DESIGN FOR SPEECH

A CASE OF UNIVERSITY OF NAIROBI LECTURE THEATRES

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DECLARATION

This thesis is my original work and to the best of my knowledge has not been presented in any other university or institution for the purpose of awarding a master degree.

Author : Signature: .... Date...

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This thesis is submitted in partial fulfilment of the examination requirements for the award of the Master of Architecture degree, in the Department of Architecture and Building Science at the University of Nairobi.

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Chairman: Signature: .... Date...

Arch. Musau Kimeu

DEDICATION

To the Almighty God for Everlasting Love and Unending Strength.

To My Family, the Rops. I love you all.

ACKNOWLEDGEMENT

To Almighty God thank you for the strength, wisdom and health, you gave me to write this thesis. You have been more than a friend, a helper and encourager through this task.

Thanks to my family and friends for the patience, you had while I was away toiling through this journey. You saw it fit to give me time to finish this noble task. God bless you so much for the support and prayers. Your love has been amazing. God bless you all.

My dear friend and love, Charlene Biwott, thanks for the efforts you put in taking photos of some of the lecture halls that were far and inaccessible at the certain times of this study. You are truly a pillar and a help in times of need. I celebrate you for being patient and kind. This journey with such support will always remain cherished in my life and you can always count on me too to extend that hand as we journey through this beautiful life that unfolds each passing day. I love you!

I am grateful to the Estates Department of the University of Nairobi for their precious time in locating some of the drawings for these lecture theatres. Your part in this work has gone along was in providing key data on how we can improve our lecture theatres to give better performance during lecture sessions.

This task would not have been possible without the help from my lecturers and staff in the Department of Architecture, University of Nairobi. Thanks to Arch. Kimeu Musau for being there to guide and point out issues that helped in fine-tuning the write up. The entire process has been truly mind opening on the various aspects that affect our surrounding in regards to speech delivery and lecture theatres dedicated for such activities.

Thanks to Arch. Bob Muhia, and Arch. James Kimanzi for the guidance through this process. The insights you gave me directed the write up journey and made it pin point as I narrowed down my focus to the study of reverberation time in regards to speech within these lecture theatres.

There are several support staff in different departments that I will not take for granted. The custodians of the various lecture halls, security guards and managers that took time to open these lecture halls and allow me to take measurements of all the aspects that were key in my study.

TABLE OF CONTENT

CHAPTER 3 RESEARCH METHODOLOGY

CHAPTER 4 DATA ANALYSIS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The conditions surrounding the transmission of speech in an enclosed auditorium are complicated, it is true, but are only such as will yield an exact solution in the light of adequate data (Sabine, 1964). Good acoustics in a building are not merely a matter of applying some patent sound absorbent material to walls or ceilings. The design of the buildings – size, shape and volume are all important factors which have a great bearing on the acoustics.

Contrary to popular opinion, good architectural acoustics is no accident. The acoustical character of a proposed building can be accurately predicted (Kinzey and Harvard, 1963). Sound is one of the subtlest pieces of nature (Sir Francis, Basic quoted in Hunt, 1992)

The ultimate evaluation of acoustical quality lies with the people who listen, speak, play, work, create, live, sleep, and otherwise use the rooms designed and built by those in the construction industry. This evaluation will differ from person to person, from activity to activity, from culture to culture, from one period in history to another, and even from one say to the next with the same person!

With increasing number of studies investigating how people hear and what they like to hear when they listen to sounds, particularly speech and musical performances, these studies begin to answer the question; “what do we mean when we say that a room has good acoustics?” (Cremer and Muller, 1982).

These are often called studies of subjective qualities of sound. People are used as test subjects to evaluate live or recorded sounds. The general findings of this body of work have been to identify the qualities most people associate with, to confirm that people can hear differences in the acoustical qualities at different seats within a room, to confirm that there are perceived differences to acoustical quality in different room, to isolate and identify some of the factors that contribute to acoustical quality, and to confirm that listening is a complex, multidimensional experience with many significant interactions among variables and difficulties in describing phenomena precisely.

CHAPTER 1

INTRODUCTION

1.1 Background of Study
1.2 Problem Statement
1.3 Research Questions
1.4 Objectives of the Study
1.5 Justification of the Study
1.6 Significance of the Study
1.7 Scope & Limitations of the Study
1.8 Assumptions
1.9 Organization of the Study

1.1 BACKGROUND OF THE STUDY

Figure 1.1: Kaufman Hall, Kansas
Source: Bower E., 2016

Auditoriums and halls are large gathering spaces used for various functions. They require specific optimal treatment for proper acoustic satisfaction. The size, shape, and finish materials that define an auditorium will control the sound quality, good or bad (**Fig 1.1**). Examples of poor sound quality are common in a large variety of spaces, and point to the need for addressing acoustics during design.

Excess room reverberation is a major source of complaints. Properly shaped auditoriums can greatly reduce the reverberant noise level of a space by as much as 40-50% (8-10 decibels). Reducing reverberation will reduce the background noise level and improve speech and music clarity.

Different shapes will give different reverberation time which translates to different functions for the auditorium. Various large spaces require different reverberations times; classrooms (0.6-0.7), band rooms (0.9-1.1), movie theaters (0.9-1.2), choral rooms (1.2-1.6), multipurpose rooms (1.6-1.8), concert halls (1.7-2.2). The amount of reverberation required for an effective classroom environment is much less than for a concert hall.

1.2 PROBLEM STATEMENT

Figure 1.2: Taifa Hall, University of Nairobi
Source: Thuita, T., 2016

Large gathering spaces are used for varied functions which may include unamplified music, music with singing, music with speech, speech, amplified music and speech and audio-visual electronic performances. These functions have specific reverberations times ranging from 0.2 to 2.6. Challenges arise when designing a multi-purpose hall which is intended to host all these functions. The floor geometry, sectional geometry, volume, number of seating levels, material finishes and seating arrangement will influence the reverberation times, sound shadows, sight lines, sound concentrations and echoes reaching the audience.

It is in line with these large gathering space qualities that the study intends to identify the design gaps within the University of Nairobi lecture halls (**Fig 1.2**), analyze the shortfalls and establish possible design for speech mechanisms that can be implemented to create apposite acoustic environment for the various functions. These rectifications mechanisms can then be proposed for application in the interior re-design of these lecture halls to ensure functional spaces that suit the university fraternity.

Figure 1.3: Upper Kabete MPH Hall, University of Nairobi
Source: Thuita T., 2016

Figure 1.4: Science II theatre, University of Nairobi
Source: Thuita T., 2016

1.3 RESEARCH QUESTIONS

1. Establish the design standards for speech in lecture halls.
2. Establish the existing conditions and design for speech gaps in the selected University of Nairobi lecture halls.
3. Establish the design for speech mechanisms that can be put forward to mitigate these gaps.

1.4 OBJECTIVES OF THE STUDY

1. What are the design standards for speech in lecture halls?
2. What are the existing conditions and design for speech gaps in the selected University of Nairobi lecture halls?
3. What design for speech mechanisms can be put forward to mitigate these gaps?

1.5 JUSTIFICATION OF STUDY

Most acoustic design researchers have majored on yet to be built large gathering spaces, proposing mechanisms on how to deal with acoustic challenges that arise as these spaces are built. However, once these spaces are built rarely do the designers go back to check whether what they intended to achieve was fulfilled as planned. University of Nairobi lecture halls have shortfalls during musical performances as well as speech delivery (**Fig. 1.3**). Performances come with uneven sound distribution, noise, echoes and sound shadows. Most of these lecture halls rely on reinforcements to project the sound to the audience sitting at the back. The study intends to look at these issues giving forth solutions to the gaps identified during the study.

1.6 SIGNIFICANCE OF STUDY

This study provides significant analysis of the University of Nairobi lecture halls (**Fig 1.4**). Its relevance can be noted in the establishment of existing acoustic design conditions of these lecture halls, identification of acoustic design gaps and the design for speech mitigation mechanisms that can be put forward to improve the existing conditions of these lecture halls. The study contributes to the realization of comfortable acoustic environments which require step by step analysis of design decisions.

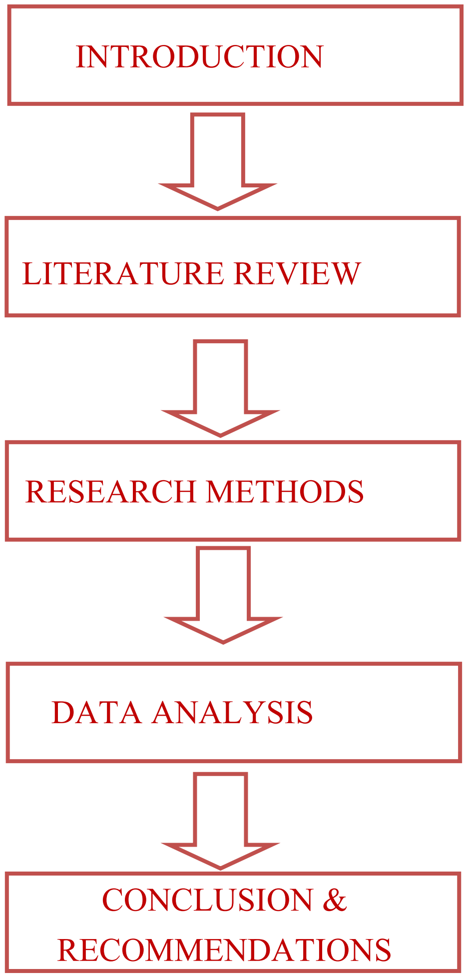


Figure 1.5: Organization of the study

Source: Author, 2016

1.7 SCOPE AND LIMITATIONS OF THE STUDY

The study will focus on design for speech of already existing lecture halls within the University of Nairobi. Due to lack of sufficient literature review on existing acoustic conditions of the halls, acoustic design gaps and rectifications mechanisms proposed to mitigate these gaps, field work will be a major tool to review these key architectural areas. Time is a limiting factor to research thus the work may not be sufficiently exhausted in all areas within the study. Lack of sufficient documented architectural materials will also limit the identification and analysis process.

1.8 ASSUMPTIONS

This research makes the assumption that the lecture halls were intended for speech. In line with these assumptions, the proposed design for speech mitigation mechanisms will touch on speech requirements aiming at re-designing the interior spaces of these lecture halls. It also assumes that the outward geometry of these lecture halls remain constant.

1.9 ORGANISATION OF STUDY

This research is divided into five chapters (**Fig. 1.5**). Chapter one gives the background of the study, problem statement, research objectives, research questions, justification of study, significance of study, assumptions, scope and limitations of the study. Chapter two covers the literature review. It documents the basic design for speech requirements; means of re-designing already built spaces to adapt to proper acoustic requirements and the possible design for speech mechanisms that can be put forward to improve these gaps. The key mitigation constants are stated at the end of this chapter based on the literature reviewed. Chapter three documents the methodology undertaken in the course of the study. It covers data collection methods, data analysis techniques and data presentation methods. Chapter four analyses and presents the information collected by the author from conducting a fieldwork research answering the research questions. Finally, chapter five draws conclusions and recommendations that help solve the problem defined in chapter one. The chapter also compares, verifies or disagrees with information obtained from the literature review in chapter two.

CHAPTER 2

LITERATURE REVIEW

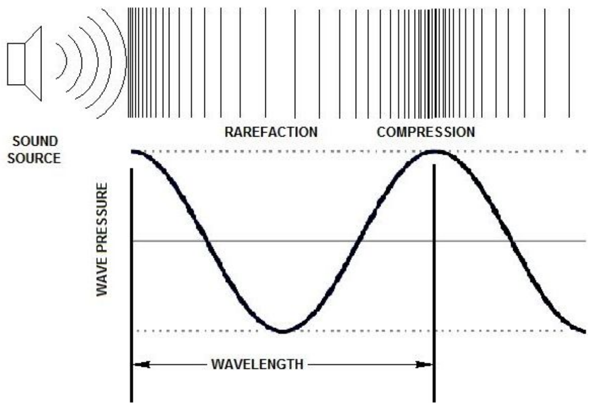


Figure 2.1: Pure sound tone
Source: Moore, 1961

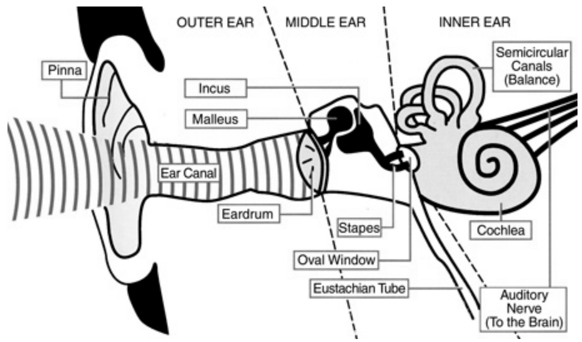


Figure 2.2: Sound through the ear
Source: NDCS, 2017

2.1 INTRODUCTION

Sound is generated by vibrating objects. Passage of sound waves causes air particles to move backwards and forwards parallel to the direction of motion of the wave. Sound waves are longitudinal rather than transverse. Movement of air particles causes localized areas of compression (higher pressure zones) or rare factions (lower pressure zones) (**Fig 2.1**). The outward movement of the vibrating membrane causes a compression in the adjoining molecules of air. When the membrane moves back, the compressed air expands and causes a compression in the air adjoining the original center of compression. All regions of compression and rare faction travel at a fixed speed of 343 m/s (Moore, 1961).

Barron (1993) asks, is there an ideal form on acoustic grounds for a performance arena? What form should one use to enhance the brilliance, harmony and depth of sound for a specific function of large gathering spaces? The author answers these questions with three logical solutions; the characteristics of sound sources these being instruments and human, the wave nature of sound produced by these sources and the use of human ear to guide us on desirable sound to listen to.

There are different types of auditoria, which include but not limited to lecture halls, concert halls, recital halls, drama theatres, opera houses and multipurpose halls. The form of any large gathering space influences the quality of sound received by the audience. Elliptical and circular plans are dangerous due to focusing of sound at certain points caused by concave surfaces. Rectangular shoebox halls have proven over the ages to be the best shapes to deal with acoustically (Smith et al, 1982).

2.2 BASIC CHARACTERISTICS OF SOUND

2.2.1 Sound Waves Perceived by the Ear

Sound propagation depends on a source of sound and a receiver. The propagating medium is all around us. This coupled with the fact that sound bends round corners and that the ear is only barely directional, makes our hearing such an invaluable sense.The ear is a remarkable organ, with a converter that tranforms the vibrations conducted from the ear drum into digital nerve pulses (**Fig 2.2**). Nerve pulses travel between the ear and the brain in both directions, allowing the listener to suppress his sensistivity to a continuous noise for instance (Barron, 1993).

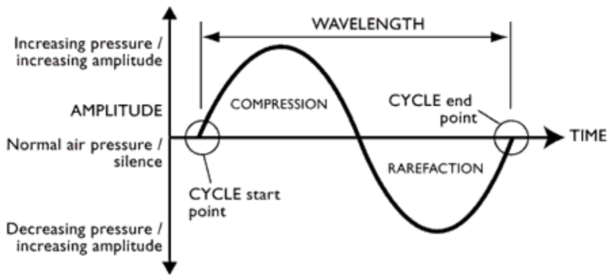


Figure 2.3: Sound wave
Source: Cavanaugh et al, 2010

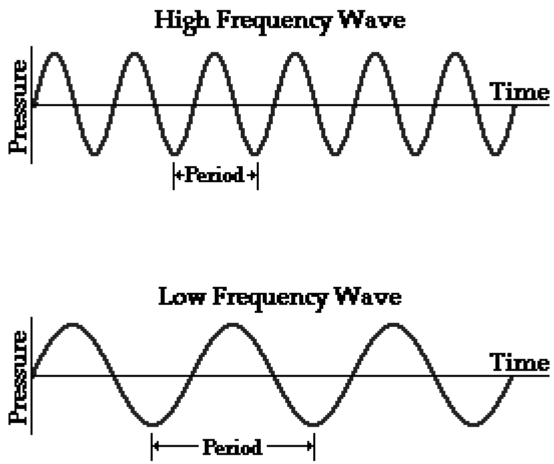


Figure 2.4: Sound Frequency
Source: Cavanaugh et al, 2010

2.2.2 Amplitude

This is the maximum extent of a vibration or oscillation, measured from the position of equilibrium (**Fig 2.3**). It is determined by the magnitude of the pressure fluctuation (Cavanaugh et al, 2010).

2.2.3 Frequency

This is the number of cycles per second expressed in hertz (Hz). A pure tone has a single frequency. Musical instruments produce complex sounds made up of several frequencies (**Fig 2.4**). The ear can perceive frequencies between 20 Hz and 20,000 Hz though the upper limit decreases with age. The fundamental musical interval is the octave, which corresponds to a doubling of frequency. Acoustic measurements are made over octave intervals, with centre frequencies of 125, 250, 500, 1000 etc (Barron, 1993).

2.2.4 Wavelength

This is the distance between adjacent pressure maxima (or minima).

2.2.5 Relationship between Frequency, Wavelength and Speed of Sound

The wavelength for a sound in the middle of the frequency range of 1000 Hz is 0.343 m. The range of wavelength of audible sounds is between 17 m at 20 Hz and 17 mm at 20 KHz. This implies that these wavelengths are comparable to dimensions of room surfaces and common objects. At low frequencies with large wavelengths sound waves commonly bend round objects but at high frequencies, objects are generally larger in dimensions than wavelenghts and sound behaves much like light, travelling in straight lines and forming shadow zones. Speed = Frequency x wavelength (Cavanaugh et al, 2010).

2.2.6 Inverse square Law of Sound

Most sound sources radiate more energy in some direction than others. The human voice is directional. Most stringed instruments radiate sound most strongly at right angles to the surrounding board. Once sound leaves the source its behaviour is similar to omnidirectional sound sources. For every doubling of

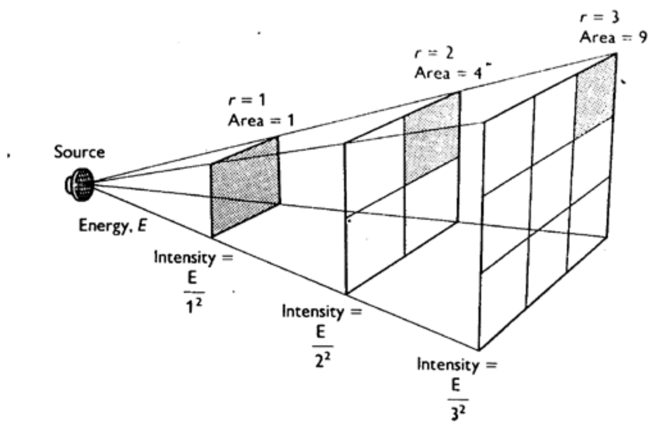


Figure 2.5: Inverse square law
Source: Barron, 1993

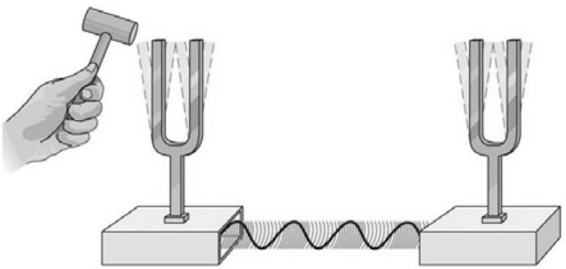


Figure 2.6: Resonance
Source: Hampton, 2017

distance from the source, the area occupied by the energy increases by a factor of four (**Fig. 2.5**). Intensity thus drops by a quarter and we get the 6 dB decrease per doubling of distance characteristic. In rooms both the direct sound and reflected sound experience spherical spreading (Barron, 1993).

2.3 NATURE OF SOUND

According to Smitthakorn (2006), both music and speech consist of brief sound events separated by silence. They both cover most of the audience frequency range 100 – 11,000 Hz. The individual sound events with speech are syllables and typical speaking rate is five syllables per second. Music is much more flexible.

2.3.1 Resonance

When sound waves strike the enclosing structure of a room it is set into vibration to a greater or less extent according to its nature. The materials vibrate at the same frequency as the incident sound waves, and in turn emit sound on both sides of the partition. Heavy walls respond less than light partitions. Any given material will respond to a varying extent according to the frequency of the sound waves striking it (**Fig. 2.6**). All materials have a frequency at which they respond best. In rooms for music, extensive areas of wood paneling are used to give richness of tone. Resonance reinforces sound without appreciably prolonging it as does reverberation. It may be employed in multipurpose halls where a short reverberation time is required for speech, yet some substitute for reverberation is desired for music (Moore, 1961).

2.3.2 Air Resonance

Bagenal (1942) states that, in rooms with parallel and plain opposite walls 'standing waves' may be set up by sounds of long wavelength. This occurs when the wavelength coincides with the distance between the walls, or is an exact fraction of this distance. According to Moore (1961) a resonant effect is produced which accentuates and prolongs sounds of certain frequencies, and creates a distortion in the balance of frequencies. In large auditoria, with dimensions greater than about 11 m these effects will not be discernable. In smaller rooms, parallel and plain opposite walls should be avoided in design especially where they flank the source of sound.

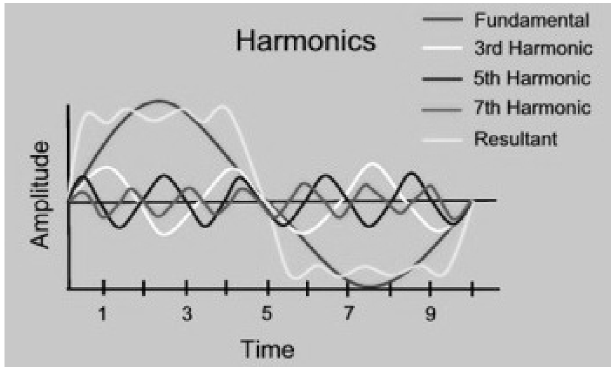


Figure 2.7: Harmonics graph
Source: Litovka, 2014

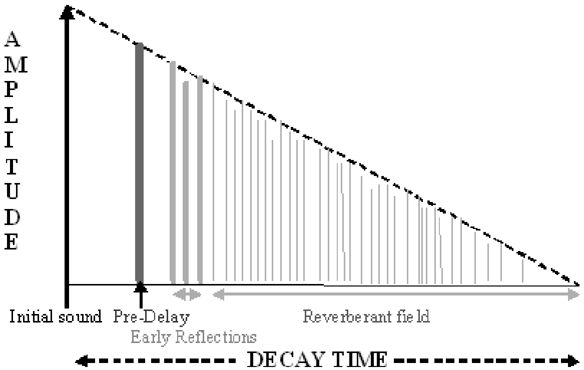


Figure 2.8: Reverberation time
Source: Roy, 2014

2.3.3 Sound Timbre

The sound character or timbre of different musical instruments is related to their frequency spectrum. For a continuous sound the spectrum consists of a series of discrete frequencies. The lowest frequency is known as the fundamental or first harmonic (**Fig. 2.7**). The higher frequencies are simple multiples of the fundamental frequency and are known as the second, third harmonic etc. Our ears interpret the mixture of frequencies in terms of its pitch, given by the fundamental frequency, while the relative strength of the harmonics characterizes the sound quality or timbre of the instrument (Barron, 1993).

2.3.4 Temporal Character of Vowels versus Constants

According to Beranek (1992), the aspects of speech and music which substantially influences room acoustics is the temporal one. Individual speech sounds (or musical notes) have particular amplitudes and durations. Vowels tend to be longer and louder than consonants. The relative strengths and durations of concurrent speech sounds or notes are of crucial importance for room acoustics.

2.3.5 Reverberation Time

This is the continuation of sound after the original sound has ceased, due to multiple reflections in an enclosed space. It can also be described as the time taken for a sound of 60 dB (Sabine standard sound loudness) to decay to inaudibility. Reverberation provides a background of the decay of previous syllables or notes against which the new speech sounds or musical notes are heard. When presented as a sound level in decibels, the build up time is short , while the decay time is much longer (**Fig. 2.8**). If the reverberation time is too long, then one sound can be rendered inaudible (i.e. masked by earlier louder sound). But with too short a reverberation time, the sound quality becomes too stark like listening in the open air (Moore, 1961).

2.3.6 Impulse Response

Lochner and Burger (1964) states that the useful energy has been proposed by several researchers to occur somewhere between 35 ms after the direct sound, up to 95 ms after the direct sound. The reverberant or late energy is that which comes after the useful energy, up to the decay of the impulse.

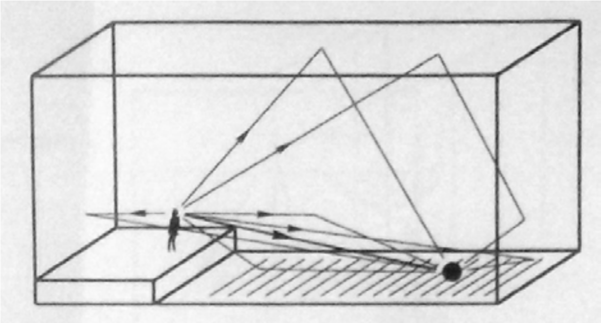


Figure 2.9: Multiple reflections
Source: Bradley, 1986

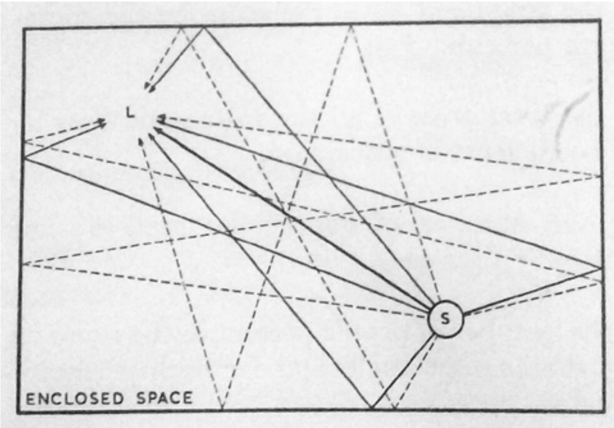


Figure 2.10: Multiple reflections in plan
Source: Moore, 1961

These measures have been used to assess speech intelligibility in rooms. Impulse response can be subdivided into several components;

2.3.6.1 The Direct Sound

This sound wave travels directly from the source to the listener without striking any of the surfaces of the room (**Fig. 2.9**). It is the first sound wave that arrives at a listener's location. It contributes to sensations of loudness, clarity and localization. It will generally decrease due to geometric spreading or divergence, as it moves farthest from the sound source (Bradley, 1986).

2.3.6.2 The Early Sound Reflection

This sound wave strikes one of the room surfaces and is reflected to the listener. Reflections that arrive within short time intervals after the direct sound (50 ms) are combined with the direct sound by the ear. These reflections added to the direct sound increases its loudness. If the reflections arrive within 40 ms or less after the direct sound, they will also contribute to a sense of intimacy. The combination of these early reflections with the direct sound is what makes it possible to have similar levels of loudness at seats located throughout a large room. Diffuse reflections that arrive between 40 ms and 80 ms after the direct sound will increase the sensation of acoustic texture (Smitthakorn, 2006)

2.3.6.3 The Reverberant Sound

This consists of sound waves that have been reflected from multiple surfaces before they arrive at the listener's ears. They travel long distances between reflections and therefore are progressively reduced in loudness from the direct sound and early reflections. The reverberant sound field may persist for 2 s or longer in concert halls. It contributes to sensations of reverberance and running liveness. If the reverberant sound, arrive from many directions and are not exactly the same at the two ears of people listening, it will also increase the sensation of acoustic spaciousness in the room (**Fig. 2.10**). If the reverberant sound field has strong low frequency or bass component, it will increase the sense of warmth in the room, if it has strong higher frequency or treble component, it will contribute to the perception of brilliance (Shultz, 1965).

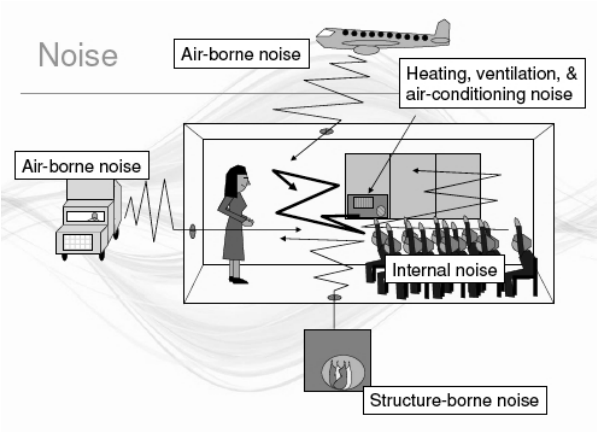


Figure 2.11: Background noise
Source: Vaughan, 2013

2.3.6.4 Background Noise

Traffic, rail or aircraft noise can necessitate substantial expenditure to achieve inaudibility inside the auditorium (**Fig. 2.11**). External sound can be transmitted to the interior of an auditorium by way of the structure or the foundations. Heavy structure transmits less sound than light construction. Transmission can also be checked by structural separation or isolation by absorbent materials. A typical approach is to place the 'box' of the auditorium within the box provided by the shell of the building; the intervening spaces are readily used for foyers. Ventilation noise has to be carefully controlled, with substantial attenuation between air-handling plants and the auditorium, as well as low air outlet velocities. Airborne sound transmission may equally offset the value of good acoustics design and should be prevented by the provision of sound absorbing lobbies, fixed and preferably double-glazing (Moore, 1961).

2.3.7 Intellegibility

Beranek (1992) states that for communication and clarity of speech, the direct sound on its own has the disadvatage that it decreases substantially in level as one moves away from the source. However for the purposes of intellegibility and clarity, the ear is able to combine the energy of the early reflections with that of the direct sound, giving a 3 dB increase in the direct sound. A common value used for the limit within which reflections contribute to speech intellegibility is 50 ms while 80 ms is usually applied for clarity in music.In large concert halls, the direct sound decreases by 12 dB between 10 and 40 m from the source, while the early energy within 80 ms typically falls only 5 dB. Hence the importance, particularly in large auditoria of considering the early reflection dstribution at all seating areas (**Fig. 2.12**).

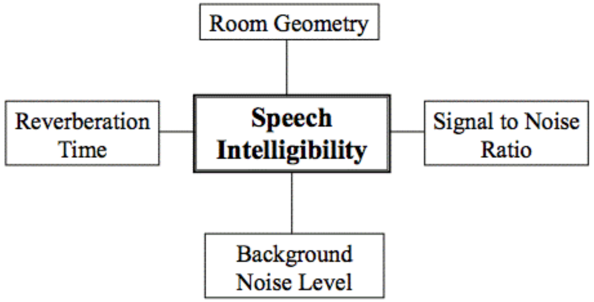


Figure 2.12: Speech intelligibility
Source: Werth, 2017

2.3.8 Intimacy

This is the sense of the relative size of the room in which sounds are heard. One generally prefers to listen in a small room where one is close to the sound source. Reflected sounds follow very closely after the direct sound in a small room because of the proximity of room surfaces to the listeners. In a large room one can provide acoustic sensations of intimacy by locating reflecting surfaces close to the listeners, so that sound reflections will follow closely after the direct sound (Beranek, 2008).

2.4 SOUND BEHAVIOR ON SURFACES

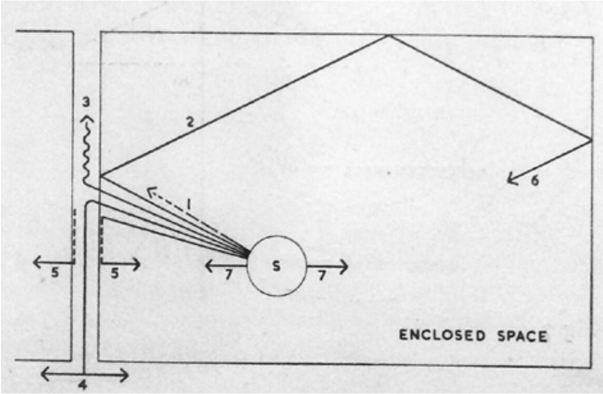


Figure 2.13: Sound behavior on surfaces
Source: Moore, 1961

According to Bagenal and Wood (1931), when sound is generated in a room it is reflected, absorbed and transmitted in various proportions in accordance with nature of construction (**Fig. 2.13**):

1. Sound absorbed in the air
2. Sound reflected from the wall surface
3. Sound absorbed at the wall surface or its surface finish
4. Sound conducted by the wall to other parts of the structure.
5. Sound emitted by resonance of the wall in both directions
6. Sound inter-reflected between bounding surface setting up reverberation.
7. Resonance of the enclosed volume of air by direct cross reflection.

2.4.1 Reflection

Most of the sound energy we receive in enclosed spaces has been reflected off walls and ceilings. The reflected wave behaves as if it had originated from the sound source position. Much larger surfaces are required owing to the much longer wavelengths involved. Sound reflected by one surface will continue to be reflected between the room surfaces until its energy is removed by absorption (Moore, 1961).

2.4.1.1 Reflections from a Flat Surface

The reflected wave fronts are spherical and their center of curvature is the 'image' of the source of sound. The image is on a line normal to the surface and at the same distance from the surface as the source.

2.4.1.2 Reflections from Curved Surfaces

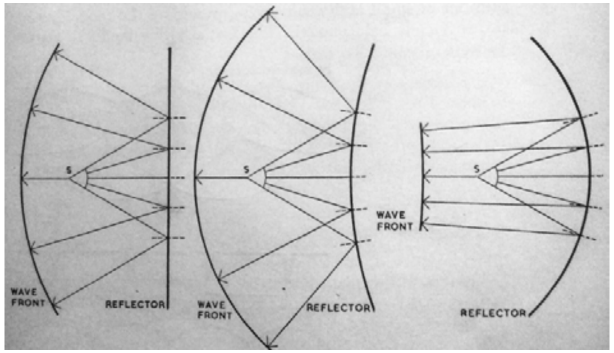


Figure 2.14: Sound behavior on surfaces
Source: Moore, 1961

The wave front from the convex surface is considerably bigger than that from the flat surface, and the wave front from the concave surface is considerably smaller (**Fig. 2.14**). Sound waves reflected from convex surfaces are more attenuated (and therefore weaker) and sound waves reflected from concave surfaces are more condensed (and therefore stronger). Concave shapes produce places with very loud

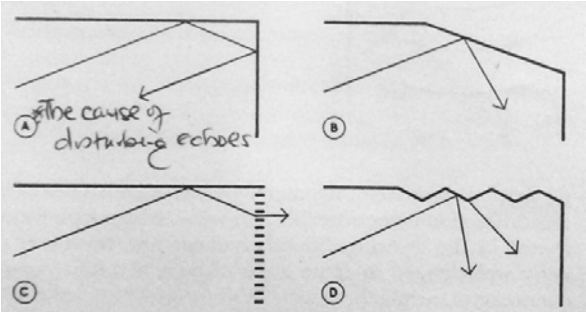


Figure 2.15: Reentrant angles
Source: Moore, 1961

sounds or dead spots, while convex surfaces can be useful in providing a diffusing surface in order to reflect the sound evenly in the hall (Bagenal and Wood 1931).

2.4.1.3 Reflections from Reentrant Angles

According to Moore (1961), sound entering a right-angled corner of a room will be reflected back towards the source, (**Fig. 2.15 A**), if the adjacent surfaces are of reflective material. In cases where this is undesirable, the corner may be treated in any of the three ways shown:

B. It may be made other than a right angle.
C. One surface may be made absorbent.
D. One surface may be made dispersive.

2.4.1.4 Lateral Reflections

These are reflections arriving from the sides within 80 ms to 100 ms after the arrival of the direct sound. These provide a sense of spaciousness, spatial impression, and envelopment, and increase the apparent width of the sound source. Early lateral reflections have been an important feature of shoe-box-shaped concert halls. The relatively narrow room width, parallel walls, and general tiers of narrow balconies on the sides and rear of the rooms combine to produce many early lateral reflections (Johnson, 1990).

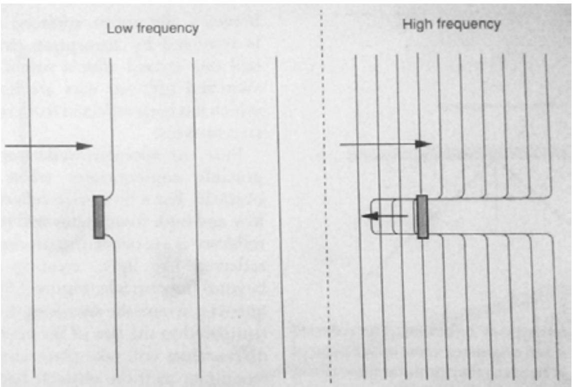


Figure 2.16: Diffraction of sound
Source: Barron, 1993

2.4.2 Diffraction

For a finite-sized reflector, high frequency sounds will be reflected like light, creating a shadow zone beyond the obstacle. But at low frequencies where the wavelength of sound is larger compared to the size of the obstacle, bending will take place and the wavefronts recombines as if the obstacle had not been there. Bending or diffraction of sound waves is thus normally a low frequency phenomenon (**Fig. 2.16**).

2.4.3 Diffusion / Dispersion

This refers to scattering of sound in all directions. For a surface to be acoustically diffusing requires an irrregular profiled surface with projections of a depth between 0.3 m to 0.6 m. Simple regular patterns

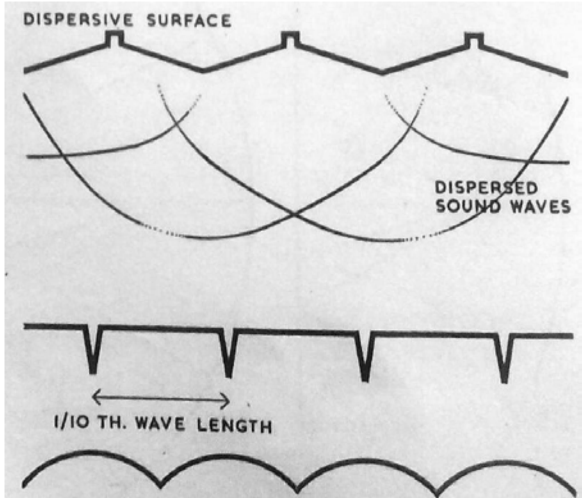


Figure 2.17: Sound diffusion
Source: Barron, 1993

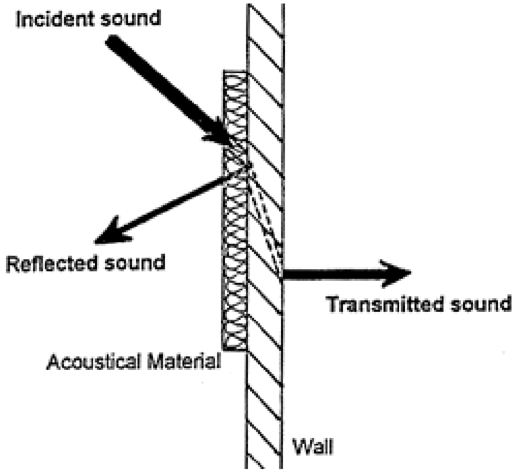


Figure 2.18: Sound absorption
Source: Acoustical surfaces, 2017

must be avoided as they are frequency selective in their scattering characteristic. The gross nature of the projections required is due to the wavelengths of audible sound. A light profiled surface will only diffuse at high frequencies. The deeper the diffusing treatment, the lower the frequency down to which the surface will scatter sound (**Fig. 2.17**). Diffusion is required for surfaces surrounding the platform to avoid sound concentration, which would be detrimental to the speaker. For the audience, lack of diffusion may be heard as poor balance and blend between the various sections (Thiele and Meyer, 1977).

2.4.4 Absorption

According to Chiang (1994), reflection, diffraction and diffusion are possible without energy loss, while absorption removes acoustic energy. Absorption is measured by absorption coefficient, which is the fraction of incident energy absorbed (**Fig. 2.18**). The most common mechanism is porous absorption; sound energy is dissipated in porous material owing to the friction involved in movement of air particles in the pores. Typical porous absorbents are fabrics, curtains and carpets; the most efficient materials are rock wool, mineral wool, fibre glass and acoustic open-cell foam. In auditoria, the major absorbing surfaces are the clothed audience and performers, who at mid-frequencies absorb about 90% of incident energy. Surfaces that are too far from the listener and/or performers cannot provide useful reinforcement by reflected sound energy. These surfaces should be made sound absorbing by means of application of massive efficient acoustical treatment. The acoustical materials used must have high absorption coefficients in the speech frequency range, particularly 250 to 4000 Hz. Sound generated in the auditorium is absorbed in four ways:

1. In the air
2. At the bounding surfaces
3. In furnishings
4. By the audience

2.4.4.1 Air Absorption

A small amount of sound is absorbed in the passage of direct and reflected sound through the air of a room. This is caused by the friction of the oscillating molecules of air and although negligible at low

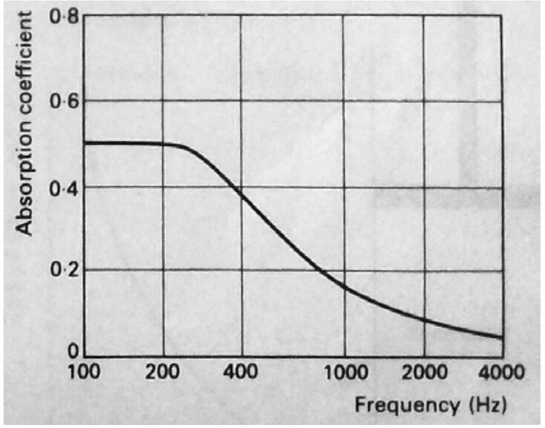


Figure 2.19: Membrane absorber
Source: Smith et al, 1982

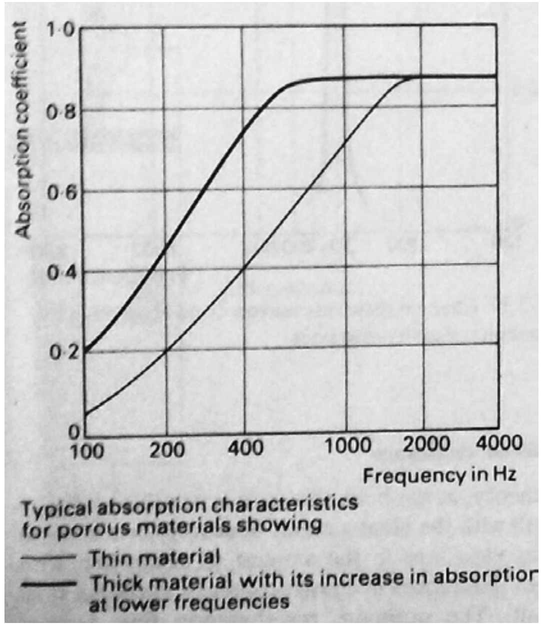


Figure 2.20: Porous material absorber
Source: Smith et al, 1982

frequencies, should be taken into account at frequencies above 1000 Hz when calculating reverberation times (Sabine, 1932).

