A Symphony Hall: L'Auditori Barcelona

by

Higini Arau-Puchades

Reprinted from

JOURNAL OF
BUILDING ACOUSTICS
Volume 19 · Number 4 · 2012

MULTI-SCIENCE PUBLISHING CO. LTD.
5 Wates Way, Brentwood, Essex CM15 9TB, United Kingdom

A Symphony Hall: L'Auditori Barcelona

Higini Arau-Puchades,
Arau Acustica,
www.arauacustica.com

(Received 27 January 2012 and accepted 8 October 2012)

ABSTRACT

This paper describes the design of the Concert Hall of Barcelona, called "L'Auditori". The acoustical design of the project was finished in 1990 but it was built later and finally opened on 22nd March 1999. The acoustics of the concert hall have been very well received by audiences.

In this manuscript, we outline several acoustic features which had to be designed using old methods because the more modern systems had not yet been developed. However, construction was delayed nine years, which meant that new computer tools were available when work was coming to an end in 1990, it allowed us to carry out an overall review of many aspects of the design,

A very important issue that required years of research before we discovered the cause of the problem was that musicians could not hear themselves on stage, yet Gade's measurements of ST1 made in 2001 were comparable with those found in the best reference halls. In this paper we discuss this issue, and conclude that the musicians were correct.

1.GENERAL ACOUSTIC DESIGN

This hall was designed with the aim of emulating the acoustics of the three most famous concert halls in the world: the Amsterdam Concertgebouw, Boston Symphony Hall and the Vienna Grosser Musikvereinssaal. It aimed to be a modern version of a classical hall. The hall nominally seats 2326 (maximum 2335) and is the home of Barcelona City & Catalonian National Orchestra

Figure 1. Barcelona Auditorium view

1) Floor shape

When the auditorium was designed, [1], it was decided that the rectangular reference halls should replicate those in the Musikverein Saal in Vienna, where possible. This section is shown in Figure 4.

Therefore, the rectangular floor from the stage applies the golden rule [5] of geometry, on first estimation, as this shape apart from providing very adequate sound distribution within the hall, also provides an excellent ITDG and optimum lateral energy.

The hall is rectangular with a length that is double its width. The width of nearly 31.1m between sidewalls. The height of the ceiling above the stage is 19.3m. There are large areas for the performers: the orchestral platform is 210m^2 and the choir occupies 60m^2. The stalls are divided into three sections: the main stalls with 594 seats in front of the orchestral platform and the side stalls in two terraces to the sides of the stage at two different heights containing 146 and 304 seats each. The main stalls are lightly raked. Beyond the main stalls are two elevated terraces, steeply raked named Amphitheatre (Tier) 1 and Amphitheatre (Tier) 2. On both sides of these terraces are sixteen boxes that seat 10 to 18 each. The first Amphitheatre contains 188 seats, the second 603 and the boxes 196. Finally, there are 8 boxes placed in each side wall, distributed in two levels over the side stalls. They seat a maximum of 19 each.

2) Hall volume evaluation for symphonic use

The air volume of the hall required, for symphonic use, was calculated using our theory, [2], [3], [4]. The graphic, below shows should the value of V for a T_{mid} close to 2s for a full hall, with an audience area of S_A = 1628.2 m^2, equivalent to an audience of N =2326 seats. The determined volume for a T_{mid} =2.03 s, is V = 24300 m^3.

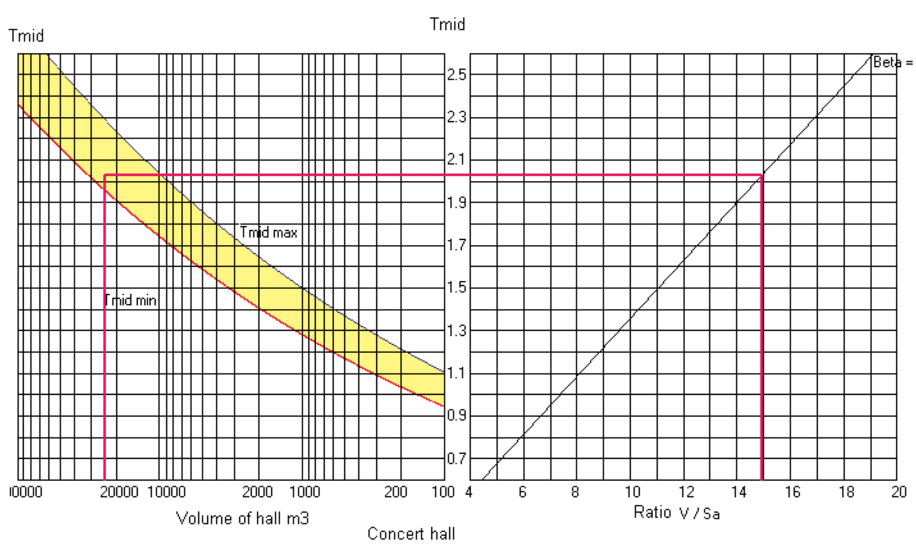

Figure 2. Volume predicted by [2] theory. before start acoustical design is T_{MID} = 2.03 s (occ.) for full hall

On the left hand side graph, in fig 2, the red curve, at the lower, limit of the yellow shaded area, indicates the minimum values for T_{mid} which dictates the acoustic criteria for a concert hall according is its volume, which in this case is T_{mid} min = 1,96 s; whilst the upper black curve indicates the maximum values to be T_{mid}= 2.29 s.

