figure 5 Computer model experiments suggest that C80 increases as the depth of side wall boxes and end wall balconies increase. The reason for this appears to be a reduction in late energy (Glate).

The vertical distance between balconies does not appear to influence 80 ms Clarity.

6 STRENGTH

Measurements in the 1980s established that acoustic Strength decreases towards the back of a hall and that the rate of decrease is typically in the range of 0.1 to 0.2 dB/m.[10,11] Some room shapes, for example a fan shape, were found to have higher rates of Strength attenuation.

The computer based experiments agree with that finding. Figure 6 shows the slope of Strength versus the Height to Width ratio predicted in the six sided boxes without balconies. The solid bars represent the fan shaped room and they can be seen to be consistently lower than the shoe-box shaped room. Note however that the Height to Width ratio of the room has a greater effect on Strength attenuation than its shape in Plan.

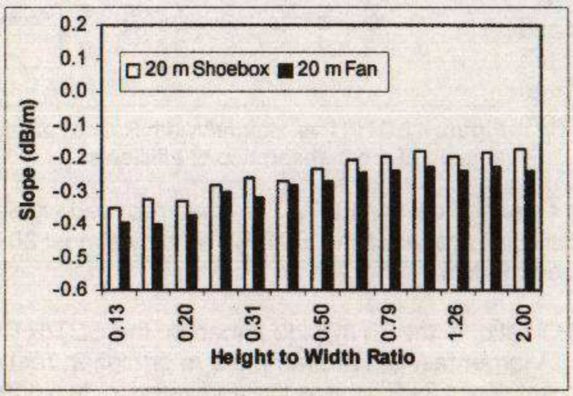

Figure 6 The rate of Strength attenuation is found to be a function of room shape both in plan *and section* (i.e. as implied by the Height to Width ratio).

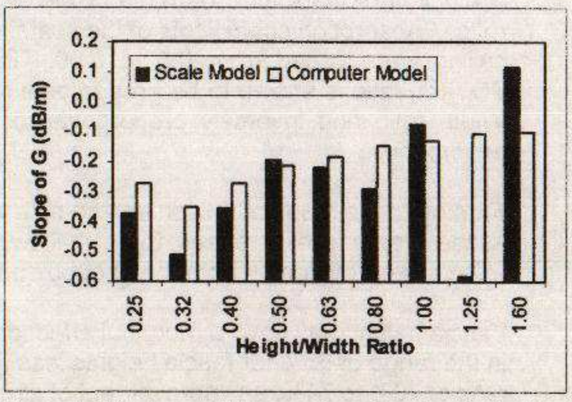

Figure 7 Scale model experiments also indicate a relation between the rate of Strength attenuation and Height to Width ratio but the correlation is not as consistent as suggested by the computer model.

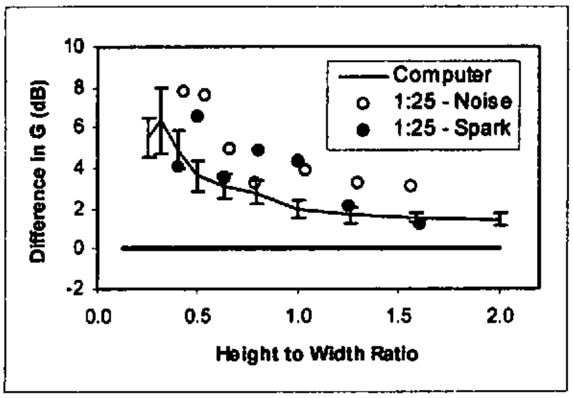

Figure 8 $G_{revised\ theory}$ minus $G_{computer}$ and $G_{revised\ theory}$ minus $G_{scale\ model}$.

Scale model Strength measurements were performed to confirm this finding, at first with at an electronic spark source then with a tweeter radiating steady state noise. Results from the spark source measurements are shown in Figure 7. General agreement is observed but in neither case was the behaviour of Strength as obvious as suggested by the computer model.

