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The acoustical design of the new lecture auditorium, Faculty of Law, Ain Shams University

Ahmed Ali Elkhateeb *,[1]

Architecture and Building Science, Department of Architecture, Faculty of Engineering, Ain Shams University, Cairo, Egypt

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Abstract This work represents the main acoustical design phases for the new lecture auditorium in the Faculty of Law, Ain Shams University, Cairo/Egypt. The work also discusses some of the architectural details that were used and have a direct effect on the acoustical environment inside the auditorium. The work compares finally among field measurements (that were recorded after the construction in the unoccupied auditorium), the values expected during the acoustic design phase (utilizing ODEON ver. 4.2, assuming the occupied case), and the optimum values for speech intelligibility indicators that were considered in this work (T_{20}, D_{50}, STI, LA_{eq}, and the background noise). Field measurements that were recorded utilizing MLSSA system showed that the finishing materials used successfully fulfilled a good level of speech intelligibility in the auditorium. The estimated reverberation time $T_{20\text{-EOC}}$ for the occupied room (based on the measured unoccupied $T_{20\text{-M}}$) was close to the optimum especially in mid and high frequency bands. The measured D_{50} (unoccupied) was found to be within its acceptable range. The measured STI value (unoccupied) was "Fair, 0.49". The measurements of LA_{eq} indicated the uniformity of the acoustical field in the room. The noticed problem was a relatively high background noise (NC-40) due to the utilization of natural ventilation which directly contradicts the principles of room isolation.

1. Introduction

Lecture auditoriums are one of the most important spaces in universities around the world. In the developed countries, the interest in the acoustics of this type of auditoriums has been increased recently as a desire to improve listening conditions. This improvement could finally help in improving the quality of the students' learning experiences.

Lecture auditoriums are distinguished from other types of auditoriums by the usual fixed positions of both: sound source and listeners. Thus, it is possible to acoustically help the speaker through the proper choice of the room finishing materials.

* Tel.: +20 33800675, mobile: +20 0167196671.
E-mail address: aaelkhateeb@yahoo.com.
[1] Professor (A) of Architecture and Building Science, Ain Shams University, Egypt.

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The new lecture auditorium in the Faculty of Law (FOL) has been built to replace an old one that was completely destroyed in the 1992 earthquake and had a capacity of around 1000 students. The new lecture auditorium (or the room as will be named later) that is directly overlooking a crowded street is bounded by two other buildings (each one contains two lecture auditoriums); the first belongs to the faculty of Arts and the second belongs to the faculty of law (Fig. 1) [1]. The author was called upon to join the design team of the room, after it was already constructed, to propose the acoustically fitting. At that time nothing could be done for room shape or form. So, only the finishing materials and the design of the suspended ceiling were considered, taking into account the architectural and economical restrictions.

1.1. Related work

Speech auditoriums are essential spaces in our contemporary life. These auditoriums include a wide range of spaces and usage. Interest in the acoustics of educational spaces in general and the acoustics of classrooms in particular has significantly increased in the past years. Nilsson [2], Hodgson and Nosal [3–5], Bistafa and Bradley [6,7], Sabeer and Abdou [8] and many others have produced a considerable body of work related to this area. The following part presents examples of this work that is more close to this paper.

Knight and Evans [9] investigated and analyzed the acoustical defects in four university lecture auditoriums built in 1961. Three of these auditoriums were identical (capacity of 138 students), and the last one was smaller (capacity of 117 students). The main acoustic defect that was complained by many users of the spaces was the speech intelligibility of students is particularly poor. The poor acoustics in the space were proven problematic due to the discussion-style teaching employed by several professors who used the space. Via many techniques such as site visit, on-site reverberation decay time (T_{60}), background noise measurements, ray diagram analysis and Sabine's formula analysis, the reasons were identified. The spaces were reverberant, flutter echoes and slap back reflections made voice sources difficult to locate. There was moderately excessive HVAC noise and intrusive corridor noise. Although the areas of acoustical treatments (absorptive and diffusive) were adequate, they were not placed correctly in the room and they were not effective. The authors proposed some recommendations including sound isolation and modifications on the walls and ceiling to remove those defects. Some of these modifications were implemented in one room. Then, the T_{60} and background noise were re-measured in this room. Results showed that the modifications were successful, largely due to the elimination of undesirable reflection patterns, the smoothing of the frequency response in the reverberation decay time in the room, and the introduction of beneficial ceiling reflections.

Hodgson [10] utilized MLSSA system to examine the acoustical characteristics of fourteen university classrooms at the University of British Columbia before and after renovation. From the measurements, and theoretical considerations, values of quantities used to assess each classroom configuration were predicted, and used to evaluate renovation quality. Room average Speech Intelligibility (SI) and its physical correlate, Speech Transmission Index (STI), were used to quantify verbal communication quality. A simplified STI calculation procedure was applied. Results showed that some renovations were beneficial, others were not. Verbal communication quality varied from 'poor' to 'good'. The effect of a renovation depends on a complex relationship between changes in reverberation and changes in signal-to-noise level difference, as affected by sound absorption and source outputs. Renovations often emphasis on adding sound absorption to control reverberation at the expense of lower speech levels particularly at the back of classrooms. The absorption and noise contributed by the occupants have often been neglected.

Elkhateeb [11,12] surveyed, assessed and analyzed the acoustical quality within the main lecture auditoria in Ain Shams University (Cairo/Egypt). Nine rooms of different shapes, volumes and capacities were investigated through field measurements (using MLSSA system), ray diagram analysis and Sabine's formula. Field works included the acoustic indicators: T_{20}, T_S, C_{50}, D_{50} and background noise level. In addition; AL_{CONS} was calculated based on the measured T_{20}. All measurements were recorded in the unoccupied rooms except one that was examined both occupied and unoccupied. The results of this room were utilized to validate the methodology applied to predict the occupied T_{20} from the unoccupied one. Results

[1] El-Za'faran Tunnel street

[2] The external auditoria for the Faculty of Arts

[3] The external auditoria for the Faculty of Law

[4] The main building of the Faculty of Law

[5] The main building of the Faculty of Arts

[6] El-Za'faran palace

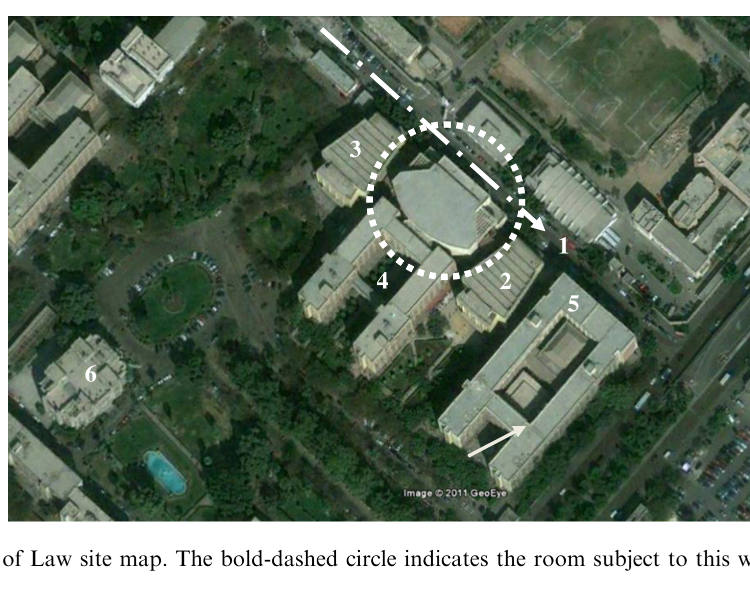


Figure 1 Faculty of Law site map. The bold-dashed circle indicates the room subject to this work.

Table 1 The acoustic objectives in speech rooms, the related objective indicators considered in this work and their optimum values.

Zone	Objective	Indicator	Optimum value
Inside the room	To fulfill good hearing conditions in addition to the classical objectives of room acoustics (a uniformly diffused sound field, free of any defects such as echoes, foci, etc.)	T	0.96 s
		SPL	65–70 dB(A) at listener ears [29]
		D_{50}	0.4–0.6 [17]
		STI	0.6–0.75 Good $>$ 0.75 Excellent
Around the room	To fulfill a minimum background noise levels	Noise criteria curves NC	NC-20 [19]