The optimum T_{mid} that the hall should have for symphonic use is T_{mid} (optimum) = $0.9T_{mid}$ max which in our case is: T_{mid} = 2.06 s. Therefore, the calculated value is extremely close to the desired acoustic criteria and we consider that this value is sufficient for this initial phase. The right hand side graphic of figure 2, relates to T_{mid} with volume V and audience area S_A, according [2]:

$$V / S_A = 7.361\ T_{mid} \tag{1}$$

Once the ideal air volume has been determined, we proceed to define the auditorium in 3D, and the materials for its surfaces

3) Ceiling definition in main hall

Ceiling acoustic design criteria:

We know that the wave lengths of sounds should be small in comparison to the surface dimensions, those of the hall and the items the sounds come into contact with. If this were not the case, then diffraction would be significant, something that is, much harder to evaluate, and can completely alter the resulting sound behaviour within a space [5]. Following these criteria we designed individual surfaces as reflector to have, dimensions, at least $L_{x,\,y} > 3\lambda_o$ where λo is the minimum length wavelength of the sound, with a specular reflection over the plane. Therefore, any wave length equal to or lesser than the value chosen one will have an adequate specular reflection.

If the wave length of the sound λ is greater than the length Lx,y of each plane considered, then sound diffraction will be produced.

We know that the reference rooms have diffraction to some extent which, has always believed to be good, because the diffuse energy delivered by scattering is less strong than a specular sound energy produced above a smooth wall.

It is, difficult to judge the amount of diffraction we need on site. We believe that everywhere in the hall, must, have first order specular reflectors where, diffraction is only significant in the low frequency bands 63,125, 250 Hz. From the middle of the hall to the rear we expect produce the gradual diffraction and specular reflection of medium and high frequencies respectively.

We have decided to define the individual planes of ceiling with a transversal and longitudinal beams distribution, the longitudinal beams following a Fibonacci's series which produces a fragmentation of the ceiling into a series, of coffers of different size, Near the stage we have large areas reducing in size slowly towards the rear of the hall, so the range covers wave lengths corresponding to, approximately 68 Hz to 7.906 Hz. These divide up the ceiling into areas that look like coffers, (see fig. 3) but with an arrangement corresponding to a desired, diffraction distribution.

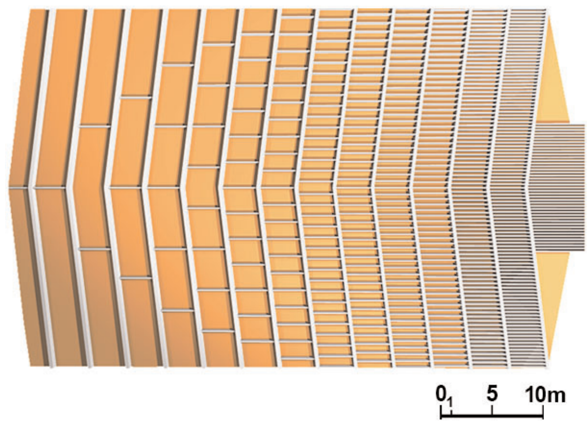

Figure 3. Definition of coffers of ceiling

Ceiling definition:
With this fragmentation proposed for the ceiling we have:

a) The ceiling is divided into two areas. The first one, over the stage, is inclined starting at a height of 11.1m above the stage and ending at 15.2m; it is divided into saw-tooth segments of approximately 2m. This stage was designed by the architect in 1997 to replace the earlier one. We checked it using a simulation programme called Epidaure, and detected no problems.

b) The second one is the main ceiling of the hall which is horizontal but subdivided by means of 14 transverse beams, defining 15 spaces in the ceiling of 3.15m wide. The transverse beams have a rhomboidal section with a 40cm depth, and widths of 30 cm at the bottom and 40 cm at the top.

All the transversal beams connect two longitudinal beams, on both sides of the ceiling, not touching the sidewalls. The transverse beams thus do not, extend to the sidewalls and the longitudinal beams, run the full length of the hall and are located just away from the cornice.

Longitudinal ribs run between the transverse beams; they have a depth of 30 cm and have a rhomboidal section with widths of 10 cm at the bottom and 20 cm at the top. The number of these longitudinal ribs varies along the length of the hall with fewer beams close to the stage.

To exception of the space 15, in rear of the hall, we have repeated the ribs distribution of the space 14 in reduced size because we have adding two triangular flat planes placed in both sides

This arrangement of beams thus defines a beautiful coffered ceiling, with big coffers near the stage and small coffers at the rear of the hall. The grid of beams, which define the coffers, harmonise specular reflection with diffraction produced by the spacing

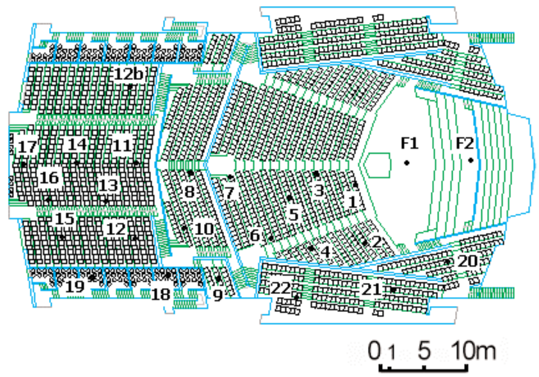

Figure 4. Barcelona Auditorium Concert Hall in plan. The numbers indicate the measurement points. F1 and F2 are source positions.

between the beams and their depth. The acoustical principle behind this ceiling is to provide diffraction, progressively from low to high frequencies. At high frequencies the ceiling section close to the stage provides specular reflections, whereas remote from the stage it diffracts the high frequencies. Listening experience verifies that there is no echo or colouration produced by reflections from the stage.

