BUILDING DIGEST

CENTRAL BUILDING RESEARCH INSTITUTE INDIA

ACOUSTIC DESIGN OF AUDITORIA, HALLS AND THEATRES

Introduction

Enquiries received at the Central Building Research Institute show that there is a demand for concise information on the acoustic design of halls and auditoria and on the corrective measures required when the acoustics of an auditorium prove unsatisfactory. This digest aims at enumerating the basic principles of auditorium design so as to assist architects and to avoid unnecessary expenditure later on.

External Noise

The function of an auditorium, hall or theatre is to provide an environment in which listening conditions are not impaired by audible unwanted sound or noise. The level of unwanted sound inside the hall should be less than that of whispering sound (40 db).

Noise is either air-borne or solid-borne. Air-borne sounds, such as the horn of a motor car or other street noises, find their way into a hall primarily through openings in walls, cracks and leaks around doors. Thin doors are often a source of major noise infiltration. To keep airborne noise transmission low, the walls and ceiling should be massive or sound-insulated. Thus for 40 db inside level and 80 db outside level the sound attenuation required is 40 db (that is 1/10,000 of the outside level). The air-borne sound attenuation provided by some common constructions is given in Table 1.

TABLE I

Air-borne sound attenuation (in db) of common walls.

Type of partition	500 c/s	Average (100-3200 c/s)
1. 22.8 cm (9 in.) thick solid brick (plastered)	48	50
2. 34 cm (13½ in.) thick solid brick (plastered)	49	52
3. 2.5 cm (1 in.) thick solid plywood door	30	—
4. 6.5 mm plate glass	—	28
5. 12.5 mm fibre insulation board	—	18

Impact noises such as those from pile-driving machines and noises from heavy vibrating machines, street cars and running trains are transmitted via the ground or other common paths to the auditorium structure. The structure, as a consequence, is set into vibration, and the noises are thus communicated to the listeners' ears. The prevention of structure-borne noise involves expensive construction, such as floating floors and walls and suspended ceilings. If the noise comes from a nearby vibrating machine, it is usually better to float the source of the noise on resilient foundations and house it in an acoustically treated room.

Halls, auditoria and theatres should, if possible, be located in quiet areas where external noises are low. This will obviate the need for the expensive construction required to deal with loud noises.

Reverberation

Reverberation is the persistence or lingering of sound in a hall after the originating sound has ceased. It arises from multiple reflections of the original sound wave as it strikes the various surfaces of the hall. Each time a sound wave strikes a surface a portion of the incident sound is absorbed, and thus the sound gradually dies out. Reverberation time is defined as the time taken for a sound intensity to decay to one-millionth part of its initial value after the source of sound has ceased. It is expressed as :

$$T = \frac{0.16\ V}{A}$$

where T=Reverberation time, sec.

V=Volume of the room, cu. metre.

A=Total sound absorption provided by the audience, vacant seats and other surfaces acoustically treated or bare, sq. metre.

The functional utility of an auditorium, hall or theatre is determined primarily by its reverberation time. If the reverberation time is short, speech syllables are distinct and intelligible and the hall is suitable for speech purposes. Somewhat longer reverberation imparts depth to musical sounds and hence is suitable for musical and orchestral items. Prolonged reverberation in halls is dangerous as it masks the clarity of the words or musical chords which follow in rapid succession. Among design considerations, the choice of a correct reverberation time deserves special consideration. Moreover, as the hall must not distort the composition of frequencies or pitch in the original sound, reverberation times at all frequencies from 100 to 5000 cycles per second should be more or less the same.

Optimum reverberation time is dependent on the volume of the hall and on the type of production i. e. speech, music, drama or concert. Suitable values for reverberation time to be used when designing halls in India are given in Table 2.

TABLE 2

Recommended values of Reverberation Time

Activity	Optimum Reverberation Time (500-1000 c/s)
1. Cinema	0.6 — 1.2 seconds
2. Lecture, convocation and similar activities using sound amplification	0.6 — 1.0 seconds
3. Chamber music	1.0 — 1.4 seconds
4. Drama, plays	0.8 — 1.2 seconds
5. Orchestra	1.2 — 1.4 seconds

Intelligibility or clarity of speech improves with a decrease in reverberation time. For music, listeners and performers prefer longer reverberation. Since economic considerations generally make it necessary to use an auditorium for everything from speech to orchestral music, a compromise reverberation time of 1.0 sec. or slightly less is recommended.

