Journal of Sound and Vibration (2001) **239**(4), 573–587
doi:10.1006/jsvi.2000.3127, available online at http://www.idealibrary.com on IDEAL®

MEASUREMENTS OF THE ABSORPTION BY AUDITORIUM SEATING—A MODEL STUDY

M. Barron

Department of Architecture and Civil Engineering, University of Bath, Bath BA2 7AY, England. E-mail: m.barron@bath.ac.uk

AND

S. Coleman

Buro Happold, Camden Mill, Lower Bristol Road, Bath BA2 3DQ, England

(*Accepted* 18 *May* 2000)

One of several problems with seat absorption is that only small numbers of seats can be tested in standard reverberation chambers. One method proposed for reverberation chamber measurements involves extrapolation when the absorption coefficient results are applied to actual auditoria. Model seat measurements in an effectively large model reverberation chamber have allowed the validity of this extrapolation to be checked. The alternative barrier method for reverberation chamber measurements was also tested and the two methods were compared. The effect on the absorption of row–row spacing as well as absorption by small numbers of seating rows was also investigated with model seats.

1. INTRODUCTION

Quantifying the sound absorption by theatre seats and seated audience poses many difficulties including the following. Firstly, seats in an auditorium are too close to one another for measurements on individual widely spaced seats to be applicable. Secondly, seating is three-dimensional with exposed edges; not only do exposed vertical edges absorb but diffraction also occurs at the edges in ways significant for total absorption. A third complication concerns measurement in test chambers, a maximum of about 24 seats can be tested in a standard reverberation chamber (with a high proportion of exposed edge) compared with up to 3000 seats in a large auditorium.

In practice, not only does seat construction vary considerably, but the density of seating also varies (what is also known as the seating standard). This leads to the question of how one assesses the absorption by seating. There are two obvious approaches: seating can either be treated as a standard material with an absorption coefficient based on the plan area (absorption by area) or seats can be considered as absorbing objects with a certain absorption per seat.

Sabine in his original article "Reverberation" of 1900 [1] appreciated that these two possibilities existed and on the basis of rather limited evidence chose to use the absorption per seat approach. However, as the 20th century progressed so seating standards became more generous and it was found that several auditoria exhibited reverberation times shorter than had been predicted. During the 1960s working from measured reverberation times in

0022-460X/01/040573 + 15 $35.00/0

auditoria, Beranek [2] demonstrated that it was more accurate to treat seating on an area basis and provided average absorption coefficients for audience seating. Beranek and Hidaka [3] have recently revised this work; a significant revision is that rather than quoting a single coefficient applicable to all seating, separate coefficients are provided for lightly, medium and heavily upholstered seating. Beranek [2] proposed that the appropriate area for seating absorption should include a 0·5 m wide strip around the perimeter of seating blocks, wherever there is floor area to which it can be ascribed.

During the design of an auditorium, accurate prediction of reverberation time is important and this requires data on the absorption of the actual seating to be used. Simply measuring the absorption of a group of seats in a reverberation chamber gives inaccurate results when applied to auditoria. This is mainly due to the proportionally large amount of exposed edge that occurs with the small sample size in standard reverberation chambers. Two methods have been proposed for dealing with this problem.

The first method was originally proposed by Kath and Kuhl [4] in 1960s; they suggested measuring a sample seating block in a reverberation chamber with screens that "cover" the edges of the block. This approach was further researched by Davies *et al.* [5]. By measuring the absorption of the seating block with and without screens, the absorption by edges of seating blocks can also be determined.

The current standard relating to absorption measurements in reverberation chambers ISO354 [6] includes the proposal that theatre seating should be measured with barriers. This should give the absorption coefficient for an infinite sample, with no edges.

The second method as proposed by Bradley [7, 8] is based on a principle already used for simple absorbing materials. It is assumed that there are two coefficients of absorption: an absorption coefficient applicable to a seating block without edges (an infinite sample) and a coefficient applied to the perimeter length of the block. To derive these two coefficients, Bradley proposed making absorption measurements on seats arranged in five different configurations. The procedure for extracting the coefficients is explained in section 5.1 below.

Acoustic scale modelling is a very convenient research technique when physical situations depend on many variables. Hegvold [9] has demonstrated the value of model studies for audience absorption. He discovered that even with barriers around seating blocks, the absorption coefficient varied with the perimeter/area ratio in a linear manner. Among other things, Hegvold also investigated the influence of seating rake.

This paper is concerned with absorption by model seating at a scale of 1 : 25 as measured in a 1 : 8 scale model reverberation chamber. The chamber is thus effectively much larger than a standard one with a volume equivalent to about 30 times the standard full-size 200 m^3 value. With such a large chamber, it is possible to make measurements on blocks of 200 seats, as opposed to typically only 24 seats in full-size chambers. This is particularly valuable for assessing the proposed chamber measurement methods.

Three separate topics will be discussed: the effect of underpass on seat absorption, the effect of row spacing and the relative merits of the two methods proposed for measuring seating in reverberation chambers.

2. MEASUREMENT PROCEDURES

Absorption measurements were made in a steel tank with a lid of transparent acrylic. The construction of the tank is similar to that developed by the BBC Research Department [10]. The tank is connected to a drying plant which reduces the relative humidity to about 2% for measurements; air is circulated to bring down the humidity before each measurement for a particular microphone position. The chamber contains fixed diffusers to ensure a diffuse sound field.

The volume of the reverberation tank is 0·389 m^3, which is equivalent at 1 : 8 scale to a full-size volume of 200 m^3, a standard value for reverberation chambers. The scale factor of the model seating was however 1 : 25 so that, as already mentioned, the effective volume of the chamber was 30 times larger than a standard chamber. This made it possible to conduct measurements on much larger numbers of seats, such as a block of 200 seats, than in a standard reverberation chamber.