2.4.4.2 Surface Absorption

According to Chiang (1994), absorption takes place whenever sound waves strikes the bounding walls or surfaces of a room, and it occurs in a number of different ways as follows (**Fig 2.13**):

a. By friction at the surface
b. By penetration into porous materials
c. By molecular friction in resilient materials
d. By molecular friction in a material during resonance
e. By transmission through the wall by resonance
f. By conduction through the structure.

Smooth, hard, dense and heavy materials absorb least sound while rough, soft, porous and light materials absorb most sound (**Fig 2.19 &2.20**). Helmholtz principle provides a further type of absorption where absorption takes place by the resonance of the pocket of air in or behind each perforation.

2.4.4.3 Absorption by Furnishings

Sound is absorbed by furniture, curtains and any other such items that are present in the room. Coefficients of absorption are published at the appendix for a limited range of furnishings and manufacturers of theatre seats in some cases publish figures for the seat as a whole (Sabine, 1932).

2.4.4.4 Absorption by Audience

This in most cases is the largest single factor of absorption in a room, and is mainly due to the absorption of their clothing. Room acoustics change perceptively in accordance with the number of people present. The absorption of a well-upholstered seat will partly take his place acoustically, when he is absent. The introduction of absorbent seating will thus greatly reduce the variation in acoustic conditions due to changing numbers of the audience (Moore, 1961).

2.5 SOUND DEFECTS

2.5.1 Echoes

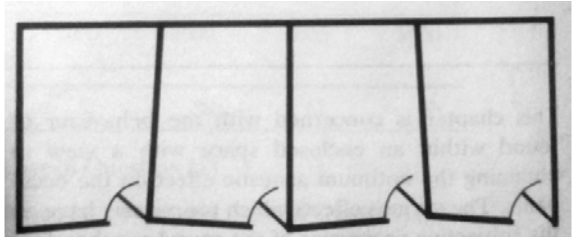


Figure 2.21: Wall treatment to avoid flutter echoes
Source: Smith et al, 1982

This is a reflection which is heard as a discrete event. The reflections arrive at least 50 ms later than the direct sound and is more prominent than its neighbors.In all rooms there are numerous reflections arriving at more than 50 ms after the direct sound. To be perceived as an echo requires either reflections from a large surface by a path simpler than other reflections of the same delay, or reflections involving focusing. Reflections off the back wall and adjacent soffit is a frequent cause of echoes on stage. To quell an echo from the back wall one can incline the wall backwards or downwards to redirect the reflection (**Fig 2.15 B,C,D**). Covering the surfaces concerned with absorbent material or making them into diffusing surfaces by means of a convex shape also solves this problem (Richardson, 1945).

2.5.2 Flutter Echoes

While echoes involves large delays and long path lengths, flutter echoes normally involve short path lengths but iterated many times. A common flutter echoe situation occurs between two parallel walls. The repeated reflections create a characteristic 'twang' which is obvious to anyone who has heard it by clapping their hands in corridors or rooms with flat parallel walls. More complicated repetitive paths are possible but rare. In auditoria, the obvious concern is that speakers should not be between the parallel surfaces. A flutter echo is one of the few acoustic problems which is relatively easy to correct. Reorientation of the parallel surfaces by only 50^{o} is adequate to cure it (**Fig. 2.21**), as is modest application of absorbent or diffusing treatment (Barron, 1993; Moore, 1961).

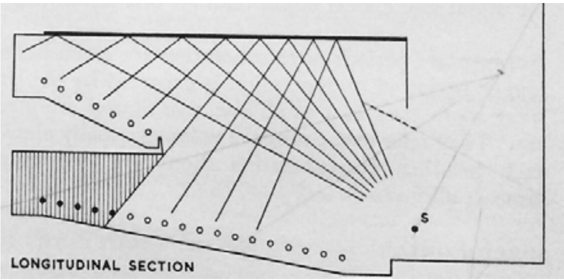


Figure 2.22: Acoustic shadow under deep gallery
Source: Moore, 1961

2.5.3 Acoustic Shadows

According to Marks (1940), sound is interrupted by an obstruction; a sound shadow is formed behind it, similar to a light shadow. Just as with light, however, diffraction occurs at the edge of the obstruction. Because of the much greater wavelengths of sound, this diffraction is considerable and wave "fringes" are formed. Sound shadows are, however, sufficiently well-defined to cause areas of poor audibility under the overhang of the deep galleries (**Fig.2.22**).

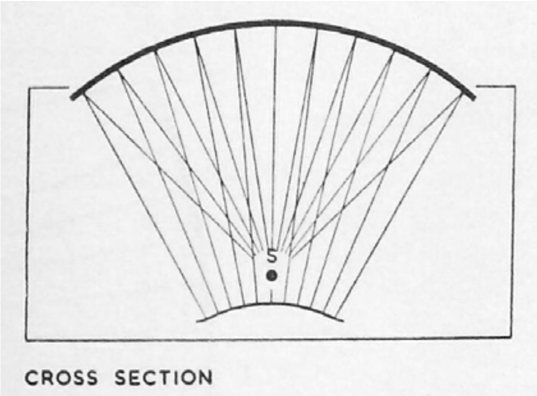


Figure 2.23: Concave surface
Source: Davis, 1934

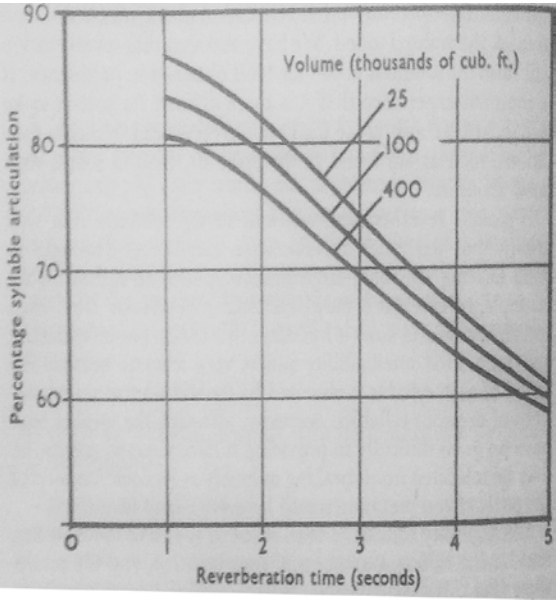


Figure 2.24: Concave surface
Source: Davis, 1934

2.5.4 Acoustic Concentrations

Focused echoes are a common problem in halls with domes or barrel-vaulted ceilings or in fan-shaped plans with curved rear walls (**Fig. 2.23**). Curing echoes in completed buildings can be difficult. Either absorptive or diffusing treatment of a reflecting surface can be used or the surface can be remodelled to direct the reflection away from performers and audience (Davis, 1934).

2.6 SPEECH SOUND

2.6.1 Nature of Speech Sounds and the Effect of Room Acoustics

Speech sounds consists of a flow of combinations of vowel and consonant sounds. These combinations are woven into a main structure consisting of certain predominant tones which are natural attributes of the person speaking. These voice tones (sometimes called formants) can be varied over a small pitch range by the speaker, to give emphasis or shades of meaning, but are always to some extent distinctive of the person. The formants give the basic tone to speech and are heard most in the vowel sounds. The consonant sounds are nearly all of a transient nature; they are short and rapidly changing sounds, very often unvoiced (i.e. containing no formant tone) and therefore having very little acoustic power. The duration of vowels is 90 ms while consonants are 20 ms. It is the correct recognition of consonant sounds, which is the principal factor in speech intelligibility in an auditorium (Parkin and Humphreys, 1958).

According to Cavanaugh, Tocci and Wilkes (2010), Long reverberation times have two effects; first, intelligibility suffers very severely because the sound of each syllable is obscured by the still present reverberations of previous syllables. Secondly, although the speaker may have no great difficulty in providing sufficient sound energy, he may be inhibited from speaking as loudly as he could because of the peals of reverberation set up by every sound he utters. The amount of syllable articulation progressively decreases as the reverberation time and the volume of the room increases (**Fig 2.24**). In practice, a speaker may naturally tend to speak more slowly and loudly when in a large room addressing a larger audience, and this will to some extent help to counter the decreasing intelligibility caused by the reverberation.

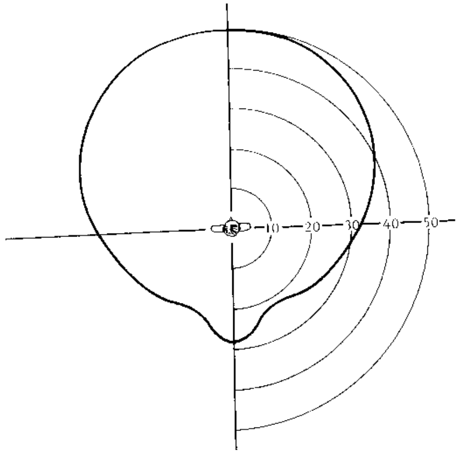


Figure 2.25: Direction of human voice
Source: Barron, 1993

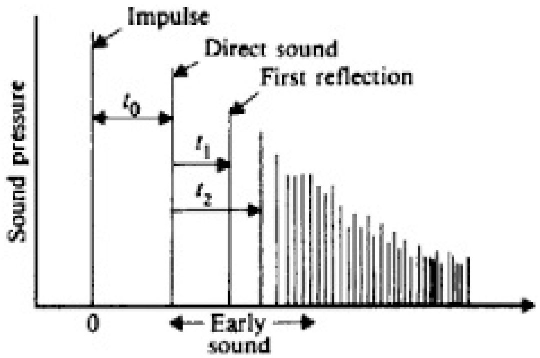


Figure 2.26: Impulse response time
Source: Barron, 1993

2.6.2 Directivity of Human Voice

There are two reasons for the directivity of the human speaker; the finite size of the mouth and the location of the mouth in the head. The mouth is small relative to the wavelengths of most speech sounds and the shadowing by the head is of a major concern (**Fig. 2.25**). The lower frequency contains less intelligibility information but is louder. The greater importance of high frequencies does have a compensating advantage that useful reflecting surfaces need not be too large. Sound will usually be localized in the direction from which the first sound waves arrive at the listener (Hass, 1977).

2.6.3 Sound Propagation

2.6.3.1 In an Open Space

For a source of sound outside, acoustic energy spreads into free space and since the surface area of a sphere is related to the square of the radius, we get inverse square law propagation (**Fig. 2.5**). For every doubling of distance the sound level decreases by 6 dB. When sound travels long distances outside, it is also influenced by wind and temperature effects. Any reflections from the surfaces close to the speaker are valuable, whether they are off hard ground, or surfaces to the side or behind (Reinchardt, 1975).

2.6.3.2 In an Enclosed Space

The first thing one hears is the direct sound. This is followed by a series of early reflections from the side walls, ceiling etc. Reflected sound has to travel further, so will arrive later; it will not be as loud as the direct components. Sound that is not absorbed continues to be reflected and one sees on the impulse response that after the early reflections the number of reflections arriving within 10 ms progressively increase (**Fig. 2.26**). In large halls, the number of reflections arriving at times later than the 100 ms of a second after the direct sound is so high that individual reflections are no longer distinguished. The later sound after about 100 ms is called reverberant sound. It usually decays in a linear manner when plotted in decibels; its duration is described by the reverberation time (Bradley, 1991).

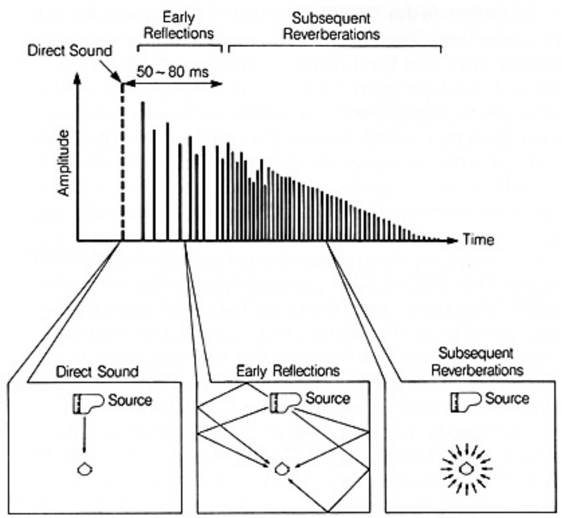


Figure 2.27: Speech intelligibility
Source: Torgny, 2015

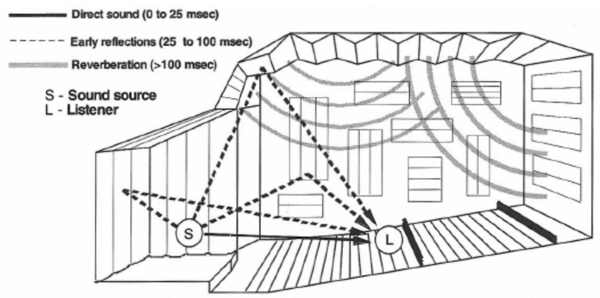


Figure 2.28: Speech in theatres
Source: Foreman, 2015

2.6.3.3 Room Acoustic Requirements

1. An adequate amount of sound must reach all parts of the room. Most of the attention in this respect needs to be given to those seats furthest from the source.
2. An even distribution of sound should be achieved through the room irrespective of distance from the source.
3. Other noise which might tend to mask the required sound must be reduced to an acceptable level in all parts of the room.
4. The rate of decay of sound within the room (reverberation time) should be the optimum for the required use of the room. This is to ensure clarity for speech or fullness for music.
5. Acoustical defects to be avoided include; long delayed echoes, flutter echoes, sound shadows, distortion, and sound concentrations.

2.6.4 Speech Intelligibility Design

The concept that early sound reflections are useful and increase the loudness of sounds, thus increasing intelligibility and that sounds from late-arriving reflections, reverberation, and background noise in the room decrease intelligibility has been established (**Fig. 2.27**) (Lochner and Burger, 1964).

2.6.4.1 Speech Intelligibility in Rooms

Early reflections that are desirable for speech are necessary while late reflections reduce intelligibility. A cathedral space with long reverberation time has late reflections which render speech incomprehensible (**Fig. 2.28**). In a small space, the reverberation time is short enough (0.5 s) for the late reflections to be too weak to undermine intelligibility. In this room, the density of early energy reflections is also high enough that even the speaker's orientation relative to the listener is almost irrelevant (Bradley, 1986).

2.6.4.2 Measuring Speech Intelligibility

A speaker reads nonsense syllables of the consonant-vowel-consonant form; listeners record what they hear, from which Percentage Syllable Articulation (PSA) is calculated. Measurements in the theatre indicate that intelligibility varies both within the auditorium and with changes of source orientation,

Reverberation Time & Speech Comprehension	
Time (RT60)	Speech intelligibility
0.8 – 1.1 seconds	Optimum
0.8 – 1.3 seconds	Good
1.4 – 2.0 seconds	Fair/poor
2.1 – 3.0 seconds	Unacceptable / requires sound system

Figure 2.29: Reverberation Time and Speech intelligibility
Source: BNP Media, 2016

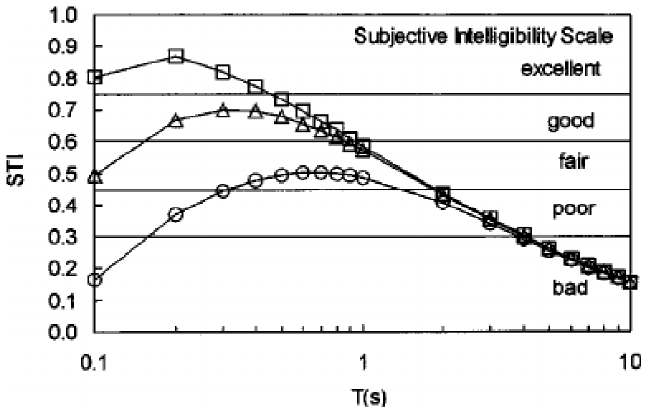


Figure 2.30: RT and Speech intelligibility
Source: Research Gate, 2017

whereas reverberation time is generally independent both of position and of the direction of the source. A short reverberation time proves to be desirable but not a guarantee of adequate speech intelligibility (**Fig. 2.29& 2.30**). Vowels are both louder and of longer duration than consonants, a long reverberation time causes masking of consonants (Lochner and Burger, 1964).

2.6.5 Reverberation Time Design

According to Schultz (1965), this is one of the single most valuable acoustic criteria that can be defined precisely and measured with reasonable accuracy. It has the advantage that is generally constant throughout the room.Sound does not die away the instant it is produced but will continue to be heard for some time because of reflections from walls, ceiling, floors and other surfaces.

2.6.5.1 Factors Affecting Reverberation

Duration of reverberation depends on:

a. The loudness of the original sound.
b. The absorbency of the bounding surfaces, furnishings and people.
c. The volume of the room and thus the length of the sound paths.

Loudness of sound tend to increase the period of reverberation, absorbent materials tend to reduce it, and greater volume tends towards an increase (Sabine, 1932).

2.6.5.2 Quality of Reverberation

Reverberation should provide a background tone and should decay evenly (Watson 1941). To effect this:

a. Ensure strong direct sound and closely following primary reflections.
b. Avoid opposite and parallel plain surfaces, which can set up strong inter-reflections.
c. Surfaces not used as reflectors should be either absorbent or dispersive, or both.
d. Absorbent and dispersive surfaces should be well distributed.

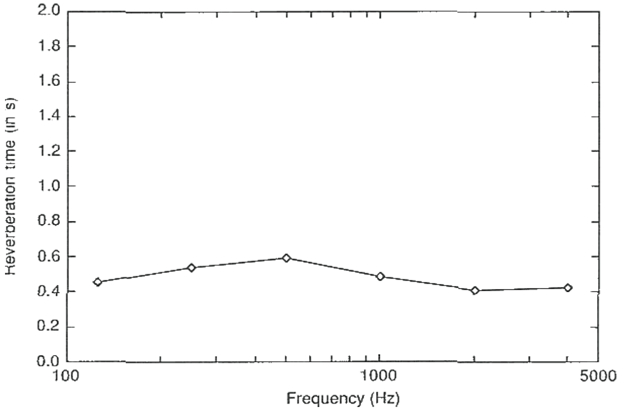


Figure 2.31: Reverberation Time and Frequency
Source: Feilding, 2016

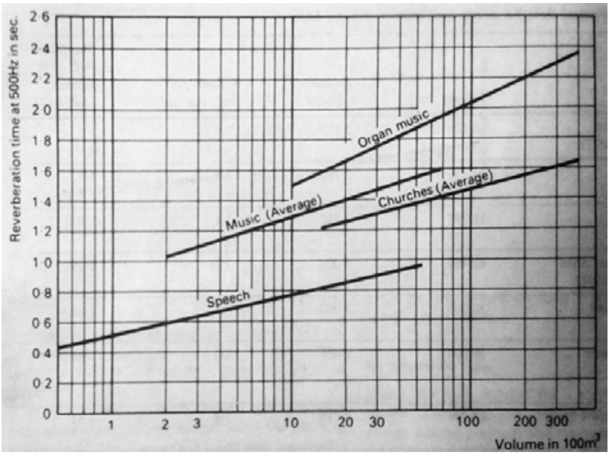


Figure 2.32: Reverberation Time for different spaces
Source: Smith et al, 1982

2.6.5.3 Reverberation and Frequency

Barron (1993) states that if a single figure is quoted for the reverberation time, it generally refers to the mid-frequency value, averaged between 500 – 1000 Hz. Reverberation time will vary with frequency. At high frequencies about 1 KHz, the reverberation time inevitably decreases due to air absorption (**Fig. 2.32**). At low frequencies the situation can be controlled by the designer. For speech, there is a good reason to keep the reverberation characteristic constant with frequency; a rise in the bass undermines intelligibility. At high sound levels, the ear is roughly sensitive to different frequencies, at low sound levels it is less sensitive to bass frequencies. A longer bass reverberation time can compensate for this.

2.6.5.4 Reverberation Time for Different Spaces

Appropriate reverberant time for an auditorium should be determined on the basis of function. Optimum reverberation time can be a function of hall volume; but this only appears relevant in small recital halls (**Fig. 2.32**). A major dilemma exists for reverberation time design for multipurpose spaces. With orchestral music requiring a 2 s reverberation time and speech only 1 s, use of one single space for speech and music is usually not possible without electronic assistance. Selecting a compromise time for such a situation can result in acoustics which are neither able to support intelligible speech nor are sufficiently live by music standards.Where reverberation is long, the earlier part is strong enough to cause a merging of consecutive sounds and has the same blurring effect as near echoes (Smith at al, 1982).

Sound	Reverberation time(Seconds)	Type of space
Speech only	0.75 – 1	Council chambers, law courts, lecture theatres, debating halls
Trained speakers and incidental music	1 – 1.25	Theatres: plays, musical comedy and variety
Reproduced music	1	Cinema (Reverberation added to sound track)
Solo instruments and small groups	1.25 – 1.5	Small concert halls
Multipurpose halls	1.25	School halls, community halls
Orchestral music	1.5 – 2.25	Large concert halls

Opera	1.25 – 1.5	Opera houses
Romantic classic music	1.8 – 2.2	Romantic theatres
Organ and choir	2.5 - 4	Churches, cathedrals

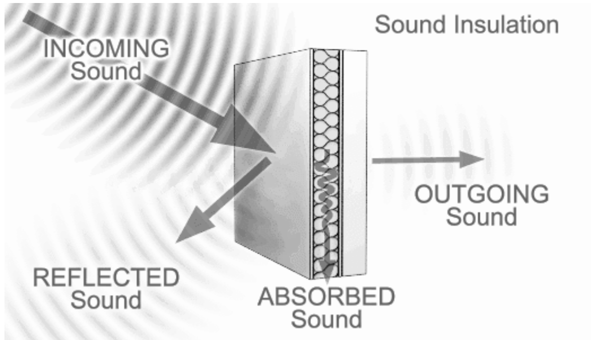


Figure 2.33: Sound waves
Source: Isover, 2017

2.6.5.5 Reverberation Time Calculation

There are three formulas used to calculate reverberation time. These are:

2.6.5.5.1 Sabine Formula

Sabine discovered that only two quantities determined the reverberation time; the room volume (V) and the total acoustic absorption (A). The total absorption is simply determined by adding the product of area (S) and the absorption coefficient (α) of all surfaces in the room (A=S1.α 1 + S2.α 2 + S3.α 3+….).The absorption coefficient for a material is the fraction of non-reflected sound energy to the incident sound energy (**Fig. 2.33**). It is usually sufficient if reverberation time is calculated at 125 Hz, 500 Hz and 2000 Hz. The aim is to achieve an approximately constant period of reverberation over the whole musical range of frequencies (Sabine, 1932).

The sabine equation (**Fig. 2.34**), when volume and acoustic absorption are measured in m^3 and m^2, is:

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

Where: t = reverberation time in seconds
V = volume of hall in m^3
A = absorption units in m^2

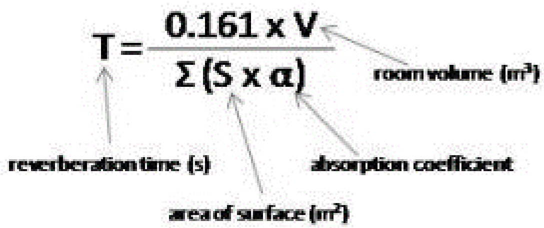


Figure 2.34: Sabine formula
Source: Rutherford & Wilson, 2017

It becomes inaccurate:

a. When used for rooms with a very high proportion of absorbent materials.
b. When used in rooms of “megaphone design” where nearly all sound is projected towards the absorbent audience and rear wall.

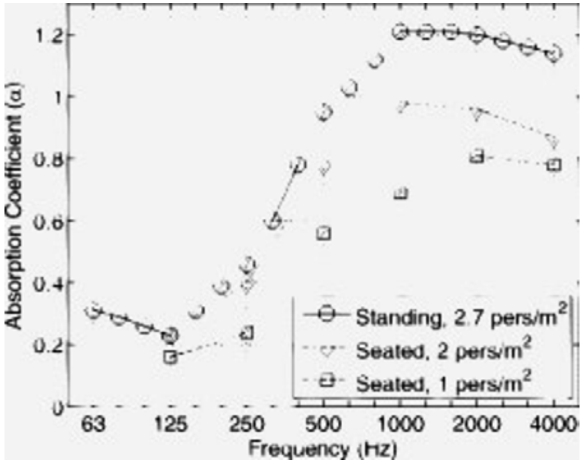


Figure 2.35: Audience absorption
Source: Adelman-Larsen, 2010

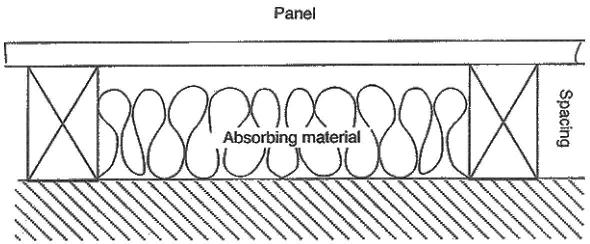


Figure 2.36: Panel absorber with porous material
Source: Feilding, 2016

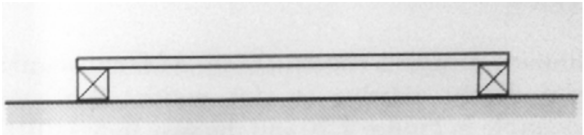


Figure 2.37: Panel absorber
Source: Barron, 1993

2.6.5.5.2 Kosten Formula

The major absorption surface in an auditorium is the audience. Historically due to Sabine, the absorption by audience was calculated on the basis of the number of seats. This, combined with coefficients, which were too small, led to reverberation time in many concert halls which where shorter than expected. Values are often quoted of the volume per seat of auditoria, on the understanding that this quality relates to reverberation time. Beranek showed that it does not and found that more accurate results were produced when the audience was treated like other materials, on the basis of absorption per unit area or absorption coefficient (**Fig. 2.35**). The absorption coefficient is insensitive to seating density (Beranek, 1969).

Reverberation time according to Kosten is calculated as follows:

$$t = \frac{0.16V}{(S_A.\alpha_{eq})}$$

Where: V = Volume
S_A = Acoustic seating area
α_{eq}= Equivalentabsorption coefficient

Kosten found that total acoustic absorption was closely related to audience area. Values for α_{eq} at mid-frequencies are 1.07 (occupied) and 0.97 (unoccupied). The audience acts as a porous absorber, which is efficient at high frequency but not at low frequencies (**Fig. 2.36 & 2.37**). Substantial additional low frequency absorption is required to produce a flat reverberation time with frequency. Panel absorption is the most likely mechanism to exploit though resonator absorbers have been used (Kosten, 1966).

2.6.5.5.3 Stephens and Bate Formula

Stephens and Bate formula is:

$$t = r\,(0.012\sqrt[3]{v} + 0.1070)$$

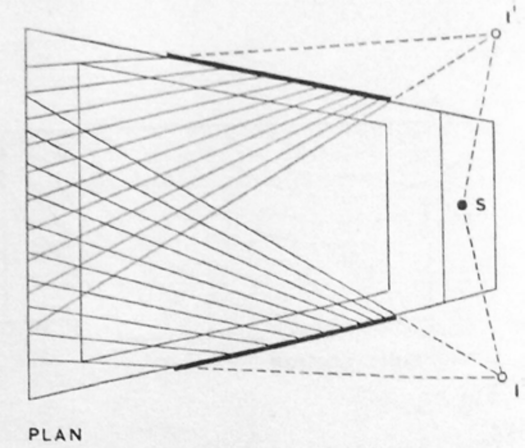


Figure 2.38: Fan shape plan
Source: Moore, 1961

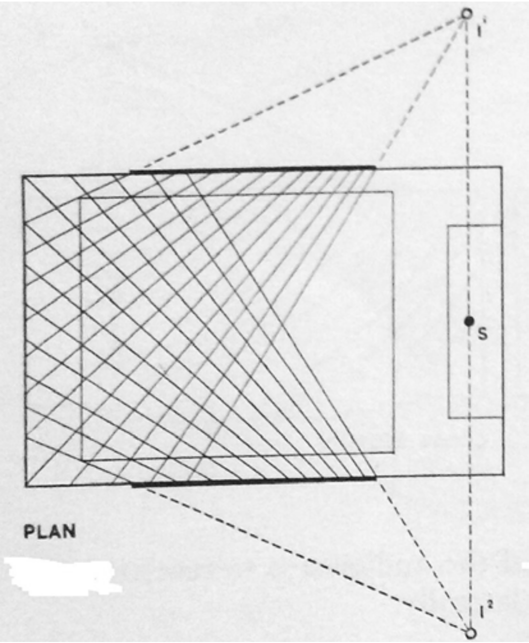


Figure 2.39: Rectangular plan
Source: Moore, 1961

Where t = reverberation time in seconds
v = volume of the hall in m^3
r = 4 for speech
r = 5 for orchestra
r = 6 for choir

2.6.5.5.4 Reverberation Graph Method

Another method uses a set of graphs (**Fig. 2.32**). A few simple calculations show that these give similar results in most cases.

2.7 DESIGN FOR SPEECH

According to Parkin and Humphreys (1958), the primary aim is designing rooms for speech to ensure intelligibility while the secondary aim is preservation of the natural qualities of a speaker's voice to ensure that the audience can appreciate the speaker's nuances and dramatic effect.

2.7.1 Optimum Theatre Profile

2.7.1.1 Floor Profile

The shape of the room should be such as to avoid any danger of long return paths for sound, giving echoes. With the fan shape plan the angle of the sidewall reflection to the direct sound is small and the degree of envelopment is small (**Fig. 2.38**). Whereas in the reverse splay plan, the angle is high and spatial impression is correspondingly greater. The rectangular plan generates many reflections, and has established a considerable reputation for its acoustics (**Fig. 2.39**). The horse-shoe has little to recommend for acoustics, when enlarged enough to achieve a satisfactory reverberation time, the reflection pattern becomes poor, and there are focusing problems associated with concave rear walls. The elongated hexagon offers a compromise with the visual advantages of the fan shape and the acoustic advantage of the reverse splay. A further compromise scheme is the gross fan-shape plan but with stepped parallel walls. This offers an improvement relative to the simple fan shape, but probably still carries some of its faults. The traditional dimension ratio is : Height: Width: Length = 2:3:5 (Barron, 1993).

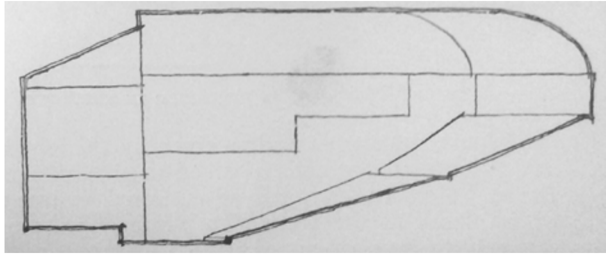


Figure 2.40: Sectional profile
Source: Moore, 1961

2.7.1.2 Sectional Profile

The average distance between the source and the receiver should be kept short (**Fig. 2.40**). Direct sound path shall not be obstructed. There should be no part of the building interposed in the path because sound is absorbed very strongly when it passes at grazing incidence over an audience. The auditorium volume should be tight and small, giving the desirable short reverberation time and limit the distance to the back audience row for visual and acoustic value. The simplest of the shapes takes into consideration ease of construction with common materials. It should provide five useful reflectors on section, namely floor, back wall, splay, ceiling and rear cove. If the volume was rightly proportioned to the seating, no extra absorbing material would be required upon walls: the audience would receive and absorb all the sound after one impact (Watson, 1941).

2.7.1.3 Volume

According to Ando (1985), there is consequently a certain approximate volume of room space which when it contains the absorption provided by one member of audience will have a reverberation time of about the right amount (**Fig. 2.41**). Allowing for the fact that the room surfaces, although nominally reflecting, will have some slight absorption, this volume comes out at about 2.85 m^3 per seat. If all surfaces are made to be useful reflectors, then it is best to design the room volume to this value, because in this way the average sound energy reaching the audience will be at a maximum. If the volume is made greater than this, then additional absorbents other than the audience will have to be introduced to achieve an acceptable reverberation time. It is therefore best to keep the volume to as near to 2.85 m^3 per seat as possible and it is recommended not to exceed 4.25 m^3 per seat, particularly in rooms for very large audiences. The volume per person is dependent upon the purpose for which the building is to be used.

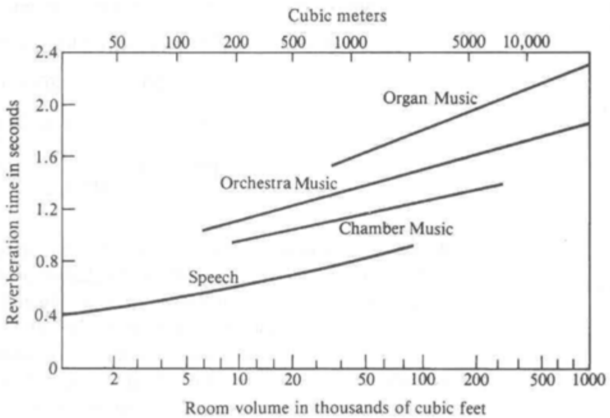


Figure 2.41: Volume versus reverberation time
Source: Moore, 1961

2.7.2 Stage Design

A fly tower introduces extra absorption, where sounds will be absorbed within it by drapes and scenery. All speakers are happier with some feedback from the auditorium without which, one tends to strain the voice, which is a problem for all open-air performance. The speaker should receive some early reflected sound followed by some reverberation from the auditorium. Reflections back to the stage, which arrive late, are heard as echoes, from such surfaces as rear walls or soffits hence diffusing surfaces are likely to

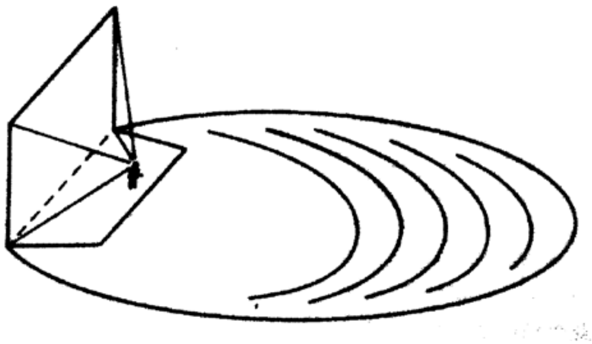


Figure 2.42: Angle subtended by speaker
Source: Barron, 1993

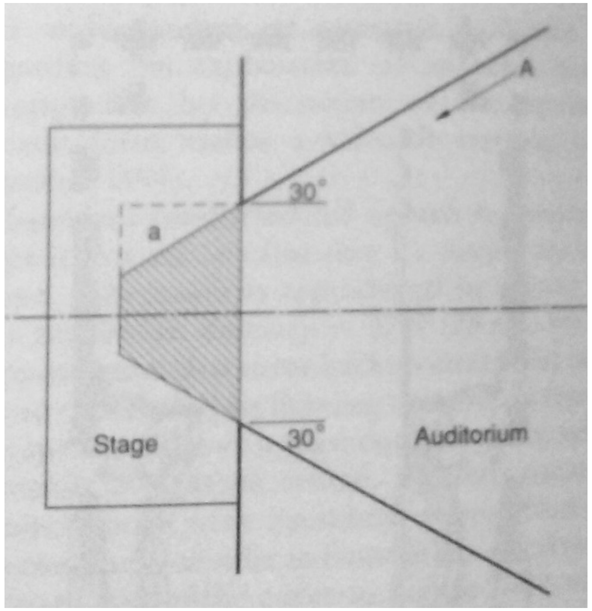


Figure 2.43: Stage walling splay
Source: Barron, 1993

be useful. Performers need reflections from an enclosure to be able to gauge the loudness at which they are performing. They also need to hear reflected sound from other performers on stage so they can achieve a sense of ensemble and perform in unison with each other. In order for the sound of the performer to blend and move into the room, the stage house volume must be high enough (Gade, 1989).

2.7.2.1 Floor

Bagenal and Wood (1931), states that the solid angle subtended at the speaker by the proscenium opening (about 140^{o}) is crucial (**Fig. 2.42**). The stage height above the stalls floor should be between 0.5 m - 1.2 m. Any value above these, leads to screening from view of the center section of the stage platform, from the front rows of the stalls. The stage height determines the setting out point for sightlines and is thus influential for much of the seating layout. Stage floor can be a useful reflector if the rear wall is screened with drapery and the ceiling is too harmful and echo producing. Theatres should have an unimpeded band of hard uncarpeted flooring immediately in front of the stage. When back wall and sidewalls near the platform are used as sound mirrors, reflections from them must follow the direct sound immediately to reinforce syllables in speech. A staged platform emits resonant sound, which would otherwise be conducted away by one of more solid construction. Wood paneling of various thicknesses and sizes responds over a wide range of frequencies. Resonant stage materials would include:

a. Staged platform with paneled apron
b. Paneling around and in contact with the platform
c. Sidewall paneling near the platform

2.7.2.2 Walls

The effect of the speaker turning away reduces the direct sound thus; there should be surfaces in front of the speaker, which reflect sound to the audience. The quantity of drapes should be such that nearly all of the energy is absorbed and is therefore unavailable for contributing to the late sound. The tendency to move forward to the edge of the stage is dangerous because the speaker will get less benefit from the back wall and/or ceiling reflections. The platform should be neither too wide nor too deep. Movable bounding walls can be installed to regulate platform depth (**Fig. 2.43**). Where these are absent, the speaker should move as far backwards as possible in order to maximize the effects of reflections from the

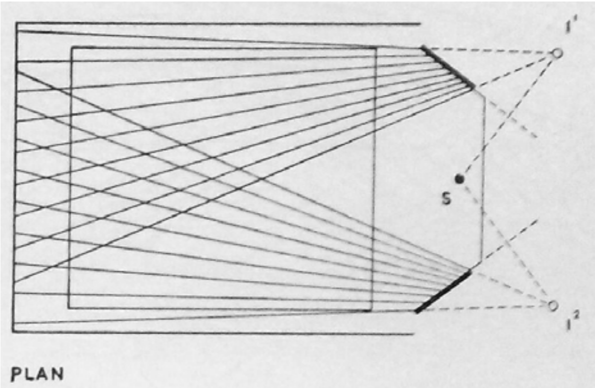


Figure 2.44: Plan of stage splay walls
Source: Moore, 1961

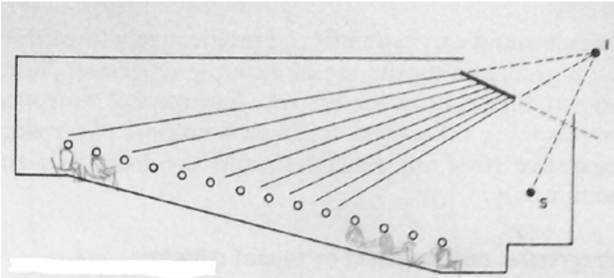


Figure 2.45: Section showing splay ceiling
Source: Moore, 1961

surrounding walls. The wall surfaces near the platform should be mainly oriented to send reflected energy back to the speaker. The walls should be made of solid materials to avoid low frequency absorption. Reflecting surfaces should be near the platform and placed at suitable angles to reflect the maximum sound outwards to the audience (**Fig. 2.44**). The lower portions of the sidewalls and a large part of the ceiling should be used for reflecting sound (Ingerslev, 1952).

2.7.2.3 Ceiling

A ceiling makes an efficient reflector because sound has generally a free path upwards from a speaker's mouth and after reflection strikes the audience at a wide angle. Stage lighting located close to proscenium opening limit early sound reflections. In halls with exposed platforms and high ceilings, an array of reflectors should be suspended over the platform. The average height of the reflectors should not exceed 6 – 8 m above the stage. If it is too high, inadequate sound is reflected down and if it is too low, sound will be prevented from reaching the upper hall volume. Smaller elements are preferred to fewer larger ones. This provides more uniform coverage, avoidance of focusing and less tone coloration, which is always a risk with overhead reflections. Slight convexity for the panels is also desirable for the same reasons. The maximum amount of sound should be directed through the shortest path from the region of the platform to the region of the audience. No reflecting surface at a greater distance than X/2 from the speaker should be at an angle as will return sound upon him. Splayed ceiling will give a better reflection covering the ground floor and gallery as well as the rear seats than the ceiling (**Fig. 2.45**). It is advisable to have a large splay to allow the speaker on stage to change his position (Parkin and Humphreys, 1958).

2.7.3 Audience Seating Area Design

2.7.3.1 Floor

Rows of people, particularly at grazing incidence to the sound, represent a most efficient absorber. It is essential in all but the smallest halls (above 200 people) to rake the seating. Adequate vision should ensure an adequate sound path. This will mean that the line of sight needs to be raised by 80 to 100 mm for each successive row. Arranging seats and gangways in fan or square rather than oblong or semicircular plan and introduction of balconies brings the audience closer to the stage (Richardson, 1945).

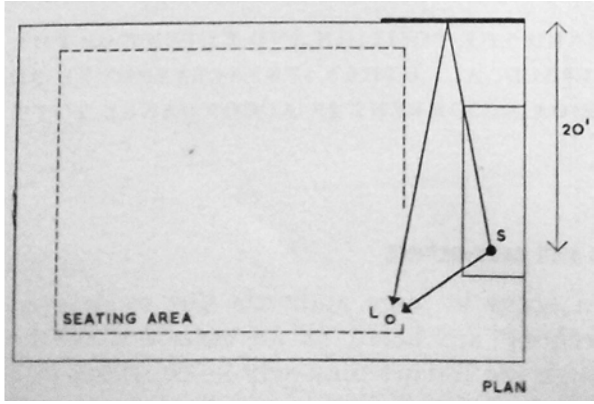


Figure 2.46: Reflective walling in advance of the source
Source: Moore, 1961

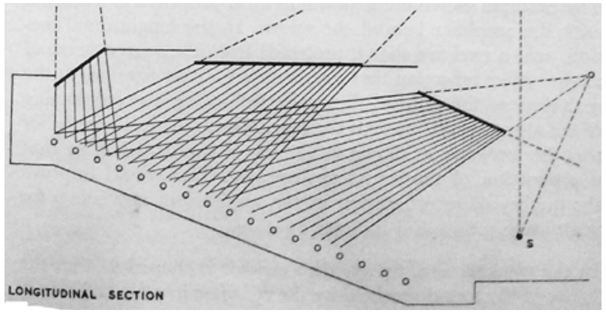


Figure 2.47: Series of reflective ceilings
Source: Moore, 1961

2.7.3.2 Walls

It is best to place the sound absorbents or diffusing surfaces at the rear walls, which produce echoes to front seats and the platform. Hardwearing absorbent materials should be used on walls where they are liable to suffer damage. Less rugged materials should be used out of reach of the audience. The next best position after ceiling reflectors for sound reinforcement is at the sides, and in advance of the source (**Fig. 2.46**). Sidewall reflectors are less effective than overhead reflectors because the audience seated on a low level receive reflections at low angle of incidence. When the source of sound moves laterally, sidewall reflectors cause fluctuations in sound level, due to changing coverage of the reflections. Dispersive or absorbent treatment should be applied in the following areas affected by standing waves (Glover, 1933);

a. Between platform and horizontal ceiling above
b. Between the parallel sides of a platform recess
c. Between opposite sides of small rooms with plain walls

2.7.3.3 Ceiling

Reflections depends on the size of the reflector and the sound wavelength. Perfect reflection occurs at high frequencies whereas with low frequency, less and less energy is reflected along the geometrical reflection path. The ceiling is usually the largest room surface with a high potential for tone coloration and false localization (the sound of a speaker suddenly appears to come from the reflector instead of from the stage). A remedy for both these faults is to add diffusing treatment to the reflector. A series of surfaces adjacent but modestly inclined relative to each other will behave at low frequencies as a single surface.A convex surface will disperse sound while a concave surface will focus sound. High curved concave surfaces remote from the audience do act as dispersers of sound, if neither the source nor the receiver are within the extended circle of the concave surface.Low ceilings reduce the auditorium volume hence reflect sound quickly to the audience no later than 30 ms after the direct sound from the source. A ceiling reflector and an angled reflector can be combined to further reinforce sound in rear seats (**Fig. 2.47**). The ceiling and wall reflecting surfaces must be coordinated with provisions for theatrical lighting positions, ventilation grilles and visual design requirements. Having determined the position and the reflectors sizes required, all other surfaces should be made dispersive or absorbent (Moore, 1961).