Volume of the Hall

The cubic volume of the hall is a further important factor in determining its acoustic quality. The louder the sound that will be generated the larger should be the volume of the hall; i.e. the volume of the hall should be proportionate to the size of the source. Auditoria and halls built in India vary from 1700 to 5700 cubic meters (60,000 to 200,000 c.ft.) in volume. These are usually multipurpose halls used to accommodate anything from speech to small orchestra. Average sized halls are designed for seating about 600 persons on a floor area of 335 sq.m.(3600 sq. ft.); i.e. a floor area of 0.46 to 0.65 sq.m. (5 to 7 sq.ft.) per seat is allotted as a compromise between comfort and economy.

Since reverberation time increases with increase in volume and with decrease in the amount of sound absorption, the volume of a hall should be chosen so as to get the correct reverberation. Various considerations show that the volume per seat of the audience should be as near to 4.2 cu. metres (about 150 c.ft.) as possible. A volume of 5.7 cu. metres (about 200 c.ft.) should not usually be exceeded. Thus, for a seating capacity of 600 persons a hall-volume of about 2500 to 3400 cubic metres (90,000 to 120,000 c.ft.) is required. Greater volumes per seat are required for higher reverberation times which are desirable for certain types of music, e.g. Western Symphony Orchestra. Volumes upto 8.5 cu. metres (about 300 c.ft.) per seat are often provided in auditoria abroad.

Design factors

The behaviour of sound in an enclosure is not as simple as in the open air. Walls and ceiling cause multiple reflections of the original sound and these reflections, if judiciously controlled, may create desirable acoustical conditions. Sounds from a source on the stage spread out more or less uniformly in all directions. The loudness of the direct sound decreases as it travels away from the source in accordance with inverse square law. It is still further reduced if it has to travel grazing over the heads of an audience, as the sound waves tend to be "sucked in" towards the absorbent surface provided by the audience. Thus seats should be raked so that the heads of one row do not intercept direct sound to people in the row behind; a clearance of about 100 mm (4 in.) should be provided between the sight lines from two consecutive rows.

When seats have been properly raked so that each member of the audience receives direct sound, the sound level often is too weak for distinct hearing. This phenomenon is noticeable in long halls where the audience at the rear seats receive practically no sound. Recourse has therefore to be had to indirect sound

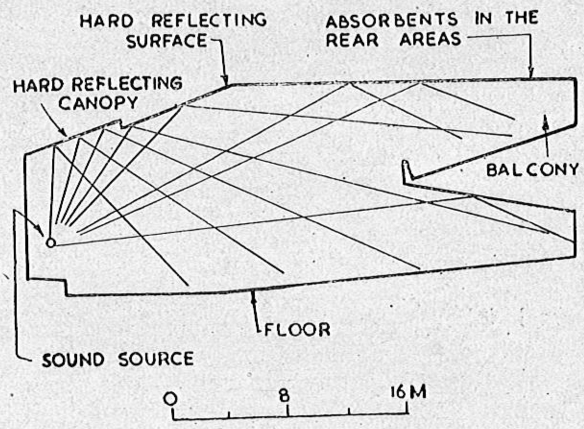

Fig. 1. Longitudinal section through a hall showing a correct ceiling layout for useful sound reflection to the rear seats. Path difference between the direct and the reflected sound at the listening point exceeds 12m (about 40 ft).

reflected from hard surfaces set up in the vicinity of the stage. All reflections of the original sound must reach the listener within 45 milliseconds of the direct sound (Fig.1,2). Any sound reaching him after 45 milliseconds of the arrival of direct sound will be heard as an echo. In order to ensure against interfering echoes, effective ceiling and wall reflectors should be within 8 m. (25 ft.) of the sound source.