4) Wall definition

The sidewalls combine vertical and inclined surfaces to provide good reflections to the audience area but at the same time, taking care to avoid echoes and long-path reflections. The wall planes follow the same reflection – diffraction which we have indicated for the ceiling. We can see in this case that the height of the inclined reflectors decreases in height in relation to the floor. See figures 5, 6, 7. The walls surrounding the stage project lateral sound reflections to the main floor.

The hall provides the intimacy and early lateral reflections typical of a rectangular hall and these reflections are supplemented by those from the walls of the lateral terraces and boxes.

One major feature of the design is the absence of any balcony overhangs, which are found in all classical halls.

In our case we have balconies integrated in the sidewalls. This was chosen in order to obtain an even absorption distribution in the hall, resulting in an improved Sabine space, and moreover getting an optimum diffraction from the sidewalls without losing specular reflections required to obtain a good lateral energy. The sidewalls alternate flat zones with inclined zones, the alternations becoming more frequent towards the rear of the hall.

Although the Concert Hall has been designed for symphonic music, it can also be used as a conference room or for amplified music. When configured for symphonic music the side wall sound absorbing curtains are not desployed. The hall is finished in plywood, covered by thin maple, throughout; there is only the absorption due to the seats, musicians and audience. For this use, the reverberation time at mid-frequencies fully occupied and with musicians on stage is 2 sec, ideal for symphonic music.

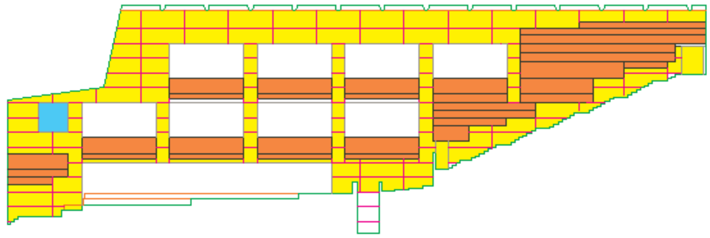

Figure 5. Sidewall elevation. Inclined walls are brown, vertical planes yellow, balconies white and windows blue.

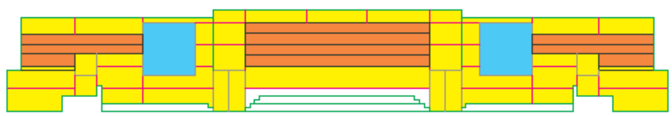

Figure 6. Rear wall elevation. Inclined walls are brown, vertical planes yellow and windows blue.

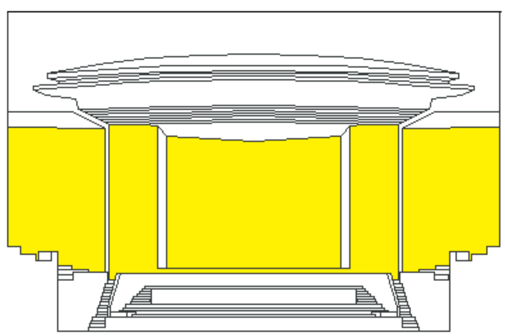

Figure 7. Transverse section through the stage.

For conference-use, several velvet curtains cover the sidewalls (second and third floor of balconies) and the rear walls and also the wall behind the stage. In this configuration, the reverberation time at mid -frequencies fully occupied is 1.3 sec, good for reinforced music and conferences. In this situation a sound system is used to improve intelligibility and coverage.

The background noise inside the hall is very low. With the air conditioning system on, it meets the NC15 criterion. The building is mounted on springs that insulate it from underground and main line train vibrations.NC 15 and ITDG values are an average across all source-receiver positions.

6) Architectural and technical details

Intended use: Symphonic music, recitals and conferences. Ceiling: 20-mm to 35-mm plywood covered with airspace behind. Side, front and rear walls: 25-mm plywood fixed to wall with a hard and elastic filling up material. Floor: Maple parquet fixed over other floor that is floting elastically. No carpet. Stage floor: 45-mm maple over plywood over deep airspace. Stage height: 0.85 m. Added absorptive material: (Only for reinforced music and conferences) Velvet curtains covering the side and the rear walls and also the back stage wall. Seating: Special designed, rigid seat back, front of seat back upholstered; top of the seat-bottom upholstered; underseat, wood linear perforated Helmholtz resonator.