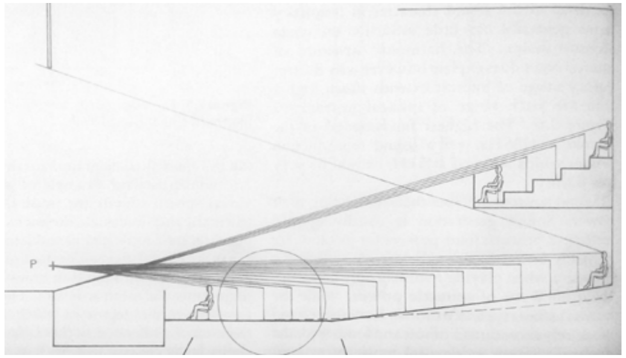


Figure 2.48: Sight line design
Source: Parkin and Humphreys, 1958

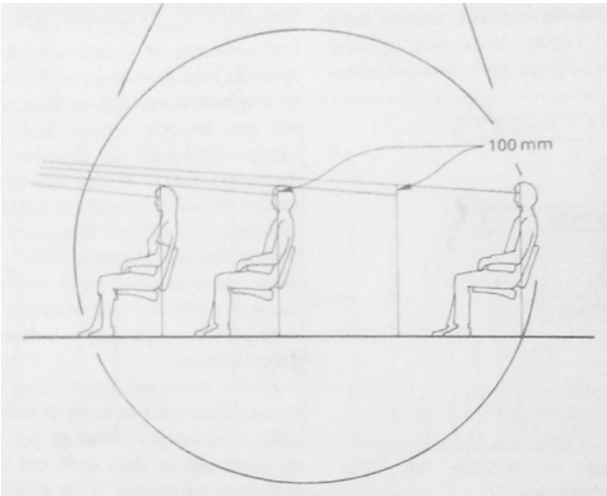


Figure 2.49: Sight line design
Source: Parkin and Humphreys, 1958

2.7.3.4 Seating Arrangement

Parkin and Humphreys (1958) states that, seats should be arranged so that none falls outside an angle of about 140^{o} subtended at the position of the speaker. This is because speech is directional, and the power of the higher frequencies on which intelligibility largely depends falls off fairly rapidly outside this angle. In the absence of an audience, or when there are many empty seats, there will be a marked change in the reverberation time. This can be overcome by using absorbent well-upholstered theatre type seats. The auditorium should be designed to provide the ideal period or reverberation for what is expected to be the more general attendance. Halls with reflecting flat ceilings and floors without fixed seating are acoustically bad for speech when a small number of audience is present, due to flutter echoes arising between the floor and the ceiling. The audience should be arranged compactly to minimize the distance to the stage. Adjustable panels, absorbent on one side and reflective on the other, may be employed in order to allow for variations in the size of the audience, or to provide suitable conditions for the various uses of a multi-purpose hall. Reducing the size of an auditorium by curtains or screens will also reduce the reverberation time for small audiences.

2.7.3.5 Sightline Design

If the audience cannot see the speaker well, there is little chance that they will hear him well. The seats should be arranged so that the heads of one row of the audience do not obstruct the people in the row behind (**Fig. 2.48**). Since our eyes are below the top of our heads by on average 100 mm, floors should be raked to allow the sightlines to pass over the heads of audience in the front row (**Fig. 2.49**). The sightline criterion generates a curved floor rake, but this is normally approximated by a series of linear rakes. The maximum permissible rake in balconies is 35^{o}. If flat auditorium floors are used, it is best to raise the speaker's platform sufficiently high to ensure that minimum clearance is obtained at the rear rows of the hall. The setting out point on the stage for stalls seating is normally taken as 0.6 – 0.9 m above the stage front and for balconies the stage front itself is often used (Barron 1993).

2.7.3.6 Gangways

The presence of gangways round the back of seating will reduce useful reflections and such gangways are therefore undesirable in a theatre in which intelligibility could be marginal (Smitthakorn, 2006)

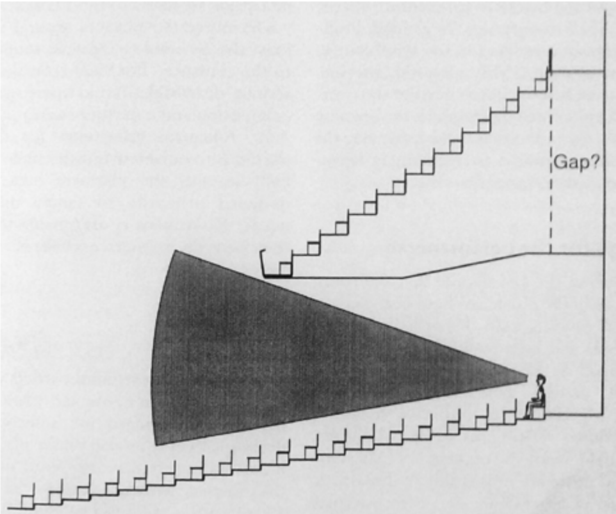


Figure 2.50: Gap behind the balcony
Source: Barron, 1993

2.7.4 Balcony Design

2.7.4.1 Floor Surface and Soffit

The free height between the audience and gallery soffit should be made great. The depth of the seating area under the gallery should not exceed the height. Deep balcony overhangs prove not to be a great problem with speech, since the early sound level is little affected but the late sound decreases as one moves beyond the balcony front. Little can be done to mitigate the effects of an overhang on the reverberant sound. A gap behind the balcony can allow sound to filter around (**Fig. 2.50**). The sound level can be increased by profiling the balcony soffit to provide extra reflections. This will only serve to increase the objective clarity and reduce reverberation. It is necessary to tilt balcony fronts downwards so that reflections reach the floor seating areas. The position of the last seat beneath any gallery should be limited by the angle of reflected sounds able to reach if from an overhead surface (Beranek, 1962).

2.7.4.2 Walls

Apart from true reverberant sound, the first early reflections contribute to the direct sound. Angled hard surfaces should be provided so that the reflected waves are directed towards the audience and preferentially to those members who are most distant from the speaker. Splayed surfaces at the sides enhance sound reinforcements. All reflected sound paths, which are no greater than 9 m more than a direct sound path, may be expected to reinforce the direct sound. Reflected sound paths that are greater than 15 m more than the direct sound path result in echoes and reduction in intelligibility (Watson, 1941).

2.7.4.3 Ceiling

Reflections from the ceiling are needed to arrive shortly after the direct sound (within the first 50 – 80 ms), especially in the rear portions of a room, to increase the sound level and to provide clarity. Where monumentality and consequent high ceilings are essential, specially shaped side balconies can help provide short-delayed sound reflections for the central main floor. Under-balcony soffits can provide reflections for the seats beneath them. The main ceiling can be shaped to reflect some sound energy quickly to the balconies and any remaining surfaces capable of producing long-delayed reflections can be treated with absorption and/or diffusion (**Fig. 2.51**) (Veneklasen, 1979).

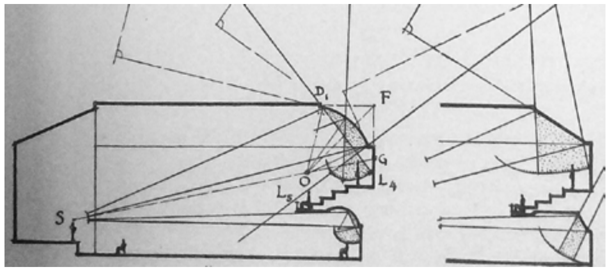


Figure 2.51: Balcony ceiling
Source: Bagenal and wood, 1931

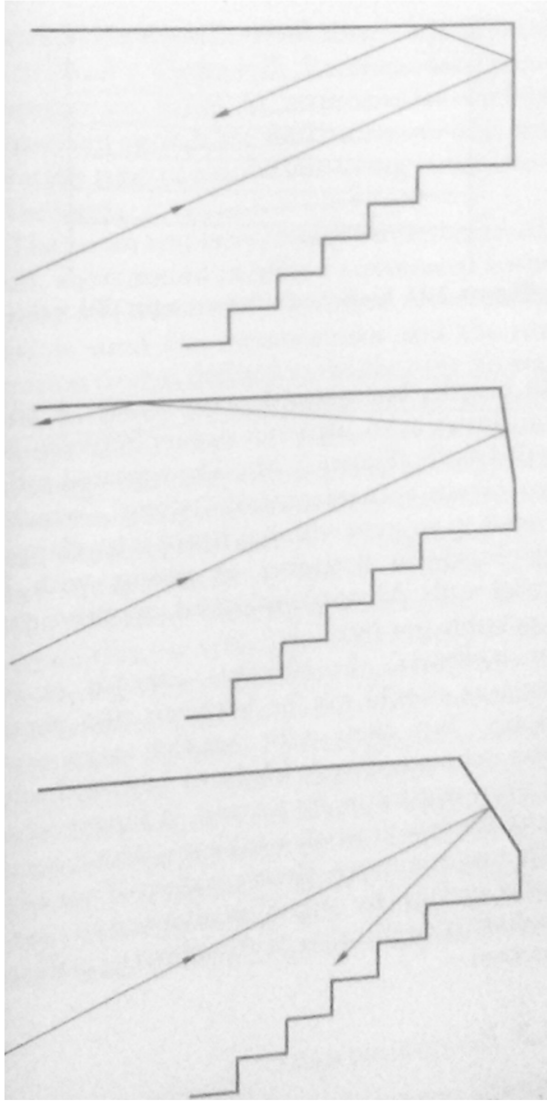


Figure 2.52: Cove Design
Source: Barron, 1993

2.7.4.4 Coves

Junctions of rear walls and ceiling above gallery level will throw back long reflected sound upon the speaker after two impacts if left hard and smooth (**Fig. 2.52**). This is a short echo and not reverberation, since it can be distinguished in suitable places. In large half empty halls long reflections may occur in this way at junctions of walls and the floor. They may also occur from the corners of a room. Coves should be designed on the cross-section of a hall as well as on the long section. Where galleries extended along the sides of a hall, coves can act as valuable reflectors to gallery seats (Parkin and Humphreys, 1958).

2.7.5 Material Finishes

Material finishes need to be chosen both for their functional, acoustic and aesthetic properties. When acoustic materials are employed certain considerations should determine their choice (Sabine, 1932):

a. Absorbent materials are easily damaged and should not be employed within reach.
b. Materials are satisfactory in the first instance but are made ineffective by subsequent decoration.
c. Fire resistance, vermin and rot-proof are desirable qualities.
d. Porous materials absorb moisture. The effects of expansion and contraction must be considered.
e. Materials with a high coefficient of absorption will be more economical than those that require use in larger quantities. Some materials may however be found to have a high absorption only over a limited frequency range.
f. Some materials may have to be rejected on grounds of appearance in the first instance, or because their appearance suffers in the process of fixing or the passage of time.
g. Since all materials absorb sound preferentially, the aim should be to use them in mixed proportions that the resultant period of reverberation is the same at all frequencies.

2.7.5.1 Absorbers

Porous and draped materials absorb preferentially at high frequencies, resilient materials at middle frequencies, and wood paneling at low frequencies. Materials designed on the Helmholtz principle generally absorb most sound in the middle or high frequency range. It is necessary to mix the materials used so that selective absorption is balanced out as much as possible in the end-result (Smith et al, 1982).

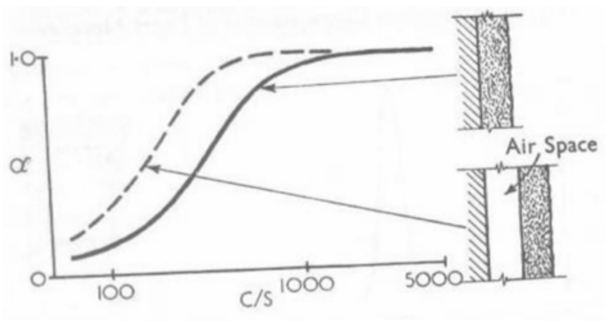


Figure 2.53: Porous absorbers characteristics
Source: Moore, 1961

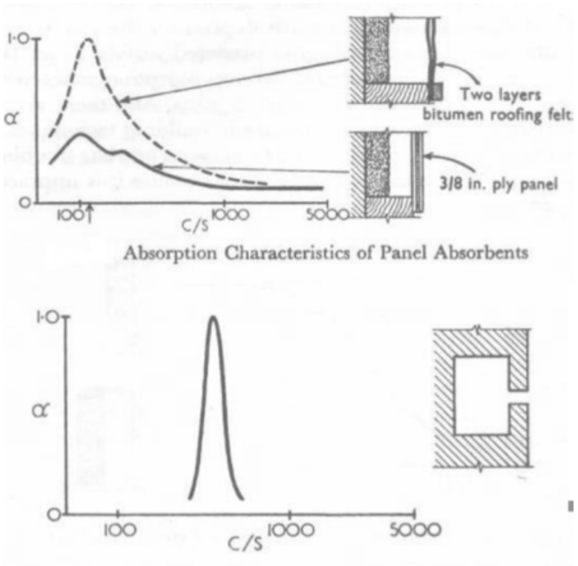


Figure 2.54: Panel & Helmholtz absorbers
Source: Moore, 1961

2.7.5.1.1 Porous absorbers

They have networks of interlocking pores, which act by converting sound energy into heat. Sound absorption is far more efficient at high than low frequencies (**Fig. 2.53**). It may be slightly improved by increased thickness or mounting with airspace behind increasing low frequency absorption. Where lack of space on walls or ceilings prevents the addition of absorbents, they may be used in the form of space absorbers. These can be made from perforated sheets of steel, aluminum, or hardboard in various shapes; cubes, prisms, spheres or cones and filled with fiberboard, mineral wools, insulation blankets, glass wool, rock wool etc. It is possible to make them with the underside reflecting while the top is absorbent. This will prevent long delayed sound reaching the listeners and provide more reflection of sound to certain parts of the audience (Smith et al, 1982).

2.7.5.1.2 Membrane or panel absorbers

They have good absorption characteristics in the low frequency range (**Fig. 2.54**). The absorption is in the range of 50 to 500 Hz. In practice, this is only an approximation as the method of fixing and stiffness of individual panels can have a large effect (Smith et al, 1982).

2.7.5.1.3 Perforated panel absorbents

These are a combination of resonant and porous absorbers and are best in medium frequencies. They can be ‘tuned’ by variation of the hole sizes, shape, spacing and of backing material and space. Any thin panel will absorb some energy in the low frequency. The panel mass and depth of the air space influences the absorption rate of frequencies. They can often be present in the form of suspended ceilings or even closed double windows (Moore, 1961).

2.7.5.1.4 Helmholtz or cavity resonators

These are containers with a small open neck and porous material introduced into the neck to increase the efficiency of absorption. Efficient absorption is only possible over a very narrow band and it is necessary to have many resonators tuned to slightly different frequencies (**Fig. 2.54**). Cavity resonators are useful in controlling low reverberation time at isolated frequencies (Moore, 1961).

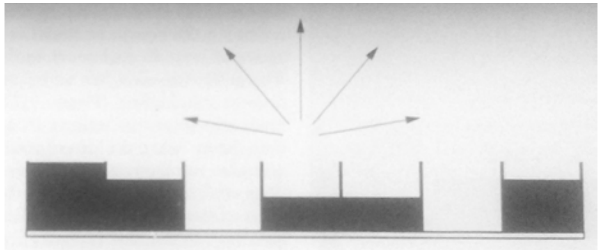


Figure 2.55: Diffusers
Source: Barron, 1993

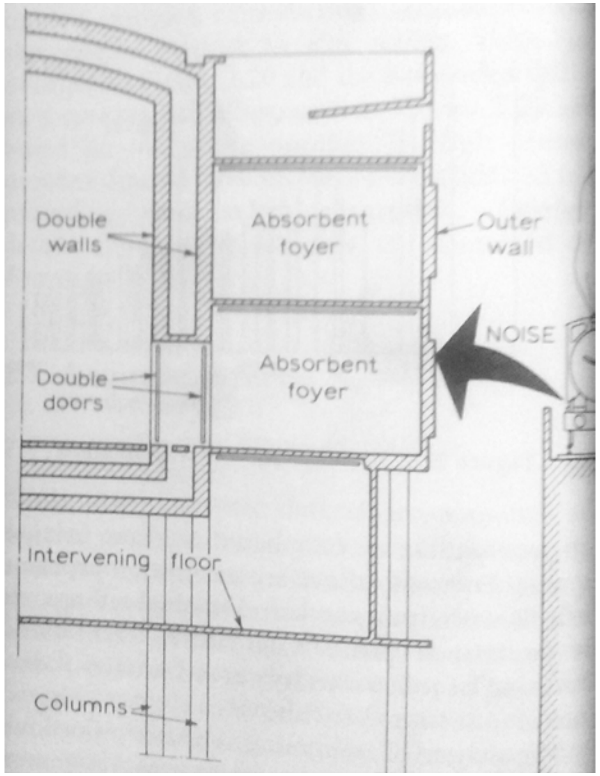


Figure 2.56: Acoustics and noise
Source: Barron, 1993

2.7.5.2 Diffusers

A diffuse sound field allows reflected sound paths to arrive at the audience from most directions. Rough surfaces will break up or diffuse sound and by doing so can prevent echoes and sound concentrations. In order to break up a sound wave the depth of relief should be at least 1/10th of the wavelength. Convex surface will diffuse sound. Concave surface of limited radius will diffuse sound after it has previously passed through a focal area. Breaking up sound by diffusing surfaces will slightly increase surface area and thus increase the small absorbing power of the hard surfaces (**Fig. 2.55**) (Cremer and Muller, 1982).

2.7.5.3 Reflectors

Reflector size influences the range of frequencies over which the reflector is efficient. Small reflectors are effective only at high frequencies. To achieve a sense of envelopment, one or more strong reflections are required from the side. Lateral reflections from above and behind are acceptable, so that reflections off sidewall/ ceiling cornices and side balcony cornices can be of value. Reflectors should never be more than slightly curved in cross section because it will lead to unbalanced reinforcement of sound over the audience where the loudness of sound change for any one member of the audience (Hass, 1972).

2.7.6 Acoustics and Aesthetics

Though acoustics and sightlines are the major considerations, they need not dominate the design. Over-emphasis of acoustics in the mind of the designer may well lead to loss of character, whether this be the spirit of entertainment in a theatre or the atmosphere of dignity in a council chamber. The occupant of an acoustically designed room may easily feel that he is the subject of a scientific experiment. Most acoustic problems have alternative solutions, both in general and in detail, so that considerable freedom is left to the designer (Moore, 1961).

2.7.7 Acoustics and Noise

According to Schultz (1965), there is need to prevent interference by structure and foundation-borne noise, air-borne noise through the windows and doors, the need for sound absorbent lobbies, acoustics baffles in ventilation trunking and the use of soft flooring materials to reduce audience noise (**Fig. 2.56**).

2.8 SUMMARY AND CONCLUSIONS

2.8.1 Basic sound characteristics

- The ear can perceive frequencies between 20 - 20,000 Hz though the upper limit decreases with age.
- Parallel and plain opposite walls cause standing waves especially where they flank the sound source.
- Direct sound contributes to sensations of loudness, clarity and localization. Early reflections arriving within 40 ms contribute to a sense of intimacy and loudness. Diffuse reflections that arrive between 40ms and 80ms increases the sensation of acoustic texture (**Fig. 2.57**).
- Reverberant sound arriving from many directions and are not exactly the same at the ears of a listener, will increase the sensation of acoustic spaciousness.
- Reverberant sound with strong low frequency will increase the warmth in the room while, high frequency will contribute to the perception of brilliance.
- The limit within which reflections contribute to speech intellegibility is 50 ms while music is 80 ms.

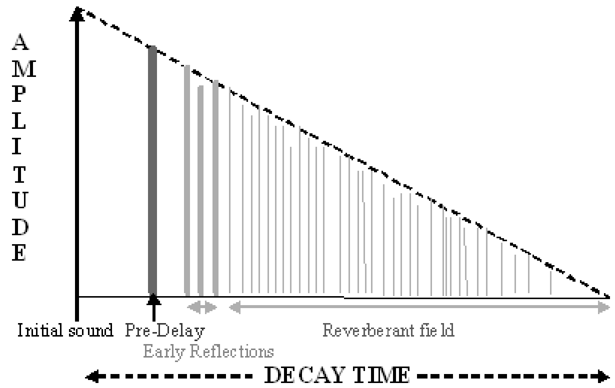


Figure 2.57: Reverberation time
Source: Roy, 2014

2.8.2 Sound behavior on surfaces

- Concave shapes produce reflections that are condensed and therefore stronger with very loud sounds or dead spots, while convex surfaces are diffused hence more attenuated and weaker (**Fig. 2.58**).
- A right-angled corner of a room will reflected sound back to the source, if surfaces are reflective.
- High frequency sounds will create a shadow zone beyond the obstacle, while low frequency sounds will be diffracted if the wavelength is larger than the obstacle size.
- A light profiled surface will only diffuse at high frequencies. The deeper the diffusing treatment, the lower the frequency down to which the surface will scatter sound.
- Major absorbing surfaces are the audience, who at mid-frequencies absorb 90% of incident energy.
- Surfaces that are too far from the listener and/or performers should be made sound absorbing.
- Air absorption is negligible at low frequencies, but should be considered at high frequencies above 1000 Hz when calculating reverberation times.

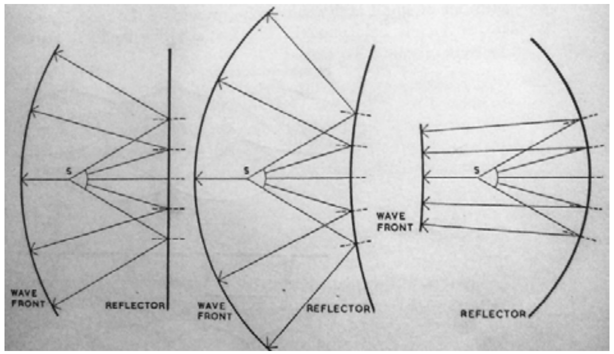


Figure 2.58: Sound behavior on surfaces
Source: Moore, 1961

2.8.3 Sound defects

- Reflections off the back wall and adjacent soffit is a frequent cause of echoes on stage.
- Flutter echoes occurs between parallel walls and can be cured by reorientation of the surfaces by 50^{o}.

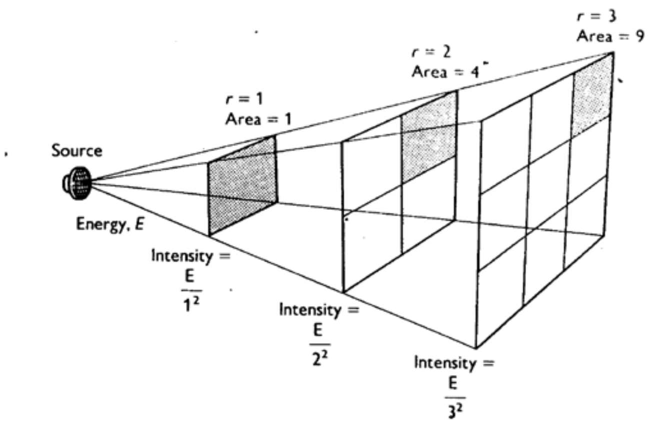


Figure 2.59: Inverse square law
Source: Barron, 1993

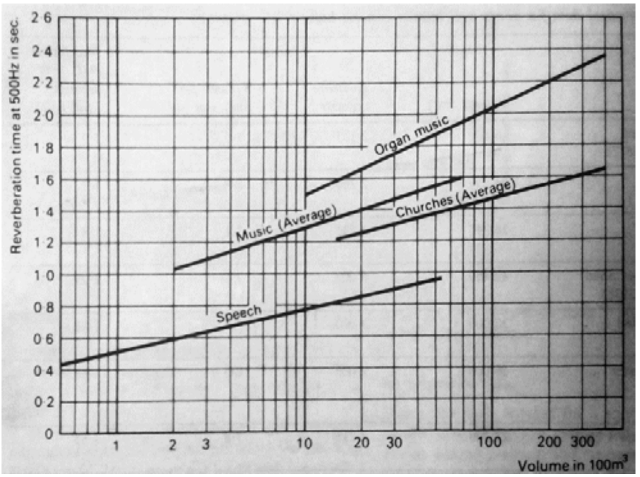


Figure 2.60: Reverberation Time for different spaces
Source: Smith et al, 1982

- Sound shadows cause areas of poor audibility under the overhang of the deep galleries.
- Domes, barrel-vaulted ceilings or curved rear walls in fan-shaped plans cause focused echoes.
- Absorptive or diffusive treatment of reflecting surfaces can be used to cure sound defects.

2.8.4 Speech sounds

- The duration of vowels is 90 ms while consonants is 20 ms. Vowels are louder than consonants.
- Syllable articulation decreases as the reverberation time and the room volume increases.
- For every doubling of distance the sound level decreases by 6 dB (**Fig. 2.59**).
- The direct sound is between 0 – 25 ms, the early reflected sound is between 25 – 100 ms and any sound arriving after 100 ms is reverberant sound.
- Speech intelligibility varies within the auditorium and with changes of source orientation, whereas reverberation time is independent of the position and the direction of the source.
- Loudness increases reverberation time, absorbent materials reduces it, and larger volume increases it.
- With music requiring a 2 s reverberation time and speech only 1 s, use of one single space for speech and music is usually not possible without electronic assistance.
- The audience acts as a porous absorber at high frequency but not at low frequencies.

2.8.5 Design for speech

- The traditional auditorium dimension ratio is: Height: Width: Length = 2:3:5.
- Designing the volume at 2.85 m^3 per seat, and if all surfaces are made to be useful reflectors, then the audience would act as the only absorbent surface required (**Fig. 2.60**).
- Speakers need reflections from the stage to be able to gauge their loudness.
- The solid angle subtended at the speaker by the proscenium opening should be about 140^o.
- The stage height above the stalls floor should be between 0.5m - 1.2m.
- Theatres should have hard uncarpeted flooring immediately in front of the stage to reflect sound.
- The speaker will get less benefit from the back wall reflections if he moves to the edge of the stage.
- The wall surfaces near the platform should be oriented to send reflections back to the speaker. Reflecting surfaces should also be near the platform and angled to reflect sound to the audience.

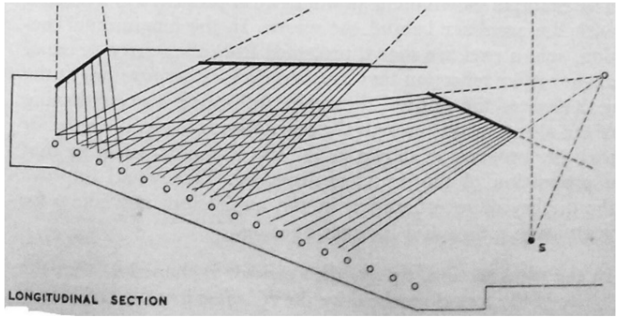


Figure 2.61: Series of reflective ceilings
Source: Moore, 1961

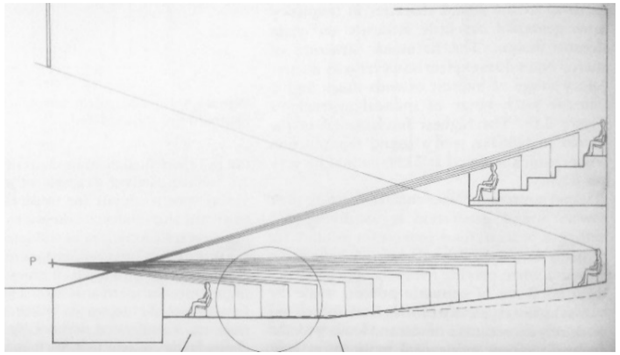


Figure 2.62: Sight line design
Source: Parkin and Humphreys, 1958

- The lower portions of the sidewalls and a large part of the ceiling should be used to reflect sound. The ceiling makes an efficient reflector because sound has generally a free path upwards from a speaker's mouth and after reflection strikes the audience at a wide angle.
- Stage lighting located close to proscenium opening limits early sound reflections.
- The average height of the reflectors should be between 6 – 8 m above the stage. If too high, inadequate sound is reflected downwards and if too low, sound will not reach the upper hall volume.
- Several smaller ceiling elements are preferred to fewer larger ones. This provides uniform coverage, avoidance of focusing and less tone coloration, which is a risk with overhead reflections. Slight panel convexity is also desirable for the same reasons (**Fig. 2.61**).
- Splayed ceiling will give a better reflection covering the ground floor, gallery and the rear seats.
- Large stage ceiling splay allows the speaker to change his position and orientation on stage.
- The line of sight should be raised by 80 to 100 mm for each successive row to allow for good sight lines as well as adequate sound path (**Fig. 2.62**).
- The next best position after the ceiling for reinforcement is at the sides, and in advance of the source.
- Absorbent well-upholstered seats will ensure good absorption in cases of varying audience numbers.
- Adjustable panels, absorbent on one side and reflective on the other, may be employed to cater for variations in audience numbers, or provide for suitable conditions in a multi-purpose hall.
- If flat auditorium floors are used, it is best to raise the speaker's platform sufficiently high to ensure that minimum clearance is obtained at the rear rows of the hall.
- The presence of gangways round the back of seating will reduce useful reflections.
- The sound level can be increased by profiling the balcony soffit to provide extra reflections.
- The position of the last seat beneath any gallery should be limited by the angle of reflected sounds able to reach if from an overhead surface.
- Splayed surfaces at the sides enhance sound reinforcements.
- Smooth, hard, dense and heavy materials absorb least sound while rough, soft, porous and light materials absorb most sound.
- Porous and draped materials absorb at high frequencies, perforated panels at middle frequencies, and membrane or panels at low frequencies. Helmholtz or cavity resonators absorption is only possible over a very narrow band.
- There is need for sound absorbent lobbies, acoustics baffles in ventilation trunking and the use of soft flooring materials to reduce internal and external noise.

CHAPTER 3

RESEARCH METHODS

Figure 3.1: G12 lecture theatre
Source: Author, 2016

3.1 Introduction

This chapter describes the research method and process involved in carrying out the research on design for speech in University of Nairobi lecture theatres. It discusses the methods used for data collection, data recording, data analysis and presentation of findings.

3.2 Justification of the Study

This study seeks to understand the acoustic qualities of five lecture theatres in the University of Nairobi and to propose various mitigation mechanisms that can be put forward to ensure that these theatres perform optimally during lecture sessions. The lecture theatres are raked and have a common problem of long reverberation times and acoustic defects which undermines speech intelligibility.

3.3 Research Purpose

The research is both exploratory and descriptive. It seeks to understand the various lecture theatres in the University of Nairobi, their capacity, material finishes, floor and sectional profile as well as different mechanisms put forward to ensure optimal sound propagation to the audience. The data collected will be used to determine whether these theatres meet the standard requirements for good speech propagation. The research will propose mitigation mechanisms to improve the current conditions of these theatres.

3.4 Research Design

Case study method was used to collecting data of the lecture theatres. This focuses on real cases in their context (**Fig. 3.1 & 3.2**). It also involves studying how these theatres were designed, the capacities intended and how best to design them to meet the requirements for a good speech intelligibility.

Figure 3.2: Taifa Hall
Source: Thuita, 2016

3.5 Time Horizon

Cross-sectional form of study was used in this research. The time assigned for the field work was 12th December, 2016 to 13th February, 2017. The area of study was the University of Nairobi campuses with specific lecture theatres selected using purposive sampling. This enabled a study on large raked theatres with capacities of between 500 – 1200 that are prone to long reverberation time and acoustic defects.

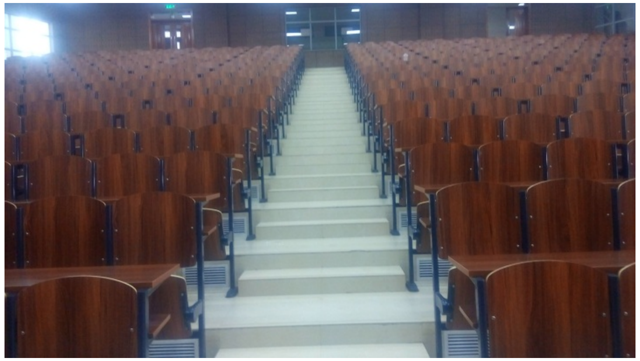


Figure 3.3: Lecture Theatre 101
Source: Author, 2016

3.6 Population Frame

There are a total of 46 raked lecture theatres distributed across the following University of Nairobi campuses: Main Campus, Chiromo Campus, Kenya Science Campus, Kikuyu Campus, Parklands Campus, Lower Kabete Campus, Upper Kabete Campus and Kenyatta National Hospital Campus (See **appendix 1**). These lecture theatres have a capacity of between 42 and 1200 persons. This research focused on raked theatres with capacities ranging from 500 to 1200 persons since they are prone to long reverberation times as well as major acoustic defects. The study explored the floor profile, sectional profile and material finishes used to counter these defects.

3.7 Sampling Method

Purposive sampling method was used to select the five lecture theatres to be studied based on the common problems these halls face. The large raked lecture theatres are prone to long reverberation times due to their large volumes and long distances from the stage to the back wall. These lecture theatres also experience acoustic defects in form of shadows, echoes, flutter echoes, standing waves and acoustic concentrations. University of Nairobi has a total of 46 raked lecture theatres and among these five theatres were purposely chosen for this study. These are:

- Taifa hall – Main Campus, Administration block
- Lecture Theatre 101 – Main Campus, University of Nairobi Towers (**Fig. 3.3**)
- Science Lecture Hall complex – Kenya Science Campus
- Multi-purpose Hall – Main Campus, 8-4-4 Building
- Millennium Hall 01 – Chiromo Campus (**Fig. 3.4**)

Figure 3.4: Millennium Hall 01
Source: Author, 2016

3.8 Data Collection Techniques

The study took a cross sectional study approach due to limited time frame. The research centered mainly on designing University of Nairobi lecture theatres for speech purposes only. Observation method was mainly used as the data collection technique, where acoustic tests were done on all the five lecture theatres. Documents and records from the university's estates department were used to regenerate the plans, sections and elevations of the various lecture theatres for acoustic analysis.

Figure 3.5: Sony DSC 350 camera
Source: Author, 2017

Figure 3.6: 25 meter Stanley distometer
Source: Author, 2017

3.8.1 Observation

There was participant observations aimed at gaining an understanding of the acoustic treatment of the five lecture theatres. The observation focused on floor and sectional profiles, floor, walling and ceiling material finishes and balcony treatments. The observation techniques used to collect data were:

1. Free hand sketching used to provide information for analysis of theatre floor and sectional profiles, material textures and shapes, seating arrangements as well as seat shapes and finishes.
2. Photography: Digital records of the theatre interior and exterior shapes, material finishes and seating arrangements were made using a Sony digital camera (**Fig. 3.5**).
3. Taking notes of the key points observed.
4. Measured drawing using Stanley distometer was employed so as to support acoustical analysis of spaces and allow for architectural analysis of different theatre shapes and sizes (**Fig. 3.6**).

The checklist for information collected was as shown:

1. Audience seating space: Floor plan profile, sectional profile, volume, ceiling heights from the floor level, ceiling profile, seating arrangement, sightlines and gangway design.
2. Stage: Floor plan profile, sectional profile, volume, ceiling heights from the stage floor level, ceiling profile and the stage height from the floor gallery seating.
3. Balcony: Floor plan profile, sectional profile, volume, ceiling heights from the floor level, ceiling profile, seating arrangement, sightlines and gangway design.
4. Audience seating space material finishes: Flooring, walling, ceiling and seats.
5. Stage material finishes: Flooring, walling, ceiling and stage curtains.
6. Audience seating space material finishes: Flooring, walling, ceiling and seats.
7. Reverberation time for each lecture theatre.
8. External profile and support spaces.
9. Acoustic defects: Echoes, flutter echoes, standing waves, sound concentrations and sound shadows.
10. Acoustics and external noise interference.
11. Acoustics and aesthetics of the five theatres picked for this study.

Figure 3.7: Agriculture theatre 1
Source: Author, 2017

Figure 3.8: Mwalimu MPH
Source: Author, 2017

3.8.2 Documentation and records

The data collected through the records were the floor plan layouts, sections, elevations and construction details used in constructing these lecture theatres. These were acquired from the university's estates registry at the Main Campus, Engineering block.

3.9 Data Processing and Analysis

Quantitative data analysis was used which allows generalizations of results from a sample to an entire population of interest and the measurement of the incidence in a given sample. The data produced were numerical, and they were analyzed using the following mathematical and statistical methods.

3.9.1 Sabine formula:

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

Where: t = reverberation time in seconds
V = volume of hall in m^3
A = absorption units in m^2

3.9.2 Stephens and Bate formula:

$$t = r\,(0.012\sqrt[3]{v} + 0.1070)$$

Where t = reverberation time in seconds
v = volume of the hall in m^3
r = 4 for speech
r = 5 for orchestra
r = 6 for choir

The aim of analyzing the data obtained from observation, records and documents was to come up with the reverberation times of these theatres (**Fig. 3.7 & 3.8**), so as to critically redesign them to fit within the

Figure 3.9: ArchiCAD 18 Sketching Tool
Source: Author, 2017

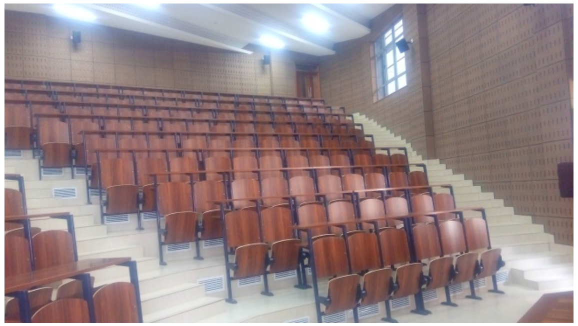


Figure 3.10: Lecture Theatre 201, UoN Towers
Source: Author, 2017

required reverberation time of speech. The sketches and photos taken were also to help analyze acoustical issues of the theatres such as: floor plan profile, sectional profile, volume, ceiling heights from the floor level, ceiling profile, seating arrangement, sightlines, gangway design, flooring finishes, walling finishes, ceiling finishes as well as stage curtain types. Descriptive and content analysis was also done with tables used for comparative purposes.

3.10 Data Presentations

It entailed use of the following;

1. Sketches generated by hand then enhanced by CAD software; these were for representation of architectural elements. It included plans, sections, elevations and construction details of theatres as well as material finishes (**Fig. 3.9**).

2. Measured drawings; provided actual representation of the theatre floor and sectional dimensions, seat sizes, heights of ceilings, stage floor height and gangway dimensions.

3. Photography; provided image representation of theatre interior and exterior shapes, material finishes and seating arrangements (**Fig. 3. 10**).

4. Graphs: Bar graph was a way of summarizing a set of categorical data. It displayed the data using a number of rectangles, of the same width, each of which represents a particular category. Bar graphs were displayed vertically and they were drawn with a gap between the bars (rectangles). Line graphs was particularly useful when showing the trend of a variable over time. Time was displayed on the horizontal axis (x-axis) and the variable in the vertical axis (y- axis).

5. Tabular data presentation: It is the clear organization of data into rows and columns to facilitate communication. Tables clearly conveyed large amounts of information that was cumbersome to write in paragraph form. By creating tables it required careful consideration to its design. Headings, dividers and appropriate variations of font sizes allowed the author to describe and organize information clearly. One way the author made tables easy to interpret was by arranging or grouping data for clarity.

CHAPTER 4

DESIGN FOR SPEECH ANALYSIS

4.1 INTRODUCTION

Figure 4.1: Taifa Hall
Source: Author, 2017

This study provides significant analysis of five lecture theatres within the University of Nairobi. The first step was to establish the existing speech design conditions of these lecture halls, identification of the design gaps and the design for speech mitigation mechanisms that can be put forward to improve the existing conditions of these lecture halls.

Five lecture theatres were studied based on the common problems these halls face. The large raked lecture theatres are prone to long reverberation times due to their large volumes and long distances from the stage to the back wall. These lecture theatres also experience acoustic defects in form of shadows, echoes, flutter echoes, standing waves and acoustic concentrations. University of Nairobi has a total of 46 raked lecture theatres and among these five theatres were purposely chosen for this study. These are:

- Taifa hall - Main Campus, Administration block (**Fig. 4.1**)
- Lecture Theatre 101 - Main Campus, University of Nairobi Towers
- Multi-purpose Hall - Main Campus, 8-4-4 Building (**Fig. 4.2**)
- Millennium Hall I - Chiromo Campus
- Science Lecture Hall complex - Kenya Science Campus

Quantitative data analysis was used which allows generalizations of results from a sample to an entire population of interest and the measurement of the incidence in a given sample. The data produced were numerical, and they were analyzed using the following mathematical and statistical methods.

Figure 4.2: 8-4-4 MPH
Source: Author, 2017

4.1.1 Sabine Formula:

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

Where: t = reverberation time in seconds
V = volume of hall in m^3
A = absorption units in m^2

4.1.2 Stephens and Bate Formula:

$$t = r\,(0.012\,\sqrt[3]{v} + 0.1070)$$

Where t = reverberation time in seconds
v = volume of the hall in m^3
r = 4 for speech,
r = 5 for orchestra,
r = 6 for choir

4.2 TAIFA HALL , MAIN CAMPUS, (EXISTING CONDITION)

Figure 4.3: Taifa Hall location **Source:** Author, 2017

Figure 4.4: Taifa Hall west facade

Figure 4.5: Taifa Hall east facade **Source:** Author, 2017

4.2.1 Location and Neighborhood

Taifa Hall is located at the heart of the administration block in Main Campus of the University of Nairobi. On the North it borders Harry Thuku Road which is full of traffic during the early morning, lunch time and late evenings. To the East it borders Gandhi Wing which acts a good buffer against the noise from the ever busy University Way. This buffer offers much quite sessions when there is less traffic on Harry Thuku road (**Fig 4.3**).