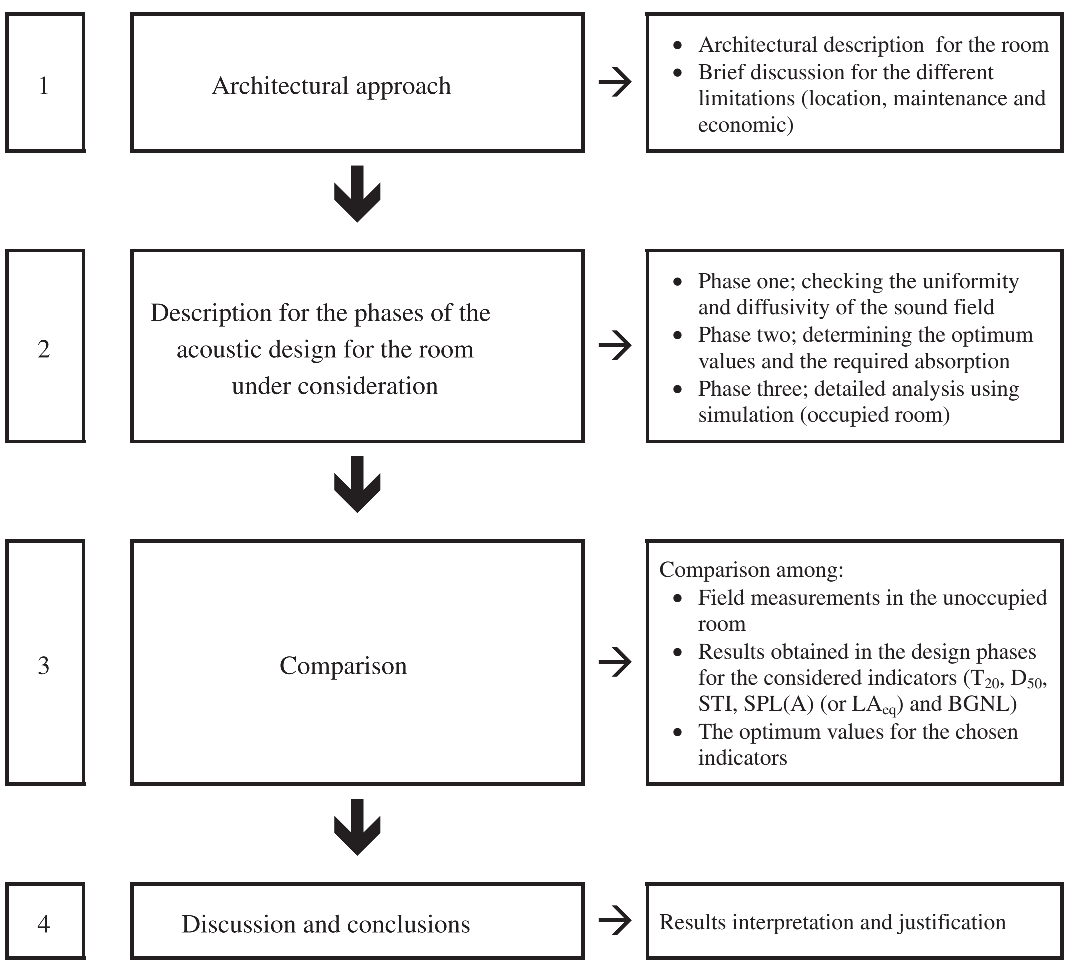


Figure 2 Methodology.

of validation showed a good agreement between the two values especially in the mid and high frequency bands. The overall findings of the work showed that four of the examined rooms having poor acoustical environment due to the excessive reverberation time that exceeds in some cases double or treble the optimum value. Two rooms are not far away from the good hearing conditions and can be easily modified. Three rooms can be classified as good lecture rooms due to their finishing materials. All rooms experience excessive background noise that in some records exceeds NC-55 when the ventilation system (usually many ceiling and wall fans) is on, in addition to noise intrusion from the surrounding urban areas. Simple and economic modifications to overcome the defects were suggested.

For the importance of high quality speech communication in most learning activities, Bradley [13] reported the results of new derivations of acoustical criteria from the recently

Table 2 The absorption coefficient α for audience area (occupied and unoccupied) (Other absorption coefficients were taken from the standard table given in ODEON).

Item	Octave band center frequency						
	125	250	500	1000	2000	4000	8000
Audience on wooden chairs, 2/m^2	0.24	0.4	0.78	0.98	0.96	0.87	0.87
Unoccupied wooden chairs	0.15	0.19	0.22	0.39	0.38	0.3	0.35

published classroom acoustics research studies and compared the new results with the existing standards. The work included a good understanding of children's ability to understand speech in noise, as a function of age, in classroom conditions. The work also described the effects of room reverberation on the intelligibility of speech for young children in conditions representative of classrooms. His findings confirmed that 35 dBA (required in the US and UK standards) is a good criterion for an ideal maximum acceptable ambient noise level in unoccupied classrooms. The optimum reverberation time *T* for occupied classroom was concluded to be 0.5–0.7 s (US and UK standards recommend that the unoccupied *T* should not exceed 0.6 s). Although values from 0.4–0.8 s would be acceptable for many situations, a discussion of other possible factors of influence concluded that lower and higher reverberation times should be avoided. These results showed that *T* criterion required in the US and UK both standards seem conservative and suggested that they should also include minimum acceptable values. The results did not provide strong arguments for major changes to these criteria for acoustical conditions in classrooms for elementary school aged children. Instead; they confirmed the importance of more careful control of background noise levels for younger children and that noise is almost always a serious problem than poor room acoustics.

Zannin and Zwirtes [14] presented the results of an evaluation of acoustic comfort of classrooms in six schools that were built according to a standard design in the metropolitan area of Curitiba (Brazil). These schools can be categorized under three constructive designs, two under each. The acoustic quality of the classrooms was assessed based on measurements of reverberation time, sound pressure level (inside and outside the classrooms), and sound isolation. Measurements of ambient noise (external and internal) followed the Brazilian standards. Measurement of reverberation time and sound isolation followed the international standards. Results of sound isolation and reverberation time were compared with reference values found in the Brazilian and the international standards. Results proved the poor acoustical quality of the surveyed classrooms for the three constructive designs studied. The surveyed designs do not meet the guidelines of either the Brazilian or the international standards employed.

1.2. Objectives

The purposes of this work are to:

- Present and shed light on the acoustical techniques and finishing materials that were applied in the room under consideration. These materials can be utilized in general in other lecture auditoriums since field measurements proved its acoustical validity. These materials have architectural suitability, and are robust from the maintenance point of view.
- Compare field measurements that were recorded after the construction of the room with the optimum values recommended for speech intelligibility, and also with the values that were early expected in design phases.

As the design of the sound reinforcement system was out of the author's scope of work, it will not be described hereafter in detail. Instead, a brief discussion will be presented as required according to the objectives of the work.

1.3. Objectives of good acoustics

It can be said that architectural acoustics in general and auditorium acoustics in particular, seek two main objectives [15,16]:

- The first one is inside the room: to provide a good acoustical environment, which is known as sound absorption and propagation.
- The second one is between the room and its surroundings: which is known as sound isolation.

The achievement of these two objectives is the main concern in every auditorium, but the strategies may differ according to the acoustical activities inside the room. These activities may vary from speech such as classrooms, lecture and conference rooms, to music such as opera houses, or could be a mix of both (speech and music) such as theaters.

To fulfill these objectives, (when the shape and form cannot be altered) it is required to use the appropriate padding materials. These materials act as boundaries or finishing materials. Their purpose is to insure the fulfillment of specific (or optimum) values for a set of acoustic indicators that are determined in the acoustical references according to the acoustical activity inside the room.

From the acoustical point of view, lecture auditoriums are classified as speech rooms where the intelligibility of speech is a vital factor that must be exist. In the modern acoustic practice, the intelligibility of speech is evaluated through a number of objective indicators that express the subjective response of the listeners to the speaker; at the top is the Reverberation Time *T*. The other indicators include (but not limited to) Definition (D_{50}), speech Clarity (C_{50}), Sound Pressure Level (SPL), sound strength (G), Speech Transmission Index (STI), Rapid Speech Transmission Index (RASTI), % Articulation Loss of Consonants (AL_{Cons}), Background noise level BGNL and others.

2. Methodology

For the purpose of this work, the paper outlines the acoustic techniques and treatments that were employed to achieve good hearing conditions in the room. Then, the paper compares