V = 24298 m^3, Volume
S_A = 1628 m^2, Audience surface area
S_c = 60 m^2, Choir area
S_o = 210 m^2, Surface area of stage
S_T = 1891 m^2, Total surface area
N = 2326, Number of seats
H = 15.75 m, average room height, measured from main floor to ceiling in the part of the main-floor audience area not covered by balconies.
Hmax= 19,4 m measured from floor in stalls to main ceiling,
h_{mean} =13.8 m, average stage height
W = 31.1 m, average width measured between side walls
L = 40.3 m, average room length
D = 41.2 m, distance from the front of stage to the most remote listener
SD = 15.26 m. average stage depth
SW = 15.3 m, average stage width.
SH = 13.15 m, mean ceiling height above the stage area.
V/S_T =12.85 m, Ratio volume /area total
V/S_A = 14.99 m, Ratio volume/ audience area
V/N = 10.45 m^3, Ratio volume /number of seats
S_A/N = 0.697 m^2, Ratio audience area /number of people in audience
H/W = 0.5
L/W = 1.29
T_{MID} = 2.06 s (occ.), Reverberation Time occupied mid frequency
EDT_{MID} = 2.4 s (unocc.), Early decay Time unoccupied mid frequency
EDT_{MID} unoc./T_{MID} occ.= 1.17
$C_{80\ MID}$ = -0.5 dB (occ.), Music Clarity
BR (occ.) = 1.18, Bass Ratio o warmth
LEF (unocc) > 0.20, Lateral Fraction
ITDG = 19.5 ms, Interval Time delay Gap
G_{MID} (unocc) = 3.5 dB, Strength unoccupied
ST1 = -14.2 dB, Early Support on stage
Conferences and Electroacoustical Music
T_{MID} = 1.3 s (occ.), RASTI > 0.6 (occ.)
Terminology given here is in references [15],[16],[17].

7) Model Tests

In the first phase of the acoustical design (1989 - 90), a 1:50 scale model of the first design was built and tested in Bath. At the time, the hall had a larger audience capacity and more volume than finally built and the stage and main ceiling were different. These model tests were valuable for the analysis of anomalous reflections (echoes) and other aspects learnt from energy measurements. A low EDT was observed, which resulted in the ceiling being raised. However during the nine-year delay, many changes were made to the auditorium design. From 1990 an in-house computer simulation program was developed, which was used to study anomalous reflections. This analysis led to prescriptions for inclining relevant surfaces to remove long delay reflections and provide useful reflections for the audience. The program has subsequently been developed to calculate objective quantities.

During this period we also modelled with the simulation programme Epidaure.

Our in-house software is not a commercial programme and currently calculates the following points:

1. Study of the reflections and acoustic paths between the sound source and receiver positions. These studies include reflection planes, determination of the intersection points in every plane and temporal delay of reflections. The optimal surface inclination of a room can be determined with the information given in order to avoid anomalous reflections.
2. Analysis of Impulse response: Determination of:
   - Echogram and reflection analysis acoustics determination of:
   - Reverberation Time (RT) in octave bands.
   - Early Decay Time (EDT) in octave bands.
   - Bass Ratio, or warmth, BR
   - Brilliance Br
   - Clarity Index (C_{80}) and (C_{50}) in octave bands.
   - Total loudness level G

3. MEASUREMENT METHODOLOGY AND SYSTEM

Measurements were carried out according to the ISO 3382-1, [6], [7], 1987 and 2007 respectively, where monophonic impulse responses were measured using sweep signals in the 125-4000 Hz octave band range. For each source – microphone couple impulse response measurements were carried out from which the following parameters were obtained:

Parameter
Reverberation Time, T_{30}
Early Decay Time, EDT
Index Clarity C_{80}
Strength G
Stage Support objective of Stage ST1.
The measurements were carried out for each individual source (F1 and F2 on stage-see fig.4) for all
To analyze the effects of the ST1stage support the measurements were performed at several points on the stage depending of year measurement. When determining the ST1, the microphone should be situated a distance of 1m and at 1.2m in height (see figure 25). There were chairs and music stands located on the stage.

Equipment used:
01dB Impulse (1999)
WinMLS 2000
WinMLS 2004
Microphone Bruel & Kjaer 4942
Preamplifier of microphone Bruel & Kjaer 2690
Sound Card digigram vxpocket v2
Omni power sound source BRÜEL & KJAER model 4296
Power Amplifier Brüel & Kjaer model 2716, 300 W.

The measurements we had of the floor of stage with chairs and music stands installed.

Nomenclature and general terminology
In general, we show values as averages in octave bands from 125 to 4000 Hz.

If X is an acoustic parameter we will express this on occasion in low, mid, and high values found as follows:

$$X_{Low} =(X_{125}+X_{250}) / 2; \quad Xmid =(X_{500}+X_{1000}) / 2: X_{high}=(X_{2000}+X_{4000}) / 2$$

4. ACOUSTICAL PERFORMANCE OF HALL

This section presents the measured and calculated values according to statistical theory and the Epidaure simulation program of halls,and values are shown in table 1:

Table 1. Acoustic Parameters values for occupied and unoccupied audience.

Frequency (Hz)	125	250	500	1000	2000	4000	T_{low}	T_{mid}	T_{high}
RT(unoc.) measured	2.75	2.64	2.35	2.41	2.55	2.40	2.65	2.38	2.47
RT(occ.), measured [3], [8]	2.45	2.30	2.09	2.03	2.02	2.00	2.37	2.06	2.01
RT (unoc.) Sabine [20]	2.77	2.53	2.37	2.40	2.52	2.03	2.65	2.39	2.27
RT(occ.), Sabine	2.39	2.33	2.15	2.00	1.98	1.79	2.36	2.07	1.88
RT (unoc.) Arau-P [21]	2.49	2.38	2.33	2.22	2.47	1.89	2.43	2.27	2.18
RT (oc.) Arau-P	2.23	2.28	2.10	2.01	1.93	1.65	2.15	2.06	1.79
RT (unoc.) Epidaure	2.78	2.64	2.42	2.22	2.27	2.06	2.71	2.32	2.17
RT (oc.) Epidaure	2.47	2.43	2.24	2.06	2.06	1.83	2.45	2.15	1.95
EDT(unoc.) measured	2.30	2.25	2.33	2.40	2.51	2.30	2.27	2.38	2.40
EDT(occ.) measured,[3], [8]	2.05	1.96	2.07	2.02	2.10	1.92	2.00	2.04	2.01
C_{80}(unoc.) measured	-3.04	-1.51	-0.24	-0.25	-0.7	-0.45	-2.27	-0.47	-0.58
C_{80} mesured (occ.),[3], [8]	-2.39	-0.73	0.42	0.72	0.30	0.58	-1.56	0.57	0.44
G (unoc),	4.29	4.12	3.52	3.61	3.92	3.62	4.20	3.56	3.77
G measured (occ.), [3], [8]	3.47	3.16	2.67	2.37	2.68	2.39	3.32	2.52	2.53