To the South Taifa Hall faces the Gandhi Court which offers a spacious break out space much needed during and after class sessions. Students would generally mingle in this court awaiting classes or hold chats and discussions after classes are over. It also acts a buffer between the Gandhi Wing and the Taifa Hall. To the West Taifa Hall borders the Administration block which formerly housed the Vice-Chancellors offices on the first floor. Beneath these offices is a thoroughfare which links Harry Thuku road to the Great court and other spaces within Main Campus

4.2.2 External Features

Taifa Hall has a blank external facade finished in grey render with a horizontal window spanning from end to end dotted by three wired glass doors on the ground floor that gives access to the Hall. The windows are made of wired glass with operable top hung windows that gives ventilation to the lecture hall.

There a planters at the entrance level which offers visual buffer to the activities on the court and along Harry Thuku road (**Fig 4.5**).

The side facing the court has a powerful covered walkway that links Education building to Mahatma Gandhi Wing. This walkway offers shade during hot afternoons and cover during rainy seasons (**Fig. 4.4**).

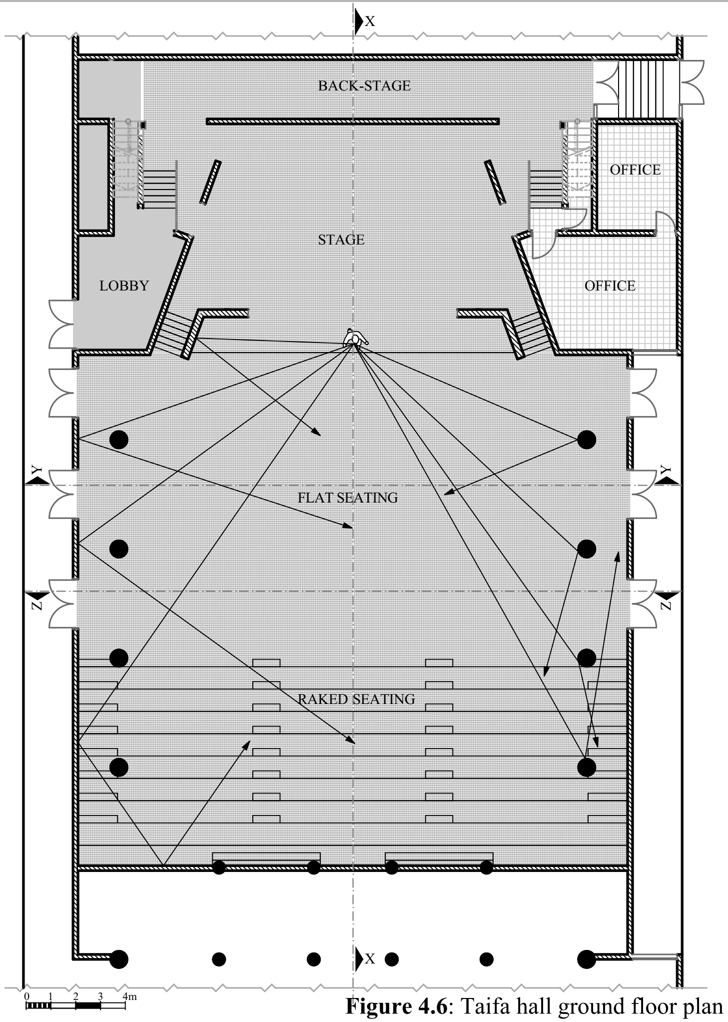


Figure 4.6: Taifa hall ground floor plan

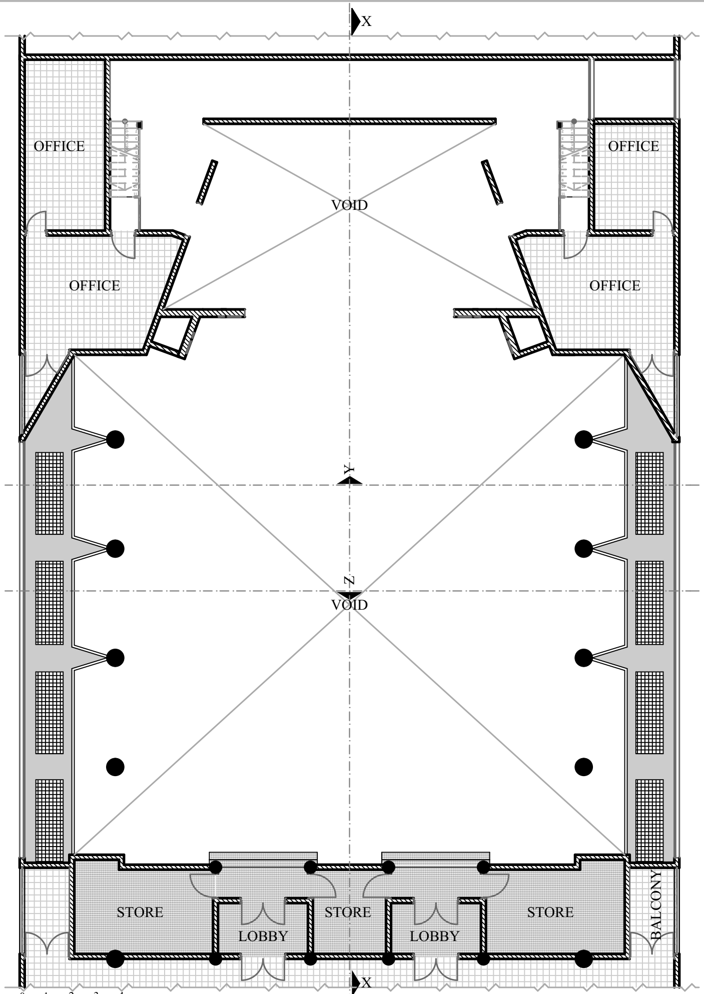


Figure 4.7: Taifa hall first floor plan

4.2.3 Floor Profile

Taifa Hall is rectangular in plan measuring 36 metres long and 22 metres wide. The audience seating area walls are parallel while stage walls are angled towards the audience. The terraced seating is rectilinear with steps leading towards two doors at the back. There are steps along the walls behind the 750mm diameter columns (**Fig 4.6**).

There are four columns and three doors on either side. These columns are finished in wood panels that run from top to bottom. On the first floor there are ventilation grilles on the side extensions housing the window space with anchors extending to each column (**Fig 4.7**).

The reflections to the back walls are not sufficient since sound falls at a greater grazing angle on these walls. A fan shaped would offer better reflections to the seated audience.

Echoes can be perceived at the stage owing to the distance from the stage to the back wall. The lack of sufficient absorbing materials on the side and back walls causes echoes at the stage.

Fig. 4.8: Thin carpet over thin felt

Fig. 4.9: Cement screed flooring finished in red oxide

Fig. 4.10: 20mm thick ceramic tiles

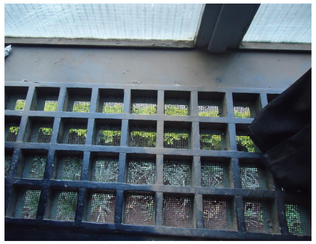


Fig 4.11: Ventilation grilles

Thin carpet over thin felt on cement screed

Cement screed flooring finished in red oxide

20mm thick ceramic tiles on cement

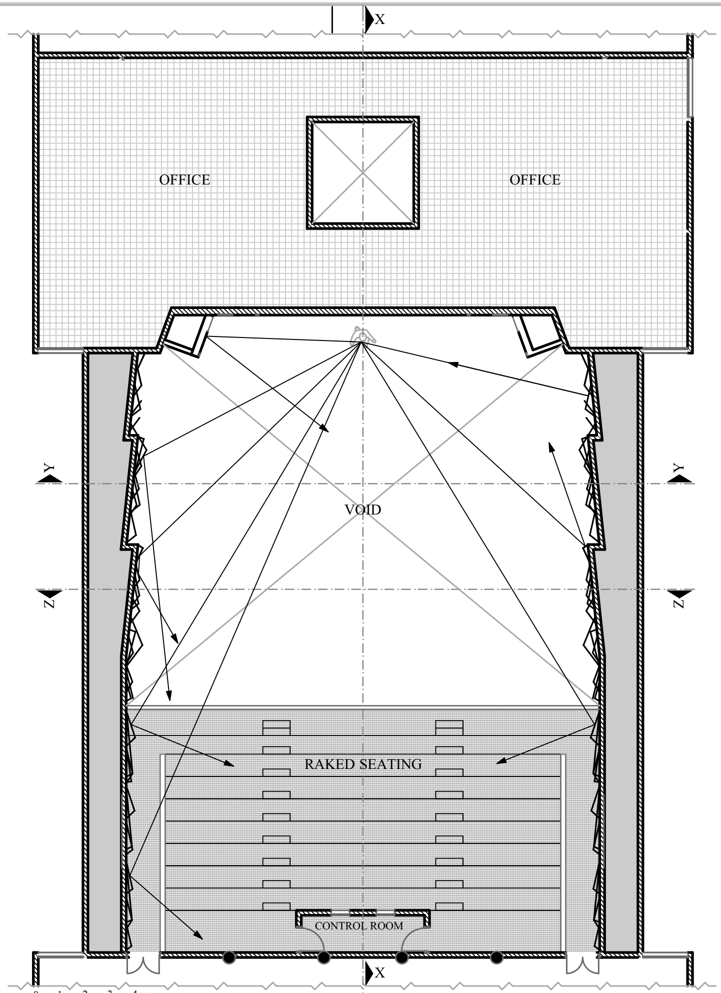


Figure 4.12: Taifa hall second floor plan

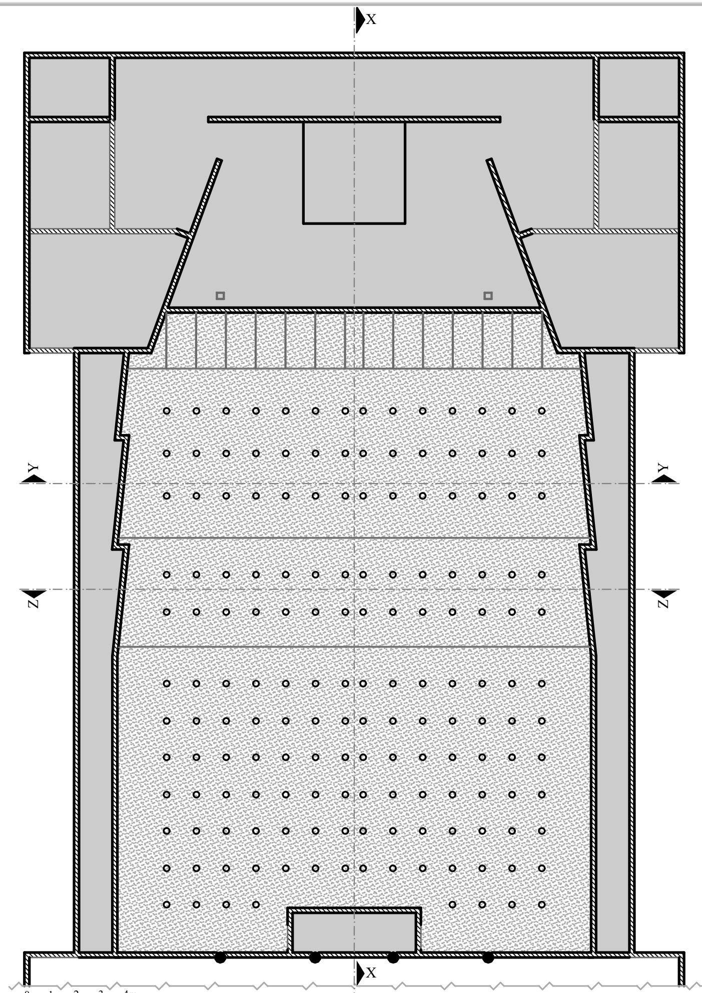


Figure 4.13: Taifa ceiling plan

4.2.4 Floor and Ceiling Finishes

The stage floor is finished in thin carpet over thin felt on wood planks while the back stage is smooth cement screed finished in red oxide. There are tiles on the floors leading to the offices on the ground floor (**Fig. 4.8, 4.9 & 4.10**).

The main audience sitting space is finished in thin carpet over thin felt on smooth cement screed. The projecting window space flooring is punctuated by series of wooden ventilation grilles with wire mesh fillers (**Fig. 4.11**).

The balcony flooring is finished in thin carpet over thin felt on smooth cement screed. The carpet is held to the terraces and access steps by thin steel strips drilled into the cement screed (**Fig 4.14**).

The ceiling is made of a mixture of curved and straight painted MDF panels with dotted lighting fixtures hanging at equal intervals (**Fig. 4.13 & 4.16**). The stage ceiling if finished in painted plaster. The bottom of the balcony is made of rough cast finished in blue ender. The splay ceiling elements meant to project sound to the audience is made of painted MDF panels (**Fig. 4.15**).

Fig. 4.14: Thin carpet over thin felt

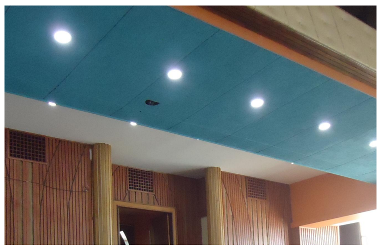


Fig. 4:15: MDF panels finished in textured paint

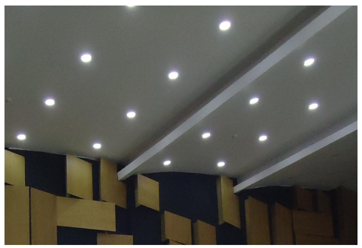
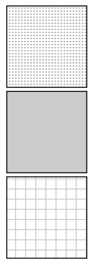


Fig. 4.16: Painted MDF panels

Fig. 4.17: Painted plaster ceiling



Thin carpet over thin felt on cement screed

Cement screed flooring finished in red oxide

20mm thick ceramic tiles on cement

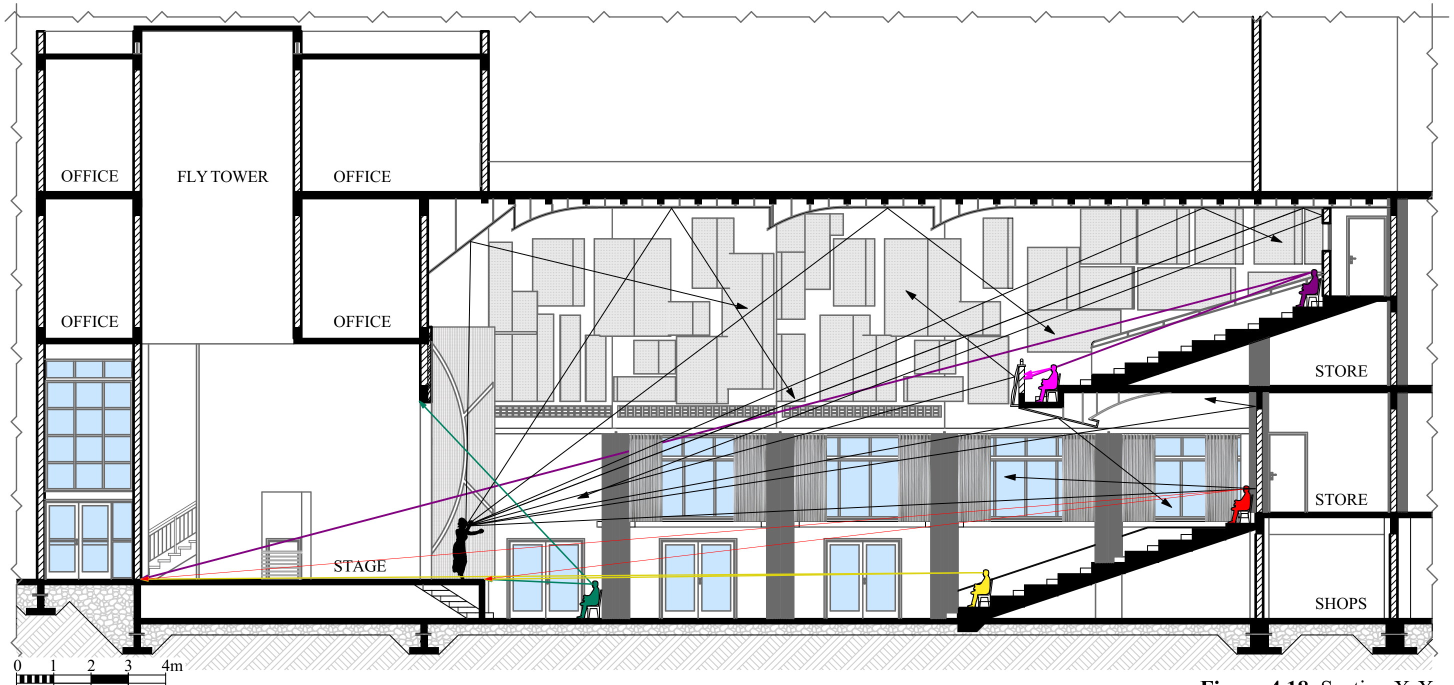


Figure 4.18: Section X-X

- Plaster and paint
- Wired glass
- Timber panels with hessian cloth backing
- Textured MDF panel
- Foam with synthetic leather cover
- Thin carpet over thin felt on cement screed
- Painted MDF panel
- Timber panels on solid backing

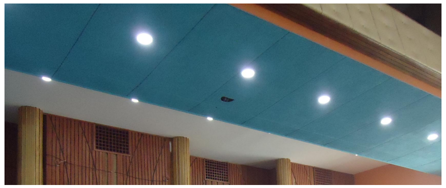


Fig. 4.19: Balcony soffit detail

Fig. 4.20: Walling detail

Fig. 4.21: Stage and audience seating detail

Fig. 4.22: Stage detail

4.2.5 Sectional Profile and Volume

The stage has a fly tower that rises 14.5 metres high from the stage level. The stage is 1.2 metres high with steps on either side of the stage leading to the podium. At the back steps on either side lead down to the lobby and the office respectively. The back stage is rectangular in shape with a ceiling height of 6.35 metres from the stage level (**Fig. 4.18, 4.21 & 4.22**).

The audience seat on a flat floor up to midway through the hall which is followed by nine risers to the back of the stage. There are two air locks that lead the audience to the break-out foyer at the back. There are 150mm high steps on each riser leading the audience to and from the terraces. Behind the hall, there are three stores sandwiched between the lobbies.

The balcony is composed of nine 300mm high risers with the control room at the top most riser. The ceiling is splayed at the front with a series of curved and straight panels mounted to reflect sound to the audience (**Fig. 4.20**).

Taifa hall volume is 5875 m^3 with the audience sitting area maximum height being 11 metres. This large volume compared to a capacity of 1200 causes long reverberation time and echoes due to the long sectional profile and high fly tower that is finished in plaster and paint.

The stage has a very large volume that distorts sound being projected to the audience. The splay and curved ceilings do not assist much in projecting the direct sound since it is too high and the angle for projecting sound effectively is too small.

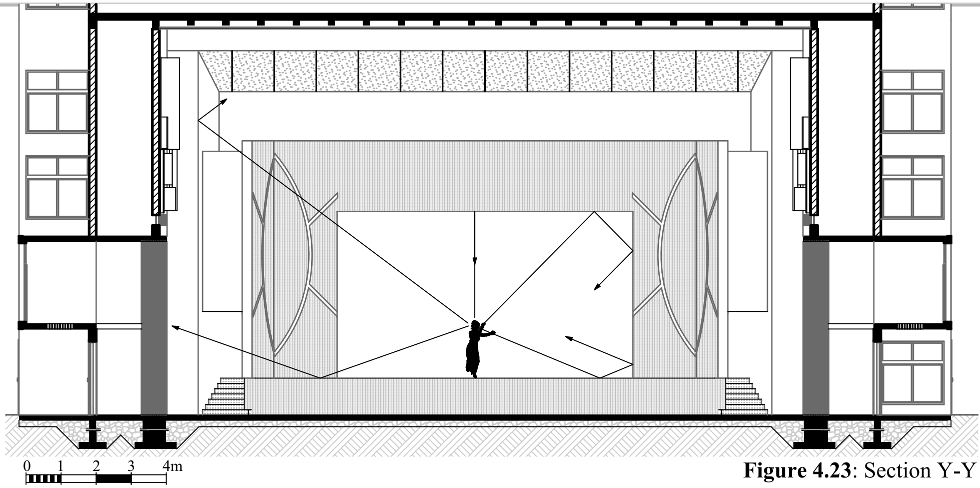


Figure 4.23: Section Y-Y

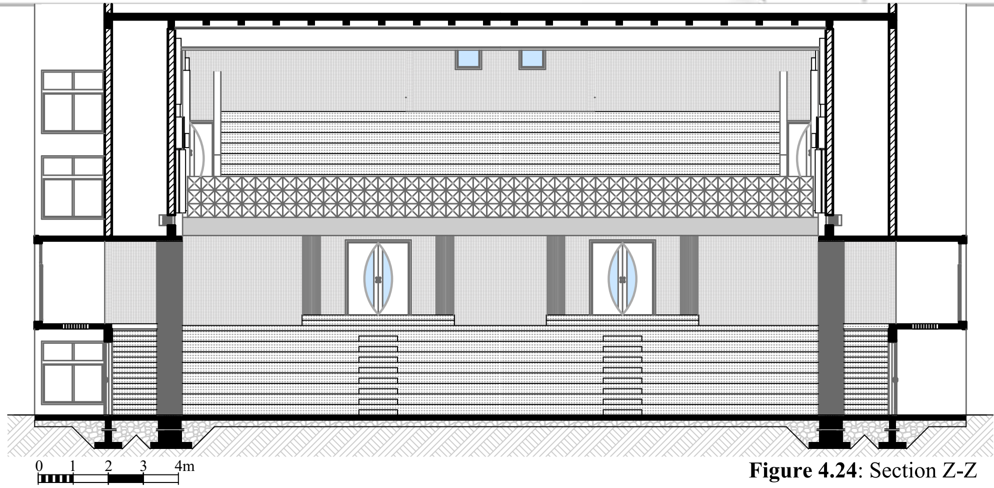


Figure 4.24: Section Z-Z


Fig. 4.25: Balcony front wall


Fig. 4.26: Timber panels with hessian cloth backing


Fig. 4.27: Stage wall and floor detail


Fig. 4.28: Air lock doors detail


Fig. 4.29: Column and window detail


Fig. 4.30: Back wall vents

4.2.6 Walling Material Finishes

The stage house walling is purely made of plaster and paint. The splay walls facing the audience seating is timber panels on hessian cloth backing. The top part of the splay walls is finished in plaster and smooth paint (**Fig 4.22**).

The ground floor side walls are made of plaster and paint with alternating wired glass doors. Medium weight curtains are used to control lighting within the ground floor (**Fig 4.20**).

The first floor walling is composed of wired glass windows from end to end with medium weight curtains used to control lighting within the hall. The second floor walling is plaster and paint. Vinyl laminated reflectors are hung to reflect sound to the audience. Ventilation is provided through gauze wire vents (**Fig 4.29**).

The balcony fron walling is finished in synthetic leather covered foam to absorb and diffuse sound. The back wall is timber panels with hessian cloth backing. The doors are finished partially in laminated timber and wired glass (**Fig 4.25**).

4.2.7 Table 2: Reverberation Time Calculation (Taifa Hall Existing Condition)

Materials	Area (M2)	OCTAVE FREQUENCY			
		125 Hz		250Hz	
	S	α	Sα	α	Sα
Flooring					
Carpet thin over thin felt on concrete (Audience Seating)	790	0.1	79	0.15	118.5
Carpet thin over thin felt on wood planks (Stage)	190	0.2	38	0.25	47.5
Walling					
Wood planks on solid walling (front)	111	0.19	21.09	0.23	25.53
Wood panels with hessian cloth backing (Front/back walls)	314	0.4	125.6	0.25	78.5
Veneer laminated MDF panels (reflectors)	216	0.35	75.6	0.2	43.2
Painted plaster	1826	0.01	18.26	0.01	18.26
4mm thick ordinary window glass	1	0.3	0.3	0.2	0.2
6 mm wired glass doors/windows	124	0.3	37.2	0.2	24.8
Wire gauze permanent vents (PVs)	42	0.6	25.2	0.6	25.2
Heavy curtains	78	0.1	7.8	0	0
Synthetic leather covered foam (Balcony front)	21	0.33	6.93	0.51	10.71
Laminated solid core doors	39	0.14	5.46	0.1	3.9
Ceiling					
Painted 16 mm MDF ceiling panels on 16 mm battens	683	0.3	204.9	0.2	136.6
Fluorescent luminaries	11	0.3	3.3	0.2	2.2
Seating					
Laminated mdf seats	729	0.2	145.8	0.25	182.25
Air (M3)	5875	0	0	0.001	5.88
Total materials absorption			794.44		723.23
Audience					
Full	1200	0.33	396	0.4	480.00
Half full	600	0.33	198	0.4	240.00
Empty	0	0.33	0	0.4	0.00
Total absorption (Fully)			1044.64		936.98
Total absorption (Half)			919.54		830.11
Total absorption (Empty)			794.44		723.23
Reverberation time (s)					
Full			**0.9**		**1.0**
Half full			**1.0**		**1.1**
Empty			**1.2**		**1.3**

4.3 LECTURE THEATRE 101, UNIVERSITY OF NAIROBI TOWER, (EXISTING CONDITION)

Figure 4.31: Lecture Theatre 101 location **Source:** Author, 2017

Figure 4.32: University Tower west facade

Figure 4.33: University Tower east facade

4.3.1 Location and Neighborhood

Lecture theatre 101 is located on the second floor of University of Nairobi Towers. Northwards, the Towers borders Harry Thuku Road which is full of traffic during the early morning, lunch time and late evenings. To the east it borders University of Nairobi Enterprises (UNES) which acts a good buffer against the noise from the ever busy University Way. This buffer offers much quite sessions when there is less traffic on Harry Thuku road (**Fig 4.31**).

To the south Taifa Hall faces the Great Court which offers a spacious break out space much needed during and after class sessions. Students would generally mingle in this court awaiting classes or hold chats and discussions after classes are over.

To the south west Tower borders the Education building which houses classrooms, offices and two lecture theatres. To the north west the tower borders the Kenya Conservatoire of Music and the Kenya National Theatre.

4.3.2 External Features

The lecture theatre has windows facing Harry Thuku road and the Kenya Conservatoire of Music. Noise along the road would interfere with happenings within the hall due to use of 3mm thick ordinary glass. The foyer is approximately a third of the lecture theatre area. This will sufficiently accommodate the audience as they exit the hall (**Fig. 4.32 and 4.33**).

Materials used on the external facade are white composite aluminium panels. The glass windows are of 3mm ordinary glass while the solid doors are of laminated panels with glass panels at the top. The foyer floors are of glazed ceramic tiles which reflect sound the audience sound as they exit the hall creating noise within the building circulation space.

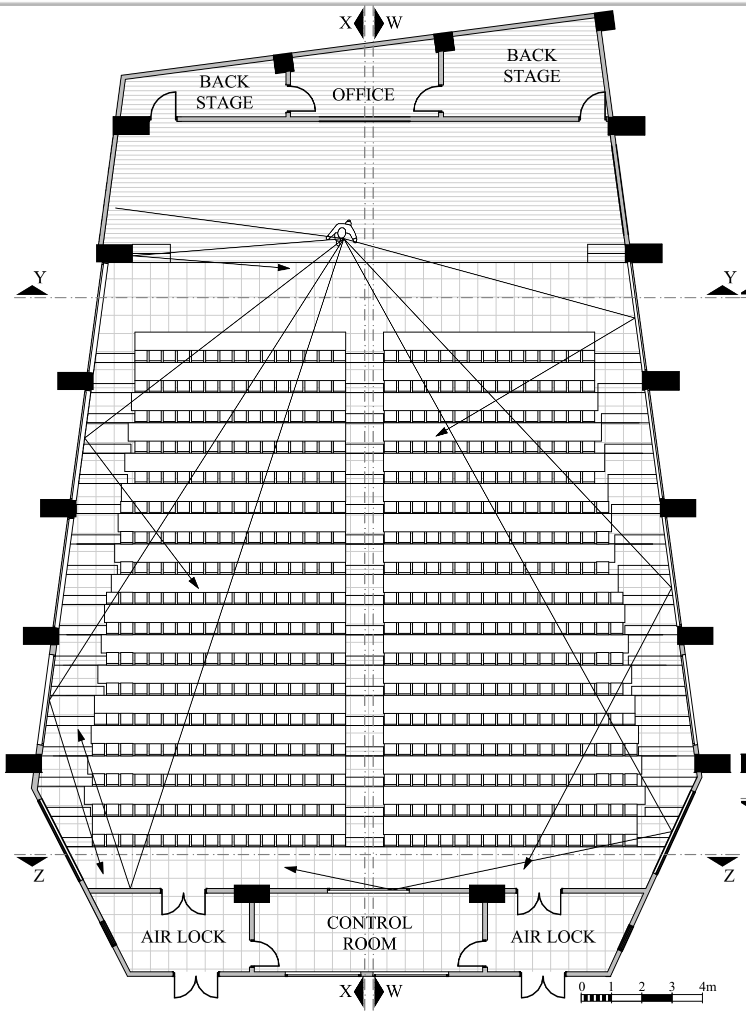


Figure 4.34: Lecture Theatre 101 ground floor plan

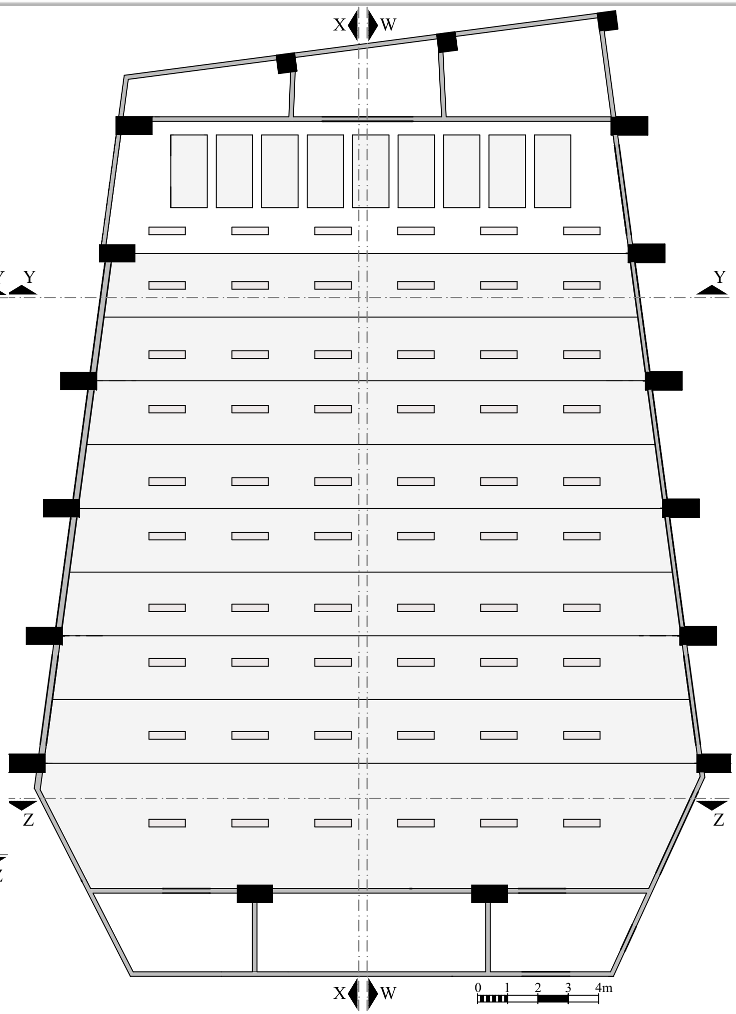


Figure 4.35: Lecture Theatre 101 first floor plan

4.3.3 Floor Profile

Lecture theatre 101 is fan-shaped in plan measuring 25 metres long, 16 metres at the shortest width and 22 metres at the longest width. The walls are angled to project sound to the audience (**Fig. 4.34**).

The control room is located at the back with the air locks on each side. The back stage has offices with two doors opening directly to the lecture hall. An exit door is provided at the left side of the lowest terrace.

4.3.4 Floor and Ceiling Finishes

The stage floor is made of polished wood planks on joists. The audience sitting is 600 x 600 mm ceramic tiles. The seats and writing tops are made of laminated timber (**Fig. 4.36 & 4.37**).

The aluminium window frames are complete with 3mm thick ordinary glass. Doors are solid with varnished timber panels and fan lights of ordinary glass at the top and sides.

The ceiling is made of painted MDF boards with sections facing the stage perforated to enhance ventilation as air flows from the vents below the seats to the perforations on the ceiling (**Fig. 4.35**).

Fig. 4.36: Wooden planks on joists

Fig. 4.37: 600 x 600 ceramic tiles

Fig. 4.38: Louvered vents on terrace risers

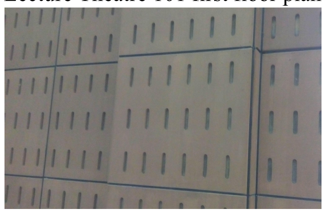


Fig. 4.39: Perforated mdf panels with hessian cloth backing

600 x 600mm ceramic tiles

Wooden planks on joists

Painted MDF panels

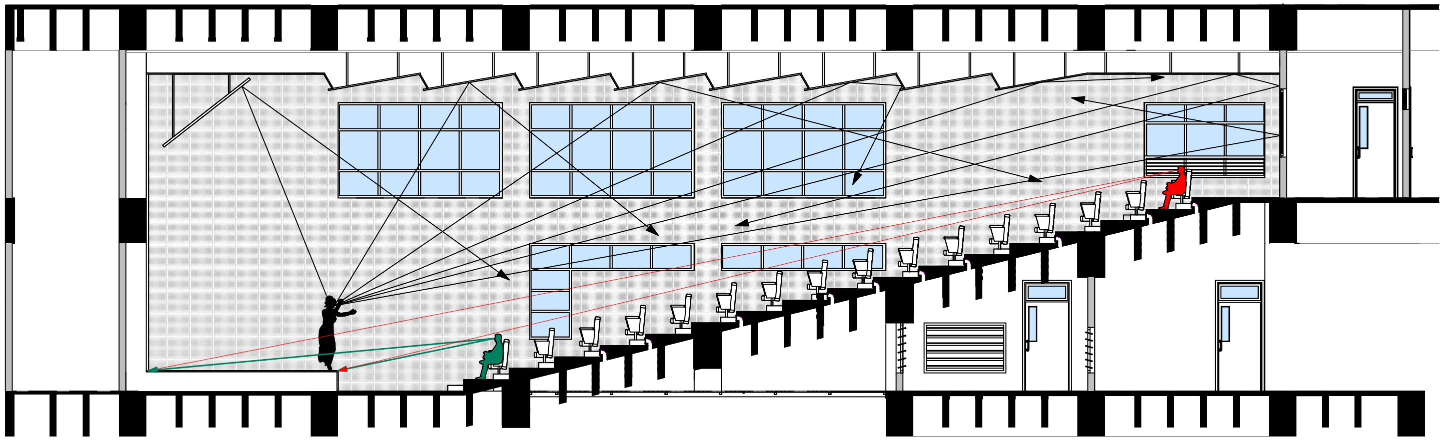


Figure 4.40: Lecture Theatre 101 section W-W

0 1 2 3 4m

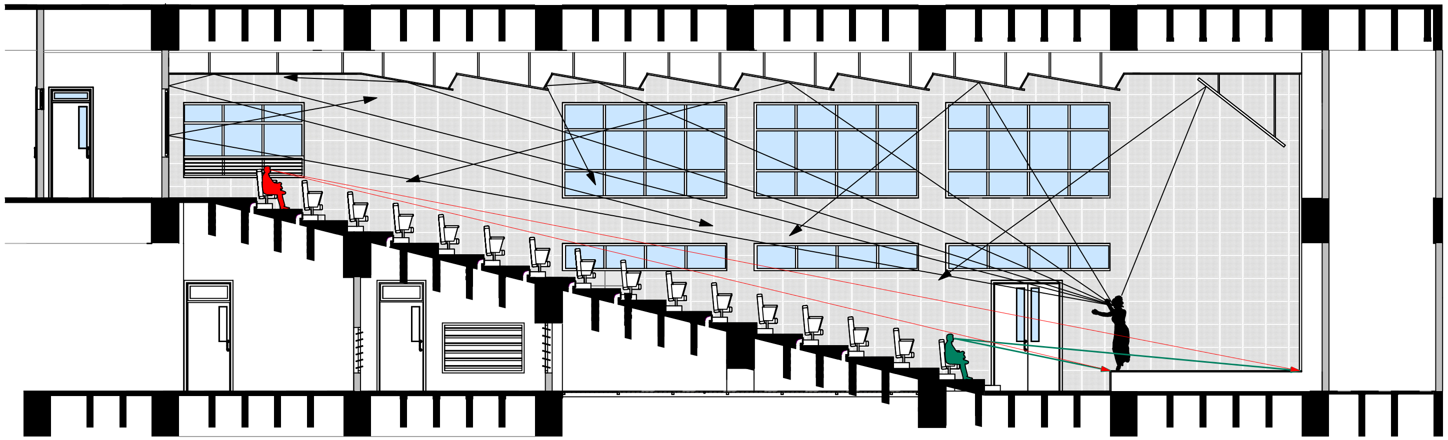


Figure 4.41: Lecture Theatre 101 section X-X

0 1 2 3 4m

Fig. 4.42: Wall detail

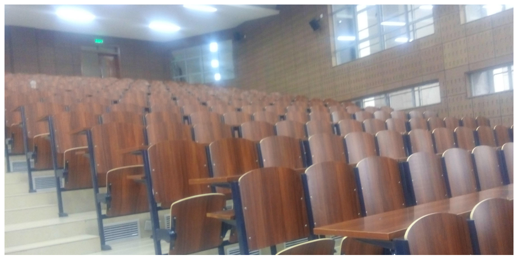


Fig. 4.43: Furniture detail

Fig. 4.44: View to the stage

4.3.5 Sectional Profile and Volume

The lecture theatre is 7 metres high at the stage and 2.7 metres at the entrance level. The stage is 450mm high with the terrace risers being 300mm high. The circulation steps are 150mm high. The terrace risers have vents at regular intervals to provide ventilation. Air gets in through the air vents at the terrace level and exits at the perforated ceiling edges (**Fig. 4.40**).

The sectional length is 25 metres. The suspended reflectors and angled ceiling reflects sufficient sound to the audience at the back. The splay should however be provided at the coves to prevent unnecessary echoes bouncing back to the stage which will eventually cause interference to the speaker. There should be a splay ceiling to reflect sound to the people at the back which will increase intelligibility of speech (**Fig. 4.41**).

The large windows should be reduced in size to avoid undesired reflections from the panels. This should be replaced with high level windows that face away from the stage. The walls should be fully absorptive while the ceiling fully reflective to ensure proper sound projection. To prevent external noise the single panel glass should be replaced with double glazed 3mm thick glass (**Fig. 4.42**).

Perforated MDF panels with hessian cloth backing

3mm ordinary glass

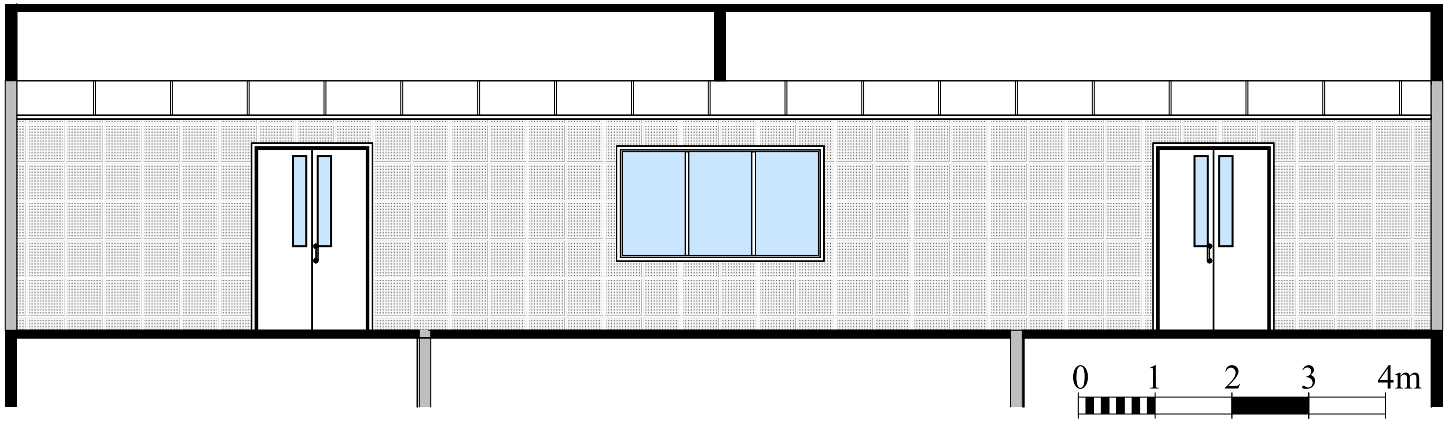


Figure 4.45: Lecture Theatre 101 section Z-Z

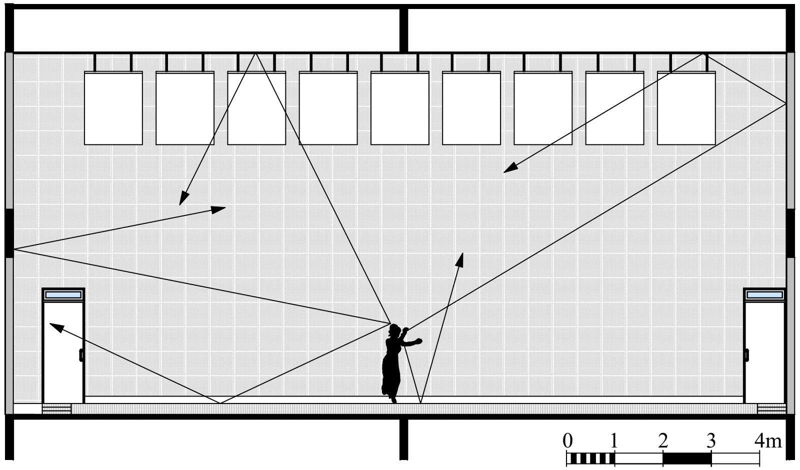


Figure 4.46: Lecture Theatre 101 section Y-Y

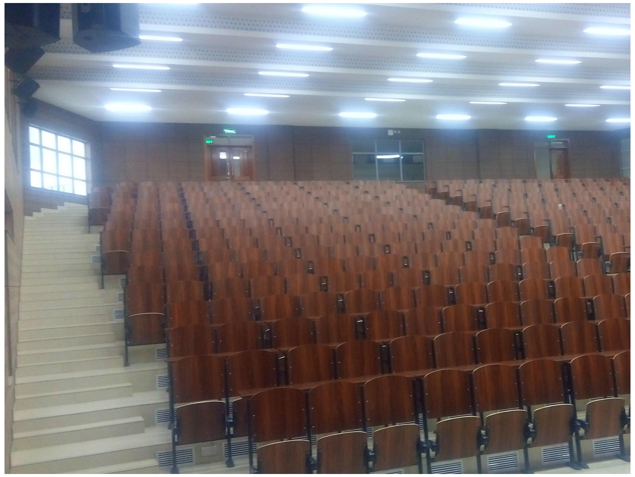


Figure 4.47: Seating arrangement

Perforated MDF panels with hessian cloth backing

3mm ordinary glass

Fig. 4.48: Self retracting seats

Fig. 4.49: Angled ceiling

The volume is 2420 m^3. This is sufficient to provide good reverberation time within the hall. A large volume elongates the reverberation time while a very small volume will reduce the reverberation time making the sound dry leading to straining both for the audience and the speaker.