The reverberation time in the tank was measured in 1/3rd octaves from 2·5 to 63 kHz, equivalent to 100–2500 Hz full-size. The traditional interrupted noise technique was used with 1/3rd octave filtering for both the source and the received signal. The switching of the source signal, the selection of the 1/3rd octave frequency, the acquisition and processing of the received signal were all controlled by computer.

Two loudspeakers were used, a typical tweeter loudspeaker in a box for the audio frequencies and a so-called leaf tweeter from Technics for the ultrasonic frequencies. The leaf tweeter radiates sound up to 100 kHz but becomes progressively more directional with frequency; a hemisphere was placed directly in front of the leaf tweeter to diffuse the high-frequency sound.

A Brüel & Kjaer Type 4135 microphone was used. This is placed on a boom to allow measurements to be taken at different microphone positions. Most reverberation time measurements were made at six microphone positions with two measurements per position; thus each 1/3rd octave reverberation time is based on 12 decay measurements. The analysis used the averaging technique proposed by Jacobsen [11] to smooth the decay prior to measurement of the slope. The absorption coefficient is obtained from reverberation times measured in the tank with and without the absorbing sample, using the Sabine reverberation time equation.

In the text below, frequencies will be given as for full-size. Absorption coefficients are quoted as octave values, derived by averaging the appropriate 1/3rd octave results. Dimensions are generally quoted as the full-size equivalents to those actually measured on the model seats. In particular, all perimeter/area (P/S) ratios are full-size equivalents.

2.1. MODEL SEAT CONSTRUCTION

The seating was constructed as 100 mm long benches (equivalent to about five individual seats). Bent metal angle is supported on narrow timber feet with a height of 16 mm (0·4 m full-size). The distance between the front and back of the bench seats was also 16 mm (0·4 m full-size). A single layer of dress velvet is used on the vertical surface and a double layer on the horizontal seat surface; the rear of the seat is acoustically hard.

Figure 1 shows the cross-sections and absorption coefficients of two designs of model seat. The absorption coefficients were measured with a block of about 200 seats at a row–row spacing of 1 m. The Mk. I seat design, as described above, can be criticised as having an unrealistic gap (the underpass) between the underside of the seat and the floor. In practice, seats are generally inclined to the vertical and the horizontal and the degree of underpass is much less than 400 mm. For the Mk. II seat a 0·5 mm thin plywood panel was added on the back of the seat to reduce the underpass to 6 mm (150 mm full-size). The surprising result shown in Figure 1 is that although no porous absorbing material was added, this modification to the model seat resulted in a significant increase in absorption at mid-frequencies.

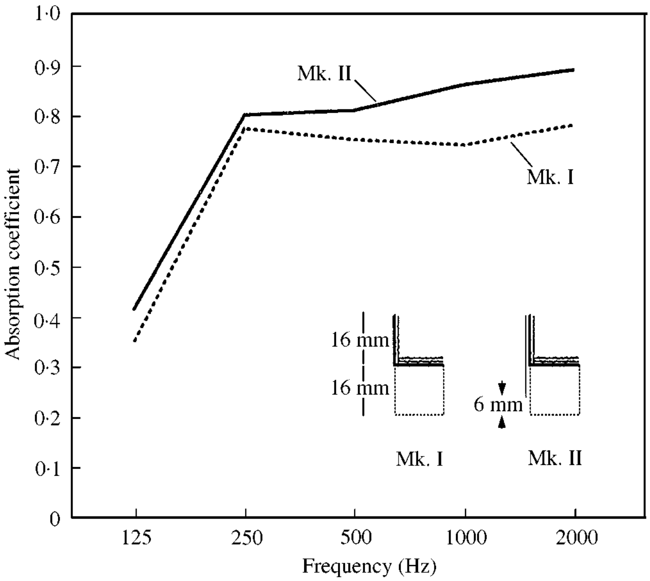

Figure 1. Cross-sections and absorption coefficients of two designs of 1 : 25 models seats. Quoted dimensions here are the true model dimensions.

The experience of changing the degree of underpass suggests that this is a significant parameter in seat absorption. In larger auditoria, seats in the Stalls tend to have some underpass whereas this will be blocked where the seating becomes steeply raked. This may result in different absorption coefficients for the two conditions. All remaining experiments were made with the Mk. II model seat.

3. EFFECT OF ROW SPACING ON SEATING ABSORPTION

3.1. REVERBERATION CHAMBER MEASUREMENTS

A simple test of whether seating should be treated as absorbing on an area basis (with an absorption coefficient) or on per seat basis was possible with the experimental system available. The absorption of a block of seating 10 m wide (full-size) with 10 rows was measured; this corresponds to about 200 seats in a roughly square arrangement in plan. The seating block was tested with three row spacings: 0·8, 0·9 and 1·0 m full-size equivalent. The results in terms of absorption coefficient and absorption per seat are given in Figure 2. If one approach (by area or per seat) is relevant, then the curves of the appropriate graph would be superimposed. From Figure 2, it can be seen that in general measured behaviour matches neither the area nor the per seat approach. However, between-row spacings of 0·9 and 1·0 m, the per seat approach works well.