Average	**Bass Ratio(T_{low}/ T_{mid})**	**Brilliance(T_{high}/ T_{mid})**
(occ)	1.15	0.97
(unocc)	1.11	1.19

Measurement **year 2001**	**ST_{Early} (dB)**
	-14.2

We can see here that the result of RT_{occ} for medium frequencies T_{mid} from table 1 agrees with the T_{mid} value calculated before the definitive design shown in figure 2.

In "L'Auditori" the occupied values have been obtained from using the experimental test values obtained in a reverberant room of "Laboratori General d'Asssaigs i Investigacions". The incremental absorption values Da between occupied and unoccupied seats were:

Table 2. Incremental absorption values $\Delta \alpha = \alpha_{occ} - \alpha_{unocc}$, between unoccupied and occupied seats in Barcelona hall.

Frequency Hz	125	250	500	1000	2000	4000
Incremental absorption: $\Delta\alpha$	0.130	0.136	0.129	0.187	0.244	0.201

From these experimental values, from a sample of 16 seats studied in a test laboratory, we apply the following formulae provided by Bradley [8] equations (3) to (5) and H. Arau [3] equation (2),

$$RT_{occ} = RT_{unoc} / \{1+ (6.14\ S_A\ \Delta\alpha\ RT_{unoc} / V)\} \quad (2),$$

$$EDT_{occ} = EDT_{unoc} \{RT_{occ} / RT_{unoc}\} \quad (3),$$

$$C_{80occ} = C_{80\ unoc} + 13 \log \{RT_{unoc} / RT_{occ}\} \quad (4),$$

$$G_{occ} = G_{unoc} - 16 \log \{RT_{unoc} / RT_{occ}\} \quad (5).$$

where V is the air volume within the Auditorium. And Appendix 1 details equation (2).

The behaviour of measured C_{80} at mid-frequencies in the unoccupied hall is compared with expectations from the Barron-Lee Revised Theory [9] using T_{mid} of the unoccupied hall in Figure 9.

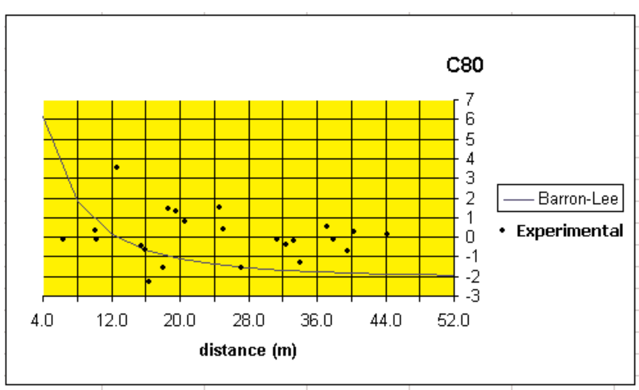

Figure 8. Measured C80 (unocc.)mid versus Barron-Lee theory

On average the C_{80} valuee up to 20 m conform to the Revised theory but after 20 m the C_{80} values are not explained by the Barron-Lee theory.

Comparing mid-frequency G values determined at each point measured to Revised Theory of Barron using the mean value of T_{mid} (unoccupied), we see in Figure **9** that there is excellent agreement between measured and predicted values.

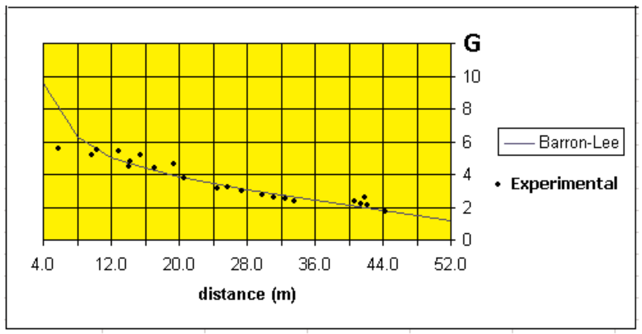

Figure 9. Measured G (unocc.)mid versus Barron-Lee Theory

5. ANALYSIS OF THE BARCELONA STAGE PROBLEM: ST1 SUPPORT OR ST_{EARLU}

The ST_{Early} is used as a descriptor of ensemble conditions, i.e. the ease with which orchestra members hear each other. This ratio is measured at 1 metre from the source, and the values are evaluated at the four octaves between 250 and 2000 Hz and also averaged to give a single value for the particular stage. Normally, measurements are carried out at three positions on stage and averaged [6].

In conclusion, we can see that the values of all acoustic parameters obtained in 1999 and 2001 year for the Barcelona's hall and stage were comparable to those of the most renowned in the world,[16]. However, two or three years after opening in 1999 there were reports that indicated that some problem existed in the stage area.

The musicians couldn't hear adequately for ensemble playing at some stage positions, [11].