Shape

An important factor influencing the acoustics of a hall is the shape of the interior. This should permit

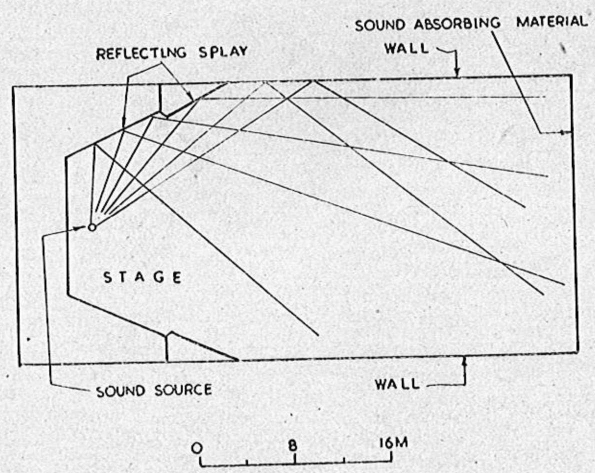

Fig. 2. Plan of rectangular hall showing useful reflections from the wall splays, and stage insets.

players and singers to hear themselves and one another and should enable the audience in all parts of the hall to enjoy the programme on the stage. In short, the shape should be such that with the minimum of ancillary equipment the performance is heard throughout the hall. Among the wide variety of floor plans, there are three basic shapes; rectangular, fan (Fig.3) and horse-shoe shaped. Other shapes such as oval or circular are sometimes adopted, but they are not common as they give rise to acoustical defects which require compensating measures including the use of expensive sound absorbing materials. While rectangular halls have certain accoustical advantages, the fan and horse-shoe shapes have the added advantage of drawing the audience nearer to the stage, reducing thereby the length of the hall.

A hall for the performance of music should be relatively long, narow and rectangular, since properly designed and relatively close parallel walls provide desirable sound reflections. First order reflections from the walls and ceilings of such halls should reach

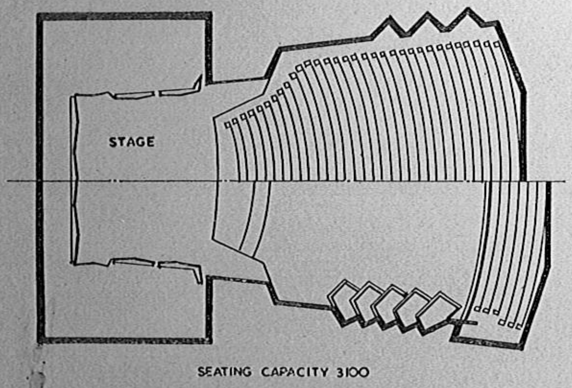

Fig. 3. LA GRANDE SALLE, PLACE DES ARTS, Montreal, showing fan shaped floor plan ; the sides are broken by tiers of boxes.

the remote seating areas within 45 milliseconds of the arrival of direct sound. Splayed hard surfaces (Fig.2) at the sides of a stage and proscenium opening are useful in reflecting sound to rear parts of the hall.

If the hall is rectangular in shape, its width should be 16 to 23 m. (about 50 to 75 ft.). A wider hall may cause long delayed reflections which are dangerous. The length of the hall should not be more than twice the width. Long halls are prone to long delayed sound reflections from the rear walls which should be treated acoustically. The dimensions (length, width and height) of a number of acoustically excellent halls are approximately in the ratio of 2 : 1 : 1 and they are rectangular in shape.

Floor

The audience should have a clear vision of the performance on the stage and direct sound should reach each individual unobstructed. Hence the floor should have a slope gradually rising towards the rear. A typical layout of a sloping floor is illustrated in Fig. 1. This design provides a clearance of 100 mm. (4 in.) between sight lines from two consecutive rows to the head of a speaker on the stage. When a hall is required to be used for other purposes, a flat floor may be designed and fitted with portable sloping gallery.

In large auditoria some form of balcony is almost essential, as otherwise the length of the hall will be excessive. The slope of the balcony should be designed so as to provide clear vision of the stage (Fig, 1). In order to admit enough sound in the areas beneath the balcony, its overhang should not be more than double the free height of the opening of the balcony recess.