A quantitative measure helpful to determine which approach is relevant is the ratio of the two total absorptions (A) for different row spacings. For the extreme spacings of 0.8 and 1.0 m, the ratio $A_{1\,\mathrm{m}}/A_{0.8\,\mathrm{m}}$ has been calculated at the different measurement frequencies (Table 1(a)). If behaviour is according to absorption per seat, then $A_{1\,m}/A_{0.8\,\mathrm{m}} = 1{\cdot}0$. If absorption behaves according to area, then $A_{1\,\mathrm{m}}/A_{0.8\mathrm{m}} = S_{1\,\mathrm{m}}/S_{0.8\,\mathrm{m}}$, where $S_{1\,\mathrm{m}}$ is the sample area with 1 m row–row spacing etc. A third possibility needs to be considered in

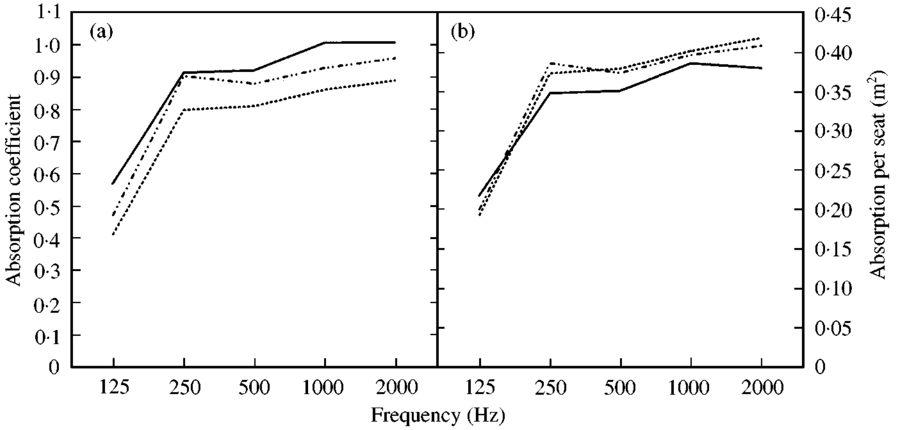

Figure 2. Absorption coefficients (a) and absorption per seat (b) for a large block of model seating with equivalent full-size row spacings of ——, 0·8 m; —··—, 0·9 m and ····, 1·0 m.

Table 1

Values of ratios of total absorption by model seating with different row–row spacings

(a) *The ratio* $A_{1\,\mathrm{m}}/A_{0\cdot 8\,\mathrm{m}}$ *for row–row spacings of* 1·0 *and* 0·8 *m* (*full-size equivalent*). $S_{1\,\mathrm{m}}/S_{0\cdot 8\,\mathrm{m}} = 1\cdot 23$

Frequency (Hz)	125	250	500	1000	2000
$A_{1\,\mathrm{m}}/A_{0\cdot 8\,\mathrm{m}}$	0·88	1·07	1·08	1·04	1·10

(b) *The ratio* $A_{1\,\mathrm{m}}/A_{0\cdot 9\,\mathrm{m}}$ *for row–row spacings of* 1·0 *and* 0·9 *m* (*full-size equivalent*). $S_{1\,\mathrm{m}}/S_{0\cdot 9\,\mathrm{m}} = 1\cdot 10$

Frequency (Hz)	125	250	500	1000	2000
$A_{1\,\mathrm{m}}/A_{0\cdot 9\,\mathrm{m}}$	0·96	0·97	1·01	1·01	1·03

which the effective absorption area is increased by adding a 0·5 m edge strip as proposed by Beranek. According to this model $A_{1\,\mathrm{m}}/A_{0.8\,\mathrm{m}} = S_{\mathrm{Beranek},\,1\,\mathrm{m}}/S_{\mathrm{Beranek},0.8\,\mathrm{m}}$. Values for this experiment of $S_{1\,\mathrm{m}}/S_{0.8\,\mathrm{m}}$ and $S_{\mathrm{Beranek},\,0.8\,\mathrm{m}}/S_{\mathrm{Beranek},\,0.8\,\mathrm{m}}$ are 1.23 and 1.21 respectively; the ratios are very similar because of the small perimeter/area ratio for the seating blocks tested.

Inspection of Table 1(a) reveals that at 250 Hz and above the absorption by the more widely spaced seating is greater. With measured values of $A_{1\,\mathrm{m}}/A_{0.8\,\mathrm{m}}$ closer to 1·0 than 1·23, it is clear that in this case behaviour is closer to absorption per seat than absorption by area. At 125 Hz there is the surprising result that the total absorption and the absorption coefficient are both greater for the smaller row spacing. This is an example where behaviour at 125 Hz differs from that at higher frequencies; different behaviour at 125 Hz arises with several measurements discussed here, as well as with measurements by others on full-size seating. Regarding possible reasons for special behaviour at 125 Hz, one notes that the height of seating equals a quarter of a wavelength within the 125 Hz octave. The frequency of maximum attenuation at grazing incidence (the seat dip effect) also occurs at around this frequency.

For comparison of the row spacings 0·9 and 1·0 m, values of the ratio of total absorptions $A_{1\,\mathrm{m}}/A_{0.9\,\mathrm{m}}$ are given in Table 1(b). In this case the ratio of sample areas $S_{1\,\mathrm{m}}/S_{0.9\,\mathrm{m}}$ is 1.10.

From the table, it can be seen that at 250 Hz and above the absorption ratios are close to 1·0, indicating that absorption per seat is basically constant in this case.

These model measurements therefore contradict Beranek's suggestion that seating absorption should be treated as absorption by area like any other material. Is there any supporting evidence, preferably from full-size measurements by others? Model measurements by the authors on 1 : 50 scale seating also gave a similar result. In the paper by Davies *et al.* [5] they include in their Figure 3 absorption coefficients for full-size seating at three row spacings between 0·82 and 1 m, as measured in a reverberation chamber. The figure of Davies *et al.* is reproduced here as Figure 3(a). The seat width for Davies' seats was 0·525 m [12]. The absorption per seat for Davies' seats is plotted in Figure 3(b). The lines in Figure 3(b) are almost coincident, confirming behaviour according to absorption per seat for this measurement. In quantitative terms, if measured values for Davies' row spacing of 0·82 and 1·0 m are compared, the maximum difference in absorption per seat is only 4%.

Bradley [13] has also measured seating in a reverberation chamber at row spacings between 0·6 and 1·05 m; the seating was church pews with seat cushions. Again the absorption per seat is much more constant than the absorption coefficient. There are thus three independent pieces of data which indicate that unoccupied seating behaves closer to a fixed absorption per seat than a fixed absorption coefficient when measured in reverberation chambers.