In figure 10 we show a zoom 3D-View and the longitudinal section of the stage. The area of musicians is 210 m^2, excluding the choir.

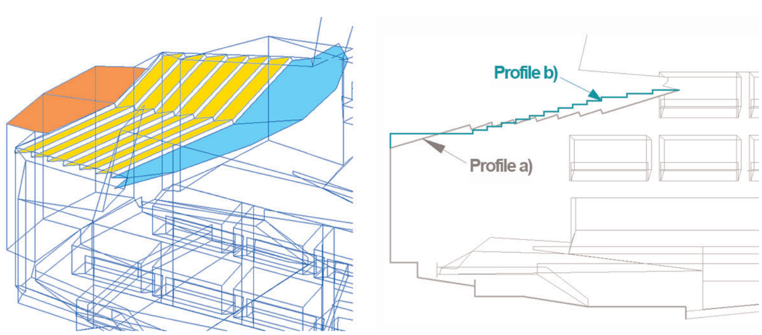

Figure 10. 3D-View and detail of longitudinal section on stage with a) profile initial ceiling, and b) profile proposed solution ceiling

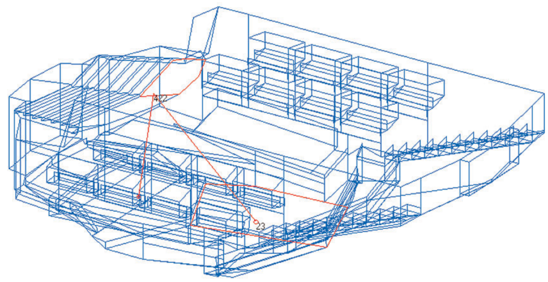

Figure 11 . Example of one acoustic path from stage toward ceiling that goes to audience and never return on stage.

The average height of the ceiling**,** to see profile a) in fig.10, in relation to the platform of stage is 13.8 m. The minimum height of the ceiling, figure 10, (beginning in the yellow zone) is 12.5 m. The maximum height is 15.25 m (in the last blue zone). The nominal volume of the orchestra area is V= 2660 m^3, which corresponds, according to Gade [12], [13] to a ST_{early} = - 14.5 dB, a value which is near to what was found experimentally in 2001.

In the years 2006-2007, we started our research by means of ray tracing calculations. And also, we carried out an in-depth analysis of acoustic paths with many tests (≈100), as shown in figures 11 and 12.The sound from musicians in, the red zone radiating towards the ceiling, produces reflections that arrive as 1st, 2nd or 3rd reflections in the green zone. No reflections, return to the musician that produced, the sound nor to neighbouring musicians as 1^{st}, 2^{nd} or 3^{rd} reflection within the 100 ms critical delay indicated by Gade.

It is as if there was a slight slope in V in the transversal section in relation to long-axis, perhaps due to poor design in construction error. This V transversal of ceiling of stage is not existent in Architectural planes.

We also found that the sound emitted from the green zone mainly goes to the lateral 1 Tier of each side. Finally, we noticed that the sound from the strings and conductor areas hits with ceiling and goes towards the stalls, but nothing goes back to the stage. After those ray tracing calculations, we conducted many measurements of ST_{early} at points on the stage area shown in Figure 13

The overall finding is that no sound produced by a musician returns to him.

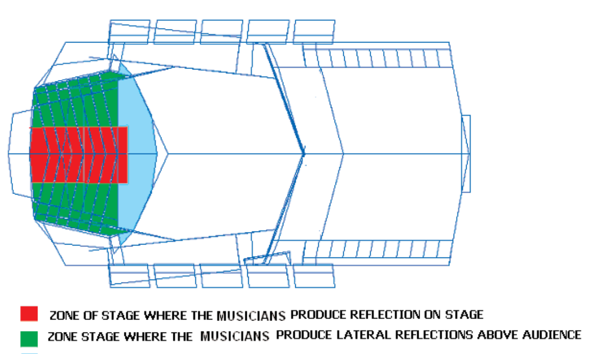

Figure 12. Areas of the stage where the reflections from the ceiling reached the stage

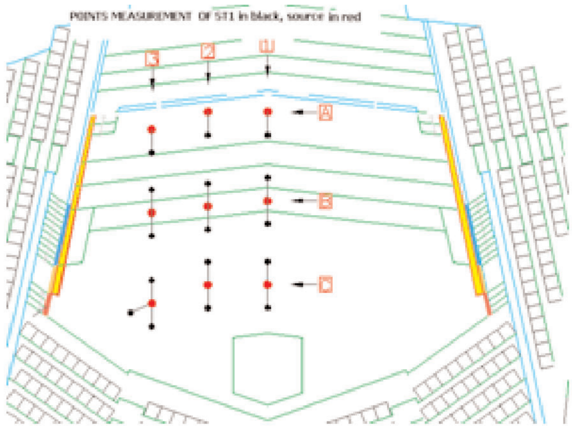

Figure 13. The notation IJ indicates position of source, it is the red point which is at the intersection of rows B, C, and the columns labeled 1, 2 and 3. a source point (the receiver is a 1m in front of the source called F, IJ – F, or behind source called B, IJ-B)

For the ST_{early} measurements the source was an omnidirectional dodecahedron and the receiver a microphone at height of 1.2 m., located at the positions indicated in figure 13.

The spacing between the source and microphone was 1m, either to the front F or behind B as indicated in figure 13. The measurement points IJ were distributed about the stage along longitudinal lines. Beacause of the symmetry of the stage and the hall, measurements were made in only half the stage area.