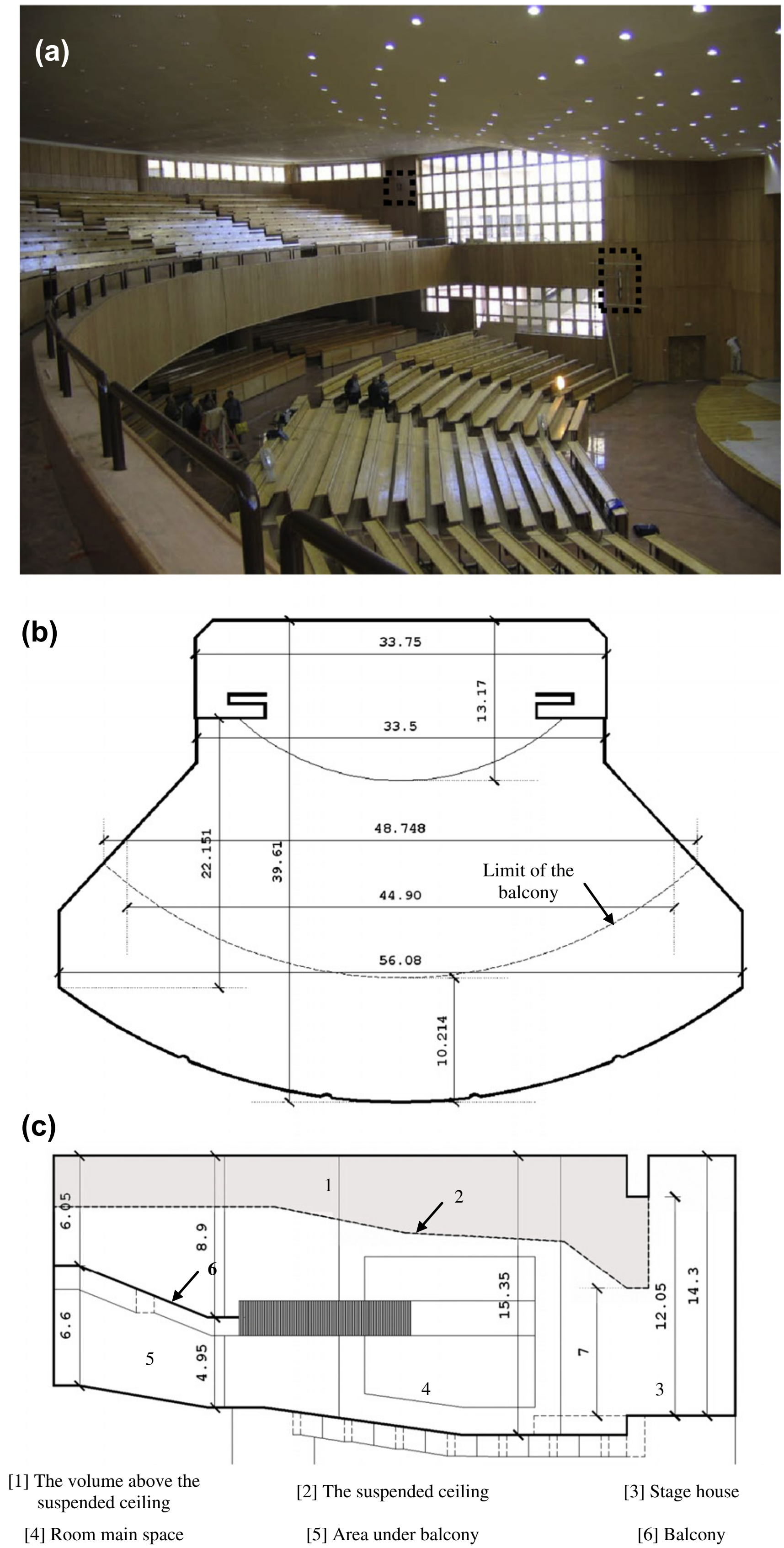


Figure 3 The new lecture auditorium in the FOL, Ain Shams University (Cairo, Egypt). (a) Interior view (The two bold-dished rectangles indicate the positions of loudspeakers, the third loudspeaker is installed under the balcony); (b) room plan; (c) room cross section.

Table 3 Room architectural and geometrical data.

1. Areas (m^2) and perimeter (m)							
Stage House	Floor	Balcony	Total (floor + balcony)	Net audience area: Floor	Net audience area: Balcony	Perimeter	Sh_f [a] m^{-1}
362.8	1287.7	603	1890.7	661	383	162.5	0.10
2. Volumes[b] m^3				3. Max. capacity (persons)		4. D_{MAX} [d] (m)	
Stage House	Whole Room	Total	F_f [c] %	Floor	Balcony	Floor	Balcony
1780.5	14426.8	16207.3	1.0	1450	850	31.8	33
5. Geometrical data							
Area/Person m^2				Volume/Person[e] m^3			$T_{OPT-500}$ s
Net		Gross		Floor	Under balcony	Balcony	
Floor	Balcony	Floor	Balcony				
0.46	0.45	0.89	0.71	9.80	4.31	3.32	0.96

[a] Shape factor (principally; it is the perimeter to area ratio) see Ref. [25]
[b] After the suspended ceiling
[c] Form Factor (principally; it is the Sh_f multiplied by room height. For the room under consideration, room height is taken as the mean room height , calculated as the total room volume /net room area = 9.82) see Ref. [25]
[d] The distance between the sound source (located in the middle of stage) and the remote listener
[e] Calculated as (gross area/person × average height of (floor, under the balcony or the balcony))

among field measurements, the values expected during the design phase for the considered indicators (T_{20}, D_{50}, SPL(A), STI and BGNL) and their optimum values (Table 1), [17]. Fig. 2 illustrates the methodology applied in this work.

In field work, data has been collected using MLSSA system that employs a Maximum-Length Sequence (MLS) signal as a stimulus to measure Room Impulse Response (RIR) [18]. MLSSA has been used in combination with Earthwork microphone (placed at a height of 1.2 m to represent a listener in a seating position) and TOA loudspeaker that has a power of 180–240 W and a sensitivity of 98 dB(A). The loudspeaker has been connected to TOA power amplifier (120–180 W, 10 kohm impedance). MLSSA has been utilized to measure the three indicators; T_{20}, D_{50} and STI.

As field measurements are always problematic when performed in the occupied room [19], the RIR's were acquired (at a full length, 1800 ms) in the unoccupied room according to the requirements and specifications of ISO-3381 [20]. Fifteen positions (distributed among floor, area under balcony and balcony) for the microphone were recorded, for each position; the signal was pre-averaged 2 times. For the STI measurements, a directional loudspeaker was used according to IEC 60268-16 [21]. During the measurements; the relative humidity RH and room temperature t_{AIR} were monitored (RH 34%, t_{AIR} 30.5 °C). For the comparison of T_{20}, the effect of occupation has been calculated and included with a simple statistical model (described in detail in references [11,19]). The absorption coefficients for audience area (occupied [22] and unoccupied [23]) used in calculation were given in Table 2. For the two indicators (D_{50} and STI), field measurements (unoccupied) were compared to the results obtained by ODEON (occupied), the effect of occupation was highlighted.

Measurements of SPL in the unoccupied room were performed using an Extech Integrating Sound Level Meter SLM [24] model 407780 that meets the requirements of ANSI S1.4 and IEC 651 and 804 standards, Type-II precision. The main purposes of these measurements were to adjust the output of loudspeakers, installed in the room as a part of the sound reinforcement system, and to check the uniformity of distribution for the sounds emitted from these loudspeakers. In these measurements, a continuous white-noise signal was pumped to the loudspeakers via the microphone of the system. Then, the SLM was used to record a set of LA_{eq} in the different positions of the room.

3. Room description

3.1. Room shape

The room (Fig. 3) is of a fan-shaped. It consists of three parts; stage, floor and balcony. The total area of the three parts is 2353.5 m^2. The total room volume (including stage house and the volume above the suspended ceiling) is around 21,000 m^3. The total room capacity is about 2300 students distributed between the floor (about 63%) and the balcony (about 37%). With this capacity, the room can be considered one of the largest lecture auditoriums in Ain Shams University. Table 3 lists the most important architectural and geometrical data of the room (the two indicators Sh_f and F_f refer to the shape factor and form factor respectively [25]).

3.2. Architectural design

The architectural design includes an elaborate study for sight lines and angles that enable a student at any position in the room to see the lecturer without any obstruction. For this purpose, stepped rows of wooden benches have been utilized with slopes from 7°48′ (main floor), 9°30′ (floor under the balcony) and 21°54′ (the balcony floor). According to the acoustical references, a good sight line helps effectively in the good acoustical perception where the ability of reading lips helps in achieving part of speech intelligibility; this requires a minimum slope of 7° [16]. Thus, the slopes of the different room floors are compatible with the requirements for good sight lines.

4. Architectural and location restrictions

The most appropriate approach to the acoustical design of this room is to reach an optimized solution between the architectural and location restrictions on one hand, and the acoustical requirements for good hearing conditions on the other. The tough working conditions (8 h daily, 6 days weekly) mandated using marble and granite as finishing materials for the floors to suit the heavy movement of 2300 students. Both materials are reflective. The same conditions also mandated wooden cladding for walls. The wooden cladding can be considered a good choice that achieve – or could be used to achieve – a good acoustic response. The reason is that the wooden panels – employed in the wooden cladding – will be fixed on an air gap, so it will act as a resonant system that could absorb the low frequency bands and reflects the mid and high frequency bands. However, it also may need an optimized solution to absorb the mid and high frequencies when required. Finally, the ceiling has been left completely to the acoustic designer.

The operation economics also mandated the utilization of natural lighting and ventilation in the room. This criterion caused a twofold problem; firstly, it directly contradicts the principles of room isolation required to limit the background noise level in the room. Room isolation cannot completely be fulfilled unless the room is completely closed [16]. Secondly, it limits to a great extent the surfaces that can be covered by the absorbing materials. For example, the room is illuminated via 4 side windows of total area 206 m^2 (about 38% of the total side walls surface area), in addition to two windows at the back of total area of 22.6 m^2. The main problem appears here is that those side windows are located in the back part of the side walls which is the most preferred position for the absorbing materials when required.

As previously mentioned, the room directly overlooks a crowded noisy street and it is enclosed between two other buildings (each one contains two lecture auditoriums) that emit high noise levels. These auditoriums are also illuminated and ventilated naturally, such that their lecturers could be heard clearly in the room under consideration. Thus, it is clear that decreasing the noise levels inside the room to fulfill the international standards will not be achieved (within the available resources). As a result, the acoustical design will only try to lower the bad effects of this noise as much as possible.

Thus, the architectural constraints can be summarized in the following three issues:

(a) Utilizing the natural lighting and ventilation.
(b) Using wooden cladding as a finishing material for the walls.
(c) Using marble and granite as a finishing material for the floors.

5. Phases of the acoustic design

The acoustic design of the room has three subsequent phases:

5.1. Phase one: checking the uniformity and diffusivity of the sound field

In this phase, utilizing the concepts of Geometrical Acoustics GA, the uniformity of the distribution of the acoustic rays was checked in both room plan and cross section respectively. In room plan; the GA analysis showed the existence of a large zone in the middle of the room free of early reflections (1st order reflections, Fig. 4a). This was typically expected due to the shape of the room [16]. In room cross section, GA analysis showed also an acoustic shadow zone in the area under the balcony (Fig. 4b) because of its overhang that obstructs the arrival of rays to this area. These irregularities in ray distribution can be treated by reforming either room boundaries (walls/ceiling) or balcony overhang to provide these zones by the early reflections. As previously mentioned, the acoustical design was started in a later stage after the construction has been finished, so it was impossible to reform either the walls or the balcony overhang, so the study has been oriented towards reforming the ceiling to:

a. Substitute the central zone (in room plan) to remedy the lack in the early reflections.
b. Eliminate the shadow zone under balcony.