Computer experiments with balconies and side wall boxes also indicate influences on the rate of Strength attenuation. As the depth of the side and end wall balconies is increased, the rate of attenuation increases, from approximately 0.2 to 0.3 dB/m. The effect was noted in both fan and shoebox shaped rooms.

The six sided box experiments revealed interesting comparisons with Revised Theory.[10,12] Revised Theory is perhaps one of the most useful developments in room acoustics in the last few decades. Some have noted however that it often predicts higher levels of Strength than are measured in actual halls.[13] Differences between Revised Theory and measurements are often in the range of 1 or 2 dB. The computer model experiments in a 10 m wide shoebox agree with this observation. Please see Figure 8. All shoebox and fan shaped variations of the computer model experiments displayed similar results, as do the measurements in the scale model. The discrepancies with Revised Theory are seen to increase as the Height to Width ratio decreases.

7 DISCUSSION

To summarise, computer and scale model studies suggest that the ratio of Early Decay Time to Reverberation Time is effected by the Height to Width Ratio of the room, the amount of acoustical absorption in the room and by the presence of balconies and side wall boxes. Thus, we can expect a room with a Height to Width ratio significantly less than unity to have shorter Early Decay Times than might be suggested by a Sabine Reverberation Time calculation. The same will be true for rooms with deep balconies and side wall boxes and for rooms with extensive side and back wall absorption, e.g. the acoustic curtains that are often found in multi-purpose performing arts centres.

Many of the same arguments hold for acoustic Strength. As the Height to Width ratio decreases, rates of Strength attenuation increase, as does the discrepancy between measured Strength and Strength predicted by Revised Theory. Adding side and end wall balconies produces similar effects.

Contrary to received wisdom, the height between balconies appears to have little influence on the measured acoustics. Parameters that were investigated included RT, EDT, Strength, 80ms Clarity, Early Lateral Fraction, the EDT/RT ratio and the rate of Strength attenuation. It was not possible to quantify late lateral energy in either the scale or computer models.

One thing that is particularly interesting about this study is the performance of fan shaped auditoria. In many of the effects noted here, the fan shape plan produced results no worse than the shoe box shaped room. Two exceptions were the rate of Strength attenuation and, of course, Early Lateral Fractions. One possible explanation is the difference between the geometry of our computer model and the (deceptive) geometry of real auditoria. The highest part of a typical fan shaped auditorium is at the front, the part of the room that everyone is looking at but few are seated in. For the majority of seats in a fan shaped auditorium the ceiling is quite low. An illustration of this is

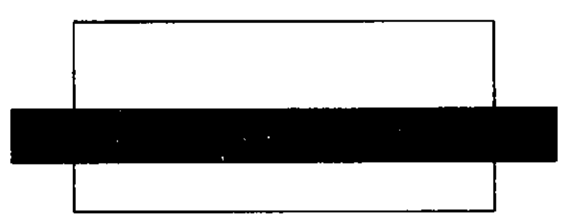

Figure 9 Cross sections at the front and back of the 3000seat fan shaped Hummingbird Centre, indicated by white and black rectangles respectively.

shown in Figure 9. This is an iconic representation of Height to Width Ratios taken from the Hummingbird (formerly O'Keefe) Centre in Toronto, Canada. The white and black rectangles indicate the cross-sections taken near the front and back respectively. At the front of the room the Height to Width Ratio is 46%. At the back, were most of the seats are located, the ratio is only 9%. The inference here is that many of the acoustical shortcomings of these rooms are not necessarily the fault of fan shape itself but the unfortunate combination of (i) a fan shaped plan (ii) a sloped floor and (iii) an end balcony. This combination can lead to extremely low Height to Width ratios. The experiments presented here suggest that these are responsible for some of the low EDTs and high rates of Strength attenuation that have been observed in fan shaped auditoria.