The results are shown, in Table 3 and figure 15 we obtain a mean value of ST_{early} = -14.8 dB. As we can see from the distributed values, we have ST_{early} = -11.4 dB in the percussion instruments zone, and to ST_{early} = -17.8 dB in the string and conductor zones. The last value is very similar to the mean value ST_{early} at the Concertgebouw in Amsterdam [10].

We found that the ST_{early} values are clearly linked to the geometry of the stage's ceiling.

The blue ceiling area has a sharp increase in slope, for architectural reasons, so that audience members seated at the upper lateral balconies can enjoy good sightlines. This design decision, and others of a similar nature, produce poor acoustic results in terms of ST1 on stage. In figure 10 profile b) we show the solution to the problem of the stage.

NOTE: It is interesting to note the average value for ST1 measured according Gade criterion normalized by ISO with intention to search if the stage has a good acoustic for the musicians. However, sometimes, it is not good for musicians because they feel bad acoustic when the criterion measured indicate a good acoustic on stage.

Table 3 - Measurement results of ST! orST_{Early}

ST1by octaves from 250 to 2000 Hz Sources point	250	500	1000	2000	ST1 averaged	ST1 averaged zone
1A-F	-11.5	-11.6	-7.4	-6.5	-9.3	
2A-F	-10.2	-8.3	-8.5	-14.1	-10.3	-11.5
3A-F	-14.5	-17.7	-17.3	-10.0	-14.9	
1B-B	-14.7	-14.2	-11.8	-15.4	-14.0	
2B-B	-15.9	-17.9	-17.2	-17.1	-17.0	-15.1
3B-B	-13.9	-14.3	-15.1	-13.1	-14.1	
1B-F	-13.7	-15.2	-17.6	-11.5	-14.5	
2B-F	-16.9	-14.8	-10.3	-12.3	-13.6	-13.5
3B-F	-16.4	-10.4	-8.6	-14.7	-12.5	
1C-B	-16.5	-14.4	-16.8	-13.2	-15.2	
2C-B	-19.0	-20.2	-20.7	-16.0	-19.0	-16.9
3C-B	-17.0	-16.5	-15.5	-16.5	-16.4	
1C-F	-19.7	-17.3	-14.3	-14.6	-16.5	
2C-F	-17.1	-16.6	-17.5	-18.1	-17.3	-17.6
3C-F	-16.3	-19.1	-20.0	-20.0	-18.9	
3C-L	-16.2	-16.9	-15.5	-11.1	-14.9	
	averaged overall on stage				-14.9	

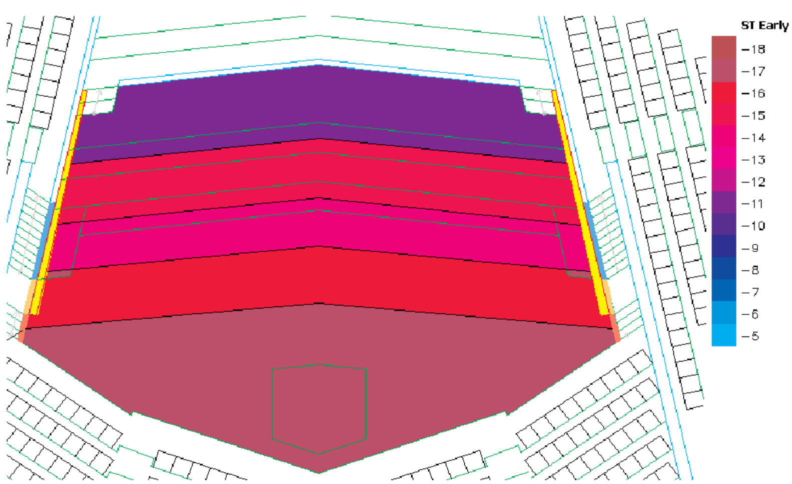

Figure 15. ST_{early} by zones on stage

In Table 3 and Figure 15 the results for ST1 are shown as coloured bands. In Figure 15 we see that the stage area for the strings and round the conductor's podium, have the worst values of ST1.

The ST1 measured in director's position on stage is comparable to the average value of ST1 on all stage of Concertgebouw [15].

We have notice of other venues where Gade's criterion fails. As for example the case of the Tonhalle St. Gallen where sound foccusings and the loud sound produced by the musicians created a strong annoyance to musicians and audience [18]. This was interpreted as loud annoying noise. When the Tonhalle St.Gallen was modified along our lines it met with great success but the measurements of the Gade criterion according ISO 3382 before and after-renewal were virtually identical,[19].

A. Findings:

1. Measurements, in 2006-07 of ST_{early} (average of 17 points on stage) were similar to the 2001 average of three points. These two average results for ST_{early} are equivalent to those of the concert halls with the best reputation, but the acoustic sensation was such that the musicians couldn't hear the reflections from their colleagues, or even their own sound.
2. The stage ST_{early} values shown in Table 3 and 15 reveal that the string instruments and conductor areas are the weakest spots. There is a good correlation between the geometry of the ceiling and the acoustics on the stage.
3. The measurement system proposed by Gade can not distinguish from which zone in the stage the measured sound comes. As a result, we can obtain a good average value but still have a bad acoustic sensation on stage. We found that the ST_{early} measure does not take into account the source directivity nor the direction of the sound reflection nor account for other effect such as echoes flutter and focussing. As a result, we can obtain poor acoustics on stage but the measurement result appears good.
4. Measurements have been traditionally made at three positions on stage and averaged [6]and [7]; but we have found it is preferable in this case to make numerous measurements of ST1, or STearly, along the stage length to calculate average values not only for the whole stage but also for zones within the stage area. Knowledge of ST1 by area allowed us to determine the cause of the problem related to geometry on the stage. For this reason, we question the standardisation of the average value.