The detailed study of ray path diagram according to GA showed that there is a long time delay between the direct and reflected rays, this delay may cause echoes especially at the front benches if it exceeds the Limit of Perceptibility [16]. This was one (among others) of the reasons that encourage lowering down room height by installing a suspended ceiling on a height less than the actual room height. This decision fulfills two acoustic features, the first; it reduces room volume by about 4760 m^3 (about 22% from the original room gross vol-

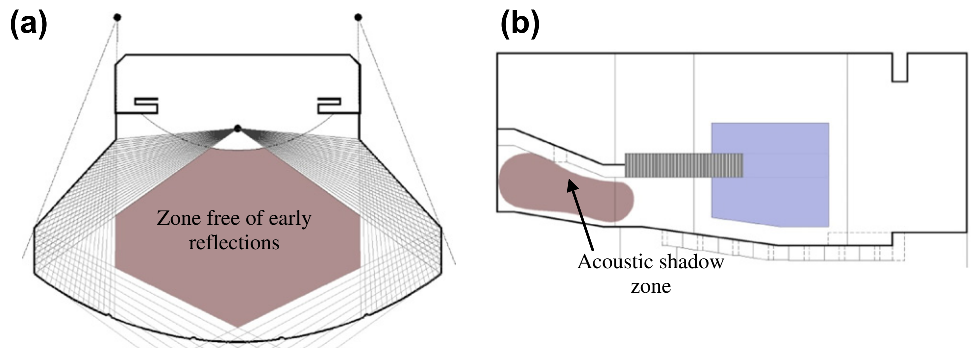


Figure 4 Checking the uniformity and diffusivity of the acoustic field utilizing GA technique. (a) In room plan; (b) in room cross section.

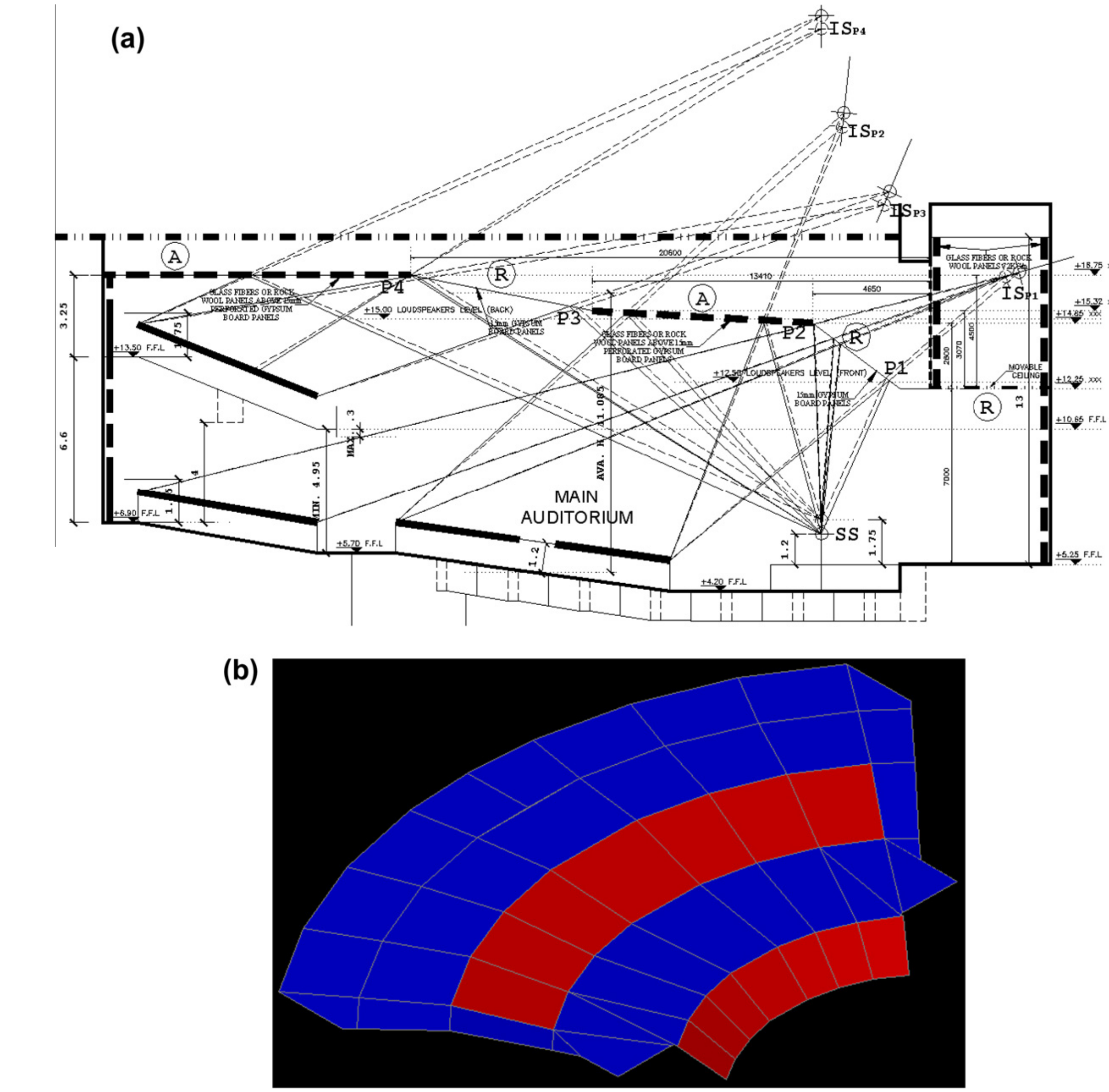


Figure 5 Utilizing GA technique in the design of room ceiling. (a) Cross section shows the shape of the suspended ceiling and the distribution of the reflective and absorbing materials; (b) 3D-representation for the final form of the ceiling (the red color for the reflective and the blue color for the absorptive surfaces). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ume), hence reduces the volume/person criterion from 9 m^3/person to about 7 m^3/person. Consequently, reduces the optimum T of the room. The second, it limits the time difference between the direct and reflected rays so as not to exceed the Limit of Perceptibility. However, this solution has some drawbacks; the most important one is that it isolates the higher part of room space which may cause a non-linear decay of T due to the phenomena of coupled spaces, unless this new space is treated properly.

The part of the suspended ceiling that appeared to be ineffective in reflections was treated as an absorbing surface. Keeping all of the previously mentioned restrictions into consideration, and using the GA technique, the final cross section of the room has been determined to be as shown in Fig. 5.

5.2. Phase two: determining the optimum values and the required absorption

The reverberation time is the most important criterion in any auditorium. As the speech consists of short discrete sounds 30–300 ms in length, and varies between low and high frequencies voices, the room with best acoustical design is the one that insures the ears undistorted reception for the speech sounds [26]. This requires keeping T at its lower accepted limit [26]. A good approximation for the optimum T ($\geqslant$500 Hz, $T_{\text{OPT-500}}$) in a speech room (of volume V, m^3) can be obtained from [26]:

$$T_{\text{OPT-500}} = 0.3 \log \frac{V}{10} \ \text{(s)} \quad (1)$$

For T (< 500 Hz), the values obtained from Eq. (1) must be corrected by the factor R according to Knudsen [27]. The optimum values for the other indicators considered hereafter were mentioned in Table 1.

The values of T obtained by the statistical model are incorrect under Schroeder's Frequency f_s as can be estimated from [28]:

$$F_s \geq 2000\sqrt{\frac{T_{60}}{V}}\ \text{(Hz)} \tag{2}$$

For our room and for an optimum T of 0.96 s (calculated from Eq. (1)), f_s is about 15 Hz. Thus, all the values of T calculated statistically are correct almost for the entire spectrum.

By redefining the shape and position of the ceiling, it was possible to calculate the final room volume, thus its optimum T. By applying Sabine's equation, this T can be converted to a metric absorption that implies a preliminary estimation for the areas required as absorptive surfaces. Sound absorption (through which the T can be controlled) includes a wide spectrum starting from low to high frequency bands. Low frequency bands ($\leqslant$250 Hz) can be absorbed via resonant systems while mid and high frequency bands (up to 10 kHz) can be absorbed via porous absorbers.

The preliminary estimation of the required absorption showed that the available areas cannot provide enough absorption according to the criteria of distributing the absorptive materials in lecture auditoriums [16]. This leads to abandon the concept of fulfilling the optimum T and only to approximate these values as much as possible. The absorptive materials have been distributed between walls and parts of the ceiling according to the suggested design of the ceiling (Fig. 5).

5.2.1. Absorbing mid and high frequencies

Sounds in these bands can be absorbed by porous materials (such as carpets, acoustic tiles, curtains, cotton and fiberglass), these materials are characterized by their relatively high absorption coefficient α in these frequency bands.

In their original form, the absorptive materials have unacceptable appearance from the architectural and environmental standpoint. So many designers prefer to cover these materials by perforated panels made of different materials such as textiles, wood (natural or manufactured), or metal sheets. In all cases, the percentage of perforation must not be less than 15–20% of the total panel area [16]. Covering the absorptive materials by perforated panels fulfills two features; firstly, it protects the absorptive materials against damage. Secondly, it improves to a great extent their appearance.