3.2. ABSORPTION IN FULL-SIZE CONCERT HALLS

The conclusion from reverberation chamber measurements with unoccupied seats thus contradicts Beranek's proposal that seating should be treated as other materials with an absorption coefficient. Rather than leave the question of absorption by area or per seat as if this were the general conclusion, some data will be considered from measurements in actual concert halls.

The unoccupied reverberation times of 17 music spaces were measured as part of the Acoustic Survey of British Auditoria in the early 1980s [14]. Details about the individual halls are to be found in reference [15]. Of the original 17, three halls have been discarded for Figure 4 because they contain significant areas of additional absorbing material (Royal

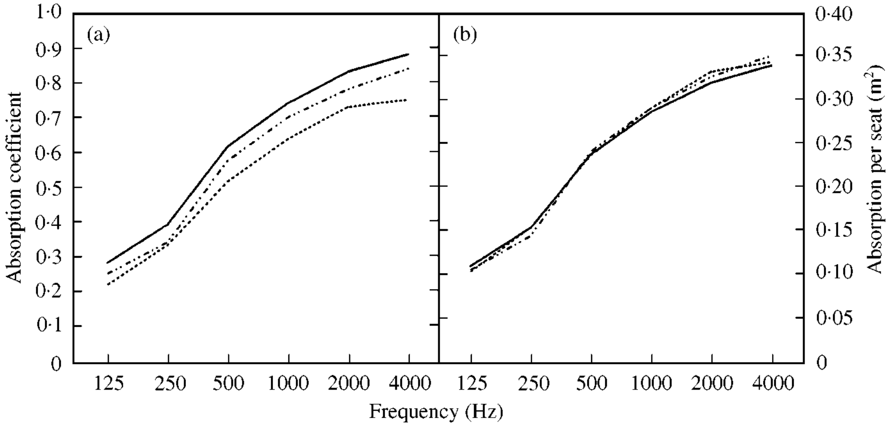

Figure 3. Absorption coefficients (a) and absorption per seat (b) for a block of full-size seating measured by Davies *et al.* [5] with row spacings of ——, 0·82 m; —··—, 0·9 m and ····, 1·0 m.

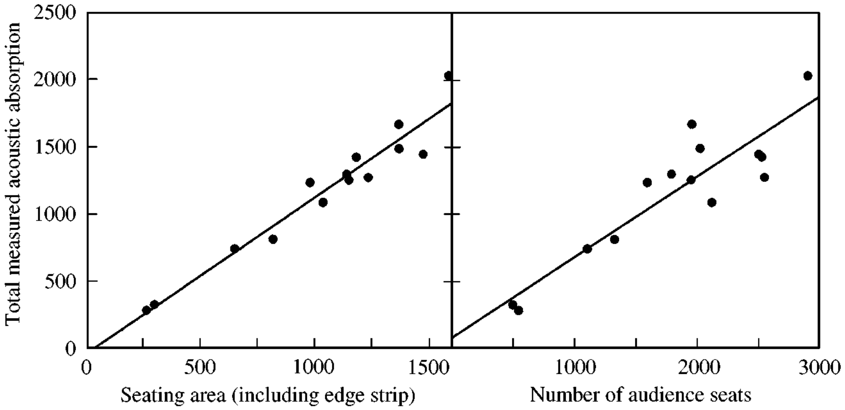

Figure 4. Measured total acoustic absorption (m^2) in 14 unoccupied British halls against seating area (m^2) and numbers of seats.

Albert Hall, London, Watford Town Hall and Wembley Conference Centre). The range of row spacings for the 14 halls is from 0·75 to 1·03 m, with a mean of 0·86 m.

For this simple analysis, the total absorption is derived from measured reverberation times averaged over the three octaves 500–2000 Hz. This total absorption is plotted in Figure 4 against the acoustic seating area and the number of seats. The acoustic seating area here is according to Beranek's prescription with a 0·5 m edge strip. The reverberation time data for the unoccupied halls was all collected as part of the survey using the same experimental equipment and analysis.

Good correlations can be seen in both graphs ($r = 0{\cdot}97$ against the seating area and 0·91 against the number of seats), with better agreement with the seating area. Occupied data is only available for seven of the larger halls (listed in the legend of Figure 5). For the seven halls only in their unoccupied state, the correlation coefficients are $r = 0{\cdot}96$ (by area) and $r = 0{\cdot}50$ (by number of seats). This last correlation is not statistically significant. The higher correlation with the larger data set is a consequence of the larger range of hall size with the 14 halls

Figure 5 is equivalent to Figure 4 using occupied reverberation time data available for the seven halls. In this case there is a very good correlation ($r = 0{\cdot}98$) with the seating area and a non-significant correlation with the number of seats.

This digression into absorption in actual halls thus supports Beranek's proposition that seat absorption should be treated by area. Measurements in reverberation chambers give the contradictory conclusion that absorption by unoccupied seating is more consistent on a per seat basis. This is something of a conundrum. The most obvious difference between the two environments which may possibly be significant is the degree of diffusion. The sound field in a reverberation chamber is highly diffusing, whereas in concert halls the degree of diffusion seems certain to be less, but the degree of diffusion is basically unquantified. The conundrum arises because one would not expect the degree of diffusion to be consistent between different concert halls.