8 APPLICATIONS

The impetus for all this work was the Queen Elizabeth Theatre renovation design. Part of the design calls for the introduction of three levels of side wall boxes. With modifications to the ceiling, it was possible to improve the existing EDTs in the Queen Elizabeth Theatre, but as soon as the side wall boxes were introduced into the 1:48 scale model, the EDTs dropped back to their original levels. The eventual design of the side wall boxes was informed by the experiments described above. Please see Figure 10. The design, proposed by architect Thom Weeks, uses fin like reflectors to effectively reduce the depth of the boxes by half. These reflectors extend from floor to ceiling. In addition to improving the Early Decay Times they should improve lateral reflected energy and, as a consequence, improve source broadening.[14,15] Scale model measurements have demonstrated improved EDT/RT ratios: from 51% with the first set of side wall boxes to 75% with the revised boxes.

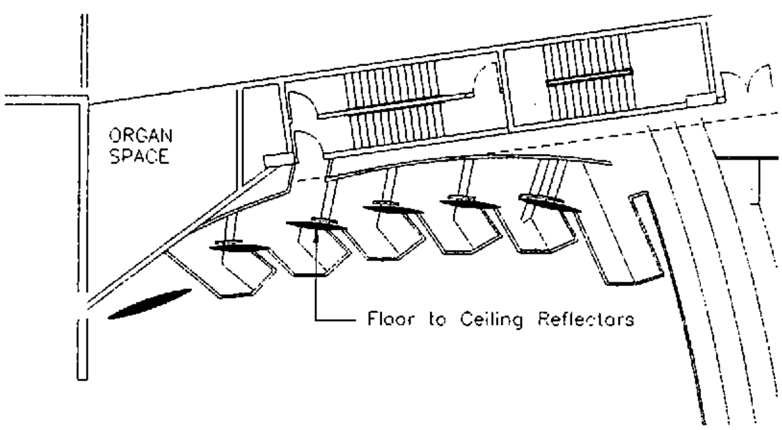

Figure 10 Plan of the proposed Queen Elizabeth Theatre renovation.

Another project that will benefit from this experimental work is the new 800 seat Magna A&E Auditorium, to be built in Aurora, just north of Toronto. The plan and longitudinal section for the room are shown in Figure 11. The width of the room was easily established from the beginning; no more than 22 m. Two more difficult questions remained: (i) should a side wall balcony be included and (ii) how high should the ceiling be? The owner preferred a low ceiling.

Three ceiling heights were considered as indicated at the extreme right of Figure 11. Acoustical tests were performed in a 1:50 scale model. The Height to Width study produced mixed results. EDT/RT ratios increased when the ceiling was raised from elevation 1 to 2, but decreased slightly when the ceiling was raised to elevation 3. (The difference between elevations 2 and 3 was less than EDT measurement accuracy.[16])

The two side wall balcony configurations that were considered are indicated by the dashed lines at the left of Figure 11. When the side balconies were introduced into the model acoustic Strength was reduced by about 2 dB. Early (G80) and late (Glate) energy both decreased, Glate more than G80. In all ten seats that were measured the RT decreased, on average by 0.25 s. The biggest change in RT, as with other parameters, happens when the first balcony is introduced. In 6 out of 10 seats C50 and C80 increased but in some cases not beyond difference limen. EDT/RT ratios were the only parameter to show both positive and negative trends, but in most cases the ratio decreased. For these and other reasons, it was decided not to include a side wall balcony.