Figure 7 Absorbing low frequencies utilizing membrane absorber.

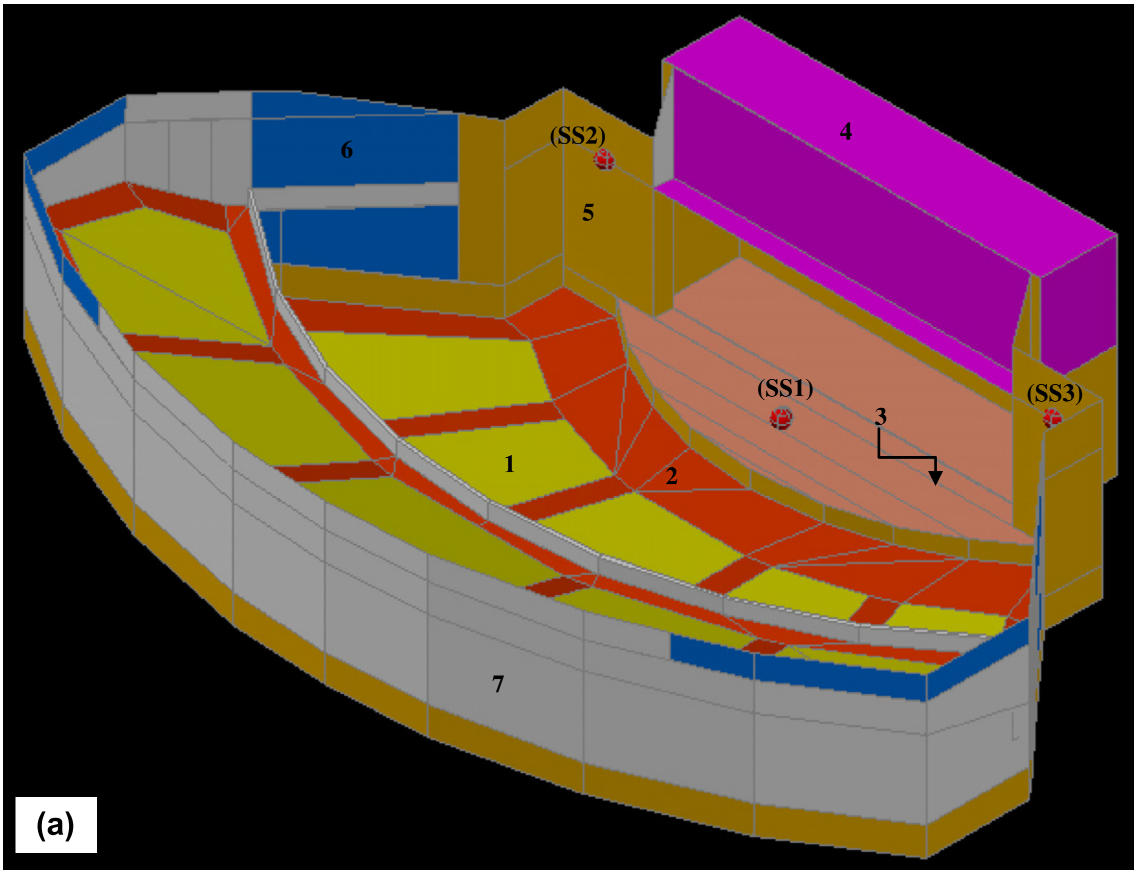
In the room under discussion, fiberglass panels FGP of density 72 kg/m^3 and 5 cm thickness were used as an absorptive material. These panels were covered by a manufactured wood (Medium Density Fiber MDF) panels 12 mm thickness in case of walls (distributed between the side and back walls) and gypsum boards GB of 15 mm thickness in case of ceiling. Both covers have a perforation of 19.6% (Fig. 6). Finally, to prevent the coupling effect, the boundaries of the space above the suspended ceiling have been completely covered by rock wool panels RWP of density 72 kg/m^3 and 5 cm thickness.

5.2.2. Absorbing low frequencies

Sounds in these bands can be absorbed using panel (or membrane) absorber. This system was employed here via MDF panels of 12 mm thick supported on studs 60 cm apart (Fig. 7). It was designed to hold 10 cm air gap behind the panels. The mass per unit area M of the used MDF panels ranges between 9 and 10 kg/m^2. Consequently, the resonant frequency

(a) **(b)**

Figure 6 Covering the absorptive materials FGP with perforated panels. (a) Manufactured wood (MDF), 12 mm thickness (case of walls); (b) GB, 15 mm thickness (case of ceiling).



[1] Audience seated on continuous wooden benches

[2] Granite floors
[3] Wooden floors (stage house)

[4] 5 cm RWP, 72 kg/m^3 density (cladding for the upper parts and ceiling of stage house)

[5] 12 mm MDF panels on 10 cm air gap

[6] Clear glass windows, (double glazing, 6 mm each)

[7] 5 cm FGP, 72 kg/m^3 density covered with 12 mm MDF perforated panels

(SS1) Omni sound source, power 70 dB re 1 pW at speaker's position (height = 1.75 m)

(SS2) and (SS3) Semi-Omni sound source, power 95 dB re 1 pW at loudspeakers positions (height = 8.25 m)

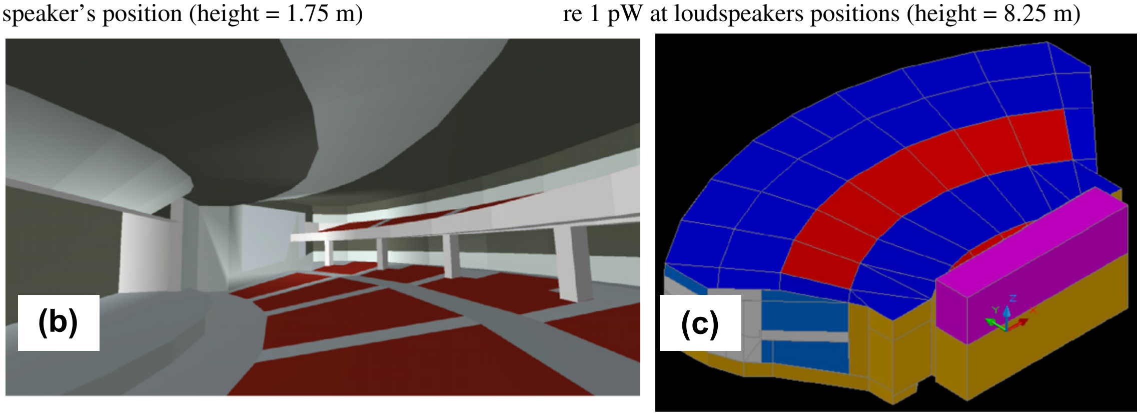


Figure 8 Different views for the CAD model studied by ODEON. (a) Inside view (ceiling omitted) represents the distribution of the different finishing materials (see Fig. 5 for ceiling); (b) inner view generated by ODEON; (c) external view for the CAD model.

f_r of the system ranges between 58 and 60 Hz as can be estimated from [28]:

$$f_R = \frac{60}{\sqrt{Md}}(Hz) \qquad (3)$$

where d is the thickness (depth) of the cavity (m).

This system was installed on the front one-third part of the side walls in addition to the walls of stage house (Figs. 7 and 8). The utilization of this system adds an important advantage, while it absorbs the unwanted low frequency bands; it acts as a reflector for the mid and high frequencies that is essential for the intelligibility of speech. Due to its location in the front near

Table 4 ODEON setups and calculation conditions.

Number of faces in the model	287	Background noise level (for STI)	NC-30
Number of rays (recommended by ODEON)	4846	Transition order	3
Max. reflection order	2000	l (mean free path)	8.5 m
Impulse response length	2000 ms	t_{AIR}	20 °C
Impulse response resolution	2 ms	RH	50%

Sound sources; 3 sound sources were considered, one in the assumed location of the lecturer, the other sources were located in the front wall to simulate the suggested locations of loudspeakers; (Fig. 8).

Table 5 Scattering coefficients.

Audience	Materials with rough surfaces (e.g. gypsum boards, wood)	Glass, marble, granite
0.7 [28]	0.3 (suggested by author based on Ref. [28])	0.1 [28]

the sound source, it reflects effectively and early the high energy sounds always required for the intelligibility of speech.

In case of walls, and in order to improve the absorptivity of FGP in these bands, 5 cm air gap has been left between FGP and the rigid wall behind [16].

5.3. Phase three: detailed analysis using simulation

Using CAD software, a 3-D model has been constructed. This model contains all of the architectural details and the different finishing materials according to the previous discussions. It also includes the suggested positions for two loudspeakers in addition to the main sound source located in the middle of stage at speaker's position. The model was acoustically analyzed using ODEON ver. 4.2 to calculate the considered acoustic indicators related to speech intelligibility and to check their compatibility with their optimum values as mentioned previously in Table 1. The calculations of STI, D_{50} and SPL(A) assume that all of the three suggested sound sources are (on). Fig. 8a shows the different materials assumed and their locations, and Fig. 8b and c show internal and external views for the model prepared for this phase of the analysis.

In simulation, the room was considered occupied. The absorption coefficients "α" for the different faces of models were chosen from the standard table given in ODEON except for the students where their "α" was taken according to Kuttruff [22] (Table 2). The different setups, calculation conditions and scattering coefficients used in simulation were listed in Tables 4 and 5.