4. QUANTIFYING EDGE EFFECTS ON ABSORPTION BY SEATING

It has long been known [7] that sample size influences sound absorption coefficients for thin porous absorbers; the coefficients tend to be higher for smaller samples. The cause of

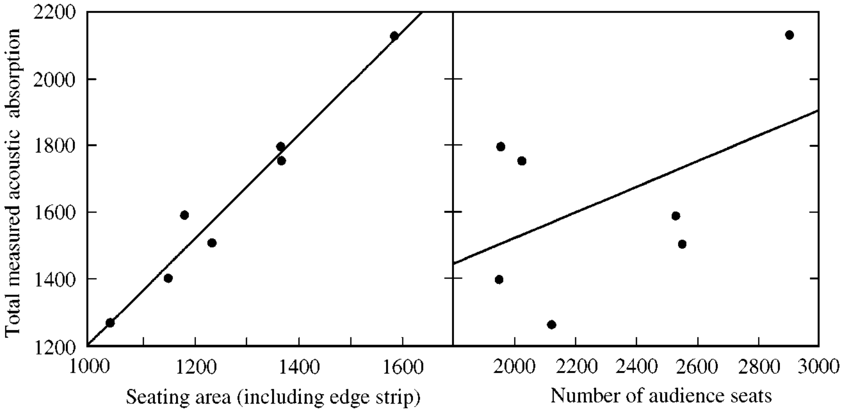

Figure 5. Measured total acoustic absorption (m^2) in seven occupied British halls against seating area (m^2) and numbers of seats. Halls were the Royal Festival Hall and Barbican Concert Hall, both in London; the Colston Hall in Bristol; St. David's Hall, Cardiff; Free Trade Hall, Manchester; Philharmonic Hall, Liverpool and the Usher Hall, Edinburgh.

this behaviour is considered to be diffraction effects at the edges. Studies have shown that the total absorption, A, by thin porous samples can be considered to be made up of two terms, one related to the sample perimeter, P, and the other the sample area, S:

$$A = P\beta + S\alpha_\infty. \tag{1}$$

The coefficient β relates to the perimeter length and has units of metres, α_∞ is the absorption coefficient for an infinite sample. The coefficients can be derived by conducting a series of absorption measurements with different perimeter/area (P/S) ratios, as outlined below.

In the case of seating, the height of the seating means that the vertical sides of seating blocks will also absorb sound. This absorption will also be proportional to the perimeter length of the sample and can thus be included within the coefficient β. Separating out the diffraction component and the vertical edge component of absorption is far from easy; fortunately in practice if β is measured by the procedure proposed by Bradley it is not necessary.

An alternative approach to deal with edge effects with seating is to allocate an edge strip of width d around the seating block to increase the effective absorbing area.

According to this model

$$A = (S + Pd)\,\alpha_\infty. \tag{2}$$

Comparison of equations (1) and (2) shows that

$$d = \beta/\alpha_\infty. \tag{3}$$

In other words, the two approaches are equivalent, edge effects can either be quantified in terms of a coefficient β or by an edge-strip width.

Beranek has proposed an edge strip width of 0·5 m [2]. From Bradley's measurements [7] measured edge-strip widths are small and sometimes negative at 125 Hz. At mid-frequencies occupied chairs and heavily absorbing unoccupied chairs have a positive edge strip width with values of around 0·3 m at 1 kHz. For unoccupied low absorbing school chairs the width is only about 0·1 m at 1 kHz. From values of α_∞ and β measured using the perimeter/area method (next section), the 1 : 25 model chairs had a measured edge strip width of around 0·4 m at all frequencies.

5. MODEL REVERBERATION CHAMBER MEASUREMENTS USING THE PERIMETER/AREA METHOD

5.1. VALIDATION OF THE METHOD

Bradley [7] suggests making five measurements in a reverberation chamber with different seat configurations. The total absorption, $A = S\alpha$, is measured, and from equation (1)

$$\alpha = \beta\, P/S + \alpha_\infty . \tag{4}$$

By plotting the absorption coefficient α against P/S, the perimeter/area ratio, and performing a linear regression the coefficients α_∞ and β can be derived. The area S is taken as the true floor area occupied by the seating block, with no allowance taken for an equivalent row–row space in front of the first row.

The ratio P/S is principally determined by the sample size, but is also influenced to a lesser extent by sample aspect ratio. This is illustrated in Figure 6. In a full-size reverberation chamber, seating blocks with P/S values between about 1·4 and 2·4 m^{-1} can be measured. In large concert halls, on the other hand, typical seating blocks have P/S values of 0·5 m^{-1}. Bradley's proposal thus relies on extrapolation.

Model measurements with the facility already described enabled absorption coefficients in the full range of P/S from 0·4 to 2·4 m^{-1} to be measured. High P/S values are achieved by splitting the seats into several small blocks in the chamber. The seating configurations varied between a single block of 10 rows, four benches wide (roughly 200 seats in total,

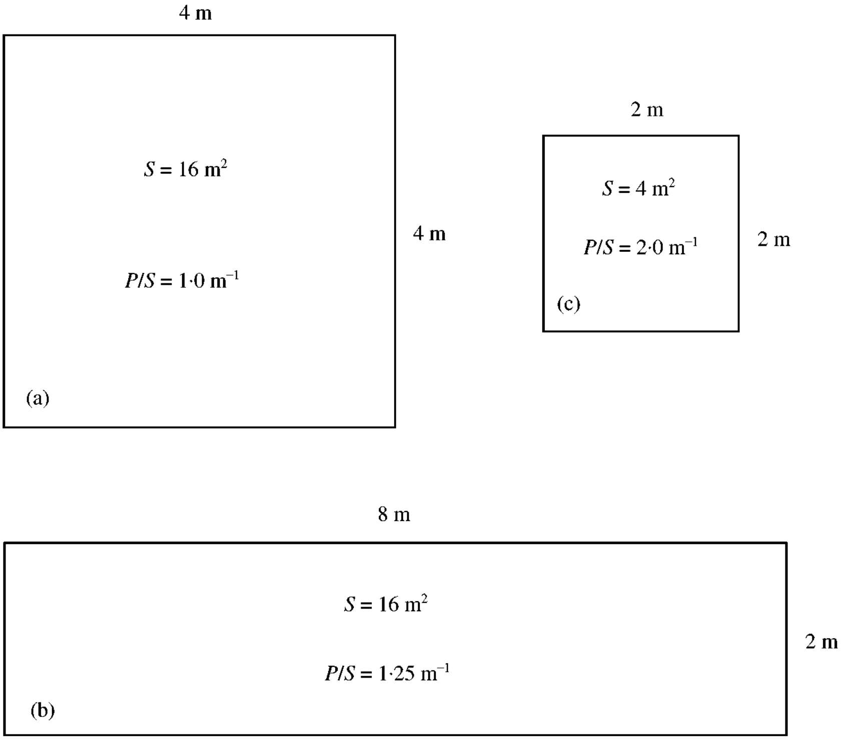

Figure 6. Examples of perimeter/area (P/S) ratio for different absorbing blocks. (a) a square block with $P/S = 1{\cdot}0$, (b) has the same area with a different aspect ratio but P/S does not change much. (c) is significantly smaller and the change in P/S is large.