4.3.6 Seating Arrangement

The raking provides good sightlines to the stage as well as audio connection to the speaker. The middle aisle distorts the sound getting to the audience since reflections from a speaker at the centre of the stage falls directly on the risers and is reflected back to the speaker as echoes. Good quality sound is lost which could otherwise have been utilized were the aisle shifted to the left or right or provided as two distinct aisle off the centre line.

4.3.7 Cove Design

Junctions of rear walls and ceiling above gallery level will throw back long reflected sound upon the speaker after two impacts if left hard and smooth. This is a short echo and not reverberation, since it can be distinguished in suitable places. In large half empty halls long reflections may occur in this way at junctions of walls and the floor. They may also occur from the corners of a room. Coves should be designed on the cross-section of a hall as well as on the long section. Where galleries extended along the sides of a hall, coves can act as valuable reflectors to gallery seats (**Fig. 4.45, 4.46 & 4.47**).

4.3.8 Table 3: Reverberation Time Calculation (Lecture Theatre 101 Existing Condition)

Materials	Area (M2)	OCTAVE FREQUENCY			
		125 Hz		250Hz	
	S	α	Sα	α	Sα
Flooring					
600 x 600 mm Ceramic tiles (Audience Seating)	542	0.01	5.42	0.01	5.42
Wood planks on joists (Stage)	79	0.15	11.85	0.11	8.69
Walling					
600 x 600 mm perforated MDF panels with hessian cloth backing (Front/sides/back walls)	371	0.3	111.3	0.2	74.2
4mm thick ordinary window glass	70	0.3	21	0.2	14
Laminated solid core doors	16	0.14	2.24	0.1	1.6
Ceiling					
Painted 16 mm MDF ceiling panels	535	0.3	160.5	0.2	107
Perforated painted 16 mm MDF ceiling panels	61	0.25	15.25	0.7	42.7
Fluorescent luminaries	18	0.3	5.4	0.2	3.6
Seating					
Laminated particle board	675	0.03	20.25	0.05	33.75
Air (M3)	2420	0	0	0.001	2.42
Total materials absorption			353.21		293.38
Audience					
Full	500	0.33	165	0.4	200
Half full	250	0.33	82.5	0.4	100
Empty	0	0.33	0	0.4	0
Total absorption (Fully)			518.21		493.38
Total absorption (Half)			435.71		393.38
Total absorption (Empty)			353.21		293.38
Reverberation time (s)					
Full			**0.7**		**0.8**
Half full			**0.9**		**1.0**
Empty			**1.1**		**1.3**

4.4 8-4-4 MULTI-PURPOSE HALL, MAIN CAMPUS (EXISTING CONDITION)

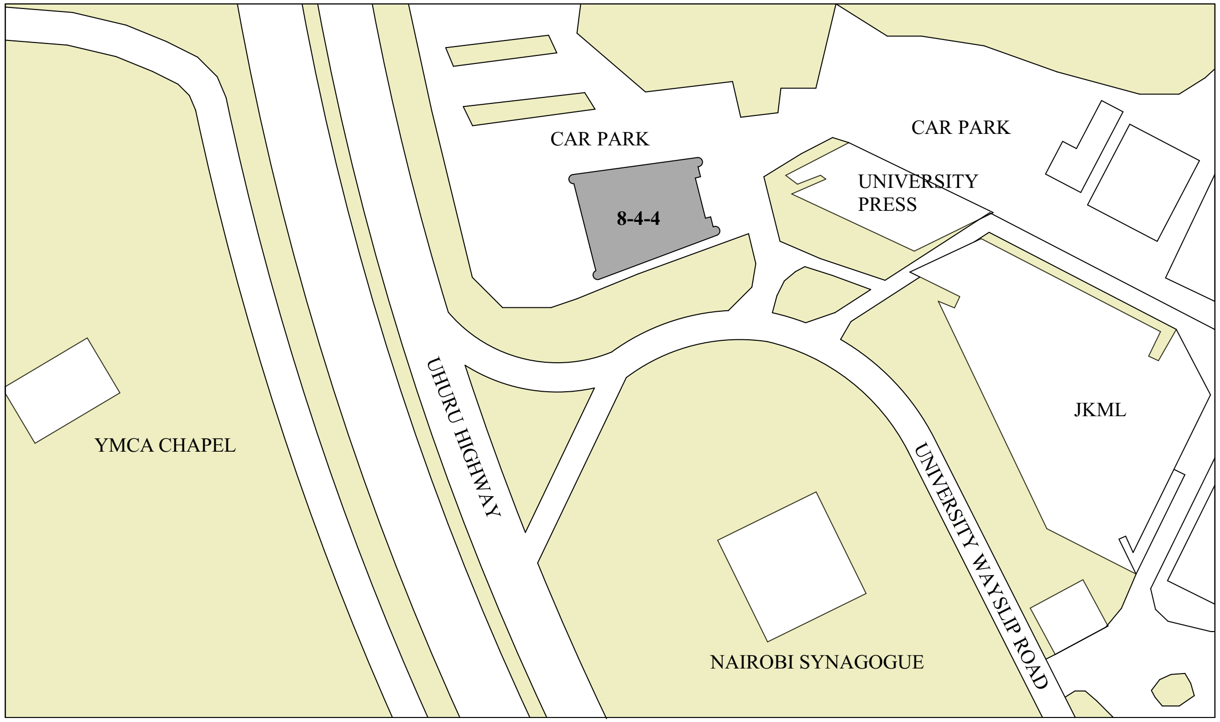


Figure 4.50: 8-4-4 location **Source:** Author, 2017

Figure 4.51: 8-4-4 West facade

Figure 4.52: South facade

4.4.1 Location and Neighborhood

8-4-4 MPH sits isolated at the West end of Main Campus of the University of Nairobi. To the North is the university car park which extends all the way to Kenya Broadcasting Corporation boundary, to the east is the university press which is linked to Jomo Kenyatta Memorial Library via a cylindrical bridge. To the south the university way slip road curves from Uhuru Highway to University Way. To the west is Uhuru highway which is the source of most external noise heard in the lecture hall.

The lecture theatre is accessed through university way slip road gate next to Jomo Kenyatta Memorial library or paved walkway linking the Great court to Uhuru high way past JKLM and Education building walkways.

The car park to the North forms part of the noise and distraction during class sessions due to the presence of ground floor windows at the entrance. One could literal watch all the external activities while seated in the lecture theatre (**Fig. 4.50**).

4.4.2 External Features

8-4-4 is a master piece externally, with beige terrazo wall finish dotted with rectangular windows on the first floor. The ground floor has covered walkway with arches formed by supporting structure running from one stair well to the next on each side. Symmetry is achieved by placing curved stair wells on the four corners (**Fig. 4.51**).

The soft landscaping on along the plinth of the building offers beautiful finish to the concrete structure and blends well with the concrete surrounding of cabro and raw parking access tarmac. The hall is triple volume with the support spaces forming offices, washrooms, kitchenettes and stores (**Fig. 4.52**).

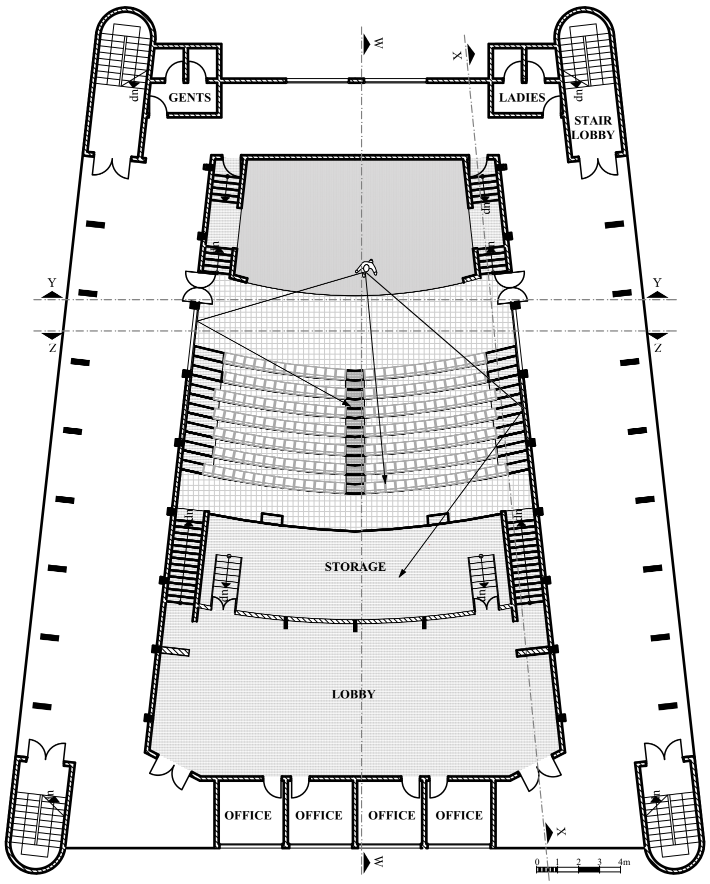


Figure 4.53: 8-4-4 Ground floor plan

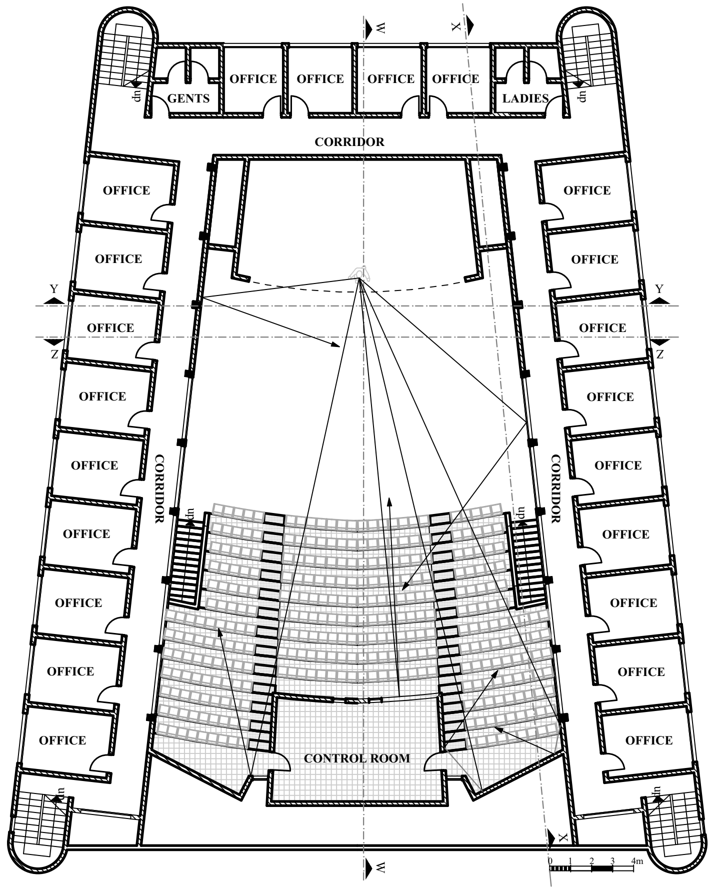
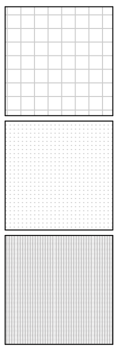


Figure 4.54: 8-4-4 First floor plan



200 x 200mm PVC tiles

Terrazzo

Wood panels on joists

Fig. 4.55: Floor detail

Fig. 4.56: Ceiling detail

4.4.3 Floor Profile

8-4-4 is fan shape in plan with a vineyard type of seating. The stage is 6.5 metres deep with a curved front wall. There are steps on the sides leading the speaker to and from the stage. Another set of steps leads down to the washrooms at the back. The floor sitting is curved with three sets of steps (two on each side and one at the centre up to to the midway gangway which the shifts sideways on the first floor to create three seating sections) (**Fig 4.53**).

There is a landing which acts as a gangway that leads the audience up the first floor seating or down to the back entry foyer through a flight of steps located along the wall on either side. The first floor of two gangways leading up to the back. The control room is at the centre within the space with seating areas on either side (**Fig 4.54**).

4.4.4 Floor and Ceiling Finishes

The stage is finished in timber panels on joists with the stage accesses on each side finished in terrazzo. The front of the stage and the seating areas is finished in PVC tiles. The gangways leading to the back and across the hall is of terrazzo due to its hardwearing qualities required for high traffic areas. The stairs leading to the back and the entrance foyer is finished in terrazzo (**Fig 4.55**).

The ceiling is of timber panels on joists with lighting fixtures fitted at regular intervals. There are beams finished with plaster and pain interrupting the timber ceiling at different positions across the hall. The back foyer is also finished with timber panels with a few areas below the first floor balcony done in plaster and paint (**Fig 4.56**).

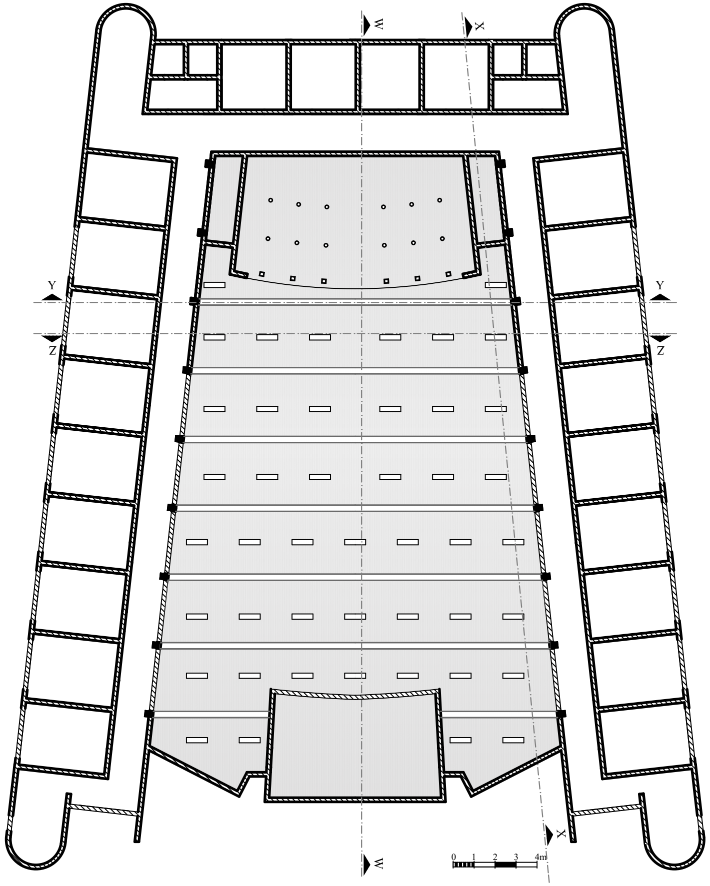


Figure 4.57: 8-4-4 Ceiling plan

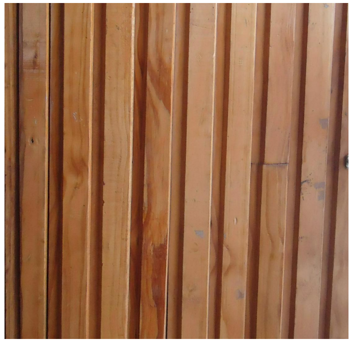


Fig. 4.59: Walling/Ceiling detail

Fig. 4.60: Window detail

Fig. 4.58: Stage detail

Fig. 4.61: Audience seating detail

4.4.5 Sectional Profile and Volume

8-4-4 has a volume of 2933 m3 which is relatively right compared to the seating capacity and the air circulation required within the space. The stage is 750 mm high with a walling on either side forming the stage house. The distance between the podium curved walling and the first terrace is 4 metres giving sufficient circulation space at the front (**Fig 4.58**).

There are 7 terraces within the ground floor which is interrupted by a 1.8 metre wide gangway cutting across the seating area. Another 14 terraces are the first floor creating the additional seating. The control room is located at the centre with a glass opening 1.2 metres above the room's slab to give an uninterrupted view to the activities on stage (**Fig 4.61**).

The ceiling profile is almost parallel to the terraced slab profile though its height is quite high leading to weak reflected sound reaching the audience. The kink at the edge of the stage also interrupts quality reflection of sound to the audience at the back of the hall. There should be a splay at the back wall to avoid long reflections to the stage which will automatically cause echoes.

There are high level windows giving light as well as low level windows at the entrance. At the back two windows 2.7 metre high by 1 metre wide give light to the gangways on the first floor (**Fig 4.60**).

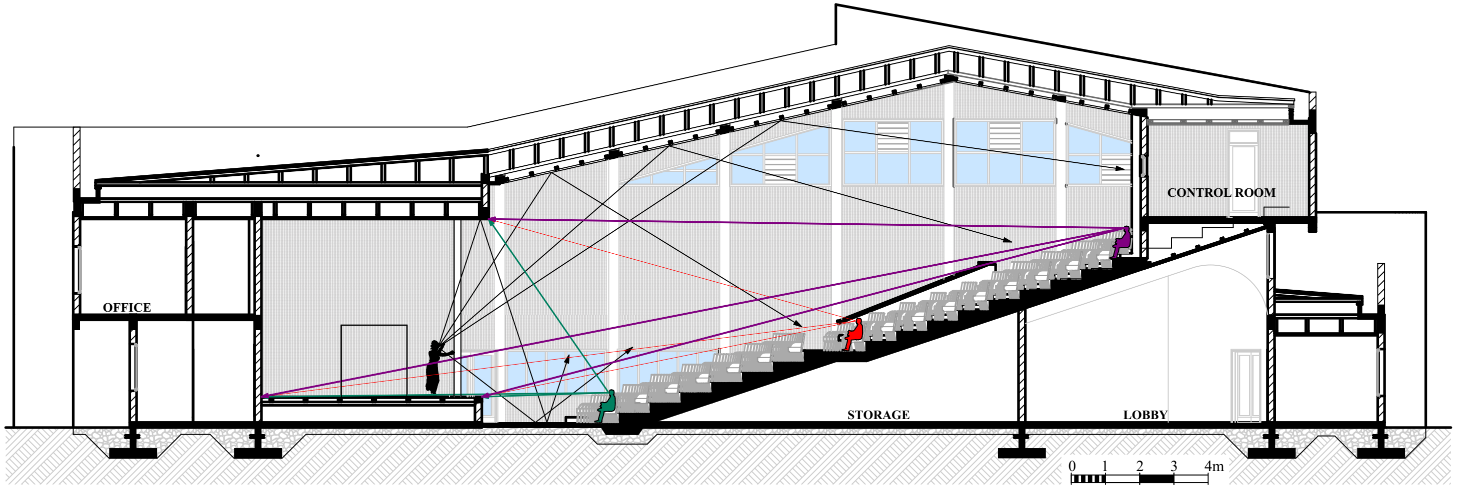


Figure 4.62: Section W-W

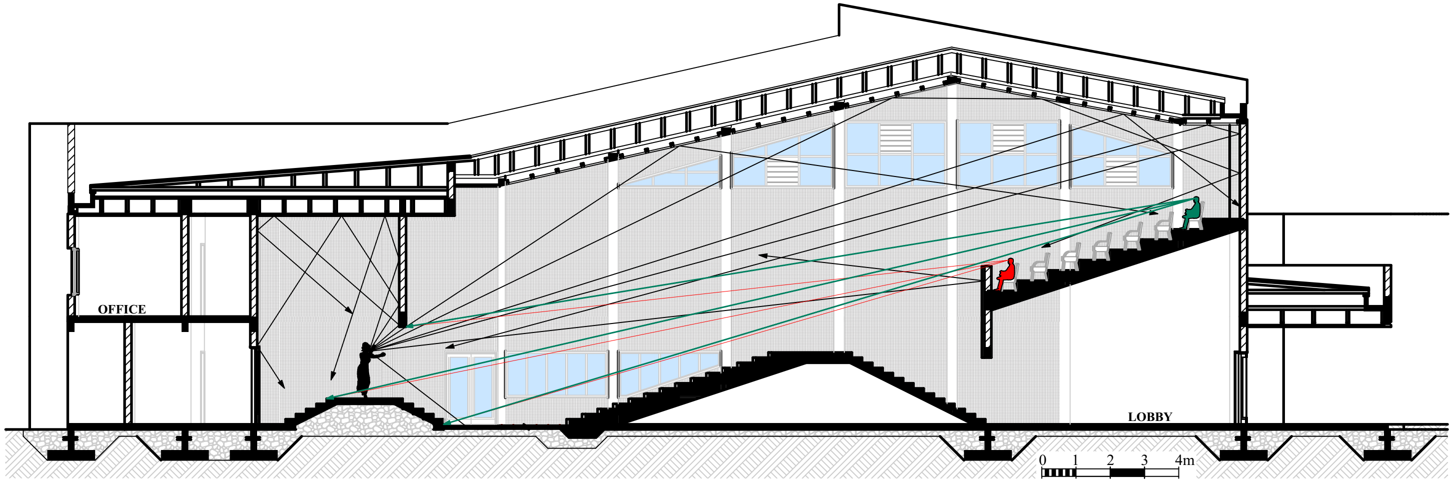


Figure 4.63: Section X-X

4.4.6 Wall Finishes

A larger portion of the front wall is made of plaster and paint its perimeter finished in timber panels on solid backing. The stage side walling is finished in timber paneling which is consistently applied along the side wall of the audience seating area to the back of the theatre (**Fig. 4.58**).

The high level window panels are of 3mm ordinary glass with the low level windows and the doors made of wired glass. The columns are finished in plaster and paint which is applied all the way to the beam supports visible on the ceiling (**Fig. 4.62**).

The back entrance foyer walls are finished in plaster and paint with large doors made of wired glass and steel frames (**Fig. 4.64**).

The seats are upholstered with synthetic leather cover over thick foam. The back is made of thick ply with the seat handles composed of hardwood timber supported by steel bars. The seats however are not self-retracting but are pushed manual to fall back. The seat bottoms are made of perforated block boards which absorbs a good amount of sound when the hall is not fully occupied (**Fig. 4.66**).

Fig. 4.64: Back entrance foyer

Fig. 4.65: Back wall window

Fig. 4.66: Seat detail

Fig. 4.67: Stair leading to back entrance foyer

Wood panels on solid backing

Plaster and paint

Wired/ordinary glass

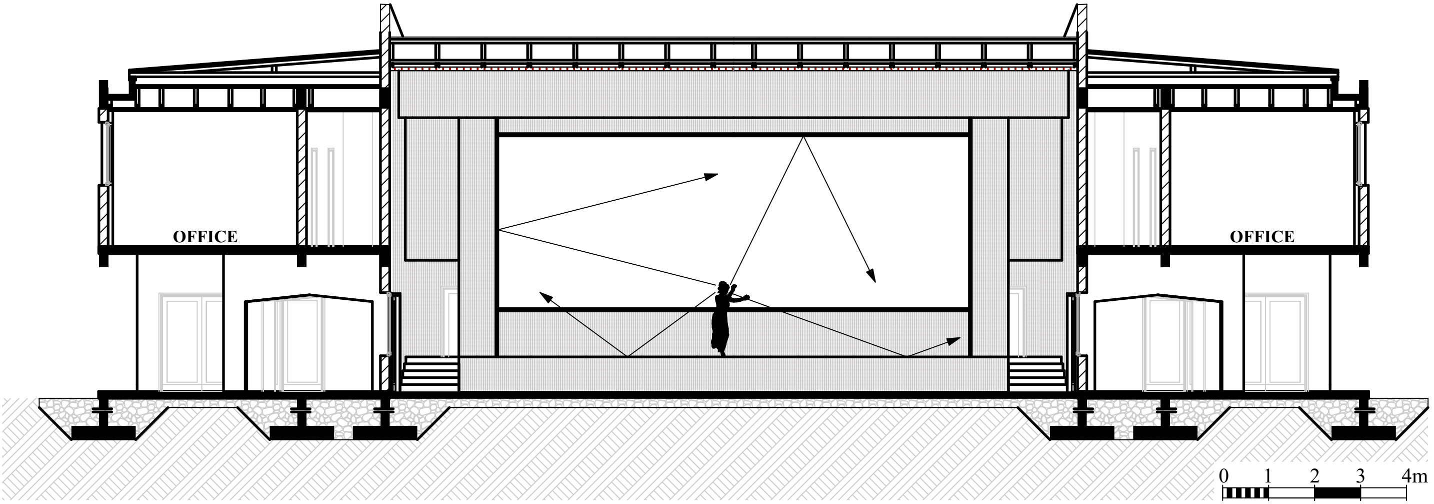


Figure 4.68: Section Y-Y

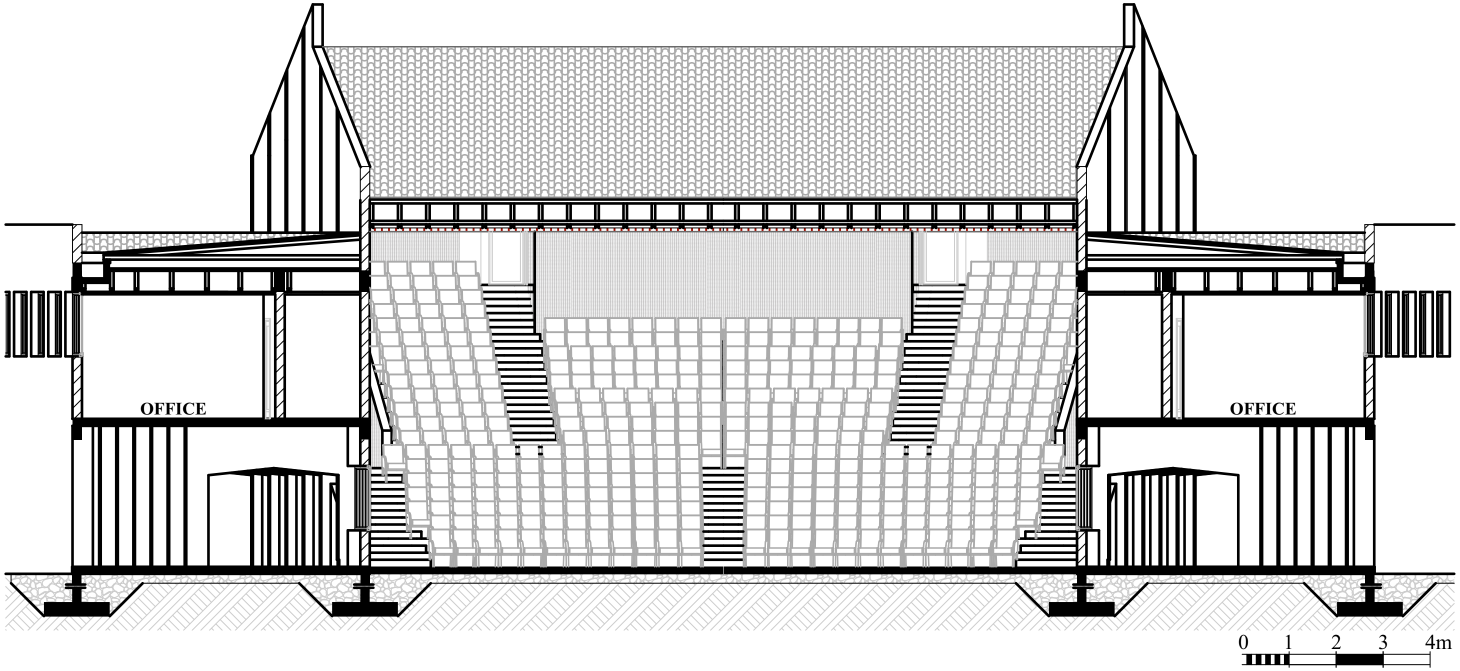


Figure 4.69: Section Z - Z

4.4.7 Seating Arrangement

The ground floor seating has two rows with gangways to the side walls as well as the centre. The middle gangway distorts the sound falling on the audience since it is located directly in front of the speaker. A shift to the side would fully utilize the direct sound which will fall on the audience at better angle (**Fig. 4.53**).

The first floor seating has two gangways leading to the back on either side of the control room. The people seating in the middle section benefit a lot from the good sound projections from the stage.

4.4.8 Cove Design

The stage back wall meets the ceiling at 90^0 angle. The amount of reflection intended to reach the audience from the stage is reduced since this sound will hit several walls and the floor before moving to the audience at reduced power (**Fig. 4.68**).

Similarly, the back wall meets the ceiling at 90^0 angle. This will generally give insufficient reflections to the audience at the back. It will also lead to unwanted echoes at the front due to direct reflections hitting the back wall and being pushed to the speaker on stage (**Fig. 4.63**).

The control room also interferes with the quality of sound since it is has filled the back middle section of the first floor seating (**Fig. 4.69**).

4.4.9 Table 4: Reverberation Time Calculation (8-4-4 MPH Existing Condition)

Materials	Area (M2)	OCTAVE FREQUENCY			
		125 Hz		250Hz	
	S	α	Sα	α	Sα
Flooring					
200 x 200 mm PVC tiles (Audience Seating)	388	0.02	7.76	0.02	7.76
Terrazzo (Stage/Audience Seating)	123	0.01	1.23	0.01	1.23
Wood planks on joists (Stage)	68	0.15	10.2	0.11	7.48
Walling					
Grooved wood planks on solid walling (front/side/back)	560	0.31	173.6	0.33	184.8
Painted plaster	65	0.01	0.65	0.01	0.65
4mm thick ordinary window glass	60	0.3	18	0.2	12
6 mm wired glass doors/windows	11	0.3	3.3	0.2	2.2
Laminated solid core doors	10	0.14	1.4	0.1	1
Ceiling					
Grooved wood planks on battens	420	0.1	42	0.36	151.2
Painted plaster	33	0.01	0.33	0.01	0.33
Fluorescent luminaries	12	0.3	3.6	0.2	2.4
Seating					
Cushions (seat tops/rest fronts)	222	0.33	73.26	0.51	113.22
Perforated hard board (seat bottoms)	120	0.27	32.4	0.85	102
Plywood rest backs	102	0.4	40.8	0.2	20.4
Air (M3)	2933	0	0	0.001	2.93
Total materials absorption			408.53		609.60
Audience					
Full	520	0.33	171.6	0.4	208.00
Half full	260	0.33	85.8	0.4	104.00
Empty	0	0.33	0	0.4	0.00
Total absorption (Fully)			580.13		817.60
Total absorption (Half)			494.33		713.60
Total absorption (Empty)			408.53		609.60
Reverberation time (s)					
Full			**0.8**		**0.6**
Half full			**0.9**		**0.7**
Empty			**1.1**		**0.8**

4.5 MILLENNIUM HALL I, CHIROMO CAMPUS (EXISTING CONDITION)

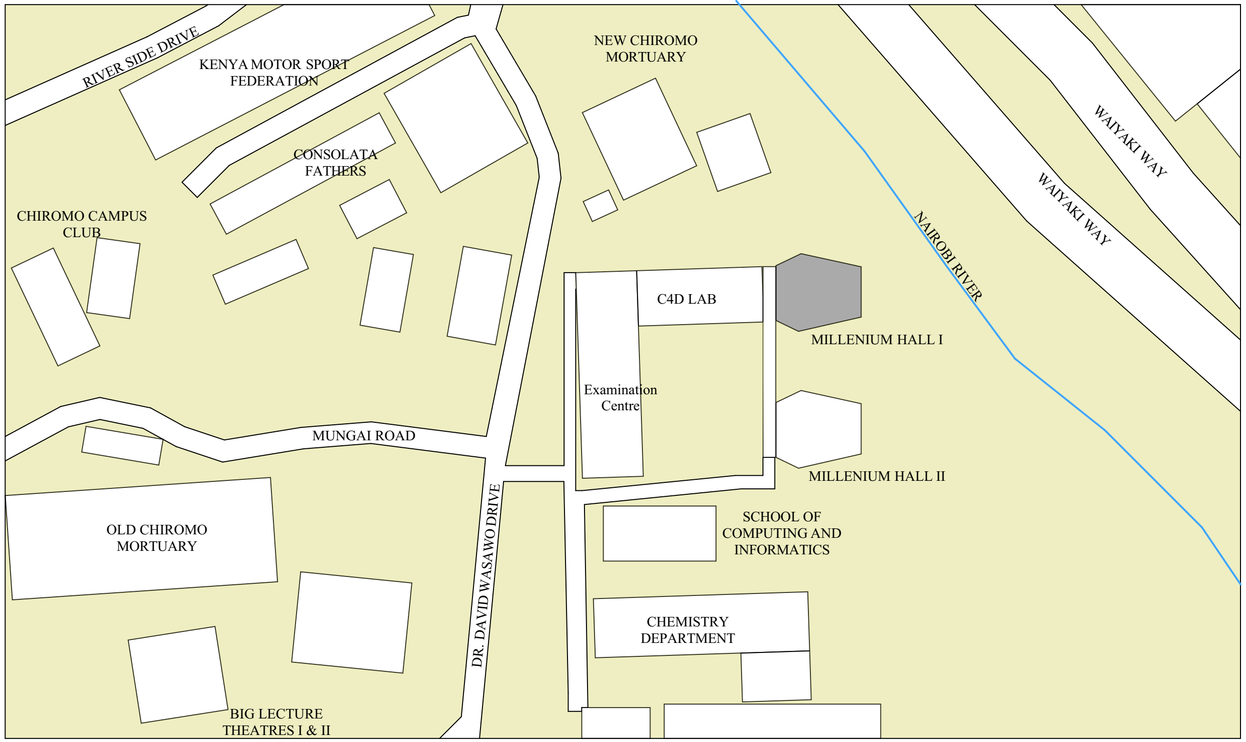


Figure 4.70: Millennium Hall I location **Source:** Author, 2017

Figure 4.71: Millennium Hall I South facade

Figure 4.72: North facade

4.5.1 Location and Neighborhood

Chiromo campus is located at a forested area within Westlands which offers the neighborhood tranquil serene environment ideal for lecture halls. Millennium hall I is within the School of Computing and Informatics. It completes a rectangular courtyard formed by the examination center, school of informatics classroom and offices, C4D laboratory and Millenium Hall II (**Fig. 4.70**).

To the east Waiyaki Way is the noisy neighbor due to high traffic during the day and at night. To the south the immediate neighbor is a court separating Millennium hall II from hall I. The C4D lab is to the west separated by a covered walkway linking the two lecture theatres. To the north is the new Chiromo mortuary with a good vegetation covering offering a good visual as well as acoustic buffer.

4.5.2 External Features

The lecture theater exterior is finished in keyed machine cut stone with strips of windows interrupting at regular intervals. A planter runs along the entire plinth of the building with a good seating space created at the entrance along the covered walkway (**Fig. 4.71**).

The covered walkway links C4D lab to Millennium hall I where the large courtyards opens up to create a good break out space for students after the classes. The courtyard is ever full of students seated while talking or searching information through the internet provided via wifi.

The volume of the theatre rises at the middle while tapering to either side. The parapet walls are finished in terrazo walling which extends to the columns taking the weight to the ground (**Fig. 4.72**).

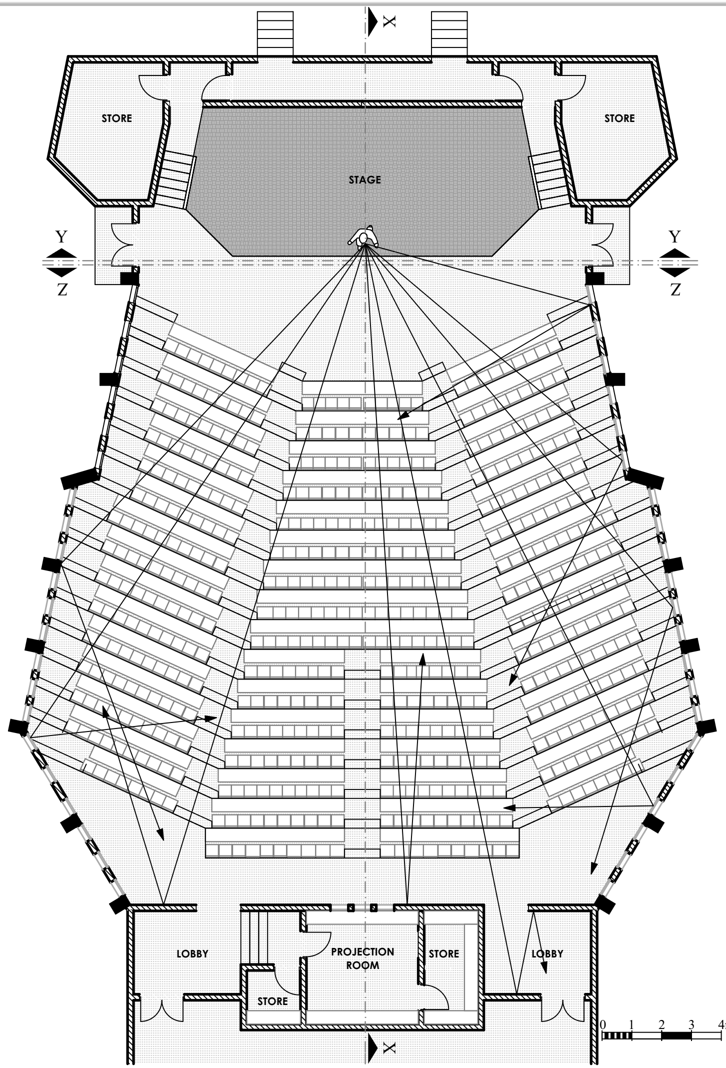


Figure 4.73: Millennium Hall I ground floor plan

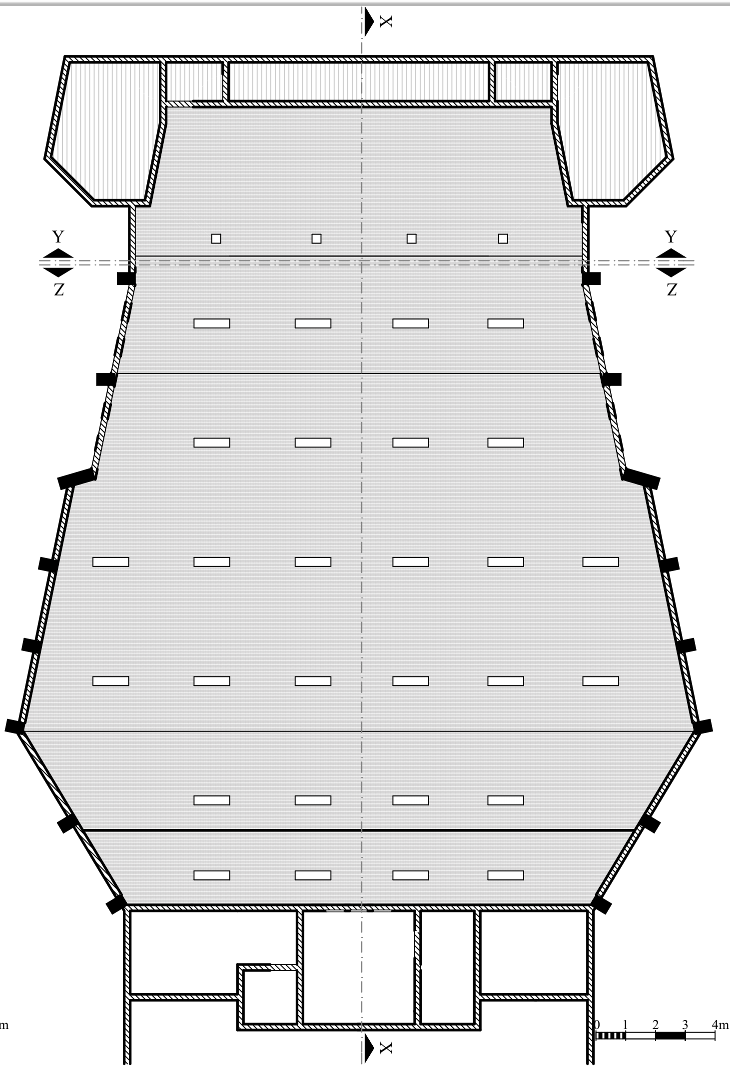
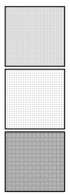


Figure 4.74: Millennium Hall I ceiling plan



Wood panel on joists

Terrazzo

Wood parquet

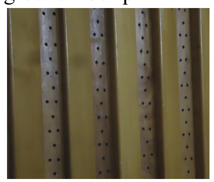


Fig. 4.75: Wall detail

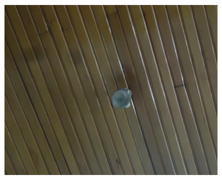


Fig. 4.76: Ceiling detail

Fig. 4.77: Stage floor detail

Fig. 4.78: Stage wall and audience seating floor detail

4.5.3 Floor Profile

The floor plan is fan shape with the back side walls angled to form a wide reverse splay. The stage is 5 metres deep with steps on either side leading to the stage and out to the back stage. The stage is chamfered at the edges to create circulation space around the front area of the audience seating.

The seating is layered into three segments separated by four gangways, two at the centre and two along the walls. There is an additional gangway from the back which centrally divides the wide central segment to allow for ease of movement to and from the seats (**Fig. 4.73**).

The gangway at the back is sufficiently wide to enhance easy movement across the back of the hall. The external lobby has only one external door with the internal ones complete as rectangular arches. The projection room is sandwiched between the two store rooms with its windows facing the stage at a good height to avoid interruption during activities on stage.

4.5.4 Floor and Ceiling Finishes

The stage is finished in polished wood parquet with the steps leading to the back stage finished in terrazzo. The entire audience seating area is also finished in terrazzo including the entrance lobby, the projection room and the two stores at the back (**Fig. 4.77**).

The ceiling is entirely finished in wood panels on joists with lighting fixtures placed at regular intervals (**Fig. 4.76**). The entrance lobby projection room and two stores ceiling is finished in plaster and paint (**Fig. 4.74**).