6. Field measurements vs. expected and optimum values

RIR measurements have been performed in 15 positions uniformly distributed across half the symmetric room according to the international standards for measuring T in the unoccupied rooms [20]. Twelve positions were distributed in the main floor and under the balcony, and three in the balcony itself (Fig. 9). The RIR's were acquired at a full length (1800 ms), in order to improve the presentation in this figure, the presented RIR's were truncated to about 700 ms, where the signal reaches a steady state oscillating around zero. The RIR's do not show any echoes. The analysis of the acquired RIR's proves the linear decay of the sound energy inside the room. A clear evidence for this linearity is the values of correlation coefficient r calculated for Schroeder's curve (obtained by MLSSA by the backward integration for the acquired RIR's). Most of r values are close to unity. This linearity reflects the success of the treatment of the volume above the suspended ceiling (Fig. 3c). As previously mentioned; and during the acoustic design, five objective indicators were considered (T_{20}, D_{50}, SPL(A), STI and BGNL). For comparison, these indicators are discussed below.

Due to the architectural constraints, the optimum values for some of the mentioned acoustic indicators cannot be achieved. Nevertheless, field measurements give values in most cases better than what is early expected in design and analysis phases. For example, T estimated for the occupied case ($T_{20\text{-EOC}}$) – based on the results of field measurements – are better than the values expected earlier in the design phase ($T_{20\text{-ODEON}}$) in the range from 250 Hz to 8 kHz. The $T_{20\text{-EOC}}$ curve seems close to the optimum values (T_{Optimum}) in the mid and high frequency bands (Fig. 10). The maximum difference between $T_{20\text{-EOC}}$ and $T_{20\text{-ODEON}}$ curves appears in the low frequency bands at 250 Hz ($T_{20\text{-EOC}}$ is about 10% less than $T_{20\text{-ODEON}}$) and in the mid frequency bands at 1 kHz ($T_{20\text{-EOC}}$ is 22% less than $T_{20\text{-ODEON}}$).

Fig. 10 also indicates that the situation is reversed in the high frequency bands ($\geqslant$2 kHz) where $T_{20\text{-ODEON}}$ seems less than $T_{20\text{-EOC}}$ (but, $T_{20\text{-EOC}}$ is much closer to T_{Optimum}). In this range, the maximum difference between the two values ($T_{20\text{-EOC}}$ and $T_{20\text{-ODEON}}$) appears at 8 kHz ($T_{20\text{-ODEON}}$ is about 16% less than the $T_{20\text{-EOC}}$). Yet; all values in this band lie under the optimum. At 4 kHz, the two values ($T_{20\text{-ODEON}}$ and $T_{20\text{-EOC}}$) are almost identical.

The maximum difference between the $T_{20\text{-EOC}}$ and T_{Optimum} appears again in the low frequency bands (Fig. 10) at 250 Hz ($T_{20\text{-EOC}}$ is about 33% higher than the T_{Optimum}), in the mid frequency bands at 500 Hz ($T_{20\text{-EOC}}$ is about 24% higher than the T_{Optimum}) and in the high frequencies at 2 kHz ($T_{20\text{-EOC}}$ is about 20% higher than the optimum). At 8 kHz, $T_{20\text{-EOC}}$ becomes less than the T_{Optimum} by about 22%.

D_{50} is the second indicator for speech intelligibility. Fig. 11 represents that all of the measured values (unoccupied case) are located in the acceptable range (the gray zone in Fig. 11), except at 8 kHz that exceeds the range and seems better than required. It is important to keep in mind that it is expected for these values to reach their best in case of occupation

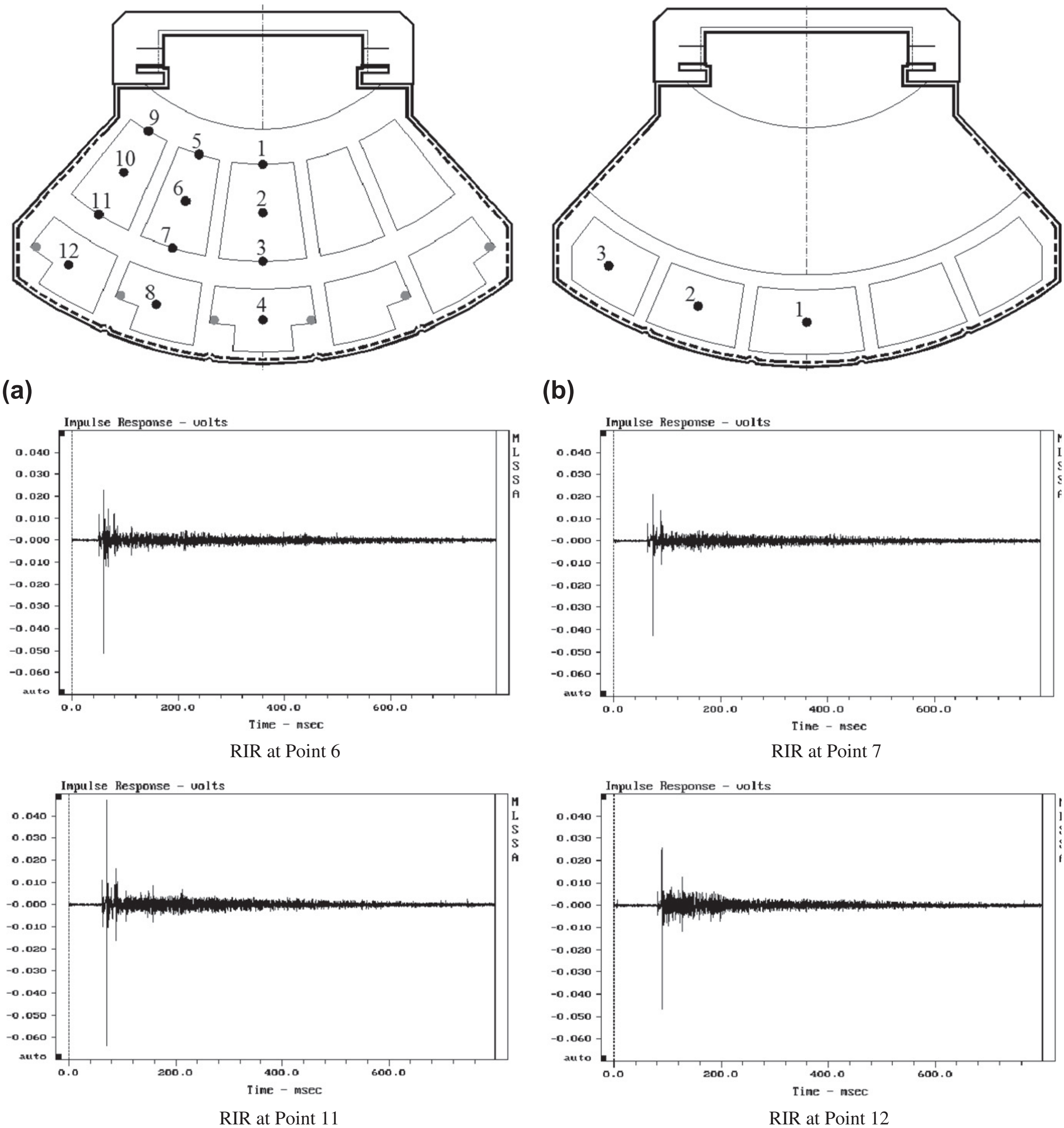
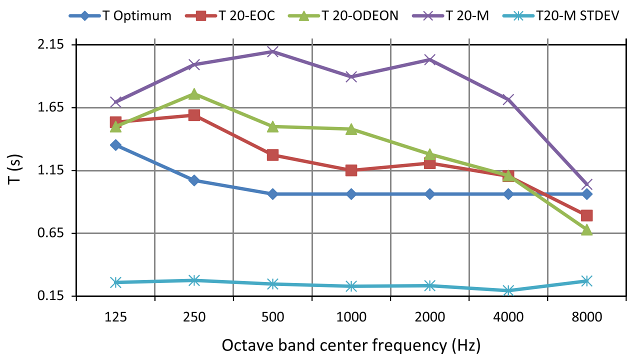


Figure 9 Positions for the acquired RIR's and examples from the responses acquired at different positions. (a) In the floor; (b) in the balcony (The gray points in (a) indicate columns).

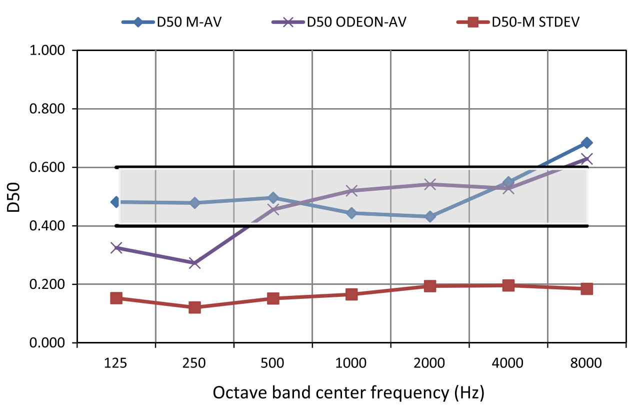
where T will noticeably decrease. The average measured D_{50} is around 0.51 which indicates speech intelligibility SI of more than 90% according to Kuttruff [22].

The quality of speech can be judged also from the values and spatial distribution of STI map calculated by ODEON in the room, values are calculated on a grid 0.5 m apart. As can be concluded from Fig. 12; two main zones can be identified; the first contains ''Excellent to Good'' STI. This zone is close and concentrated around the main sound source SS (located in the middle of the stage), occupies almost the front part of the floor level away from the balcony. The second zone contains ''Fair'' STI; it is much larger and directly follows the previous one. This zone also contains small areas located at the corners of the room where there are slight increase in the values of STI due to the reflections of the side and back walls. From the statistical point of view, about 37.5% of the students receive intelligibility between ''Excellent and Good'', and about 62.5% receive ''Fair'' intelligibility.