$P/S = 0{\cdot}4$) to 12 blocks of two rows each, one bench wide ($P/S = 2{\cdot}34$). With multiple blocks, they were randomly oriented on the floor of the model reverberation chamber, with no point of one block closer than 1 m (full-size equivalent) to any other block. A row–row spacing of 0·9 m (full-size) was used throughout. From this experiment the validity of the extrapolation could be checked using a single measurement procedure rather than having to rely on comparing reverberation chamber measurements with absorption measurements taken from reverberation times measured in actual auditoria.

Absorption by the model seating was measured in nine seating configurations, the absorption coefficients are plotted in Figure 7 against perimeter/area ratio. For clarity, values for only three frequencies are shown in the figure; the correlation coefficients between α and P/S for all five frequencies are given in Table 2. At all frequencies the correlations are significant at the 0·1% level and linear with no evidence of curvature. Derived values of the coefficients α_∞ and β for the model seating are plotted in Figure 8 (P/S method lines).

The perimeter/area approach thus appears to be valid and therefore appropriate for the measurement of seating absorption in reverberation chambers.

The perimeter/area method has been criticized by Davies *et al.* [16] because it requires measurements on five seat configurations whereas the barrier method requires only three. However, if measurement time in the reverberation chamber is at a premium, the perimeter/area method can be used with three points only. If the range of P/S used in the reverberation chamber is maximized, the error compared with five points will be modest. The errors associated with this simplification are at least random errors.

5.2. ABSORPTION BY THE FRONT AND SIDES OF MODEL SEATING

A further refinement can be made to the model proposed in section 4 in equation (1), by dividing the edge absorption into that by the front (and back) of the seating block and that by the sides:

$$A = S\alpha = F\beta_f + L\beta_l + S\alpha_\infty, \tag{5}$$

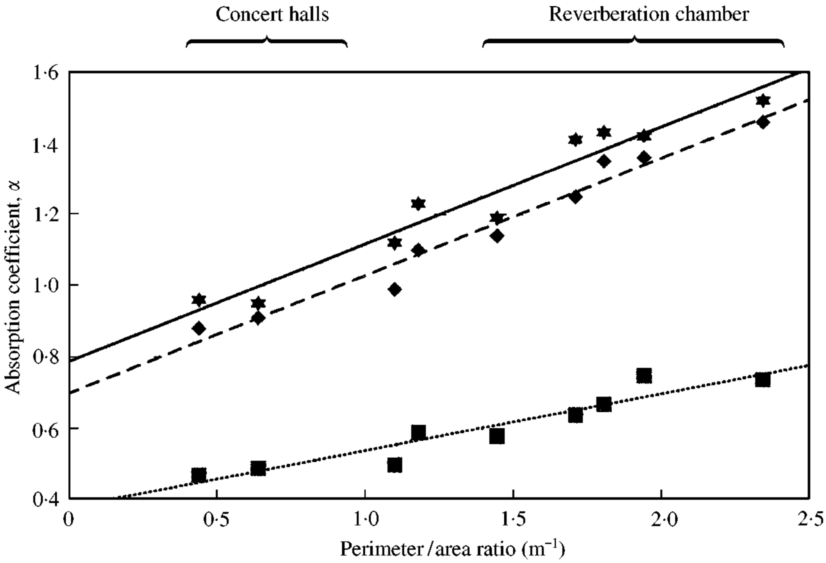

Figure 7. Variation of absorption coefficient of model seats with P/S ratio at ····■····, 125; ····◆····, 500 and –★– 2000 Hz equivalent. Ranges of typical P/S values at full-size are given above.

Table 2

Correlation coefficients for correlations between α and P/S (nine points)

Frequency (Hz)	125	250	500	1000	2000
Correlation coefficient (r)	0·95	0·94	0·98	0·99	0·97

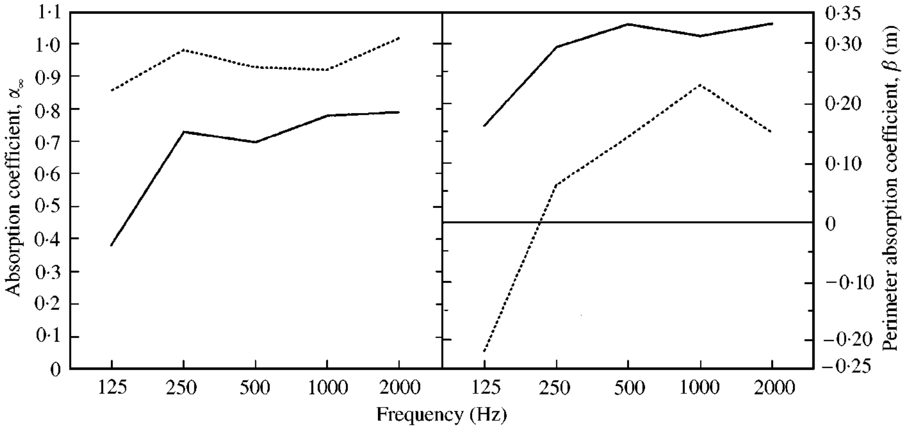

Figure 8. Values of α_∞ and β for model seating, as measured by the perimeter/area method (——) and the barrier method (····).

where F and L are the length of the front and side of the seating block and β_f and β_l are the corresponding edge coefficients. By tabulating values of F/S and L/S for the same nine configurations discussed in the previous section, β_f and β_l were derived by multiple regression on α as a function of F/S and L/S. The measured coefficients are given in Table 3.