Ceiling

The ceiling plays a vital role in reflecting sound to the rear areas of the hall where it is most needed. As a general rule, a hard reflective ceiling that slopes away from the speaker's position (Fig. 1) with a splay at the far end is ideal. When ceilings are laid out, they should be planned to reflect sound directly to the audience or sometimes via the walls, in such a way that it will not be concentrated at certain spots or be reflected to and fro between parallel surfaces, or reach the audience after 45 milliseconds of the direct wave.

When a ceiling is not correct in shape, or is flat and horizontal, suspended reflectors may be used with advantage over the proscenium front (Fig 4, 5). The shape of these reflectors may be flat or slightly convex or pyramidal. They should be large, atleast 2.5x1.3m. (8x4 ft.) and heavy enough not to vibrate with sound waves. Portions of the ceiling towards the far end of

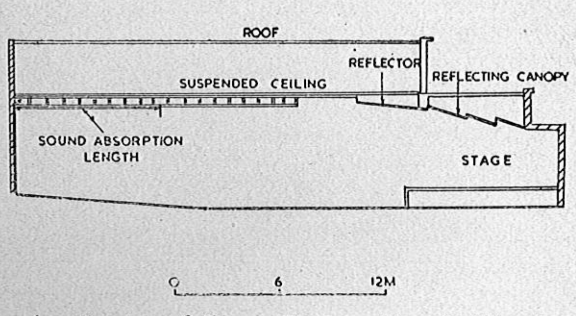

Fig. 4. Section of Sapru House, New Delhi, showing suspended reflectors over the proscenium. Rear portion of the ceiling is acoustically treated. The hall is rectangular in plan and the acoustics is considered "very good", particularly when column type loudspeakers are used.

the hall may, if necessary, be treated with sound absorbing materials (Fig. 4). When balconies are used special measures are necessary to feed the seats on and below the balcony by means of sound waves reflected from the ceiling and the balcony soffit (Fig. 1).

The part of a hall that plays the most significant role in its acoustical success is the "sending end" : the surfaces in the vicinity of the stage. These may be in the form of proscenium splay, suspended canopies or independent suspended panels. In particular, a stage having a large volume and a high ceiling should be provided with a suspended large sized heavy canopy (Fig.4)

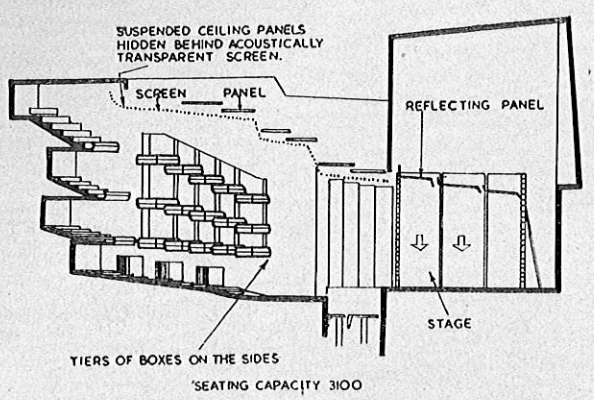

Fig. 5. Sectional Elevation of the LA GRANDE SALLE, PLACE DES ARTS, Montereal, showing suspended ceiling panels required for short-time delay reflections. The space above the panels is used to support reverberation.

or a set of panels (Fig. 5). The acoustical advantage of these reflectors is that useful reflections are obtained and at the same time the space between the canopy and roof may provide the desired reverberation.

Sound Absorption

In auditoria, halls and theatres the bulk of sound absorption is provided by the audience. In order to calculate the sound absorption, the present practice is to assume that two-thirds of the audience is present. An average adult provides nearly 0.46 units (sq. metre) of sound absorption (Table 3), which is equivalent to 0.92 sq. metres of absorbing area having an absorption coefficient of 0.5 (i.e. absorbing half of the incident sound energy). The total absorption by the audience at the middle frequencies (500 to 1000 cycles per second) is 0.46 x number of persons. Upholstered seats are usually used in auditoria. Each of these seats when unoccupied, also provide nearly 0.4 units (sq. metre) of absorption. Thus the reverberation times of the empty and full hall will be nearly the same if suitably unholstered theatre chairs are used.