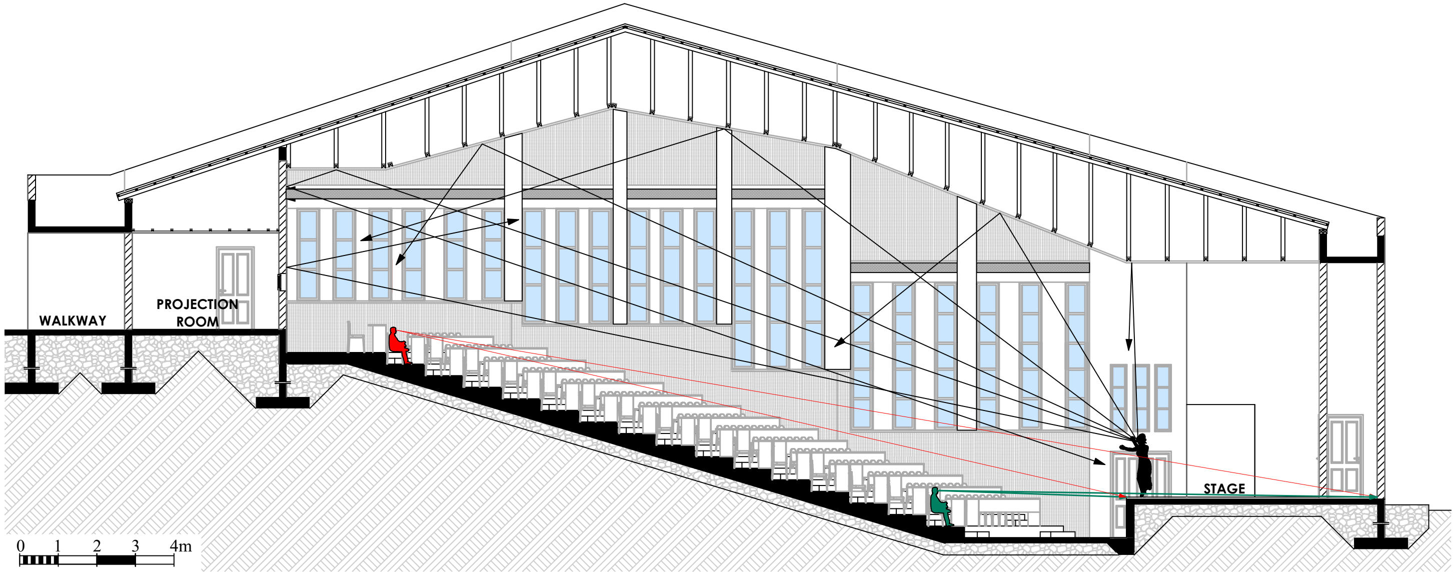


Figure 4.79: Millennium Hall I section X - X

Figure 4.80: View from the front

Figure 4.81: View from the back

4.5.5 Sectional Profile and Volume

The theatre has a volume of 3640 m^3. This volume is slightly large compared to the seating capacity as well as the nature of materials used on walling and flooring. The stage is 1 metres high with a 2.4 metre high wall separating the steps leading to the stage and the podium. The stage ceiling is 6 metres high. This would limit the quality of reflections to the back.

The slanted ceiling reflects sound to the audience but is too high to reflect strong sounds to the back. The sounds arriving at the back will be faint and have poor intelligibility (**Fig. 4.79**).

At the back, the ceiling meets the back wall at 90^0 angle hence lack of reflected sound to the person seated at the back. This will also cause echoes to the speaker on stage since sound is reflected back to the speaker strongly (**Fig. 4.81**).

The side walls are punctuated by a series of different sizes of strip windows which provide sufficient lighting but distorts the sound quality within the lecture hall.

The projection room windows are at a proper height hence gives an uninterrupted view to the events on stage (**Fig. 4.80**).

The entrance lobby lacks a door thus external noise gets into the lecture hall from the covered walkway outside. Thus, a second door should be installed to ensure sound isolation (**Fig. 4.79**).

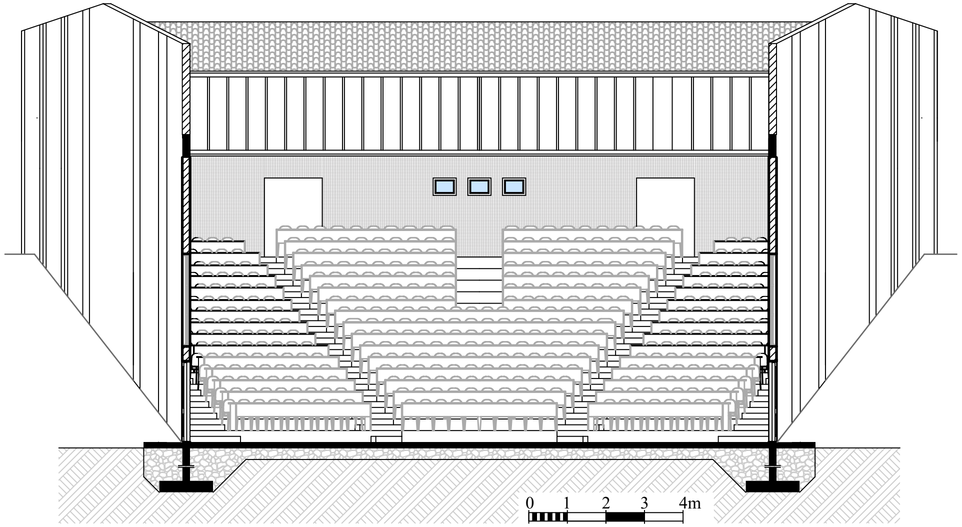


Figure 4.82: Millennium Hall I section Z - Z

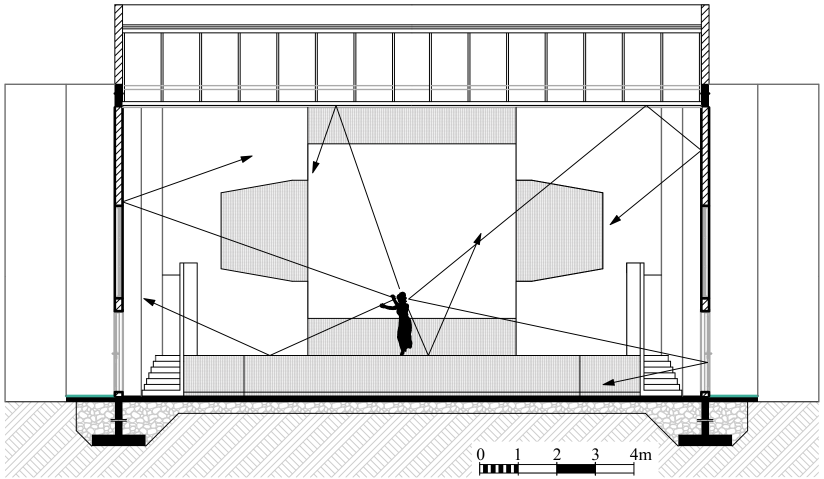


Figure 4.83: Millennium Hall I section Y-Y

Ordinary glass Plaster and paint Wood panels on joists

Figure 4.84: Stage

Figure 4.85: Seat detail

Figure 4.86: Back gangway

4.5.6 Wall Finishes

The stage front wall is composed of plaster and paint with a touch of timber panels on solid backing forming the projector screen framing. The stage side walls are finished in plaster and paint which reflects all the sound generated on stage to the audience (**Fig. 4.83**).

The audience seating side walls are made of timber panels on perforated block board backing with strip windows placed at the middle segment while the wire gauze is at the top with timber panels on perforated backing filling the remaining portion to the ceiling (**Fig. 4.79 & 4.80**).

The windows are made of steel frame with 3mm ordinary glass panels. All the doors are solid core with a steel grill door to the outside for security purposes. The entrance foyer walling is of plaster and paint with the windows made of steel and 3mm ordinary glass panels (**Fig. 4.79**).

4.5.7 Seating Arrangement

The seating is on 300mm high raked terraces with clear sightlines to the stage. The gangways leading to the back are on the sides as well as on either side of the middle seating column. The audience seating on the middle column have an extra central aisle from the back which ends midway into the seats. This offers an extra circulation space to ease movements in and out of the hall (**Fig. 4.82**).

4.5.8 Table 5: Reverberation Time Calculation (Millennium Hall I Existing Condition)

Materials	Area (M2)	OCTAVE FREQUENCY			
		125 Hz		250Hz	
	S	α	Sα	α	Sα
Flooring					
Terrazzo (Stage/Audience Seating)	559	0.01	5.59	0.01	5.59
Wood parquet (Stage)	55	0.04	2.2	0.04	2.2
Walling					
Grooved wood planks on solid walling (front)	21	0.19	3.99	0.23	4.83
Grooved wood planks on perforated block board on solid walling (side/back)	219	0.31	67.89	0.33	72.27
Painted plaster	312	0.01	3.12	0.01	3.12
4mm thick ordinary window glass	43	0.3	12.9	0.2	8.6
Wire gauze permanent vents (PVs)	10	0.6	6	0.6	6
Laminated solid core doors	13	0.14	1.82	0.1	1.3
Ceiling					
Grooved wood planks on battens	551	0.1	55.1	0.36	198.36
Fluorescent luminaries	11	0.3	3.3	0.2	2.2
Seating					
Cushions (seat tops/rest fronts)	221	0.33	72.93	0.51	112.71
Perforated hard board (seat bottoms)	101	0.27	27.27	0.85	85.85
Block board seat backs and writing tables	722	0.4	288.8	0.2	144.4
Air (M3)	3640	0	0	0.001	2.93
Total materials absorption			550.91		650.36
Audience					
Full	500	0.33	165	0.4	200.00
Half full	250	0.33	82.5	0.4	100.00
Empty	0	0.33	0	0.4	0.00
Total absorption (Fully)			715.91		850.36
Total absorption (Half)			633.41		750.36
Total absorption (Empty)			550.91		650.36
Reverberation time (s)					
Full			**0.8**		**0.7**
Half full			**0.9**		**0.8**
Empty			**1.1**		**0.9**

4.6 SCIENCE LECTURE HALL COMPLEX, KENYA SCIENCE (EXISTING CONDITION)

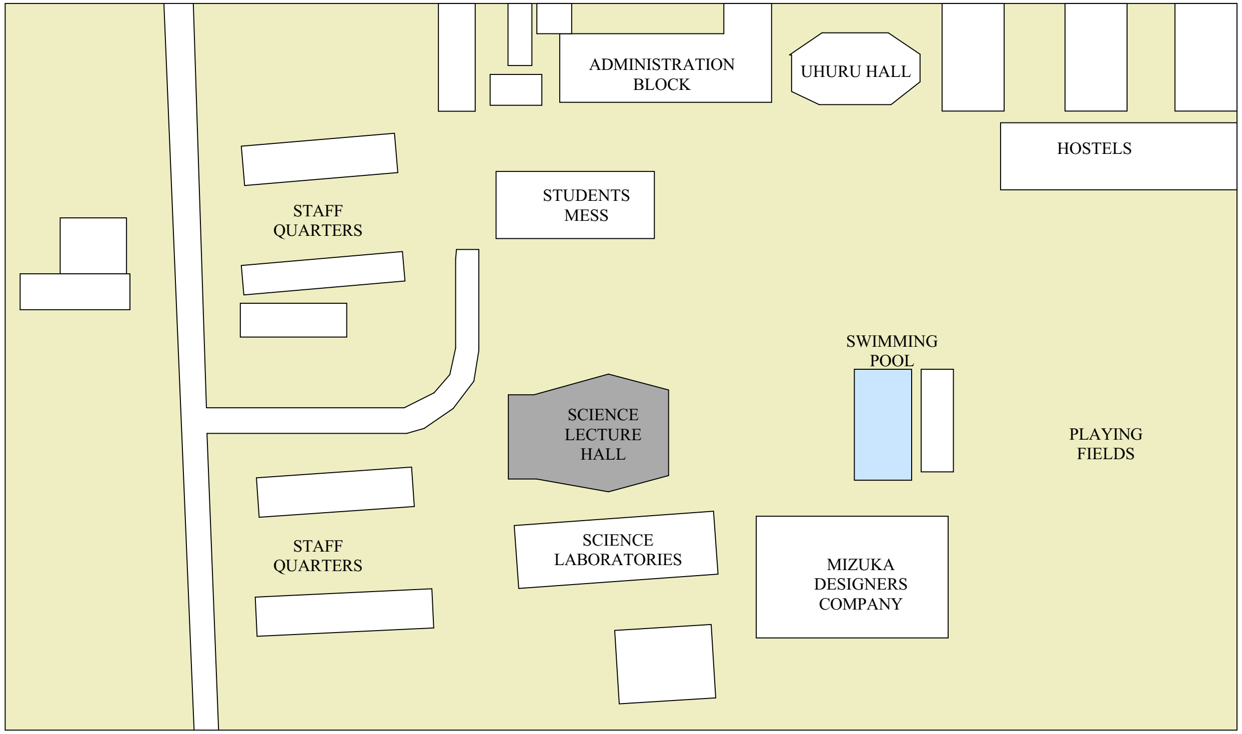


Figure 4.87: Science Lecture Hall location **Source:** Author, 2017

Figure 4.88: Science Lecture Hall west facade

Figure 4.89: East facade

4.6.1 Location and Neighborhood

Science lecture theatre is located in Kenya Science Campus within Dagoretti area. The theatre is isolated from other structures with the nearest blocks being the Science labs to the south. To the north is a wide court which separates the student's mess from the theatre and is linked by a nicely landscaped walkway. To the immediate east is the fenced swimming pool which is a good distance away from the theatre hence there is minimal interruption from activities within the pool area (**Fig. 4.87**).

The playing fields are to the east bordering the pool to the west. To the west of the theatre is open space with staff quarters located within the forested area. There are beautifully done linkages that allow students to access the theatre from all directions.

4.6.2 External Features

The building exterior is finished in plaster and paint with parts between the columns done with keyed machine cut stones. The parapet walling is finished in plaster and paint. The inverted U shaped window detail is done in steel framework with 3mm ordinary glass panels.

Planters are done around the plinth of the building with paved walkways linking the theatre to other areas within the school. Trees are planted along the walkways provided shade as one walks from the theatre to the administration blocks to the north (**Fig. 4.88**).

The main entrance has an open balcony break out space with a covered walkway below linking the two stair wells on either side. The toilets are at the back facing the east with all the windows opening in this direction (**Fig. 4.89**).

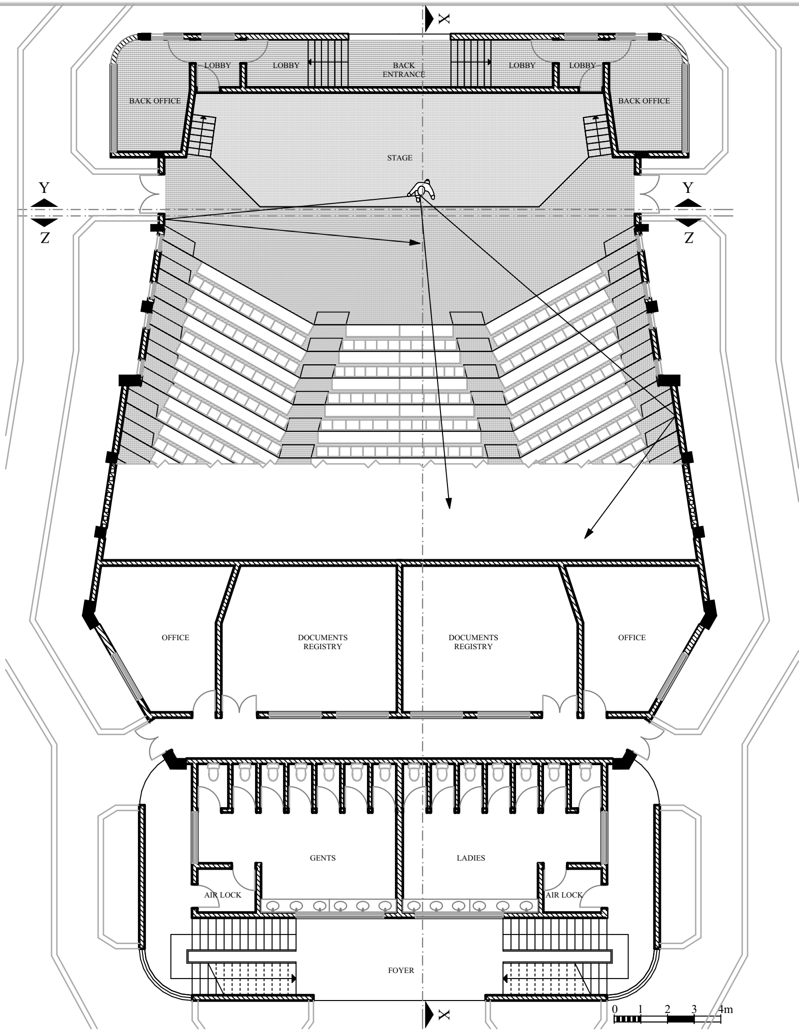


Figure 4.90: Science Lecture Hall ground floor

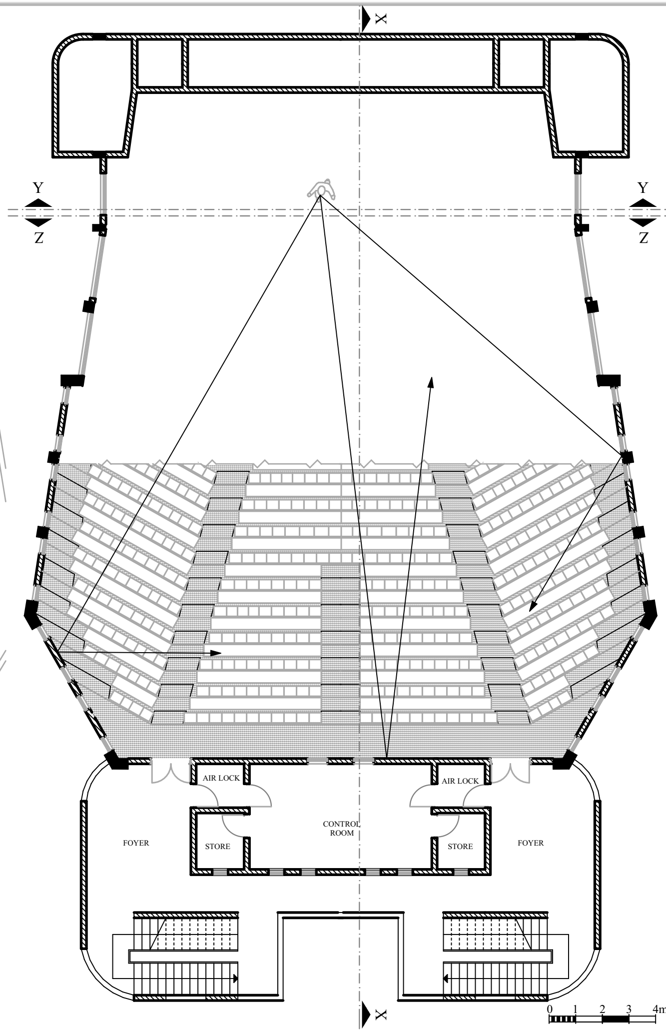


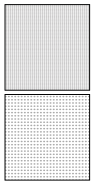
Figure 4.91: Science Lecture Hall first floor

4.6.3 Floor Profile

The theatre is fan shaped with windows at regular intervals along the splay side walls. The stage is 4 metres deep with chamfered edges creating a wide front circulation space between the stage and the first terrace (**Fig. 4.90**).

There are two sets of steps on either side of the stage leading to the stage and back stage rooms. The ground floor has five terraces with four gangways leading to the back. The middle column has two gangways on either side which enhances quick access by the audience to the seating areas eliminating deep seating spaces (**Fig. 4.91**).

The first floor has five gangways with an additional one cutting the middle seating column from the back to ease movements within the wider back seating section. The back gangway is 1.5 metres wide and leads from end to end to allow for the audience to walk across the back of the theatre.



Wood panel on joists

Terrazzo

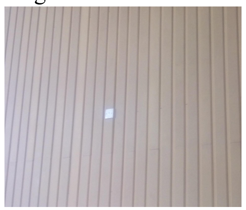


Fig. 4.92: Wall detail

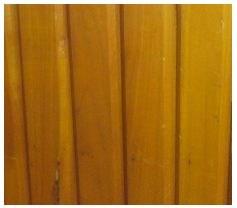


Fig. 4.93: Stage wall detail

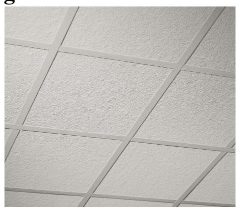


Fig. 4.94: Ceiling detail

Fig. 4.95: Flooring detail

4.6.4 Floor and Ceiling Finishes

The stage is finished in wooden planks on joist while the audience seating space is finished in terrazzo flooring (**Fig. 4.90**).

The ceiling is of 600 x 600 mm acoustic panels on suspended steel structure with lighting fixtures placed at regular intervals (**Fig. 4.94**).

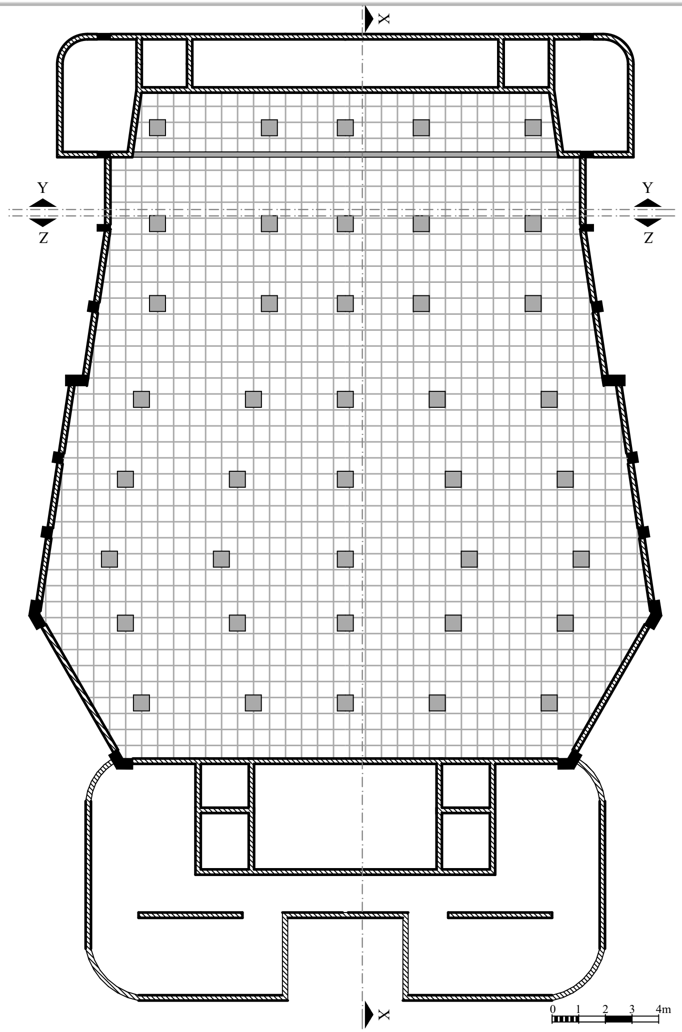


Figure 4.96: Science Lecture Hall ceiling plan

600 x 600 acoustic ceiling panels

Wood panel on joists

Terrazzo

Figure 4.97: Stage

Figure 4.98: View from the back

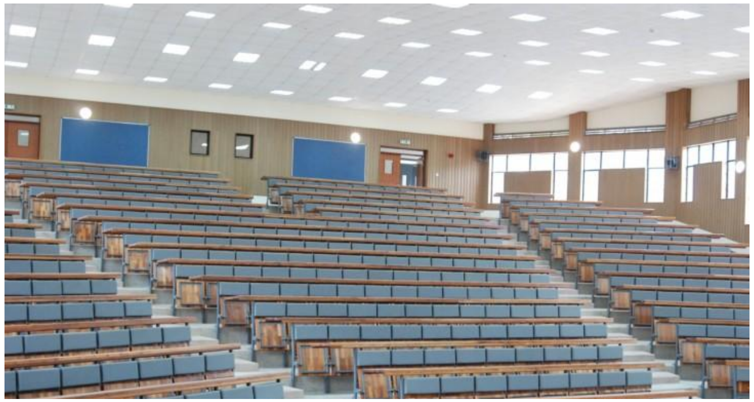


Figure 4.99: View from the front

4.6.5 Sectional Profile and Volume

The volume of the lecture theatre is 2936 m^3. This is quite large compared to its seating capacity and the material finishes used within the walling, flooring and ceiling. This will generally lead to long reverberation time and acoustic defects such as echoes within the hall. The stage is 1 metre high and 4 metres deep. The first terrace is 4.5 metres from the stage. There are 16 terraces of 300mm riser heights (**Fig. 4.97**).

The ceiling profile will distort the sound reflections due to its height and angle. Those seated at the back will have weak sound reflections reaching them from the stage. The sound hits the ceiling a greater grazing angles which lowers its strength hence become weak as it reaches the back of the hall. The ceiling at the back meets the wall at 90^0 which would tend to send echoes to the speaker on stage as well as produce poor reflections to the people at seated at the back (**Fig. 4.98**).

4.6.6 Wall Finishes

The stage walling is done with grooved timber panels with plaster strips at the top and bottom. The main theatre walling is timber panels with windows of ordinary glass and steel frames dotting the entire wall at regular intervals dictated by the column and beam distribution.

Above the windows, wire gauze strips used for ventilation purposes are installed with plaster and paint filling the remaining space to the ceiling soffit. The back wall is finished with grooved timber panels except for two enamel black walls, two solid core doors and two ordinary 3mm glass control room windows (**Fig. 4.99**).

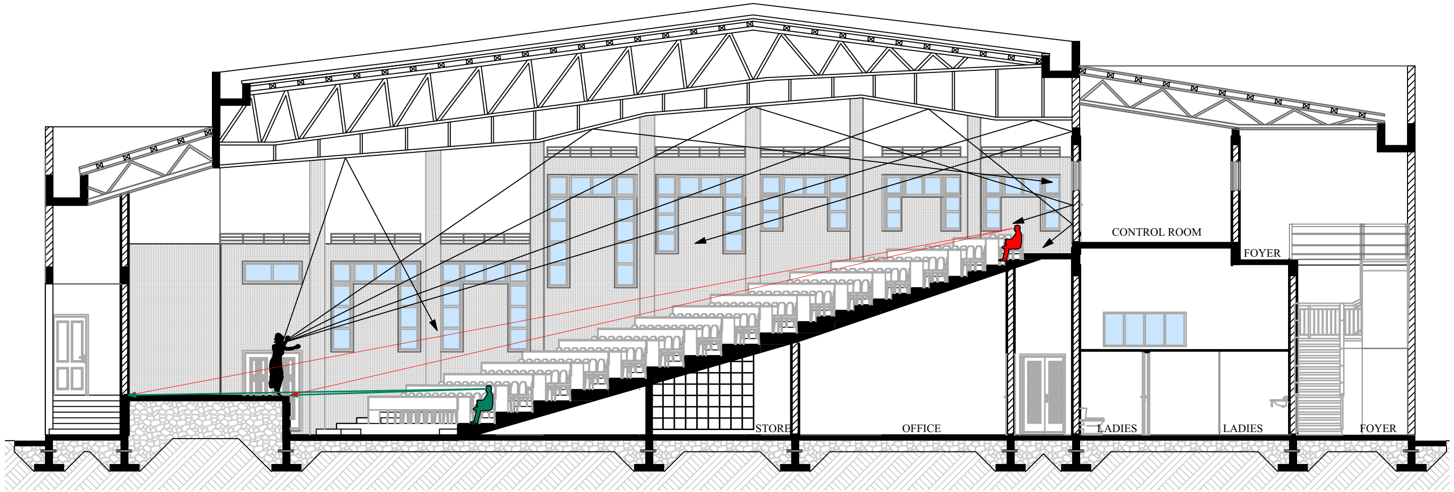


Figure 4.100: Science Lecture Hall section X - X

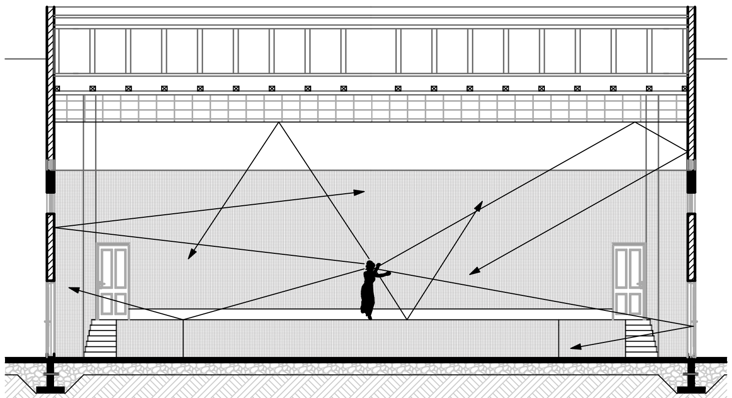


Figure 4.101: Science Lecture Hall section Y - Y

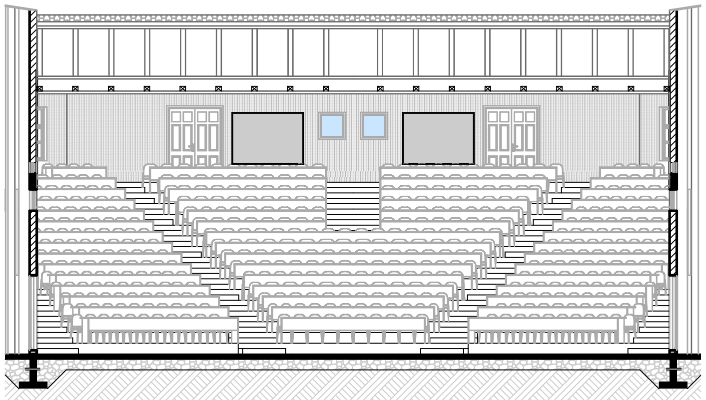
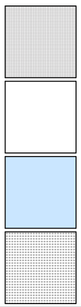


Figure 4.102: Science Lecture Hall section Z - Z



Wood panel on joists

Plaster and paint

3mm thick ordinary glass

Terrazzo

Fig. 4.103: Seating

Fig. 4.104: Stage

Fig. 4.105: Ceiling soffit

4.6.7 Seating Arrangement

The seating is raked with risers being 300mm high enhancing good sightlines and audio path to the stage. There are four gangways leading to the back (two on the sides and the other two being sandwiched between the three seating columns).

The movement to the seats is enhanced by short distances between aisles which would allow one to enter the central seat from either side with ease. The back end has an extra walkway leading to the wide middle seating column. This allows for ease exit and entry to the deep seats located at the back (**Fig 4.100**).

4.6.8 Cove Design

The front wall and ceiling should have a better splay angle so as to enhance quick powerful reflections from the speaker on stage to the audience at the back. The ceiling is too high and thus sound loses power as it hits the ceiling at wider grazing angles hence diffusing as opposed to reflecting sound. The back wall suffers the same fate since the wall meets the ceiling at 90^0 angle (**Fig 4.105**).

The use of acoustic panels generally absorbs sound which would otherwise have been a very useful surface to reflect sound to the back. The audience will generally suffer front faint sounds as well as poor speech intelligibility especially if the speaker does not project the sound loud enough (**Fig 4.105**).

4.6.9 Table 6: Reverberation Time Calculation (Science Lecture Hall Complex Existing Condition)

Materials	Area (M2)	OCTAVE FREQUENCY			
		125 Hz		250Hz	
	S	α	Sα	α	Sα
Flooring					
Terrazzo (Stage/Audience Seating)	557	0.01	5.57	0.01	5.57
Wood planks on joists (Stage)	93	0.04	3.72	0.04	3.72
Walling					
Grooved wood planks on solid walling (front)	238	0.31	73.78	0.33	78.54
Painted plaster	100	0.01	1	0.01	1
4mm thick ordinary window glass	47	0.3	14.1	0.2	9.4
Wire gauze permanent vents (PVs)	10	0.6	6	0.6	6
Laminated solid core doors	17	0.14	2.38	0.1	1.7
Porcelain black wall (back wall)	6	0.03	0.18	0.05	0.3
Ceiling					
Acoustic ceiling panels	485	0.45	218.25	0.7	339.5
Fluorescent luminaries	15	0.3	4.5	0.2	3
Seating					
Cushions (rest fronts)	45	0.33	14.85	0.51	22.95
Mahogany (seat/rests/writing tables)	563	0.03	16.89	0.05	28.15
Air (M3)	2936	0	0	0.001	2.94
Total materials absorption			361.22		502.77
Audience					
Full	500	0.33	165	0.4	200.00
Half full	250	0.33	82.5	0.4	100.00
Empty	0	0.33	0	0.4	0.00
Total absorption (Fully)			526.22		702.77
Total absorption (Half)			443.72		602.77
Total absorption (Empty)			361.22		502.77
Reverberation time (s)					
Full			**0.9**		**0.7**
Half full			**1.1**		**0.8**
Empty			**1.3**		**0.9**

4.7 TAIFA HALL , MAIN CAMPUS, (REDESIGNED CONDITION)

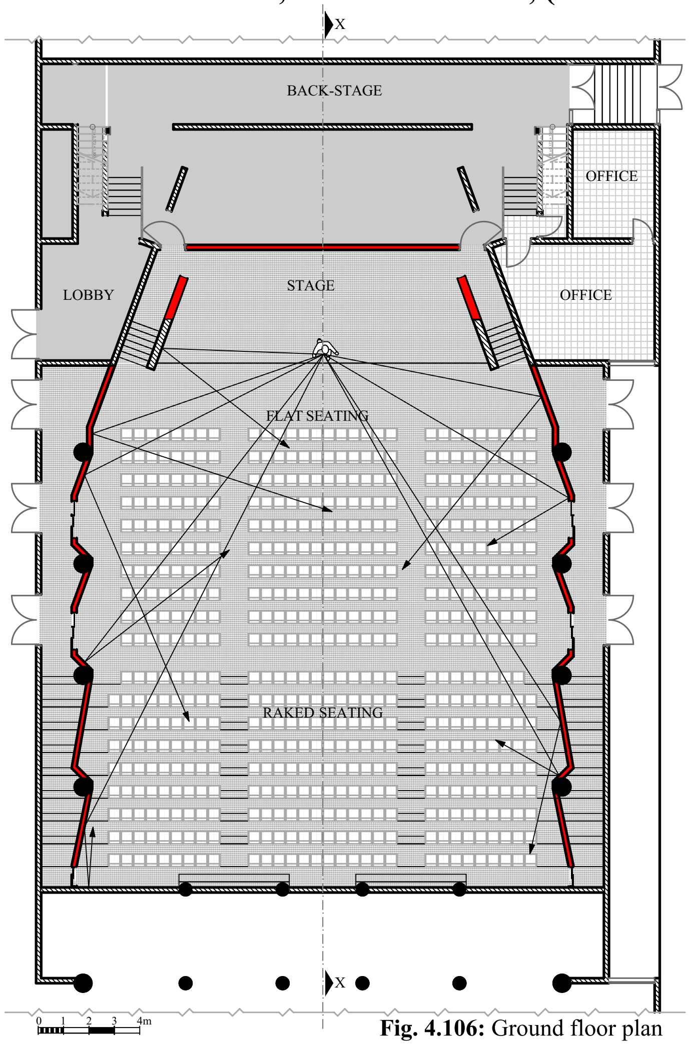


Fig. 4.106: Ground floor plan

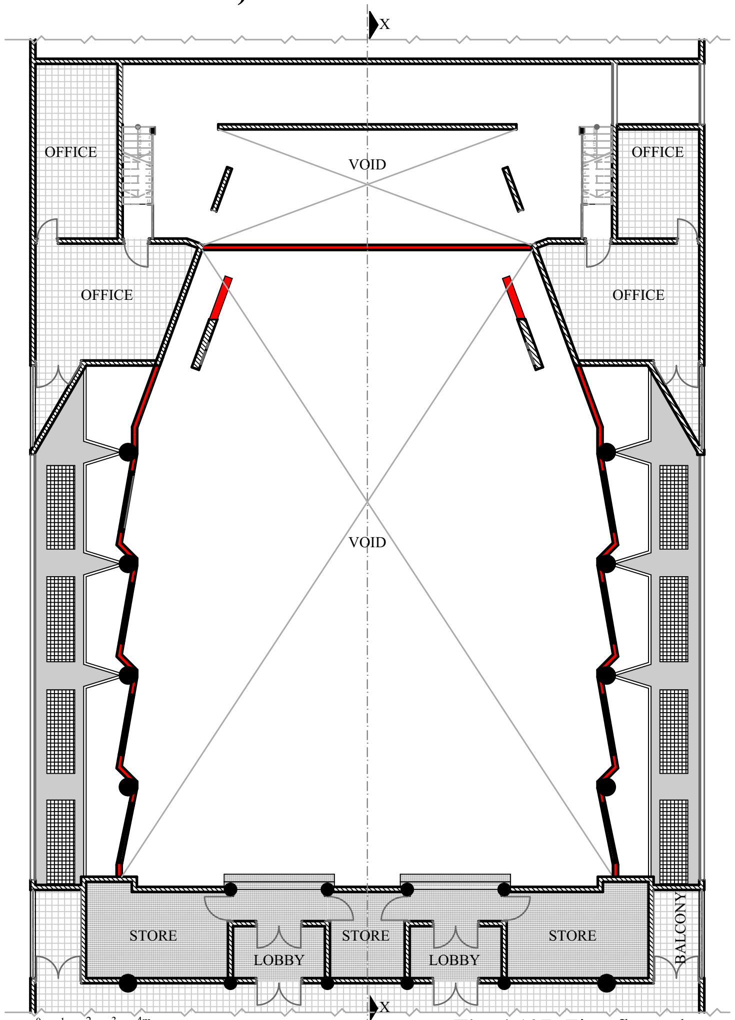


Fig. 4.107: First floor plan

Fig. 4.108: Ceiling layout at LRC

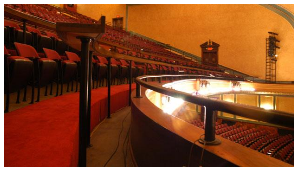


Fig. 4.109: Balcony railing

Fig. 4.110: Diffusive walling

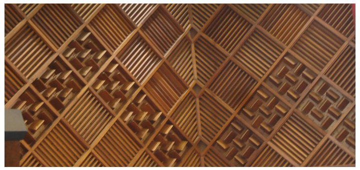


Fig. 4.111: Stage diffusive walling

4.7.1 Floor Profile

Taifa hall has a rectilinear floor profile that reflects sound as desired though the extra volumes at the sides and the stage needs to be reduced to effectively reflect sound to the audience. The stage back wall should be moved to have a stage depth of 4.5 metres. The side walls on audience seating area should be sinusoidal to enhance sound diffusion as well as reflect sound to the audience. This wall redesign will be effected both the ground and first floor (**Fig. 4.106, 4.107, 4.110 & 4.111**).

4.7.2 Sectional Profile

The large volume and high ceiling elongates the reflection path leading to delayed sound to the audience. The ceiling should be lowered and broken into several slanted series of panels to ensure effective reflection and elimination of tonal coloration during speeches (**Fig. 4.108**). The balcony front wall blocks the stage view of the audience seated. A railing should be introduced and the walls removed up to a desired height where the audience on stage have undistracted view to the stage (**Fig. 4.109**).

- Redesigned walls
- Thin carpet over thin felt on cement screed
- Cement screed flooring finished in red oxide
- 20mm thick ceramic tiles on cement

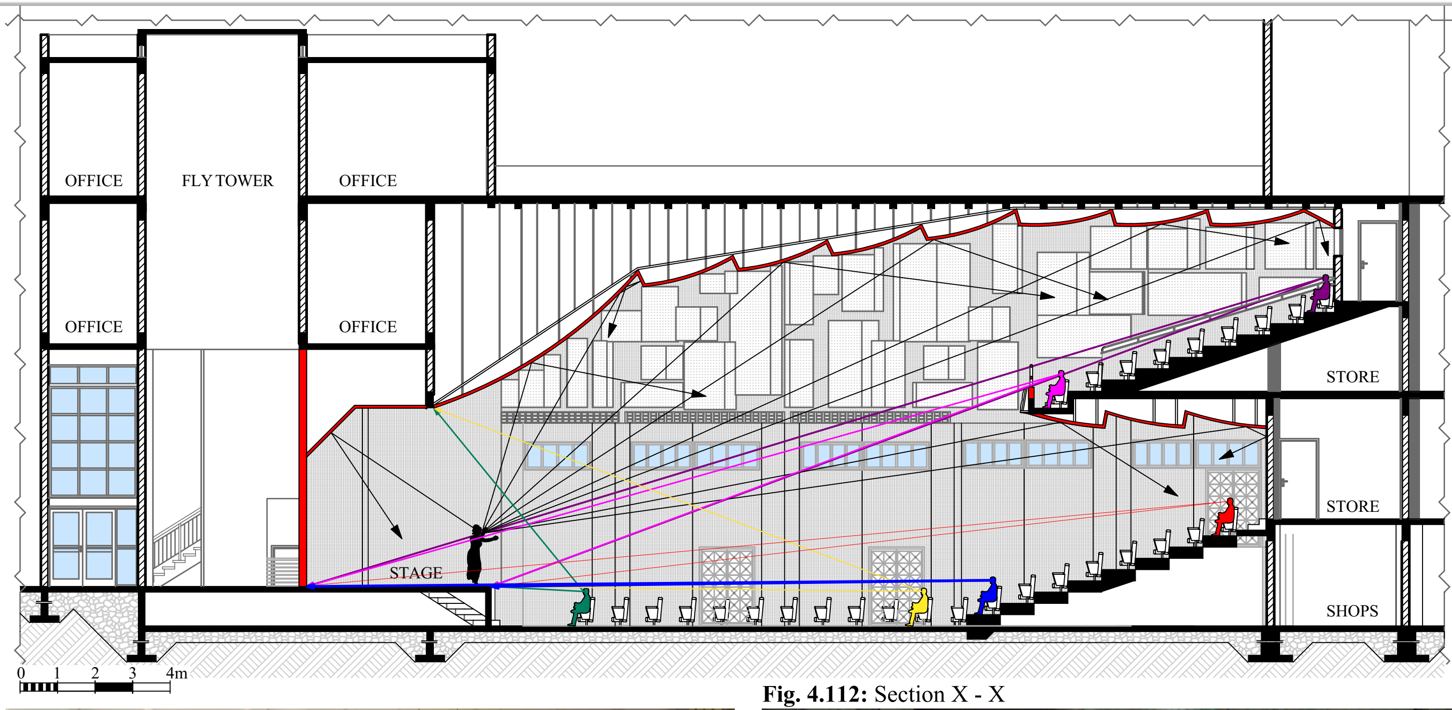


Fig. 4.112: Section X - X

Fig. 4.113: Large ceiling panels at LRC

Fig. 4.114: Absorbent padded doors at LRC

4.7.3 Stage Design

The stage volume is too large. The back wall should be moved to give a stage depth of 4.5 metres hence allow for immediate reflections to the audience. Two doors on each side will lead to the back stage. The splay walls in advance of the stage should be extended and that parallel to the stage edge eliminated to enhance reflections of sound outward to the audience seating area (**Fig. 4.112**).

The back stage walling should be made of diffusing material such as timber panels with hessian cloth backing. The splay wall should be of reflective material so as to push the sound to the audience. Splay ceiling should be added at the back wall to reduce the reflected sound path and eliminate possibilities of echoes. A large ceiling panel should be placed immediately in front of the stage to reflect all the sound generated by the speaker (**Fig. 4.113**).