$T_{Optimum}$	= T optimum
$T_{20\text{-}EOC}$	= T estimated for the occupied case
$T_{20\text{-}ODEON}$	= T calculated occupied (by ODEON) in design phase
$T_{20\text{-}M}$	= T measured unoccupied
$T_{20\text{-}M\ STDEV}$	= Standard deviation for the measured T_{20}

Figure 10 Reverberation time, optimum, calculated and measured.



$D_{50\ M\text{-}AV}$	= Average D_{50} measured (unoccupied)
$D_{50\ ODEON\text{-}AV}$	= Average D_{50} calculated by ODEON (Occupied)
$D_{50\text{-}M\ STDEV}$	= Standard deviation for D_{50} measured (unoccupied)

Figure 11 Definition D_{50} (measured unoccupied and calculated occupied by ODEON) (Shaded area indicates the acceptable range).

The average value of the measured STI is about 0.49 (Fair on the STI rating scale), where the average of the designed value (calculated by ODEON, assuming the occupied case) is around 0.58 (also "Fair" on the STI rating scale, but near to the lower limit of the "Good" zone). The difference between the two values can be explained as field measurements were recorded in the unoccupied room while the simulation assumes the occupied case.

The values of the actual SPL inside the room depend on many parameters; among the most important are the type and nature of the sound source (usually in this case is a human), the position and power of the loudspeakers and the position of the listener. This means that the sounds that will actually reach students' ears will vary from one position to another and from a lecturer to another assuming the constancy of loudspeakers power. The room at hand contains six wall-mounted column type loudspeakers (Fig. 3). All loudspeakers are installed on the side walls and distributed symmetrically around the stage. Two of these loudspeakers (of 100 W each) are installed in the front part of the side walls. The other four loudspeakers (of 40 W each) are installed and oriented to serve the balcony and the area under the balcony. When the sound system is (on), the recorded LA_{eq} proved the uniformity; the average LA_{eq} is about 81 dB(A) with a small standard deviation (about 2 dB(A)). The average of the maximum measured SPL is about 81 dB(A) with almost the same standard deviation, and the average of the minimum measured SPL is around 77 dB(A) with a standard deviation of about 5 dB(A).

It is known that ODEON does not calculate L_{eq} (or LA_{eq}) as one of its standard outputs, instead it calculates the instantaneous SPL (and SPL(A)). Although these quantities (SPL and L_{eq}) are not acoustically the same, they can be considered equivalent from the mathematical point of view if we run ODEON many times (under the same settings) and calculate the equivalent of the resultant SPL (or SPL(A)). Based on this assumption, it is clear that the measured LA_{eq} is higher than the optimum ones; this is due to the absence of audience. It is expected for these values to decrease few decibels in case of occupation. Fig. 13 indicates the values calculated by ODEON (occupied room) and LA_{eq} obtained in the different positions in the unoccupied room. The effect of occupation is also clear from the differences between SPL(A) calculated (by ODEON) and LA_{eq} measured in site.

Another problem in this room is the relatively high background noise. The measured L_{eq} exceed almost all of the recommended values (NC-25) [19] except at the low frequency bands ($\leqslant$250 Hz) where the values are almost equal to the recommended ones (Fig. 14). In the mid and high frequency bands; L_{eq} exceeds the recommended values to reach its maximum at 2 kHz with a difference of about 13 dB. This makes the spectrum of the measured L_{eq} so close to NC-40. If we consider the time of measurements (August, during the students' summer vacation) where the noise levels inside the university campus are generally low, it is expected that the difference between the measured and recommended values will considerably increase in case of the actual operation. Unless a radical solution is taken, it is not expected to solve this problem in the nearest future.

7. Discussion

The new lecture auditorium in the FOL is one of the largest auditoriums in the university. The administration of the university and the design team of the auditorium are interested in making this room matched-well with the acoustic requirements for the modern lecture auditoriums. Thus, the new lecture auditorium in the FOL undergoes a complete acoustical analysis to insure that it will fulfill – as practically possible – the international standards of speech rooms.

To achieve a good hearing conditions, the excessive sound energy inside the room has been absorbed by FGP, these panels were installed in the appropriate places of the walls and ceiling to absorb the mid and high frequency bands. The MDF cladding for the walls and GB's for ceiling were employed to protect and improve the appearance of the FGP both architecturally and environmentally. The MDF panels and GB's were perforated by about 20%. To absorb the low frequency bands, membrane absorber was utilized. Membrane

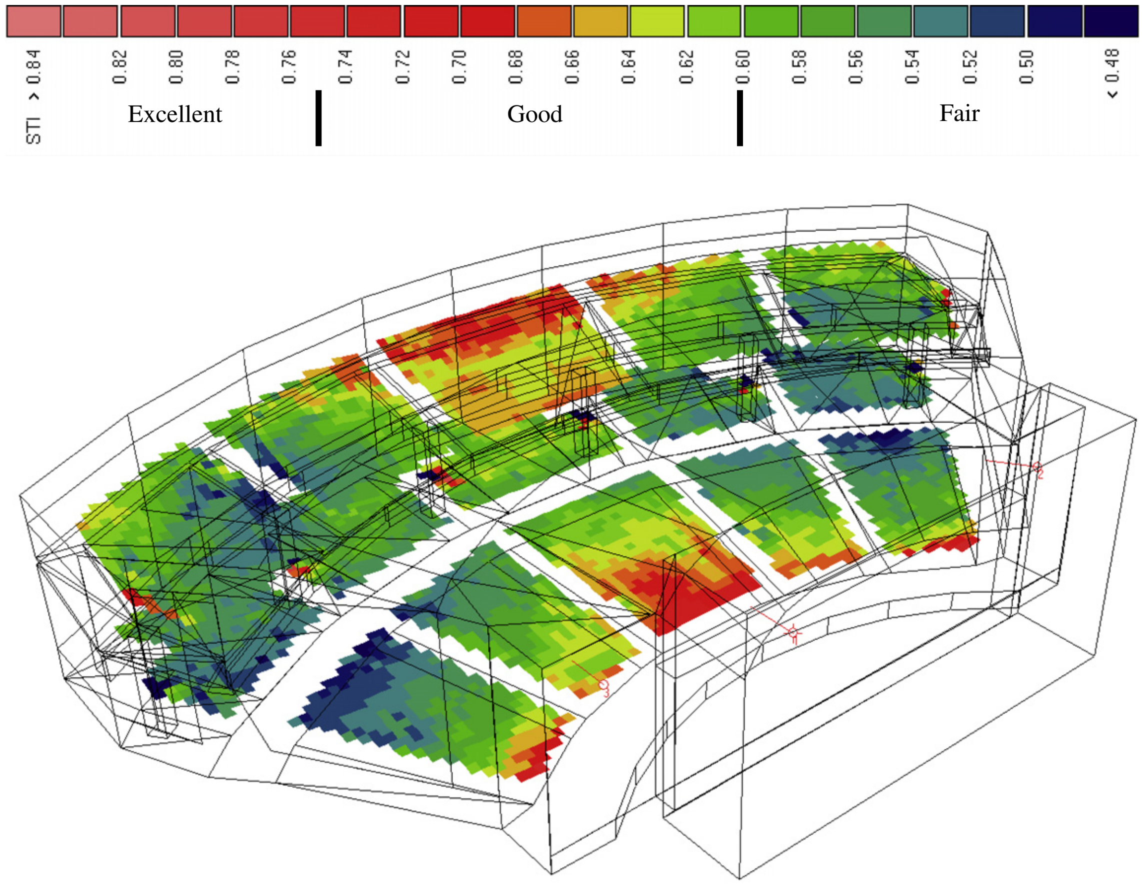


Figure 12 STI map calculated by ODEON (occupied room).

absorber was installed in the front part of the room near the speaker. Fig. 15 summarizes areas, ratios and the main acoustic properties for the different surfaces defining room boundaries.

Field measurements of the acoustic indicators related to speech intelligibility prove the success of room finishing materials in offering good hearing conditions. The form of ceiling helps in the uniformity and homogeneity of the sound field inside room based on the measured LA_{eq}.

The differences between $T_{optimum}$ and $T_{20\text{-EOC}}$ (Fig. 10) can be justified primarily from the volume/person criterion. Volume/person is a preliminary indicator for the quality of speech, from which the total room volume can be estimated. The recommended volume/person for speech rooms ranges between 3 and 5 m^3/person [16] (i.e. total volume between 6900 and 11,500 m^3) while the average current value (even after decreasing room volume by the suspended ceiling) is about 7 m^3/person. This value still exceeds the optimum by about 40% due to the huge room volume. Practically, it was difficult to decrease more volumes from the room because of many other considerations not limited to the acoustical requirements. Another factor that must be considered in this discussion is the limited area that can be covered with the absorptive materials.

Fig. 10 also indicates the effects of employing membrane absorber to absorb low frequency bands. It is clear from the figure that the estimated values in this range ($T_{20\text{-EOC}}$) are less than the designed ones ($T_{20\text{-ODEON}}$) except at 125 Hz where the two values are almost identical.