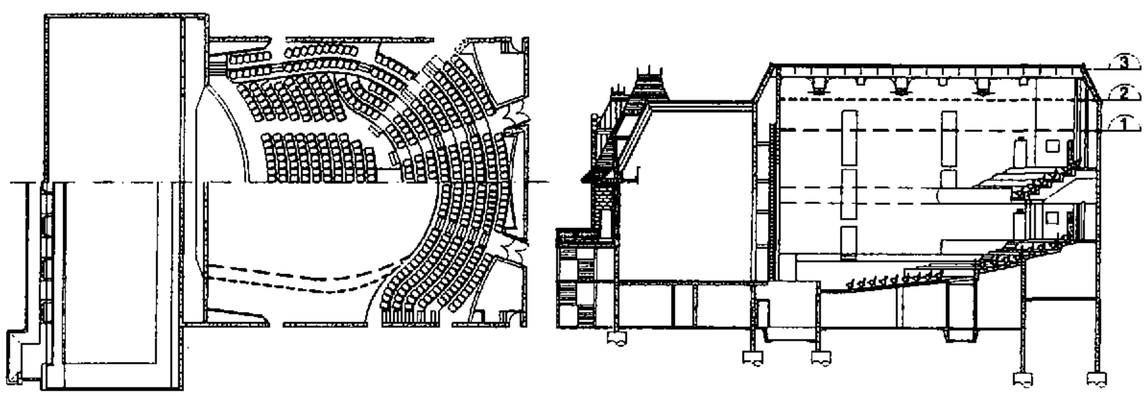

Figure 11 Composite Plan and Longitudinal Section of the proposed Magna A&E Auditorium.

9 CONCLUSION

Through the initial computer model experiments, Height to Width ratios were found to have a significant effect on a number of room acoustic parameters, notably the Early Decay Time and acoustic Strength. Later, the computer experiments revealed that side and end wall balconies had similar influences. Scale model experiments have confirmed these findings although the trends are not as obvious or as consistent as the computer model. Nonetheless, the findings have proved useful for acoustic design, two examples of which have been provided above.

10 REFERENCES

1 BERANEK L.L., Music Acoustics and Architecture New York 1960, pp 215-220

2 ATAL, B.S., SCHROEDER, M..R. & SESSLER, G.M., "Subjective Reverberation Time and its Relation to Sound Decay", Proc. 5th International Congress on Acoustics, Liege, Paper G32

3 HODGSON, M, Private Communication

4 O'KEEFE, J., "Small scale modelling of stage to pit balance - a pilot study", Proc. 16th International Congress on Acoustics, Seattle, USA, pp 341-342, (1998)

5 POLACK, J.D, MARSHALL, A.H & DODD, G. J. Acoust. Soc. Am. 85 (1) pp 185-193 (1989)

6 Morset, L., "WinMLS - Acoustical Measurements using MLS", http://www.nvo.com/winmls

7 CREMER, L., MULLER, H.A. & SCHULTZ, T.J. "Principles and Applications of Room Acoustics, Vol. 1", Applied Science, 1978 p. 505

8 BERANEK, L.L., Concert and Opera Halls, How they Sound, Acoust. Soc. Am. New York (1996), Appendix 4

9 COX, T.J., DAVIES, W.J. AND LAM, Y.W. "The Sensitivity of Listeners to Early Sound Field Changes in Auditoria" Acustica 79, pp 27-41 (1993)

10 BARRON, M., LEE, L.J. 'Energy relations in concert auditoriums. Part I', J. Acoust. Soc. Am. 84, pp 618-628 (1988)

11 BRADLEY, J.S. 'Hall Average Conditions of 10 Halls', Proc. 13th Int. Congress on Acoustics 2 pp 199-02, Belgrade (1989)

12 BARRON, 'Auditorium Acoustics and Architectural Design', E & F Spon, London, (1993)

13 HYDE, J.R., "Sound strength in concert halls I: Role of the early sound field with objective and subjective measures", Proc. 16th International Congress on Acoustics, Seattle, USA., pp. 9-10 (1998)

14 BARRON, M. "The subjective effects of first reflections in concert halls - the need for lateral reflections", J. Sound & Vibration 15, pp 481-502

15 BRADLEY, J.S., SOULODRE, G.A. "Influence of late arriving energy on spatial impression", J. Acoust. Soc. Am, 97 p.2263-2271 (1995)

16 BRADLEY, J.S., HALLIWELL, R.E., "Accuracy and reproducibility of auditorium acoustics measures", Proc. of IOA, 10, pp 399-406, Cambridge (1988)

Things to Do

do a final catt model with variable room diffusion
search all question marks.
compare std. dev of computer & scale model EDT/RT ratios.
For the side box studies, find out which receivers are covered by the box.

11. ACKNOWLEDGEMENTS

Part of this work was supported by the Industrial Research Assistance Programme, National Research Council of Canada. Figures 10 and 11 were provided by the project architects: Proscenium Architecture & Interiors and Thomas Brown Architects for the Queen Elizabeth Theatre and Magna A&E Auditorium, respectively.