4.7.4 Audience Seating Design

The floor should be made of absorbent hardwearing material. Thin carpet over thin felt on concrete floor backing is recommended to ensure all sound falling on the floor is absorbed. The walling should be completely absorbing as well as diffusive to effectively break sound and avoid focusing. The doors should be padded double seals, double sheeting with absorbent air space to prevent (**Fig. 4.114**)

Fig. 4.115: Array of reflective ceiling at LRC

Fig. 4.116: Gangway and seating arrangement design at LRC

Fig. 4.117: Tip-up seats at LRC

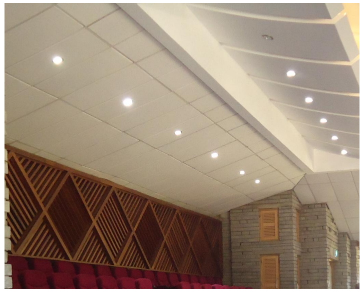


Fig. 4.118: Splay ceiling at the back

Fig. 4.119: Balcony balustrading

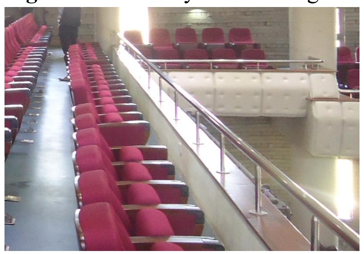


Fig. 4.120: Low balustrade

external noise as well as absorb incident sound. The windows should be reduced to high level strip windows double glazed with 3mm glass and 10mm air gap to prevent external noise. The ceiling should be a series of reflective curved panels to diffuse strong reflections as a means of preventing tonal coloration as well as distribute sound equally around the theatre (**Fig. 4.115**). Splay ceilings should be placed at the back to enhance reflections of sound to the people seated at the back hence eliminating the echoes arriving at the stage caused by right angled wall-ceiling joints (**Fig. 4.118**).

4.7.5 Balcony Design

The balcony front wall should be porous or low to allow for proper sightlines to the stage. The stone walling finished in plaster and paint should be reduced in height and replaced with railing (**Fig. 4.120**). The ceiling should be splayed at the back to eliminate echoes to the stage and audience on the front rows. The ceiling below the balcony should be replaced with angled reflectors and splayed wall-ceiling joint to reflect sound to the rear audience.

4.7.6 Seating Arrangement

Permanent upholstered tip up theatre seats are ideal to replace the temporary steel or laminated MDF ones used during classes (**Fig. 4.117**). There should be three columns of seats with four gangways (two at central area and two on either side) (**Fig. 4.116**). The balcony seating should be staggered to allow for the person seated behind to see the stage between the heads of the persons in front. This will enhance sightlines as well as audio paths of direct sound from stage.

4.7.7 Cove Design

All coves should be splayed to prevent direct sound from being reflected back to the stage causing echoes. The splay ceiling also enhances reflections to the audience seated at the back.

4.7.8 Table 7: Reverberation Time Calculation (Redesigned Taifa Hall)

Materials	Area (M2)	OCTAVE FREQUENCY			
		125 Hz		250Hz	
	S	α	Sα	α	Sα
Flooring					
Carpet thin over thin felt on concrete (Audience Seating)	892	0.1	89.2	0.15	133.80
Carpet thin over thin felt on wood planks (Stage)	190	0.2	38	0.25	47.50
Walling					
Grooved wood planks on 16mm battens on hessian cloth backing (front/side/back)	1659	0.31	514.29	0.33	547.47
Heavy curtains	78	0.1	7.8	0	0.00
50mm rigid polyurethane foam with leather cover (Balcony front)	21	0.2	4.2	0.4	8.40
200mm dense veneer chipboard over air gap (reflectors)	216	0.06	12.96	0.1	21.60
Wire gauze permanent vents (PVs)	42	0.6	25.2	0.6	25.20
Double glazed windows, 3mm glass, with 10 mm air gap	125	0.15	18.75	0.05	6.25
Padded double seals, double sheeting acoustic doors with absorbent air space	39	0.35	13.65	0.39	15.21
Soffits					
Wood planks slotted and modified on 16 mm battens, mineral wool in air space	256	0.2	51.2	0.62	158.72
Ceiling					
Painted 16 mm MDF ceiling panels on 16 mm battens	917	0.2	183.4	0.25	229.25
Fluorescent luminaries	11	0.3	3.3	0.2	2.20
Seating					
Upholstered tip up theatre seats	1200 no.	0.33	396	0.51	612.00
Air volume (M3)	5875	0	0	0.001	5.88
Total materials absorption			1357.95		1813.48
Audience					
Full	1200	0.33	396	0.4	480.00
Half full	600	0.33	198	0.4	240.00
Empty	0	0.33	0	0.4	0.00
Total absorption (Fully)			1357.95		1681.48
Total absorption (Half)			1357.95		1747.48
Total absorption (Empty)			1357.95		1813.48
Reverberation time (s)					
Full			**0.7**		**0.6**
Half full			**0.7**		**0.5**
Empty			**0.7**		**0.5**

4.8 LECTURE THEATRE 101, UNIVERSITY OF NAIROBI TOWER, (REDESIGNED CONDITION)

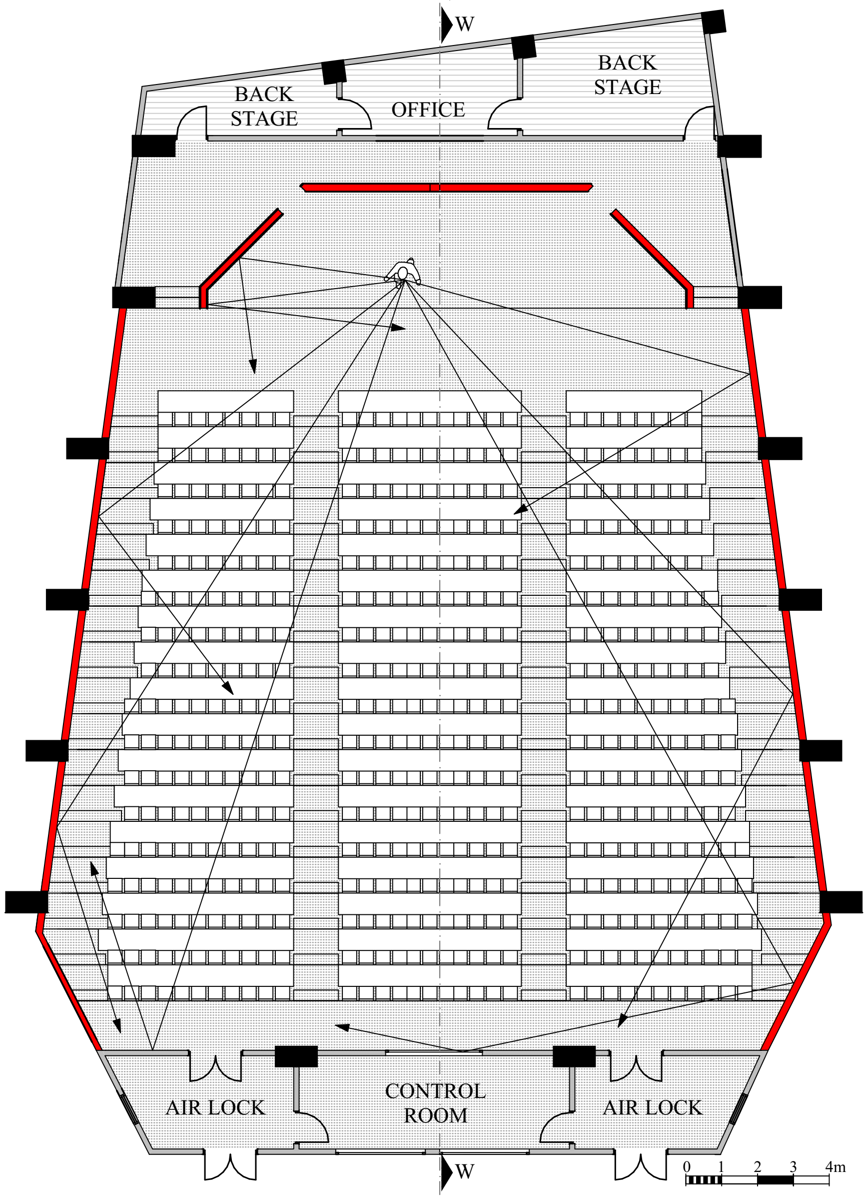


Fig. 4.121: Lecture Theatre 101 ground floor plan

Fig. 4.122: Ribbon windows

Fig. 4.123: Curved reflective ceiling panels

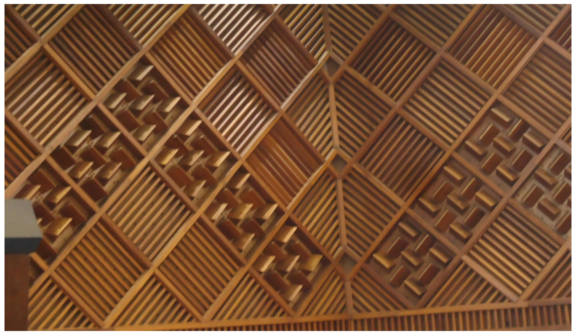


Fig. 4.124: Stage backwall design at LRC

Redesigned walls

Thin carpet over thin felt on cement screed

4.8.1 Floor Profile

Fan shape is ideal for sound propagation to the audience however, the large window openings should be reduced in size to allow for absorptive/diffusive materials. The stage house should be reduced to allow the back walls to propagate sound to the audience (**Fig 4.121**). The stage wall/ceiling junction should be splayed to reflect sound to the audience as well.

4.8.2 Sectional Profile

The large windows should be replaced with ribbon openings for natural lighting (**Fig 4.122**). The reflective ceiling should be slightly curved to ensure a diffused sound hence eliminating instances of tonal coloration (**Fig 4.123**). A splay ceiling should be introduced on stage to reflect immediate sound to the audience. The stage back wall should be moved to reduce the stage depth to 3 metres hence creating a back stage room as well as ensure proper sound propagation to the audience.

4.8.3 Volume

The current volume is 2430 m^3 which will give 1.1 s for 125 Hz and 1.3 s for 250 Hz. The recommended volume is 2200 m^3 which will give reverberation times of 0.7s for 125 Hz and 0.6 s for 250 Hz.

4.8.4 Stage Design

The stage back wall should be moved so as to give the speaker feedback to gauge the loudness and speed at which he is speaking (**Fig 4.124**). This set up will also

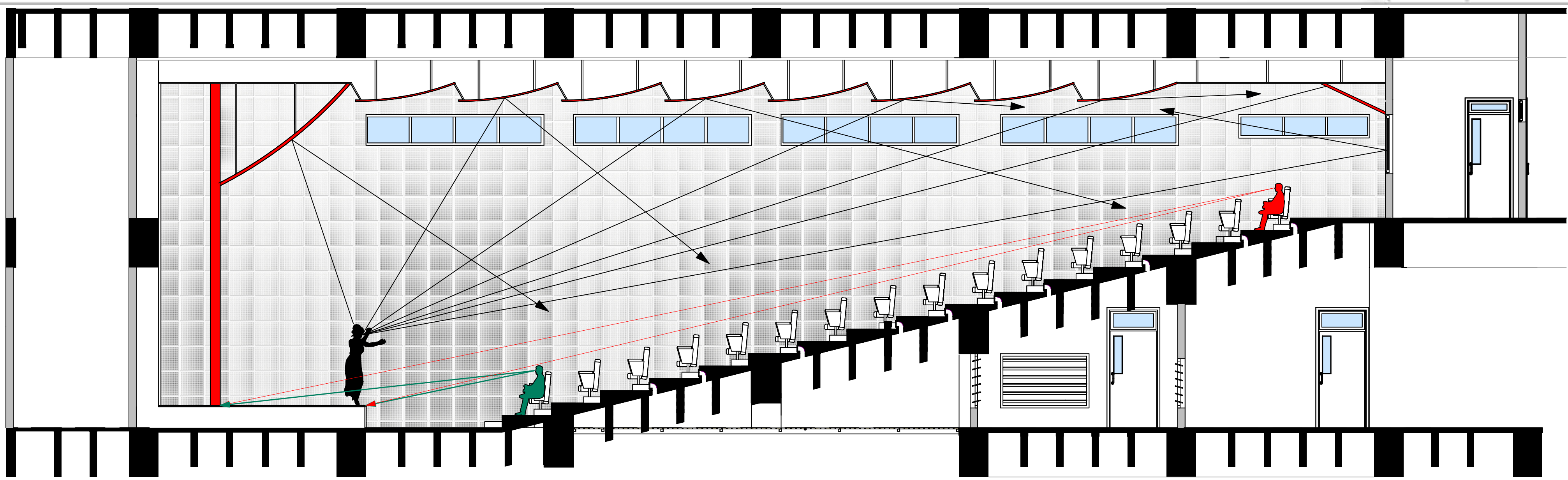


Fig. 4.125: Section W - W

allow sound to blend before moving into the audience seating area. The stage side walls are splayed to send reflected energy to the audience. The walls should be of solid materials to avoid low frequency absorption. The stage ceiling makes an efficient reflector since sound generally has a free path upwards from a speaker's mouth. Splay ceilings will give a better reflection covering the ground floor and rear seats. This will also allow the speaker to change position without losing speech intelligibility (**Fig 4.125**).

4.8.5 Audience Seating Design

The 600 x 600 mm ceramic tiles floor should be covered with thin carpet over thin felt to absorb sound hence eliminating defects. The 600 x 600 mm perforated MDF walling with hessian cloth backing should be used to cover the area initially occupied by the large windows which shall be replaced with ribbon windows. The ordinary glass panels will be replaced with double glazed 3mm glass with 10mm air gap to eliminate external noise. The array of ceiling reflectors will be curved to eliminate tonal coloration and false localization (**Fig 4.125**).

4.8.6 Seating Arrangement

The most ideal gangway position is off the central axis. This is where the best direct and reflected sound from the speaker falls. Having the gangway at the central axis will thus distort the direct and reflected sound to the audience. The gangways should be shifted to either side of the central axis. This will also ease entry and exit of the audience (**Fig 4.121**).

The laminated particle board seating should be replaced with absorbent upholstered tip up seats to cater for the missing audience during class sessions (**Fig 4.126**).

4.8.7 Cove Design

The front and back walls should have coves angled to direct sound from the stage to the rear seats and eliminate strong reflections from the rear walls back to the speaker creating echoes (**Fig 4.125**).

Fig. 4.126: Upholstered tip up seats

4.8.8 Table 8: Reverberation Time Calculation (Redesigned Lecture Theatre 101)

Materials	Area (M2)	OCTAVE FREQUENCY			
		125 Hz		250Hz	
	S	α	Sα	α	Sα
Flooring					
Carpet thin over thin felt on concrete (Audience Seating)	542	0.1	54.2	0.15	81.3
Carpet thin over thin felt on wood (Stage)	79	0.2	15.8	0.25	19.75
Walling					
600 x 600 mm perforated MDF panels with hessian cloth backing (Front/sides/back walls)	371	0.3	111.3	0.2	74.2
Double glazed windows, 3mm glass, with 10 mm air gap	70	0.15	10.5	0.05	3.5
Padded double seals, double sheeting acoustic doors with absorbent air space	16	0.35	5.6	0.39	6.24
Ceiling					
Painted 16 mm MDF ceiling panels on 16 mm battens	596	0.2	119.2	0.25	149
Fluorescent luminaries	18	0.3	5.4	0.2	3.6
Seating					
Upholstered tip up theatre seats	500 no.	0.33	165	0.51	255
Mahogany writing tables	270	0.03	8.1	0.05	13.5
Air volume (M3)	2200	0	0	0.001	2.2
Total materials absorption			495.1		608.29
Audience					
Full	500	0.33	165	0.4	200
Half full	250	0.33	82.5	0.4	100
Empty	0	0.33	0	0.4	0
Total absorption (Fully)			495.1		553.29
Total absorption (Half)			495.1		580.79
Total absorption (Empty)			495.1		608.29
Reverberation time (s)					
Full			**0.7**		**0.7**
Half full			**0.7**		**0.6**
Empty			**0.7**		**0.6**

4.9 8-4-4 MULTI-PURPOSE HALL, MAIN CAMPUS (REDESIGNED CONDITION)

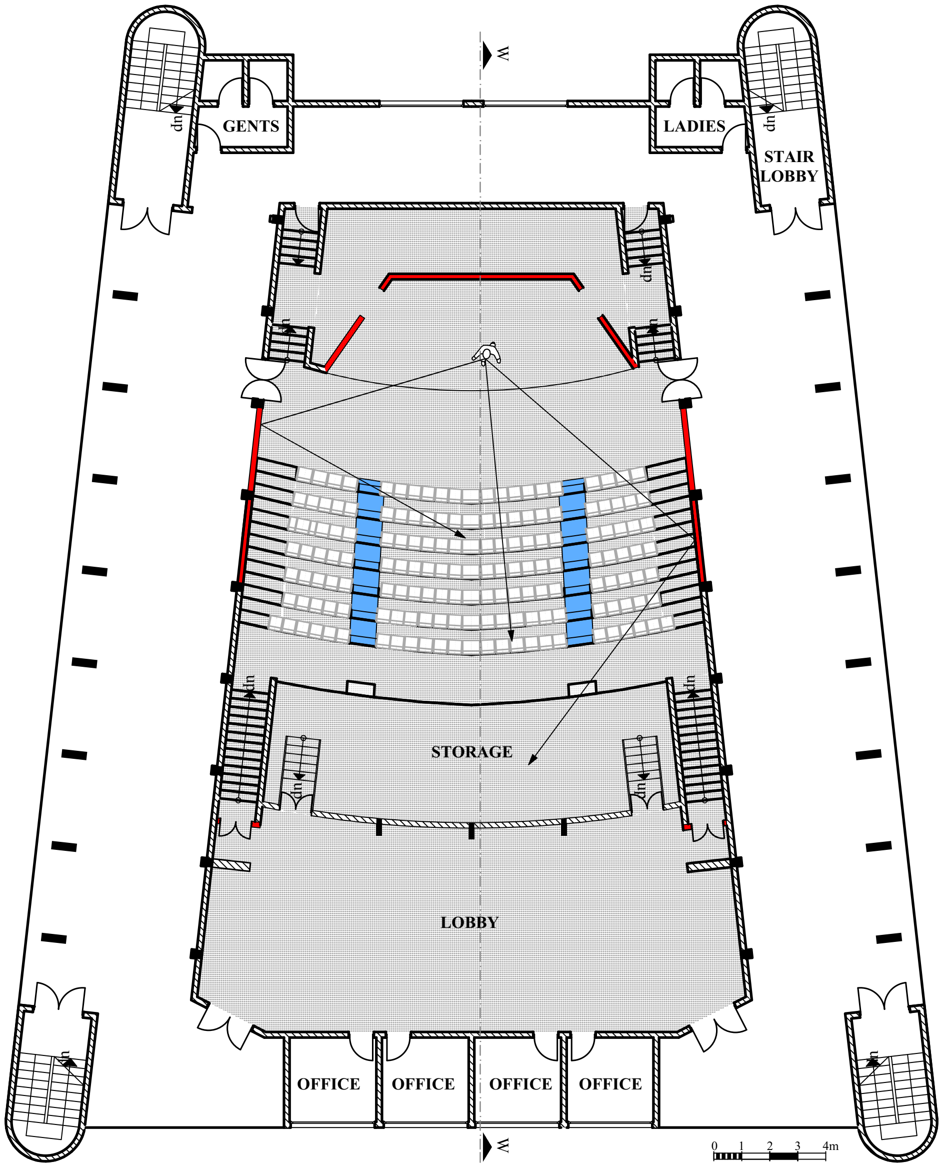


Fig. 4.127: Ground Floor Plan


Fig. 4.128: Padded door at LRC


Fig. 4.129: Absorbent walling at LRC

Redesigned walls

Thin carpet over thin felt on cement screed

New gangway

4.9.1 Floor profile

Fan shape is ideal for sound propagation to the audience. The entrance at the back however will have to be closed with a padded door introduced to minimize on disruptive resonance (**Fig 4.128**). A movable stage wall should be introduced to reduce the stage depth as well as allow sound to be fully propagated to the audience(**Fig 4.127**).

4.9.2 Sectional profile

The windows at the entrance next to the stage should be replaced with absorbent walls (**Fig 4.129**). The side entrances should fully padded to absorb sound and avoid distractive reflections once the sound leaves the stage. A large ceiling should be introduced at the edge of the stage to reflect all the sound. An array of small curved ceiling panels should also be installed to aid in sound propagation to the audience. This will not only reflect sound through short paths but eliminate tonal colorations and false localizations. A splay ceiling at the stage and at the back will be suitable for quick reflections.

4.9.3 Volume

The current volume is 2933m^3 which will cause long reverberation times and sound delays to the back seats. An ideal volume will be 2300m^3 which will give 0.6s for 250 Hz and 0.7s for 125 Hz. This can be achieved by lowering the ceiling height, reducing the stage depth and adding padded doors to the back entrance foyer.

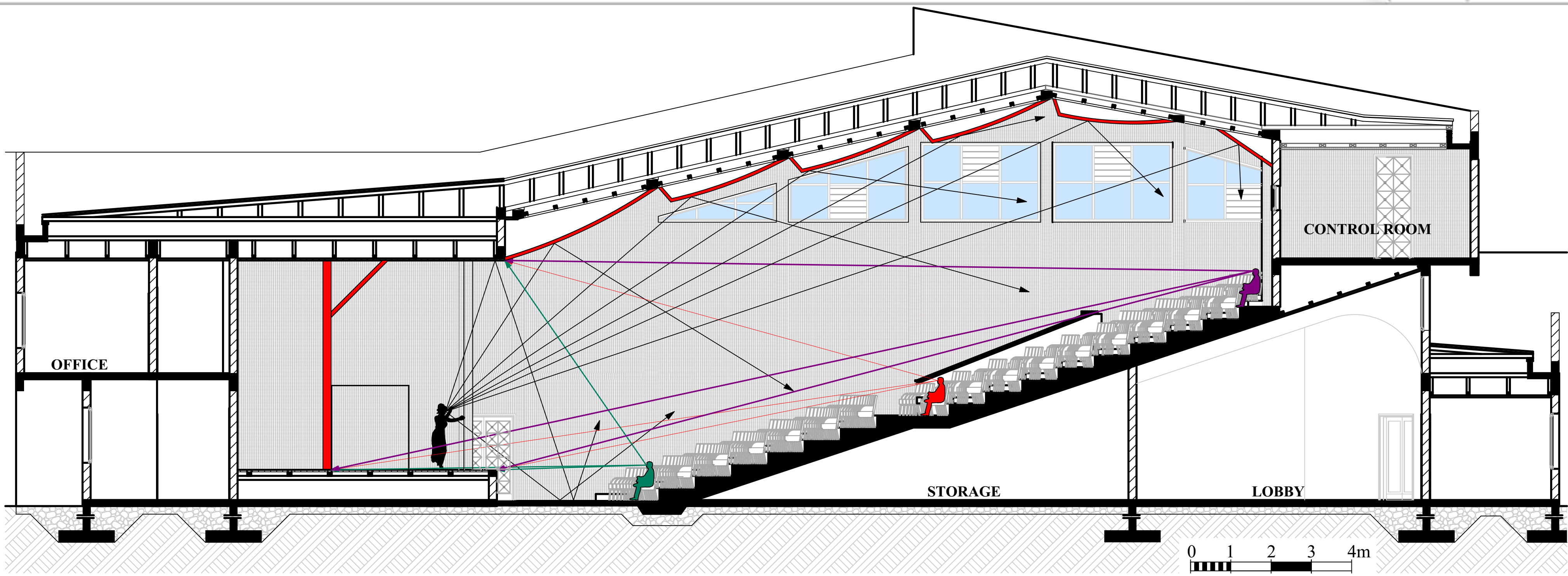


Fig. 4.130: Section W - W

4.9.4 Stage Design

The wooden floor should be covered with thin carpet on thin felt. Movable back stage wall should be introduced to reduce the stage volume as well as allow for better sound propagation to the audience. The stage side walls should angled and reflective to enhance sound propagation as well as visual connection. A splay ceiling is required at the front wall to project immediate sound to the audience (**Fig 4.130**).

4.9.5 Audience seating Design

The floor should be covered with thin carpet over thin felt to absorb sound as well as reduce the noise generated by human movement. The side and back walls should be sound diffusing and absorbing with the low level windows at the front entrance replaced with timber panels on hessian cloth backing. All the plaster and paint columns should be covered with absorbent materials. The flat ceiling should be replaced with an array of curved slanted reflective ceiling. Splay ceilings should be introduced at the back to reflect sound down to the rear audience as well as eliminate echoes to the stage. The back wall should be fully absorbent with timber panels on hessian cloth backing. All doors should be fully padded (**Fig 4.130**).

4.9.6 Seating Arrangement

The most ideal gangway position is off the central axis where the speakers lectern is located. Having a gangway at the central axis distorts sound received by the audience. It will also cause echoes on stage. The audience will also have difficulty accessing the seats at the middle of the columns. The gangway should be shifted to the left and right to solve acoustic and accessibility challenges.
The seats should be replaced with efficient upholstered tip up seats to cater for the missing audience.

4.9.7 Table 9: Reverberation Time Calculation (Redesigned 8-4-4 Multi-Purpose Hall)

Materials	Area (M2)	OCTAVE FREQUENCY			
		125 Hz		250Hz	
	S	α	Sα	α	Sα
Flooring					
Carpet thin over thin felt on terrazzo/PVC tiles (Audience Seating)	511	0.1	51.1	0.15	76.65
Carpet thin over thin felt on wood (Stage)	68	0.2	13.6	0.25	17
Walling					
Grooved wood planks on 16mm battens on solid wall (front/side/back)	625	0.31	193.75	0.33	206.25
Double glazed windows, 3mm glass, with 10 mm air gap	71	0.15	10.65	0.05	3.55
Padded double seals, double sheeting acoustic doors with absorbent air space	10	0.35	3.5	0.39	3.9
Ceiling					
Wood panels 18mm alternate, 15mm slots & 35mm wooden slat, 25 mm rock wool backing	455	0.1	45.5	0.36	163.8
Fluorescent luminaries	12	0.3	3.6	0.2	2.4
Seating					
Upholstered tip up theatre seats	520 no.	0.33	171.6	0.51	265.2
Air volume (M3)	2300	0	0	0.001	2.3
Total materials absorption			493.3		741.05
Audience					
Full	520	0.33	171.6	0.4	208
Half full	260	0.33	85.8	0.4	104
Empty	0	0.33	0	0.4	0
Total absorption (Fully)			493.3		681.55
Total absorption (Half)			493.3		710.15
Total absorption (Empty)			493.3		741.05
Reverberation time (s)					
Full			**0.7**		**0.6**
Half full			**0.7**		**0.5**
Empty			**0.7**		**0.5**

4.10 MILLENNIUM HALL I, CHIROMO CAMPUS (REDESIGNED CONDITION)

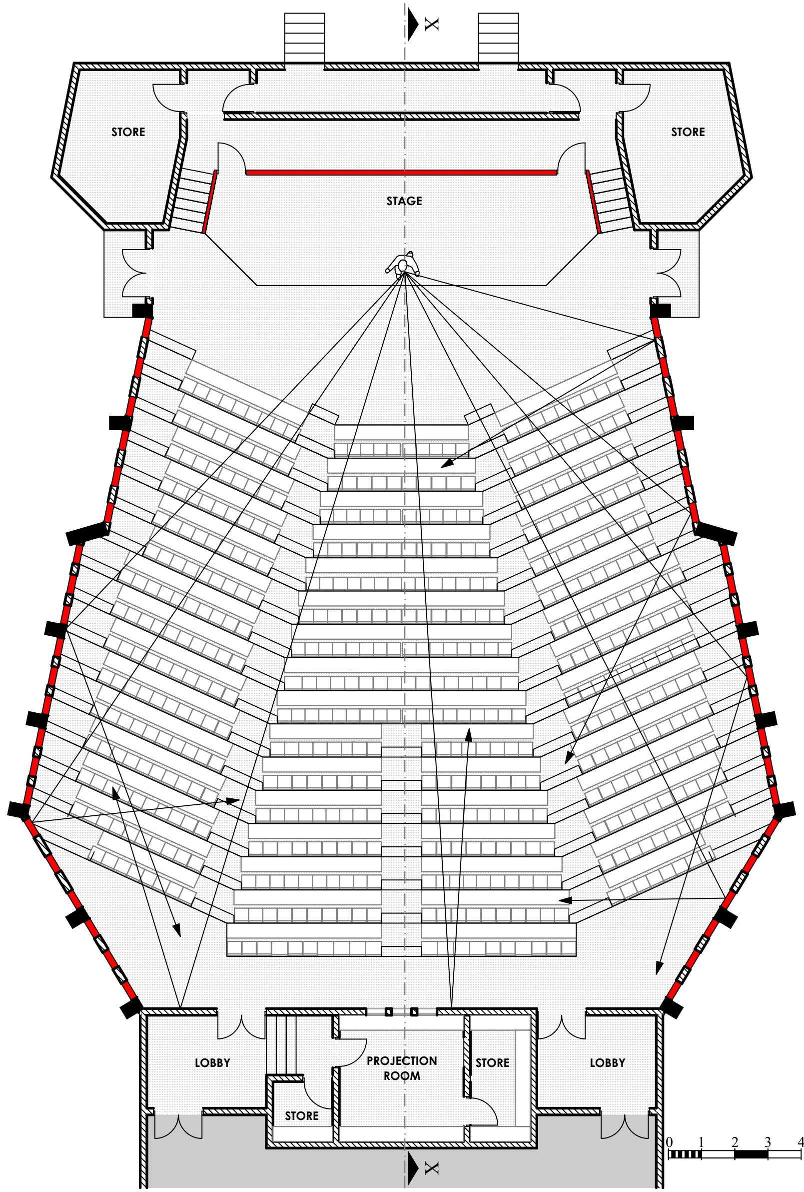


Fig. 4.131: Ground Floor Plan

Fig. 4.132: Perforated panel with hessian cloth backing

Fig. 4.133: Large reflective ceiling panels at LRC

Redesigned walls

Thin carpet over thin felt on cement screed

Terrazzo floooring

4.10.1 Floor Profile

Millennium Hall I is fan shaped in plan which is ideal for sound propagation to the audience once sound exits the stage. The stage is deep for sufficient reflections to be propagated on the audience. A movable stage back wall should be introduced to reduce the stage depth. A padded door should be introduced at the back to create an enclosed air lock hence eliminating all external noise as well as the extra volume causing resonance (**Fig 4.128**).

4.10.2 Sectional Profile

The stage movable wall should have a splay ceiling to project sound to the audience. Immediately in front of the stage a large curved angled ceiling should project sound to the audience at the rear seats. An array of curved angled ceilings should also be installed to project sound to the audience. The back wall should be replaced with fully absorbent material as well as a splay ceiling to reflect sound downwards to rear audience (**Fig 4.133**).

4.10.3 Volume

3640m^3 is large for an ideal reverberation time for speech. The reverberation time is 1.39s for 125Hz and 1.36s for 250Hz. The most appropriate volume that will give 07.2 for 125 Hz and 260Hz is 2000m^3. With the addition of a movable stage wall, padded doors on entrance foyer as well as lowering the ceiling heights, the volume can be reduced significantly. With this reduced volume then a proper reverberation time can be achieved.

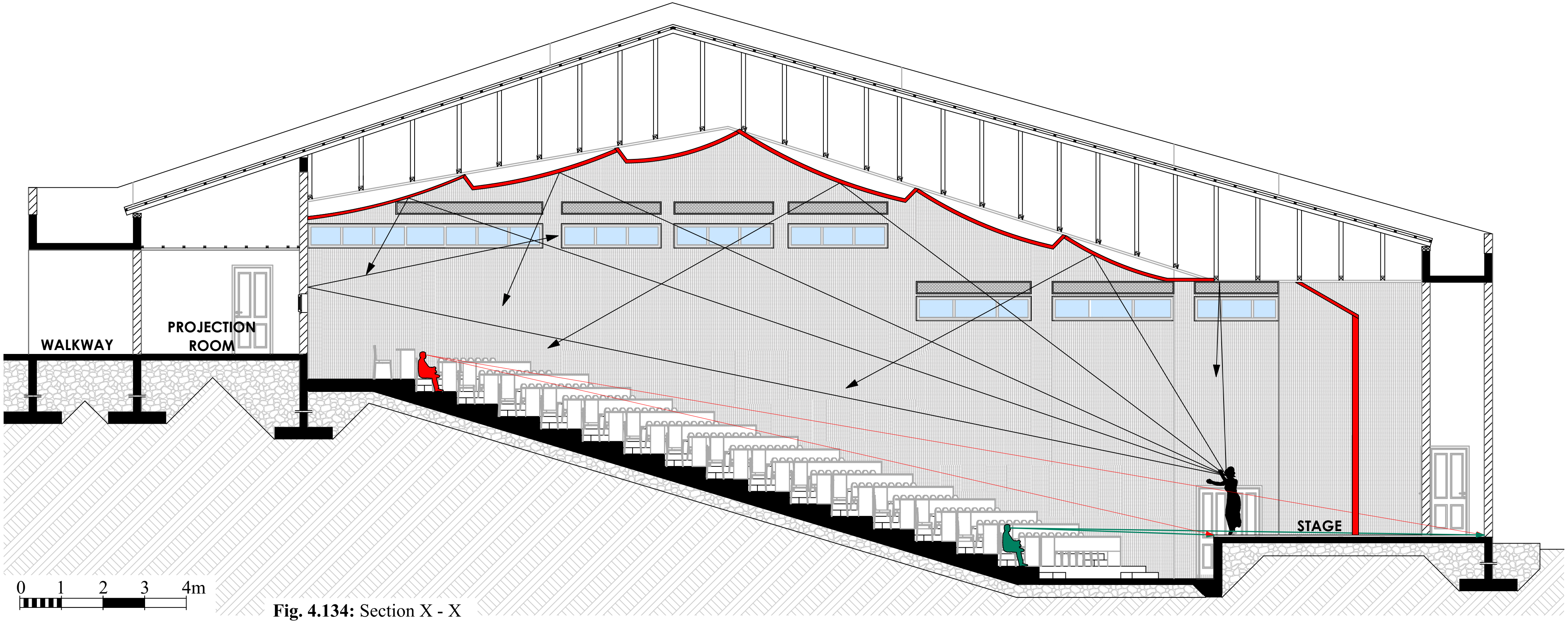


Fig. 4.134: Section X - X

4.10.4 Stage Design

The wood parquet flooring should be covered with thin carpet over thin felt to make it absorptive and reduce resonance caused by wood elements. The side walls should be angled and reflective to push sound to the audience seated at the back and ensure minimal sound retention on stage (**Fig 4.134**).

4.10.5 Audience Seating Design

Terrazzo flooring should be covered with sound absorbing thin carpet on thin felt. The walling should be fully absorbent or diffusing to ensure elimination of echoes and reduced reverberation time ideal for speech. The low level windows should be replaced with high level strip windows finished in double glazed panels with air space gap. This will eliminate sound defects within the hall as well as external noise. The ceiling should be slanted and curved to eliminate tonal coloration and false localization.

4.10.6 Seating Arrangement

The gangway designs are ideal for sound propagation since the middle column is centrally located along the speaker's optimum sound path. The theatre seats should be replaced with upholstered tip up seats to fully cater for absent audience hence eliminating sound alteration when the theatre is half full or partially empty. The floor and walling should be fully absorptive while the ceiling reflective and broken into smaller panels.

4.10.7 Cove Design

Junctions of rear walls and ceiling above gallery level will throw back long reflected sound upon the speaker after two impacts if left hard and smooth. The front, back and side coves should be splayed to reflect sound to the audience. The front cove splay will reflect to front audience while the back splay will focus sound on the audience at the rear seats. This will also eliminate possibilities of echoes to the stage which would distract the speaker.

4.10.8 Table 10: Reverberation Time Calculation (Redesigned Millennium Hall I)

Materials	Area (M2)	OCTAVE FREQUENCY			
		125 Hz		250Hz	
	S	α	Sα	α	Sα
Flooring					
Carpet thin over thin felt on terrazzo/PVC tiles (Audience Seating)	559	0.1	55.9	0.15	83.85
Carpet thin over thin felt on wood parquet (Stage)	55	0.2	11	0.25	13.75
Walling					
Grooved wood planks on 16mm battens on solid wall (front/side/back)	552	0.31	171.12	0.33	182.16
Wire gauze permanent vents (PVs)	10	0.6	6	0.6	6
Double glazed windows, 3mm glass, with 10 mm air gap	43	0.15	6.45	0.05	2.15
Padded double seals, double sheeting acoustic doors with absorbent air space	13	0.35	4.55	0.39	5.07
Ceiling					
Wood panels 18mm alternate, 15mm slots & 35mm wooden slat, 25 mm rock wool backing	551	0.1	55.1	0.36	198.36
Fluorescent luminaries	11	0.3	3.3	0.2	2.2
Seating					
Upholstered tip up theatre seats	500 no.	0.33	165	0.51	255
Mahogany writing tables	602	0.03	18.06	0.05	30.1
Air volume (M3)	2200	0	0	0.001	2.2
Total materials absorption			496.48		780.84
Audience					
Full	500	0.33	165	0.4	200
Half full	250	0.33	82.5	0.4	100
Empty	0	0.33	0	0.4	0
Total absorption (Fully)			496.48		695.64
Total absorption (Half)			496.48		723.14
Total absorption (Empty)			496.48		780.84
Reverberation time (s)					
Full			**0.7**		**0.5**
Half full			**0.7**		**0.5**
Empty			**0.7**		**0.5**

4.11 SCIENCE LECTURE HALL COMPLEX, KENYA SCIENCE (REDESIGNED CONDITION)

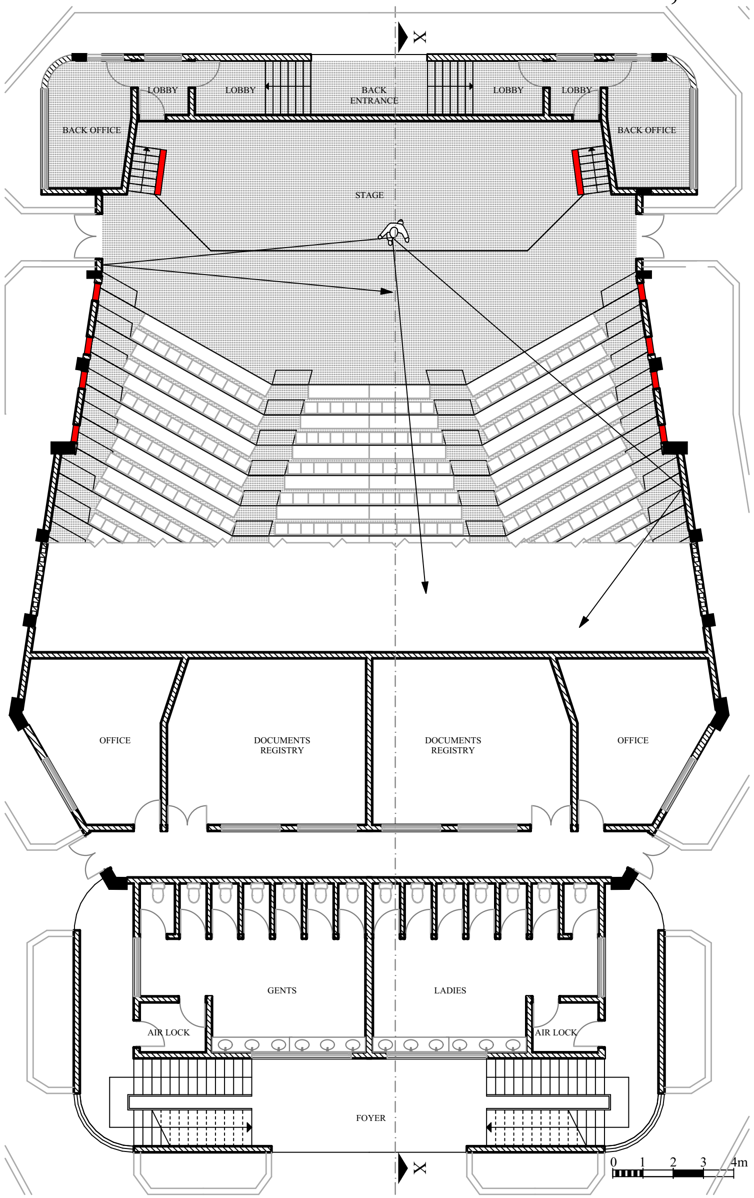


Fig. 4.135: Ground Floor Plan

Fig. 4.136: Minimal window openings at LRC

Fig. 4.137: Side ceiling splays at LRC

Redesigned walls

Thin carpet over thin felt on cement screed

Terrazzo floooring

4.11.1 Floor Profile

The fan shaped floor profile is ideal for good sound propagation to the audience. The stage splay walls should be added to reflect sound immediately to the audience. The stage has a narrow depth which is also good for sound propagation (**Fig 4.135**).

4.11.2 Sectional Profile

The stage ceiling should be splayed to reflect sound to the audience seated on the front rows (**Fig 4.137**). The ceiling immediately in front of the stage should be large, angled, curved and fully reflective to propagate sound to the audience especially those on the rear seats. An array of small curved and angled ceiling reflectors should be hung at optimum heights to reflect sound all over the theatre room. This will eliminate tonal coloration and false localization caused by very large, monolithic panels. At the back, splay ceiling should be installed to reflect sound downwards to the audience at the back.

4.11.3 Volume

2936 m3 is large for proper reverberation time. It falls within 1s for 125 Hz and 0.7s for 250Hz. With a reduced volume of 2700m3, it will lead to a reverberation time of 0.75s for 125Hz and 0.6s for 250Hz which is comfortable for speech.