The relatively small value for STI obtained by ODEON (0.58, Fair) can be justified from the relatively high BGNL (NC-30) and the limited number of loudspeakers (only two) assumed during the simulation (Table 4). The locations of those loudspeakers in front of the room may explain the existence of Excellent and Good zones in floor away from the balcony and near to stage (Fig. 12). This result encourages sound system designer to add four loudspeakers for the balcony and area under the balcony (as mentioned in Section 6) in order to achieve the required SPL at these area according to the international standards [29]. These additional loudspeakers improve to a great extent LA_{eq} measured in both areas. On the other hand, the small STI value obtained by field measurements (0.49, Fair) can be justified from the absence of audience during measurements that make T is relatively high, in addition to the moderately excessive background noise that is close to NC-40.

A compromised solution to decrease the BGNL measured or expected in this room is to completely abandon the concept of natural ventilation via open windows and utilizing instead a "forced ventilation" system. This solution will not affect the intrusion of natural lighting required to illuminate the room, yet; it will block the intrusion of the outside noise (from adjacent rooms and street noise) and keep the room quieter. This forced ventilation system must be carefully designed by an expert so as not to be itself a source of noise.

Based on the previous discussions and field measurements, it can be concluded that the finishing materials employed can

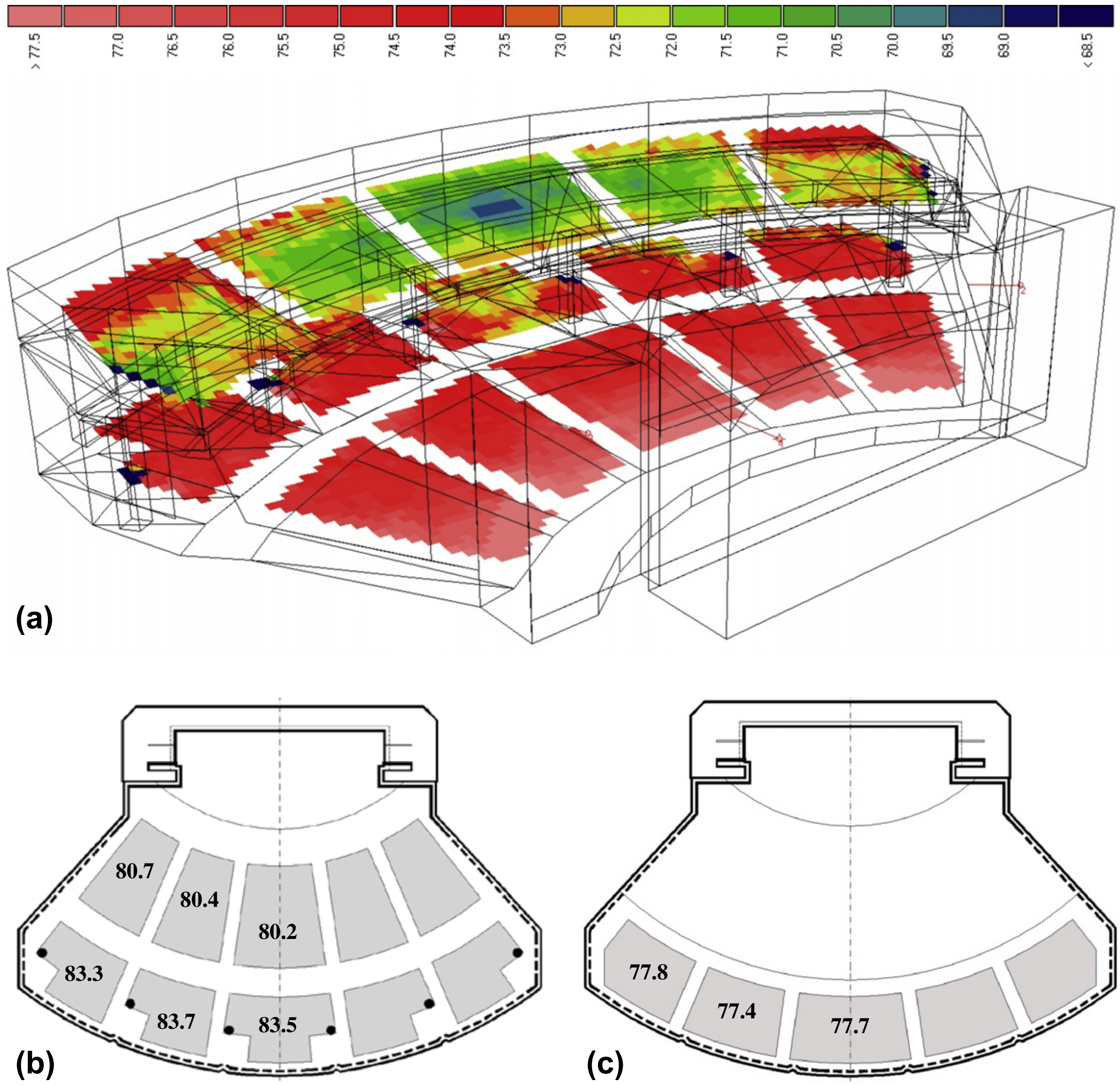


Figure 13 SPL(A) and LA_{eq} (dB). (a) SPL(A) calculated by ODEON (occupied room); (b) LA_{eq} measured in the floor (unoccupied); (c) LA_{eq} measured in the balcony (unoccupied) (The bold points in (b) indicate columns supporting the balcony, see Fig. 3(a) and Fig. 8(b)).

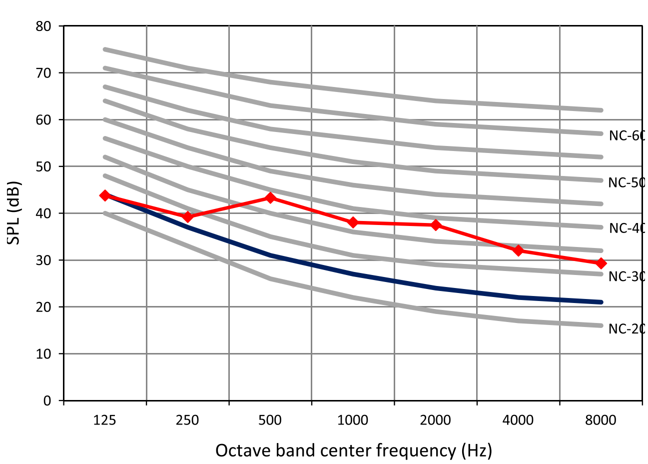


Figure 14 The measured L_{eq} (red curve) vs. the recommended (NC-25, blue curve). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

be utilized generally in the similar lecture rooms as they are acceptable from the acoustical and architectural standpoint.

8. Conclusions

This work presents the phases of the acoustical design of the new lecture auditorium in the FOL, Ain Shams University (Cairo/Egypt). These restrictions imposed using reflective finishing materials (marble and granite for floors, MDF panels for the walls and gypsum boards for the ceiling). In addition; natural lighting and ventilation must be used. The work compares among the results obtained from field measurements (unoccupied room), the values early expected in design phases (assuming the full occupation) for the considered acoustic indicators and the optimum values of these indicators.

Field measurements that were recorded using MLSSA digital system proved the success of the finishing materials utilized in creating good hearing conditions as can be concluded from the presented results. The estimated reverberation time $T_{20\text{-EOC}}$

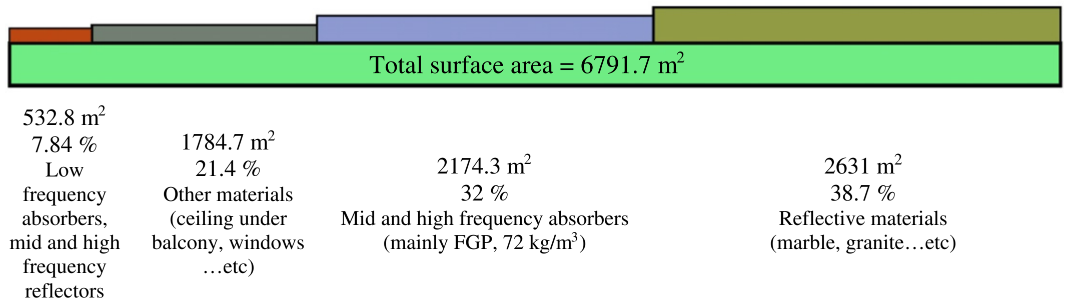


Figure 15 Areas, ratios and the main acoustic properties for the surfaces defining the space of the new lecture auditorium, FOL, Ain Shams University.

for the occupied room (based on the measured $T_{20\text{-M}}$) was close to the optimum especially in mid and high frequency bands. D_{50} (measured "$D_{50\ \text{M-AV}}$" and calculated by ODEON "$D_{50\ \text{ODEON-AV}}$") was found to be within its acceptable range. The measured STI value (unoccupied room) was 0.49 (Fair) whereas the calculated by ODEON was 0.58 (Fair). The measurements of LA_{eq} indicate the uniformity of the acoustical field in the room. The difficulty appears to be the relatively high background noise (NC-40) due to the utilization of natural ventilation which directly contradicts the principles of room isolation.

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Ahmed Elkhateeb is an associate professor at Ain shams university, Faculty of Engineering, department of architecture(Cairo, Egypt) from which he graduated in 1990. He completed his M.Sc. and Ph.D. in the field of architectural acoustics which is his primary area of interest, in addition to mathematics and its relation with architecture. He has many published researches in national and international scholarly journals in the field of building science,in addition to three published books in the same research area. He also supervised manythesesin different areas related to architecture.