Table 3 : Sound Absorption Coefficients

Material	Absorption Coefficients 125 c/s	500 c/s	2000 c/s
1. Audience seated in fully upholstered seats (per person)	0.18*	0.46*	0.51*
2. Seats (unoccupied) fully upholstered (per seat)	0.16*	0.4*	0.44*
3. Glass wool or mineral wool 25 mm (1 in.) thick on solid backing	0.1	0.5	0.85
4. Glass wool or mineral wool 50 mm (2 in.) thick on solid backing.	0.2	0 8	0.85
5. Curtain (medium fabrics) hung in folds or spaced away from wall	0.1	0.4 .	0.5
6. Asbestos spray 25 mm (1 in.) on solid backing unpainted	0.15	0.5	0.7
7. Plaster, lime or gypsum on solid backing	0.02	0.02	0.04
8. Linoleum, cork tiles, wood blocks	0.02	0.05	0.1

*Absorption units expressed in square metres.

Where the calculated reverberation times are in excess of the optimum, extra absorption must be provided by treating suitable areas with sound absorbing materials, The total absorption is found by multiplying the area of each different types of surfaces by its absorption coefficient (fraction of the incident sound energy it absorbs) and then adding these products together.

As an example, the reverberation time of a hall 3,000 cubic metres in volume and accommodating 600 persons is chosen as 1.2 seconds. The total absorption required is :

$$A = \frac{0.16 \times 3,000}{1.2} = 400 \text{ units (sq. metre)}$$

Of this total absorption, 0.46 x 400 = 184 units (sq. metre) are provided by 400 occupants (two thirds of the total audience) and the rest 216 units are required to be provided by the vacant seats, sound absorbing materials plastered surfaces, wooden panelling on wainscot and floor cover on the aisles. Of these balance 216 units, 100 units (sq. metre) may be obtained from 200 sq. metres of sprayed asbestos having absorption coefficient 0.5 at 500-1000 cycles per sec. The rest 116 units (sq. metre) should be provided by the vacant seats and other materials just mentioned.

The location of the absorbing treatment should be chosen carefully. Areas that serve as beneficial reflectors and areas close to the stage should not be covered. Rear walls should be covered particularly when they are concave in shape, as these are likely to cause long delayed reflections to the front seats. It is always well to instal soft acoustical materials at heights above 2.4 m. (about 8 ft.) thus preventing their damage by rough handling. Corners and edges between ceiling and and walls should be acoustically treated.

Sound Amplification System

The need for a suitable sound amplification system arises where the natural sound and the reflections are not of sufficient intensity to be heard distinctly at the rear of the hall. For detailed information on the public address system in enclosures, reference should be made to the relevant ISI code of practice. Briefly stated, two loudspeakers should be used, one on either side of and close to the proscenium opening. These should be mounted at a height 3.6 to 4.5 m. (about 12 to 15 ft.) Column type loudspeakers consisting of a vertical column of loudspeakers fixed in one cabinet is preferable when the hall is highly reverberant or has other acoustical defects.

Faults and their Correction

Acoustical defects in auditoria, halls and theatres mostly result from the wrong shape of the bounding walls and ceiling. In general, any reflecting concave surface is dangerous unless measures are taken to counteract their focussing effect.

When ceilings are shaped like a parabola or a hemisphere, they may cause sharp concentrations of sound in some places and dead spots at others. A possible corrective measure against this fault is to suspend reflecting surfaces (so called 'clouds') below the main ceiling and over most of the audience area. These clouds' should be heavy and large sized, not less than 2.5 sq. metre (about 27 sq. ft.) and be architecturally pleasing in shape. Alternatively, in order to preserve the architecture, sound absorbents like acoustic plaster (20 mm thick or more) should be applied on the offending surfaces.

Floor plans that involve large concave reflecting walls (as in circular or elliptical plans) should be avoided. To reduce sharp echoes, these areas may be treated with sound absorbing acoustical materials. Alternatively, small irregular surfaces may be fixed in front of the offending surfaces breaking up thereby clear reflections.

Echoes due to delayed reflections particularly from rear walls, should be carefully eliminated by installing sound absorbing materials or diffusing irregular surfaces.

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There is a demand for short notes, summarising available information on selected building topics for the use of Engineers and Architects in India. To meet the need, this Institute will bring out a series of Building Digests from time to time and the present one is the sixth in the series.

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