Because $P = 2(F + L)$, the coefficients β_f and β_l are of the order of twice those of β in equation (1), etc. The table also includes the ratio of the coefficients to indicate the relative importance of absorption by the front and sides. It is probably reasonable to assume that the back of the seating being hard exhibits little absorption. If that is the case, then at all frequencies the front of the seating absorbs more than the sides. At 125 and 250 Hz the absorption by the sides is particularly small.

One can speculate that calculation of seat absorption in auditoria would be more accurate with separate coefficients for the front and sides of seating blocks. But whether these separate coefficients can be derived with sufficient accuracy from five measurements at full-size in a reverberation chamber is debatable.

Table 3

Coefficients of absorption for the front (and back), β_f, and sides, β_l, of seating blocks

Frequency (Hz)	125	250	500	1000	2000
β_f (m)	0·36	0·67	0·71	0·65	0·70
β_l (m)	0·14	0·19	0·42	0·51	0·48
Ratio β_f/β_l	2·6	3·6	1·7	1·3	1·5

5.3. ABSORPTION BY ONE OR TWO ROWS OF SEATING

Measurements were made on single and double rows of model seating. It is of interest whether the perimeter/area approach (or edge strip approach, since they are equivalent) extends to these cases. Single seat rows are not uncommon, particularly in traditional horseshoe-plan theatres.

The points corresponding to a P/S ratio of 2·34 in Figure 7 were in fact for double rows of length 2·5 m full-size. This case is seen to conform to the general linear relationships.

Measurements were made on the individual benches, which have equivalent full-size dimensions in plan of $2{\cdot}5 \times 0{\cdot}4$ m (area $= 1$ m^2). If one applies the P/S ratio to the literal plan of these benches, they have a P/S ratio of 5·8 m^{-1}. The measured absorption coefficient on the basis of 1 m^2 area per bench is around 2·5 at mid-frequencies, considerably higher than values for multiple-row seating blocks in Figure 7. This is not surprising since with single rows none of the porous absorption is shielded by other seating rows. If one compares the measured absorption coefficient with the prediction according to the perimeter/area method with $P/S = 5{\cdot}8$, the agreement is close: within 11% at 125 Hz and within 7% between 250 and 2000 Hz. This agreement was unexpected and may of course not extend to other seat designs. This measurement provides one piece of data for dealing with the situation of single seat rows.

6. MODEL REVERBERATION CHAMBER MEASUREMENTS USING THE BARRIER METHOD

Measurements were made with barriers around seating blocks, duplicating as far as possible the details of the method used by Davies *et al.* [5]. Whereas Davies had used four rows of six chairs, four rows of benches with a length equivalent to five seats per bench were used to model scale. A row–row spacing equivalent to 0·9 m as used by Davies was employed. The model barrier was of 1·5 mm thick aluminium, which is equivalent according to simple scaling principles to a mass of 100 kg/m^2. Davies used 18 mm chipboard, which would have a mass of 11 kg/m^2. Barrier heights of 0·9 m were used both by Davies and for model measurements. The two measurement procedures did however differ in one respect: Davies placed his sample in the corner of the reverberation chamber and used barriers on one exposed front and one side. The reason for using a corner position was to minimize low-frequency barrier absorption. In the model measurements, seating blocks were surrounded by barriers on four sides. Since the model barriers are proportionally "more massive", it seems unlikely that they would exhibit much low-frequency absorption. The Davies and scale model procedures might be expected to deliver equivalent results except at the lowest frequency 125 Hz.

With the barrier technique, one derives α_∞ with all barriers in place. The coefficients β, β_f and β_l can be obtained by making measurements with the relevant barriers removed. Figure 8 compares the measured values for α_∞ and β by the perimeter|/area and barrrier methods. The differences between them are quite large.

The comparison of results of the two measurement methods can concentrate on differences between the values for α_∞. The ratio between the two model values of α_∞ are listed in Table 5. Bradley [7] quotes α_∞ data for his full-size modern theatre chair type-E, measured using both the perimeter/area method and by the barrier method. These values are reproduced here in Table 4; the ratios of Bradley's α_∞ values are included in Table 5.

Model and full-size values for the ratio in Table 5 are generally similar except at 125 Hz. The barrier approach appears to overestimate α_∞ at all frequencies. Bradley [7] also shows

TABLE 4

Values of α_∞, the absorption coefficient for an infinite sample, measured by Bradley [7] *for full-size unoccupied highly absorbing Type E modern theatre chairs. Values using the perimeter/area method taken from Table* 2 [7] *and with barriers from Figure* 11(*a*) (*edges screened*) [7]

Frequency (Hz)	125	250	500	1000	2000
α_∞ measured by the P/S method	0·47	0·70	0·88	0·99	0·94
α_∞ measured by the barrier method	0·53	0·90	1·00	1·09	1·14

TABLE 5

Values of the ratio of α_∞ measured by the barrier method to α_∞ measured by the P/S method. Full-size values are taken from Table 4 *after Bradley* [7]

Frequency (Hz)	125	250	500	1000	2000
Barrier $\alpha_\infty/(P/S\ \alpha_\infty)$ for model seats	2·32	1·32	1·30	1·21	1·28
Barrier $\alpha_\infty/(P/S\ \alpha_\infty)$ for full-size seats	1·13	1·29	1·14	1·10	1·21

that even with barriers the absorption coefficients of seating varies with perimeter/area ratio. The same observation was made by Hegvold [9] for model seating, as already mentioned in section 1.