6.CONCLUSIONS

L'Auditori of Barcelona was designed before1990 but its construction was only finally completed in 1999. This meant that the project design was carried out without the use of today's sophisticated modelling tools. However the building work took considerably longer than anticipated owing to economic difficulties. After the acoustic design was completed we could check the work of the early stages undertaken fairly basic computing systems with far more advanced methods.

In this paper we have developed the room design based on combining specular reflections and diffraction, having an order based on Fibonnacci series. The acoustic results have been very satisfactory.The measured values are comparable with halls of repute.

However, there was one problem on the stage which has taken us some 10 years to understand.

The average values on stage assessed by the Gade's criterion have always been good as judged in other concert halls, but the musicians were unable to perceive their own music.

This is possibly a common error in halls, but since the majority are smaller in size, the problem is less noticeable.

APPENDIX I: [3]

Equations are the well-known formulae by J.W.C. Kosten [14], LL.Beranek [15], [16], [17]:

$$T_{occ} = 0.16\ V/\ (S_A\ a_{occ} + S_R\ a_R + 4mV) \quad (I.1),$$

$$T_{unocc} = 0.16\ V/\ (S_A\ a_{unocc} + S_R\ a_R + 4mV) \quad (I.2),$$

From both equations, we can obtain the following:

$$S_A\ (\alpha_{occ} - \alpha_{unocc}) = (0.16\ V/T_{occ}) – (0.16\ V/\ T_{unoc}) \quad (I.3),$$

$$S_A\ \Delta\alpha\ /\ 0.16\ V = (1/T_{occ}\ ) - 1/T_{unocc}) \quad (I.4),$$

Resulting in the following final expression:

$$T_{occ} = T_{unoc}\ /\ \{1+ 6.14\ \Delta\alpha\ S_A\ T_{unoc}/\ V\} \quad (I.5),$$

where V is the air volume within the Auditorium and m is the coefficient of air absorption.

7. REFERENCES

[1] H. Arau, (2002) *Procedings of the Institute of Acoustics*, Imperial College London, 19-21 July, 2002.

[2] H. Arau (1997). Variation of the Reverberation Time of places of public assembly with audience size. *Building Acoustics*, 4(2), pp. 87-97.

[3] Higini Arau (1999) ABC de la Acústica Arquitectónica, CEAC (Barcelona), p.268, formula (7.102),(1).

[4] H. Arau-Puchades (2008), Es el criterio Acustico el paradigma de la excelencia acústica en el diseño de salas? SPA-SEA, Coimbra 20-22 Octubro 2008.

[5] Willi Furrer (1964), *Room and Buildings Acoustics and Noise Abatement*, Ed, London Butterworths.

[6] M. Barron, (1993) First edition, Auditorium acoustics and architectural design; 2nd Edition 28/09/2009, E&FN Spon, London.

[7] ISO 3382 Part 1, 1999, 2001, 2007.

[8] J.S. Bradley (1991) A comparison of three classical concert halls, *J. Acoust. Soc. Am.,* 89, pp 1176-1192.

[9] M. Barron and L-J.Lee (1988) Energy Relations in Concert Auditoria I, *J. Acoust. Soc. Am.,* 84, pp. 618-628.

[10] L.L. Beranek (1996) How They Sound: Concert and Opera Halls, *Acoust. Soc. Am.,* (New York).

[11] H. Arau-Puchades (2010) Is Gade's "Support" parameter STearly a sure method to forecast stage acoustics? *Internoise 2010*, June 10, Lisbon.

[12] A.C. Gade (1986) *Acoustics for Choirs and Orchestra platform*, issued by Royal Swedish Academy of Music, no. 52,1986.

[13] A.C. Gade (1989) *Acoustical Survey of eleven European Concert Halls,* Rep. No. 44, Acoustics Laboratory, Technical University Denmark.

[14] J.W.C. Kosten, (1965-66), New method for the calculation of the reverberation time of halls for public Assembly, *Acustica,* Vol. 16, No. 6, p. 325.

[15] L.L.Beranek, (1969) Audience and chair absorption in large halls, II, *J. Acoust. Soc. Am.,* Vol. 45, No. 1.

[16] L.L. Beranek (2004) Concert halls and opera houses, *Musics, Acoustics and Architecture*, 2nd edition, Ed. Springer Verlag.

[17] L.L. Beranek (1965) *Musics, Acoustics and Architecture,* Ed. John Wiley & Sons, Inc.

[18] Arau H. (2010), *Internoise 2010*, Is Gade's "support" parameter stearly a sure method to forecast stage acoustics?

[19] Higini Arau-Puchades, (2011) An acoustics miracle of "Tonhalle St. Gallen" has been produced. but the criterion of Gade on stage has failed before and after the refurbishment of the hall. *Proceedings of the Institute of Acoustics,* Vol. 33, Pt. 2. 2011, Dublin congress.

[20] W.C. Sabine (1900) Dover Pub; 1664

[21] H. Arau - Puchades, (1988) "An improved reverberation formula," *Acustica* 65, No. 163-180