In Figure 8 one sees that whereas the values of α_∞ for model seating are higher with the barrier method, values of β are lower with the barrier method. This is in fact inevitable because for both measurement methods a measurement was made on unscreened blocks of four rows and five seats wide, $P/S = 1{\cdot}45$. For the barrier method, the values of α_∞ and β relate to this particular block size. For the perimeter/area method, points for $P/S = 1{\cdot}45$ in Figure 7 lie close to their respective regression lines, indicating that the derived values of α_∞ and β are appropriate for this P/S ratio.

Thus both pairs of values of α_∞ and β will give the same total absorption for the P/S ratio of $1.45\ \mathrm{m}^{-1}$. Though the barrier method would predict accurately for this P/S ratio, there will be inaccuracies when the barrier method values of α_∞ and β are used to predict the seating absorption in auditoria, where P/S ratios will be significantly less than 1·45. Bradley [17] has pointed out that screens introduce new diffraction situations of their own and that is the likely explanation for the two measurement methods giving different results.

7. CONCLUSIONS

Given the expense of testing full-size seats, model testing allows many different situations to be tested cheaply and has the potential to reveal behaviour which can subsequently be checked at full-size. In this experimental exercise, the use of a reverberation chamber effectively many times larger than the standard one allowed a linear relationship to be checked that would be difficult to check at full-size. This paper began by referring to the many problems associated with absorption by audience seating. Reinforcing the point, this study has revealed yet one more complication (item (2) below).

The principal conclusions of this exercise are as follows:

(1) The degree of underpass (the distance between the lowest point of the chair and the floor) may influence absorption by seating. In larger auditoria the degree of underpass is likely to be finite in the Stalls and zero in steeply raked seating areas.
(2) In a reverberation chamber, absorption by seating consistently behaves more closely according to an absorption per seat model when the row–row spacing is changed. However, evidence from full-size auditoria suggests that the standard absorption coefficient is more appropriate (absorption by area). The reason for one approach being appropriate in reverberation chambers and another in auditoria is not clear. For reverberation chamber measurements the conclusion is that they should be made with the correct ultimate row–row spacing.
(3) Bradley's proposal [7] that seating absorption should be treated in terms of a standard absorption coefficient (α_∞) plus a coefficient for the perimeter of the seating block was tested for a wide range of the P/S ratio. Good linear relationships were found. These validate the extrapolation procedure that has to be used when full-size reverberation chamber coefficients are applied to large auditoria. It is not possible to check this in a full-size reverberation chamber.
(4) Surprisingly the perimeter/area method was also found to work for single rows of model seating.
(5) The alternative barrier method for measurement in reverberation chambers was also tested but gave different absorption coefficients to the perimeter/area method. The advantage of the perimeter/area method is that it contains an internal check in the linearity of points on the α versus P/S graphs.
(6) The main criticism of the perimeter/area method is that it requires measurements on five seat configurations whereas the barrier method requires only three. But when reverberation chamber measurement time must be kept short, the perimeter/area method can still be used with measurements on only three seat configurations with only small loss of accuracy.

REFERENCES

1. W. C. Sabine 1922 *Collected Papers on Acoustics*. Cambridge, MA: Harvard University Press (reprinted 1964 New York: Dover).
2. L. L. Beranek 1969 *Journal of the Acoustical Society of America* **45**, 13–19. Audience and chair absorption in large halls, II.
3. L.L. Beranek and T. Hidaka 1998 *Journal of the Acoustical Society of America* **104**, 3169–3177. Sound absorption in concert halls by seats, occupied and unoccupied, and by the hall's interior surfaces.
4. U. Kath and W. Kuhl 1964 *Acustica* **14**, 50–55. Messungen zur Schallabsorption von Personen auf ungepolsterten Stühlen.
5. W. J. Davies, R. J. Orlowski and Y. W. Lam 1994 *Journal of the Acoustical Society of America* **96**, 879–888. Measuring auditorium seat absorption.
6. ISO354 : 1985 Acoustics — Measurement of sound absorption in a reverberation room.
7. J. S. Bradley 1992 *Journal of the Acoustical Society of America* **91**, 1514–1524. Predicting theater chair absorption from reverberation chamber measurements.
8. J. S. Bradley 1996 *Journal of the Acoustical Society of America* **99**, 990–995. The sound absorption of occupied auditorium seating.
9. L. W. Hegvold 1971 *Applied Acoustics* **4**, 257–278. The sound absorption of an audience on unupholstered seating.
10. N. F. Spring, K. E. Randall and M. K. E. Smith 1971 *BBC Research Department Report No.* 1971/3. Acoustic scaling: a one-eighth scale model reverberation room.
11. F. Jacobsen 1987 *Journal of Sound and Vibration* **115**, 163–170. A note on acoustic decay measurements.

12. W. J. Davies 1997 Personal communication.
13. J. S. Bradley 1997 Unpublished results — personal communication.
14. M. Barron and L.-J. Lee 1988 *Journal of the Acoustical Society of America* **84**, 618–628. Energy relations in concert auditoriums, I.
15. M. Barron 1993 *Auditorium Acoustics and Architectural Design*. London: E&FN Spon/Routledge.
16. W. J. Davies, Y. W. Lam and R. J. Orlowski 1993 *Journal of the Acoustical Society of America* **93**, 2238–2240. Comment on "Predicting theater chair absorption from reverberation chamber measurements" [*Journal of the Acoustical Society of America* **91**, 1514–1524 (1992)].
17. J. S. Bradley 1994 *Journal of the Acoustical Society of America* **95**, 1155–1157. Reply to "Comments on 'Predicting theater chair absorption from reverberation chamber measurements'" [*Journal of the Acoustical Society of America* **93**, 2238–2240 (1993)].