4.11.4 Stage Design

The wood panel flooring should be covered with absorptive thin carpet over thin felt. The stage back wall should be absorptive to eliminate sound resonance

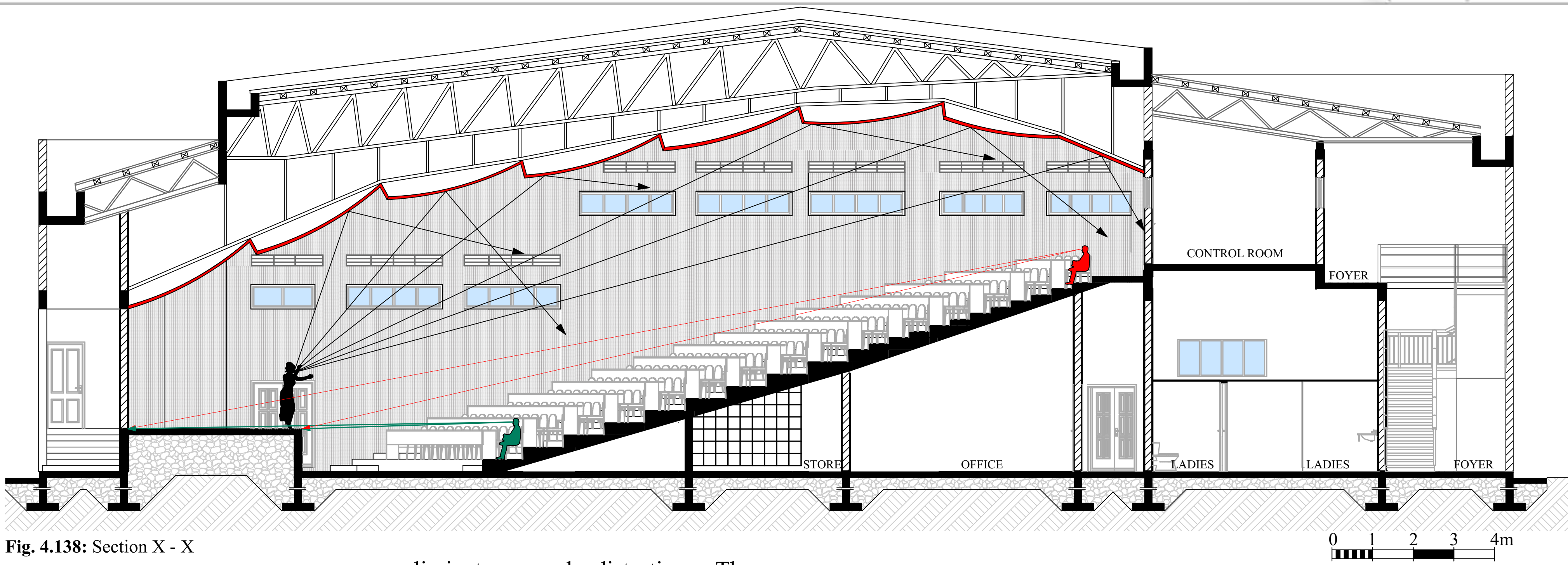


Fig. 4.138: Section X - X

within the stage house. The ceiling should be fully reflective with the stage splay introduced to reflect sound to the audience. Splay side walls should be fully reflective to push sound to the audience.

4.11.5 Audience Seating Design

The terrazzo flooring should be covered with thin carpet over thin felt to absorb sound. The walling should be fully absorptive to eliminate all sound within the theatre. The large low level windows should be replaced with strip high level windows so as to eliminate sound distortion. The windows should be double glazed, 3mm glass with 10mm air gap to eliminate external noise (**Fig. 4.138**). The ceiling panels should be fully reflective MDF panels. A large curved angled MDF panels should be introduced immediately in front of the podium to reflect all the sound from the stage to the audience. An array of smaller curved, angled reflectors should be installed at optimum heights to propagate sound throughout the theatre. All the doors should be padded, double seal, double sheeting acoustic door.

4.11.6 Seating Arrangement

The gangway is ideal for good sound behavior within the theatre hall. The central column is best placed to receive optimum sound from the stage. The alleys on its sides are sufficient to allow for ease of movement to the seats at the centre of the column. The wooden seats should however be replaced with properly upholstered tip up seats that will cater for empty and half-filled theatre. These seats will absorb sound regardless of whether it is in use or not hence give a balance reverberation time.

4.11.7 Cove Design

Junctions of rear walls and ceiling above gallery level will throw back long reflected sound upon the speaker after two impacts if left hard and smooth. The front, back and side coves should be splayed to reflect sound to the audience. The front cove splay will reflect to front audience while the back splay will focus sound on the audience at the rear seats (**Fig. 4.138**). This will also eliminate possibilities of echoes to the stage which would distract the speaker (**Fig. 4.118**).

4.11.8 Table 11: Reverberation Time Calculation (Redesigned Science Lecture Hall Complex)

Materials	Area (M2)	OCTAVE FREQUENCY			
		125 Hz		250Hz	
	S	α	Sα	α	Sα
Flooring					
Carpet thin over thin felt on terrazzo (Audience Seating)	557	0.1	55.7	0.15	83.55
Carpet thin over thin felt on wood planks (Stage)	93	0.2	18.6	0.25	23.25
Walling					
Grooved wood planks on 16mm battens on solid wall (front/side/back)	341	0.31	105.71	0.33	112.53
Wire gauze permanent vents (PVs)	10	0.6	6	0.6	6
Double glazed windows, 3mm glass, with 10 mm air gap	47	0.15	7.05	0.05	2.35
Padded double seals, double sheeting acoustic doors with absorbent air space	17	0.35	5.95	0.39	6.63
Ceiling					
Wood panels 18mm alternate, 15mm slots & 35mm wooden slat, 25 mm rock wool backing	488	0.1	48.8	0.36	175.68
Fluorescent luminaries	15	0.3	4.5	0.2	3
Seating					
Upholstered tip up theatre seats	500 no.	0.33	165	0.51	255
Mahogany writing tables	270	0.03	8.1	0.05	13.5
Air volume (M3)	1900	0	0	0.001	1.9
Total materials absorption			425.41		683.39
Audience					
Full	500	0.33	165	0.4	200
Half full	250	0.33	82.5	0.4	100
Empty	0	0.33	0	0.4	0
Total absorption (Fully)			425.41		628.39
Total absorption (Half)			425.41		655.89
Total absorption (Empty)			425.41		683.39
Reverberation time (s)					
Full			**0.7**		**0.5**
Half full			**0.7**		**0.5**
Empty			**0.7**		**0.5**

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 SUMMARY OF FINDINGS

Design elements	Taifa Hall	Lecture Theatre 101	8-4-4 Multi Purpose Hall	Millennium Hall I	Science Lecture Hall
Floor Profile Existing	- Rectilinear in shape - Too many door openings	- Fan shape - Reflective floor material	- Fan shape - Reflective floor material	- Fan shape - Reflective floor material	- Fan shape - Reflective floor material
Redesigned	- Sinusoidal wall profile - Reduce door openings	- Install sound absorbing floor material	- Install sound absorbing floor material	- Install sound absorbing floor material	- Install sound absorbing floor material
Sectional Profile Existing	- High large ceiling panel - Large window openings - Fly tower design - Obstructive columns along the sound paths	- Large window openings - Straight reflective ceiling panels - Large ceiling panels	- Low level window openings - Diffusive ceiling panels - Large entrance foyer hence increasing the overall volume - Reflective walling materials	- Low level window openings - High diffusive ceiling panels - Missing door at the entrance foyer creates extra volume.	- Low level window openings - High level diffusive ceiling panels - Reflective walling materials
Redesigned	- Low smaller ceiling panels - Ribbon window openings - Block off the fly tower - Introduce walling along the columns	- Ribbon window openings - Slightly curved reflective ceiling panels -Small ceiling panel modules	- High level ribbon window - Curved reflective ceiling - Padded doors at the foyer - Install absorptive walling materials	- High level ribbon window - Low reflective ceiling - Padded doors at the foyer to reduce the volume as well as prevent external interference	- High level ribbon window - Low level curved reflective ceiling - Absorptive/ diffusive walling materials
Volume Existing	- Volume is large for an ideal reverberation time - Stage house has a big volume - Side entry spaces adds to the large volume	- Volume is large for an ideal reverberation time - Stage house depth should be reduced.	- Volume is large for an ideal reverberation time - Stage house depth should be reduced. - Back entrance foyer creates disruptive resonance effect	- Volume is large for an ideal reverberation time - Stage house depth should be reduced. - Back entrance foyer creates disruptive resonance effect	- Volume is large for an ideal reverberation time - Ceiling is too high hence leads to long reflected sound paths.
Redesigned	- Reduce the volume - Reduce the stage house volume - Eliminate the extra space at the entrances	- Reduce the volume - Reduce the stage house depth	- Reduce the volume - Reduce the stage house depth -Add padded doors at back entrance foyer	- Reduce the volume - Reduce the stage house depth -Add padded doors at back entrance foyer	- Reduce the volume - Low ceiling height to reduce the volume hence create much shorter reflection paths.
Stage design Existing	- Fly tower adds volume - Large Stage house - Stage walling material should be diffusive	- Deep Stage house hence creates extra volume - Stage walling material should be diffusive	- Deep Stage house hence creates extra volume - Stage walling material should be diffusive	- Deep Stage house hence creates extra volume - Stage walling material should be diffusive	- Perpendicular ceiling-front wall junction. - Stage walling material should be diffusive
Redesigned	- Block off the fly tower - Reduce the stage house - Install diffusive walling material	- Reduce the stage house depth - Install diffusive walling material	- Reduce the stage house depth - Install diffusive/reflective walling material	- Reduce the stage house depth - Install diffusive/reflective walling material	- Splay ceiling at the ceiling-front wall junction - Install diffusive/reflective walling material

Design elements	Taifa Hall	Lecture Theatre 101	8-4-4 Multi Purpose Hall	Millennium Hall I	Science Lecture Hall
Audience Seating Design Existing	- Many glass door openings - Large window openings - High ceiling - Reflective walling materials	- Reflective door openings - Large window openings - Straight ceiling modules - Reflective flooring materials	- Reflective door openings - Low level window openings - Diffusive ceiling material - Reflective flooring materials	- Reflective door openings - Low level window openings - Diffusive ceiling material - Reflective flooring materials	- Reflective door openings - Low level window openings - Diffusive ceiling material - Reflective flooring materials
Redesigned	- Few padded door openings - High level ribbon windows - Low level ceiling - Absorptive walling materials	- Padded door openings - High level ribbon windows - Curved ceiling modules - Absorptive floor materials	- Padded door openings - High level ribbon windows - Reflective ceiling modules - Absorptive floor materials	- Padded door openings - High level ribbon windows - Reflective ceiling modules - Absorptive floor materials	- Padded door openings - High level ribbon windows - Reflective ceiling modules - Absorptive floor materials
Balcony Design Existing	- Low balcony raking - Reflective walling materials - High soffit ceiling - Obstructive balustrading	N/A	N/A	N/A	N/A
Redesigned	- Lower balustrade walling - Stagger seating arrangement - Low level soffit ceiling - Introduce porous railing	N/A	N/A	N/A	N/A
Seating Arrangement Existing	- Temporary seats distorts sound patterns. - Poor sightlines at the balcony - Gangways on the flat seating interferes with exit and entry to seats	- Reflective seats and work tops. - Gangways placement interferes with sound propagation and entry/exit patterns of the audience	- Partially reflective seats. - Gangways placement interferes with sound propagation and entry/exit patterns of the audience	- Partially reflective seats and work tops. - Gangways placement interferes with sound propagation and entry/exit patterns of the audience	- Reflective seats and work tops. - Gangways placement interferes with sound propagation and entry/exit patterns of the audience
Redesigned	- Permanent tip up upholstered theatre seats. - Stagger seating arrangement at the balcony - Have four gangways to ease movement	- Permanent tip up upholstered theatre seats. - Have four gangways to enhance sound propagation and ease audience movement	- Permanent tip up upholstered theatre seats. - Have four gangways to enhance sound propagation and ease audience movement	- Permanent tip up upholstered theatre seats. - Have four gangways to enhance sound propagation and ease audience movement	- Permanent tip up upholstered theatre seats. - Have four gangways to enhance sound propagation and ease audience movement
Cove Design Existing	- Perpendicular stage and back wall cove leading to echoes at the stage.	- Perpendicular stage and back wall cove leading to echoes at the stage.	- Perpendicular stage and back wall cove leading to echoes at the stage.	- Perpendicular stage and back wall cove leading to echoes at the stage.	- Perpendicular stage and back wall cove leading to echoes at the stage.
Redesigned	- Splay ceiling at the stage and back wall coves for good sound propagation.	- Splay ceiling at the stage and back wall coves for good sound propagation.	- Splay ceiling at the stage and back wall coves for good sound propagation.	- Splay ceiling at the stage and back wall coves for good sound propagation.	- Splay ceiling at the stage and back wall coves for good sound propagation.

Design elements	Capacity	Taifa Hall 125Hz	Taifa Hall 250 Hz	Lecture Theatre 101 125Hz	Lecture Theatre 101 250 Hz	8-4-4 Multi Purpose Hall 125Hz	8-4-4 Multi Purpose Hall 250 Hz	Millennium Hall I 125Hz	Millennium Hall I 250 Hz	Science Lecture Hall 125Hz	Science Lecture Hall 250 Hz
Reverberation Time (s) Existing	Full	0.9	1.0	0.7	0.8	0.8	0.6	0.8	0.7	0.9	0.7
	Half	1.0	1.1	0.9	1.0	0.9	0.7	0.9	0.8	1.1	0.8
	Empty	1.2	1.3	1.1	1.3	1.1	0.8	1.1	0.9	1.3	0.9
Redesigned	Full	0.7	0.6	0.7	0.7	0.7	0.6	0.7	0.5	0.7	0.6
	Half	0.7	0.5	0.7	0.6	0.7	0.5	0.7	0.5	0.7	0.5
	Empty	0.7	0.5	0.7	0.6	0.7	0.5	0.7	0.5	0.7	0.5

Design elements	Taifa Hall	Lecture Theatre 101	8-4-4 Multi Purpose Hall	Millennium Hall I	Science Lecture Hall
Main Material Finishes Existing	**Flooring** - Thin carpet on thin felt - Ceramic tiles - Smooth cement screed **Walling** - Wood planks on solid wall - Plaster and paint - Wood planks on hessian cloth backing **Ceiling** - Painted MDF panels - Plaster and paint	**Flooring** - 600 x 600 mm ceramic tiles - Wood planks on joists **Walling** - 600 x 600 mm perforated MDF panels with hessian cloth backing **Ceiling** - Painted 16mm MDF panels - Perforated and painted 16mm MDF panels	**Flooring** - 200 x 200 mm PVC tiles - Terrazzo - Wood planks on joists **Walling** - Grooved wood planks on battens on solid wall - Plaster and paint **Ceiling** - Grooved wood planks on battens. - Plaster and paint	**Flooring** - Terrazzo - Wood parquet **Walling** - Grooved wood planks on battens on solid wall - Grooved wood planks on perforated block board. - Plaster and paint **Ceiling** - Grooved wood planks on battens.	**Flooring** - Terrazzo - Wood planks on joists **Walling** - Grooved wood planks on battens on solid wall - Plaster and paint **Ceiling** - Acoustic ceiling panels
Redesigned	**Flooring** - Thin carpet on thin felt **Walling** - Polyurethane foam - Wood planks on hessian cloth backing - Slotted wood planks with mineral wool backing **Ceiling** - Painted MDF panels	**Flooring** - Thin carpet on thin felt **Walling** - 600 x 600 mm perforated MDF panels with hessian cloth backing **Ceiling** - Painted 16mm MDF panels on 16mm battens	**Flooring** - Thin carpet on thin felt **Walling** - Wood planks on hessian cloth backing - Slotted wood planks with mineral wool backing **Ceiling** - Wood panels 18mm alternate, 15mm slots and 35 mm wood slats	**Flooring** - Thin carpet on thin felt **Walling** - Wood planks on hessian cloth backing - Slotted wood planks with mineral wool backing **Ceiling** - Wood panels 18mm alternate, 15mm slots and 35 mm wood slats	**Flooring** - Thin carpet on thin felt **Walling** - Wood planks on hessian cloth backing - Slotted wood planks with mineral wool backing **Ceiling** - Wood panels 18mm alternate, 15mm slots and 35 mm wood slats

5.2 CONCLUSION

The information generated from the study is aimed at providing a reference point for design for speech in the five lecture theatres within the University of Nairobi. It presents critical design for speech mechanisms that can be put forward to mitigate the design gaps established. This will go a long way in creating apposite acoustic environment for speech purposes.

Figure 5.1: 8-4-4 MPH
Source: Author, 2017

5.3 LIMITATIONS OF THE STUDY

The study focused on design for speech of existing lecture halls within the University of Nairobi (**Fig 5.1**). Due to lack of sufficient literature review on existing acoustic conditions of the halls, acoustic design gaps and rectifications mechanisms proposed to mitigate these gaps, field work was a major tool to review these key architectural areas. Time was a limiting factor to research thus the work was not sufficiently exhausted in all areas within the study. Lack of sufficient documented detailed architectural materials also limited the identification and analysis process.

5.4 RECOMMENDATIONS

The research findings calls for proper interior design of the five halls to create ideal spaces for speech purposes. Taking into consideration the spatial requirements for lecture sessions within the university and owing to the increase in number of students, properly designed lecture halls would be a much needed amenity to suit these needs. It would therefore be suitable to check the floor profiles, sectional profiles, stage design, audience seating area design, balcony designs, seating arrangements, gangway patterns and cove designs of the existing halls and use the recommended standards to achieve desired reverberation time.

Figure 5.2: Millennium Hall I
Source: Author, 2017

5.5 FURTHER AREAS OF RESEARCH

The research focused on design for speech for the existing lecture theatres within the University of Nairobi (**Fig 5.2**). In future, further areas of research can be done to focus on:-

1. Design for music in the main theatres such as Taifa Hall and 8-4-4 Multi Purpose Hall.
2. Comparative study of sound patterns within the five lecture theatres.
3. Effect of external noise on lecture sessions within the five lecture theatres.
4. Acoustic defects: Echoes, flutter echoes, standing waves, sound concentrations and sound shadows, within the lecture theatres.
5. Acoustics and aesthetics of the five theatres.
6. Comparative analysis of music and speech performances of the five lecture theatres.

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GLOSSARY

Absorbent	This is a material, structure, or object that takes in sound energy when sound waves are encountered, as opposed to reflecting the energy.
Absorption coefficient	It is defined as the ratio of energy absorbed by a material to the energy incident upon its surface.
Acoustic brilliance/ Acoustic warmth	It refers to the reverberation time at low frequencies relative to that at higher frequencies. Above about 500 hertz, the reverberation time should be the same for all frequencies. But at low frequencies an increase in the reverberation time creates a warm sound, while, if the reverberation time increased less at low frequencies, the room would be characterized as more brilliant.
Acoustic clarity	It is produced when a room has a high ratio of early sound energy to later reverberant sound energy
Acoustic concentration	This refers to focusing of sound waves to a focal point caused by concave surfaces
Acoustic defect	This is an imperfect sound received by the listener caused by echoes, concentrations, shadows and background noise.
Acoustic shadow:	It is an area through which sound waves fail to propagate, due to topographical obstructions or disruption of the waves via phenomena such as wind currents, buildings, or sound barriers.
Acoustic spaciouness	A scenario where reverberant sound arrive from many directions and are not exactly the same at the two ears of people listening in the room.
Acoustic texture	A scenario where diffuse reflections arrive between 40ms and 80ms after the direct sound.
Acoustics	The properties or qualities of a room or building that determine how sound is transmitted in it.
Air resonance	This occurs when the wavelength coincides with the distance between the walls, or is an exact fraction of this distance.
Amplitude	It is the objective measurement of the degree of change (positive or negative) in atmospheric pressure (the compression and rarefaction of air molecules) caused by sound waves.

Audience absorption Audience absorption is due to people's clothing, it acts as a porous absorber. At low frequencies, the absorption coefficient is lower than at mid and high frequencies.

Audience breathing noise This is internal noise generated by the audience while breathing which will contribute to background noise.

Auditorium A large building or hall used for public gatherings, typically speeches or stage performances

Background noise This is the distractive noise caused by audience breathing, quiet HVAC systems, and external noise.

Balcony The upstairs seats in a theater, concert hall, or auditorium.

Broadband A high-capacity transmission technique using a wide range of frequencies, which enables a large number of messages to be communicated simultaneously.

Consonant sound These are nearly all of a transient nature; they are short and rapidly changing sounds, very often unvoiced (i.e. containing no formant tone) and therefore having very little acoustic power.

Corner echo These are echoes produced by the introduction, at a distance from the source, of right-angled corners with both surfaces reflective.

Cove A concave arched molding, especially one formed at the junction of a wall with a ceiling.

Decibel The subjective sense of loudness is determined by the objective sound level measured in decibels (dB)

Direct sound This sound wave travels directly from the source to the listener without striking any of the surfaces of the room. It is the first sound wave that arrives at a listener's location. It contributes to sensations of loudness, clarity and localization.

Early sound reflection This sound wave strikes one of the room surfaces and is reflected to the listener's location.

Echo This is a reflection which is heard as a discrete event. The reflections arrive at least 50ms later than the direct sound and is more prominent than its neighbors.

False localization	An effect where the sound of a speaker suddenly appears to come from the reflector instead of from the stage.
Flutter echo	These consists of a rapid succession of noticeable echoes which can be detected after short bursts of sound such as a hand clap.
Gangway	A passageway through which to enter or leave, such as one between seating areas in an auditorium
Grazing incidence	The incidence of a wave on a surface at a very small grazing angle.
Harmonic	It is any member of the harmonic series, the divergent infinite series. A harmonic series is the sequence of sounds where the base frequency of each sound is an integer multiple of the lowest base frequency.
Helmholtz/ cavity resonator	These are containers with a small open neck and they work by resonance of the air within the cavity.
Hertz (Hz)	Hertz is a measure of frequency. Specifically, it's one cycle per second.
Intelligibility	It is a measure of how comprehensible speech is in given conditions.
Interaural time delay	A reflection is lateral when there is a time difference between its arrival at the near and far ear.
Inverse square law	It states that for every doubling of the distance from the sound source in a free field situation, the sound intensity will diminish by 6 decibels.
Loudness	It is the characteristic of a sound that is primarily a psycho-physiological correlate of physical strength (amplitude).
Panel/membrane absorber	They are useful because they can have good absorption characteristics in the low frequency range.
Pitch	It is the quality that makes it possible to judge sounds as "higher" and "lower" in the sense associated with musical melodies.

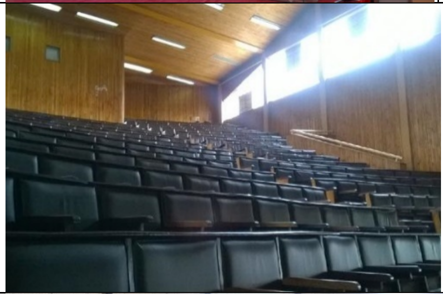
Porous absorber	It is efficient at high frequencies but not low. The low frequency range can be extended by making the material thicker.
Proscenium	The part of a theater stage in front of the curtain.
Resonance	When one object vibrating at the same natural frequency of a second object forces that second object into vibrational motion.
Reverberant sound	These consists of sound waves that have been reflected from multiple surfaces before they arrive at the listener's ears. It is the later sound after about 100ms.
Reverberation radius	The distance at which the direct and reflected components are the same.
Reverberation time	This is the continuation of sound after the original sound has ceased, due to multiple reflections in an enclosed space.
Sightline	A line extending from an observer's eye to a viewed object or area (such as a stage).
Sinusoidal	Of, relating to, shaped like, or varying according to a sine curve or sine wave
Soffit	The underside of a part or member of a building (as of an overhang or staircase)
Sound blend	The ability to build words from individual sounds by blending the sounds together in sequence.
Sound decay	The physical process by which a sound gradually dissappears from the audible spectrum until it no longer exists.
Sound delay	The physical process by which a sound takes long to arrive at the listener.
Sound diffraction	The distortion of a wave front caused when an Incident Sound Wave encounters an obstacle in the sound field.
Sound directivity	This is a measure of the directional characteristic of a sound source.
Sound dispersion	Separation of the sinusoidal components of a wave that results from change of speed of sound with frequency.

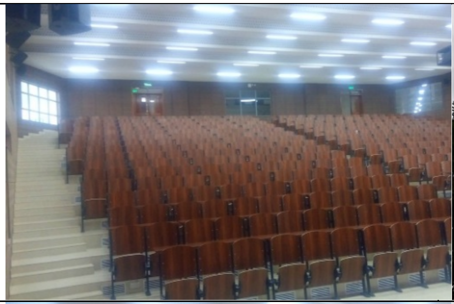
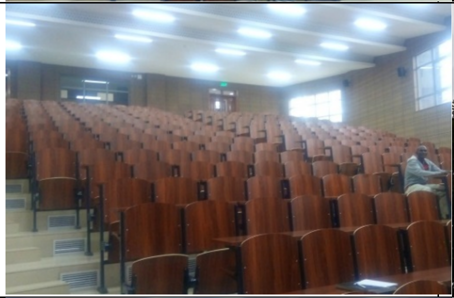
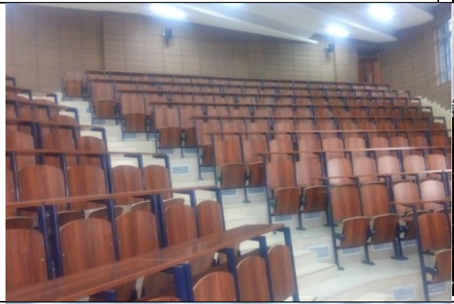
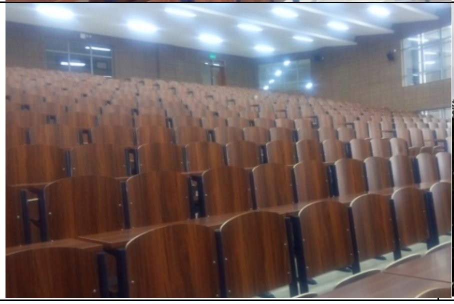
Sound energy	It is a form of energy associated with the vibration of matter. The SI unit of sound energy is the joule (J). Sound is a mechanical wave and as such consists physically in oscillatory elastic compression and in oscillatory displacement of a fluid.
Sound feedback	This is a special kind of positive feedback which occurs when a sound loop exists between an audio input and an audio output.
Sound focusing	The conversion of plane or of diverging spherical or cylindrical sound waves into converging waves.
Sound intimacy	This refers to the feeling that listeners have of being physically close to the performing group. A room is generally judged intimate when the first reverberant sound reaches the listener within about 20 milliseconds of the direct sound.
Sound pressure	This is the force of sound on a surface area perpendicular to the direction of sound.
Splay	A surface making an oblique angle with another.
Standing wave	These consists of a rapid succession of noticeable echoes which can be detected after short bursts of sound such as a hand clap.
Terminal reverberation	The room response which can be heard after a loud short sound or after a continuos sound is turned off.
Timbre	It is the perceived sound quality of a musical note, sound, or tone that distinguishes different types of sound production, such as choir voices and musical instruments.
Tonal coloration	It is what allows a listener to identify a sound as being produced by a specific instrument and to differentiate between instruments of the same type.

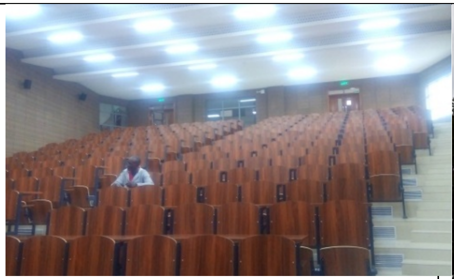
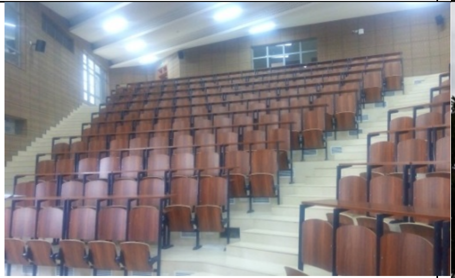
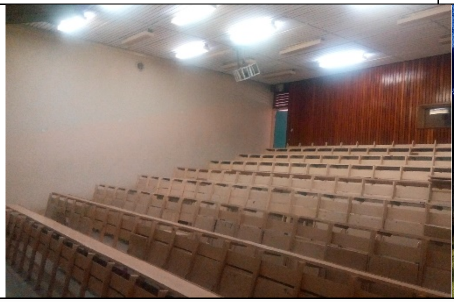
APPENDIX 1: Lecture Theatres in the University of Nairobi

NO.	THEATRE NAME AND LOCATION	CAPACITY	INTERNAL PERSPECTIVE	EXTERNAL PERSPECTIVE
	MAIN CAMPUS			
1	Lecture theatre Mechanical engineering block	220 Fixed seating		
2	Celt 1 Civil block	176 Fixed seating		
3	Lecture theatre 201 Civil block	72 Fixed seating		
4	Room 207 Gandhi Wing	50 Fixed seating		

5	Room 209 Gandhi Wing	70 Fixed seating		
6	Room 311 Gandhi Wing	50		
7	ED 1 Education Building	180 Fixed seating		
8	ED 2 Education Building	305 Fixed seating		

9	Taifa Hall Administration Block	1200 Movable seating		
10	Multi-purpose hall 844 Building	520 Fixed seating		
11	Science Lecture 1 Hyslop Building	165 Fixed seating		
12	Science Lecture 2 Hyslop Building	70 Fixed seating		

13	Lecture theatre 101 University of Nairobi Towers	500 Fixed seating	 
14	Lecture theatre 102 University of Nairobi Towers	300 Fixed seating	 
15	Lecture theatre 201 University of Nairobi Towers	300 Fixed seating	 
16	Lecture theatre 301 University of Nairobi Towers	500 Fixed seating	 

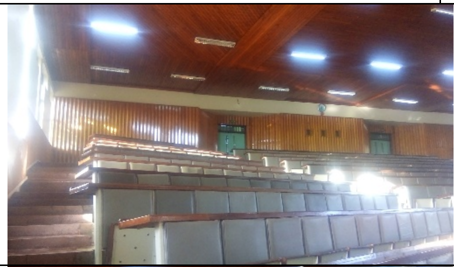
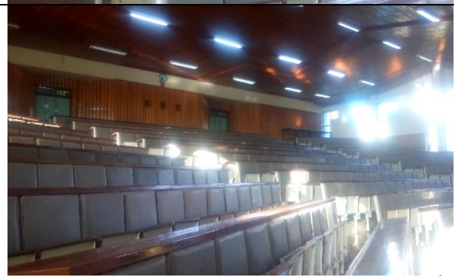
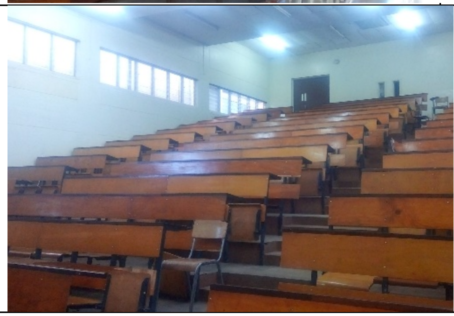
17	Lecture theatre 302 University of Nairobi Towers	300 Fixed seating		
18	Lecture theatre 401 University of Nairobi Towers	300 Fixed seating		
19	Chandaria Centre for Performing Arts University of Nairobi Towers	500 Fixed seating		
	CHIROMO CAMPUS			
20	Large Lecture Theatre (LLT) School of Mathematics	162 Fixed seating		

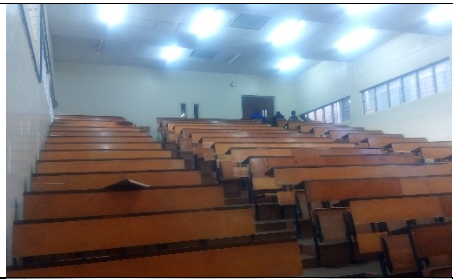
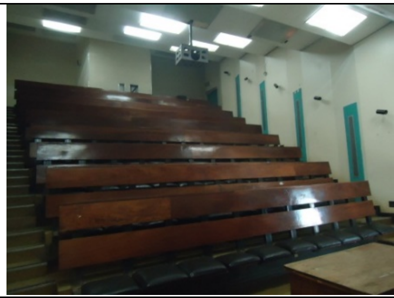
21	Small Lecture Theatre (SLT) School of Mathematics	108 Fixed seating		
22	Millennium Hall 1 School of Computing and Informatics	500 Fixed seating		
23	Millennium Hall 2 School of Computing and Informatics	500 Fixed seating		
24	Small Lecture Theatre A (SLT A) College of Biological and Health Sciences	200 Fixed seating		

25	Small Lecture Theatre B (SLT B) College of Biological and Health Sciences	120 Fixed seating	 
26	G12 College of Biological and Health Sciences Block 2	42 Fixed seating	 
27	Lecture Room College of Biological and Health Sciences Block 2	42 Fixed seating	 
28	Big Lecture Theatre 1 (BLT 1) College of Biological and Health Sciences	100 Fixed seating	 

29	Big Lecture Theatre 2 (BLT 2) College of Biological and Health Sciences	150 Fixed seating		
	KENYA SCIENCE			
30	Uhuru Hall Administration Block	500 Movable seating		
31	Lecture Theatre Administration Block	200 Fixed seating		
32	Lecture Hall Science complex	500 Fixed seating		

	KIKUYU CAMPUS			
33	Mwalimu Multi-Purpose Hall College of Education and External Studies	500 Movable seating		
34	Lecture Theatre 1 College of Education and External Studies	300 Fixed seating		
35	Lecture Theatre 2 College of Education and External Studies	300 Fixed seating		
	PARKLANDS CAMPUS			
36	Lecture hall Administration block	450 Fixed seating		

	LOWER KABETE			
37	Lecture theatre Administration block	450 Fixed seating		
	UPPER KABETE			
38	Lecture Theatre 1 844 PHPT Building	450 Fixed seating		
39	Lecture Theatre 2 844 PHPT Building	450 Fixed seating		
40	Agriculture Theatre 1 Department of Agriculture	200 Fixed seating		

41	Agriculture Theatre 2 Department of Agriculture	200 Fixed seating		
42	Lecture Theatre Faculty of Veterinary Medicine	208 Fixed seating		
	FADD			
43	Space 108 School of Built Environment	250 Movable seating		
	KENYATTA NATIONAL HOSPITAL			
44	Lecture Theatre LT 1 Administration Block	110 Fixed seating		

45	Lecture Theatre LT 2 Administration Block	110 Fixed seating		
46	Lecture Theatre LT 3 Pediatrics and Child Health Building	300 Fixed seating		

APPENDIX 2: Effects of room architectural features on Acoustical Measures

Acoustic Quality	Acoustic Feature	Description of Event
Loudness	• Room size (1000-2000 seats) • Proximity to source and sight lines • Shallow room depth	Sound reflections from the ceiling and walls shortly after the direct sound
Reverberance	• Large room volume • Sound reflecting materials • Shoe-box shape • Acoustical banners and reverberation chambers	Prolonging of sound in a room
Envelopment and source width	• Narrow rooms from 70-80 ft across • Multiple tiers of narrow balconies and side boxes	Early sound reflections arriving at the listener from the side (up to 80-100ms after the direct sound)

	• Rectangular, reverse-fan and vine-yard shaped rooms	
Texture and diffusion	• Surface texture • Shape of diffusion panels	Dense, low-level reflections from all directions immersing listener
Background noise	• Quiet HVAC systems • Very low levels of intruding noise	• Design of equipment isolation • Design of building shell
Clarity	• Sound reflecting ceiling canopy • Parterre walls • Acoustic drapes or banners • Other variable acoustic elements	Sound reflections that arrive shortly after the direct sound
Spaciousness	• Surface texture • Sound diffusing materials • Large room volume	Late sound energy arriving from the sides (after 80-100ms)
Intimacy	• Orchestra in same room volume as audience	Arrival of first sound reflections from a building surface shortly after the direct sound
Warmth	• Heavy massive building materials	Persistence of sound at low frequencies or extended low frequency reverberation.
Brilliance	• Heavy massive building materials	Persistence of sound at high frequencies or extended high frequency reverberation
Localization of sound	• Clear sight lines between listener and source • Clear sound lines between listener and source	Strength of direct sound relative to subsequent reflections
Ensemble	• Overhead reflecting surfaces at performer's area • Side-wall reflecting surfaces at performer's area	Sound reflections that allow the musicians across the stage to be heard
Blend	• Orchestra enclosure	Allow sound to build up around the musicians and blend before entering main volume of the hall.
Avoidance of acoustical defects		Design to reduce echoes, flutter echoes, focusing, glare etc.

APPENDIX 3: **ABSORPTION COEFFICIENTS OF COMMON BUILDING MATERIALS**

		Frequency in Hz					
MATERIAL	THICKNESS	125	250	500	1000	2000	4000
MASONRY WALLS							
Rough concrete		0.02	0.03	0.03	0.03	0.04	0.07
Smooth unpainted concrete		0.01	0.01	0.02	0.02	0.02	0.05
Smooth concrete, painted or glazed		0.01	0.01	0.01	0.02	0.02	0.02
Porous concrete blocks (no surface finish)		0.05	0.05	0.05	0.08	0.14	0.20
Clinker concrete (no surface finish)		0.10	0.20	0.40	0.60	0.50	0.60
Smooth brickwork with flush pointing		0.02	0.03	0.03	0.04	0.05	0.07
Smooth brickwork with flush pointing, painted		0.01	0.01	0.02	0.02	0.02	0.02
Standard brickwork		0.05	0.04	0.02	0.04	0.05	0.05
Brickwork, 10mm flush pointing		0.08	0.09	0.12	0.16	0.22	0.24
Lime cement plaster on masonry wall		0.02	0.02	0.03	0.04	0.05	0.05
Glaze plaster on masonry wall		0.01	0.01	0.01	0.02	0.02	0.02
Painted plaster surface on masonry wall		0.02	0.02	0.02	0.02	0.02	0.02
Plaster on masonry wall with wall paper on backing paper		0.02	0.03	0.04	0.05	0.07	0.08
Ceramic tiles with smooth surface		0.01	0.01	0.01	0.02	0.02	0.02
Breeze block		0.20	0.45	0.60	0.40	0.45	0.40
Plaster on solid wall		0.04	0.05	0.06	0.08	0.04	0.06
Plaster, lime or gypsum on solid backing		0.03	0.03	0.02	0.03	0.04	0.05
STUDWORK AND LIGHT WEIGHT WALLS							
Plasterboard on battens, 18mm airspace with glass wool		0.30	0.20	0.15	0.05	0.05	0.05
Plasterboard on frame, 100mm airspace		0.30	0.12	0.08	0.06	0.06	0.05
Plasterboard on frame, 100mm airspace with glass wool		0.08	0.11	0.05	0.03	0.02	0.03
Plasterboard on 50mm battens		0.29	0.10	0.05	0.04	0.07	0.09
Plasterboard on 25mm battens		0.31	0.33	0.14	0.10	0.10	0.12
2 x plasterboard on frame, 50mm airspace with mineral wool	2 x 13mm	0.15	0.10	0.06	0.04	0.04	0.05
Plasterboard on cellular core partition		0.15	0.00	0.07	0.00	0.04	0.05
Plasterboard on frame 100mm cavity	13mm	0.08	0.11	0.05	0.03	0.02	0.03

Plasterboard on frame, 100mm cavity with mineral wool	13mm	0.30	0.12	0.08	0.06	0.06	0.05
2 x 13mm plasterboard on steel frame, 50mm mineral wool in cavity, surface painted	26mm	0.15	0.01	0.06	0.04	0.04	0.05
GLASS AND GLAZING							
4mm glass	4mm	0.30	0.20	0.10	0.07	0.05	0.02
6mm glass	6mm	0.10	0.06	0.04	0.03	0.02	0.02
Double glazing, 2-3mm glass, 10mm air gap		0.15	0.05	0.03	0.03	0.02	0.02
WOOD AND WOOD PANELING							
3-4mm plywood, 75mm cavity containing mineral wool		0.50	0.30	0.10	0.05	0.05	0.05
5mm plywood on battens, 50mm airspace filled		0.40	0.35	0.20	0.15	0.05	0.05
12mm plywood over 50mm air gap		0.25	0.05	0.04	0.03	0.03	0.02
12mm plywood over 150mm air gap		0.28	0.08	0.07	0.07	0.09	0.09
12mm plywood over 200mm air gap containing 50mm mineral wool		0.14	0.10	0.10	0.08	0.10	0.08
Plywood mounted solidly		0.05		0.05		0.05	0.05
12mm plywood in framework with 30mm airspace behind	12mm	0.35	0.20	0.15	0.10	0.05	0.05
12mm plywood in framework with 30mm airspace containing glass wool	12mm	0.40	0.20	0.15	0.10	0.10	0.05
Plywood, hardwood panels over 25mm airspace on solid backing		0.30	0.20	0.15	0.10	0.10	0.05
Plywood, hardwood panels over 25mm airspace on solid backing with absorbent material in air space		0.40	0.25	0.15	0.10	0.10	0.05
12mm wood paneling on 25mm battens	12mm	0.31	0.33	0.14	0.10	0.10	0.12
Timber boards, 100mm wide, 10mm gaps, 500mm airspace with mineral wool	22mm	0.05	0.25	0.60	0.15	0.05	0.10
t & g board on frame, 50mm airspace with mineral wool	16mm	0.25	0.15	0.10	0.09	0.08	0.07
16-22mm t & g wood on 50mm cavity filled with mineral wool		0.25	0.15	0.1	0.09	0.08	0.07
Cedar, slotted and profiled on battens mineral wool in airspace		0.20	0.62	0.98	0.62	0.21	0.15
Wood boards on joists or battens		0.15	0.20	0.10	0.10	0.10	0.10
20mm dense veneered chipboard over 100mm air gap		0.03	0.05	0.04	0.03	0.03	0.02
20mm dense veneered chipboard over 200mm air gap		0.06	0.10	0.08	0.09	0.07	0.04
20mm dense veneered chipboard over 250mm air gap containing 50mm mineral wool		0.12	0.10	0.08	0.07	0.10	0.08
6mm wood fiber board, cavity > 100mm, empty		0.30	0.20	0.20	0.10	0.05	0.05
22mm chipboard, 50mm cavity filled with mineral wool		0.12	0.04	0.06	0.05	0.05	0.05
Acoustic timber wall paneling		0.18	0.34	0.42	0.59	0.83	0.68

Hardwood, mahogany		0.19	0.23	0.25	0.30	0.37	0.42
Chipboard on 16mm battens	20mm	0.20	0.25	0.20	0.20	0.15	0.20
Chipboard on frame, 50mm airspace with mineral wool	22mm	0.12	0.04	0.06	0.05	0.05	0.05
MINERAL WOOL AND FOAMS							
Melamine based foam 25mm		0.09	0.22	0.54	0.76	0.88	0.93
Melamine based foam 50mm		0.18	0.56	0.96	1.00	1.00	1.00
Glass wool 25mm 16 kg/m3		0.12	0.28	0.55	0.71	0.74	0.83
Glass wool 50mm, 16 kg/m3		0.17	0.45	0.80	0.89	0.97	0.94
Glass wool 75mm, 16 kg/m3		0.30	0.69	0.94	1.00	1.00	1.00
Glass wool 100mm, 16 kg/m3		0.43	0.86	1.00	1.00	1.00	1.00
Glass wool 25mm, 24 kg/m3		0.11	0.32	0.56	0.77	0.89	0.91
Glass wool 50mm, 24 kg/m3		0.27	0.54	0.94	1.00	0.96	0.96
Glass wool 75mm, 24 kg/m3		0.28	0.79	1.00	1.00	1.00	1.00
Glass wool 100mm, 24 kg/m3		0.46	1.00	1.00	1.00	1.00	1.00
Glass wool 50mm, 33 kg/m3		0.20	0.55	1.00	1.00	1.00	1.00
Glass wool 75mm, 33 kg/m3		0.37	0.85	1.00	1.00	1.00	1.00
Glass wool 100mm, 33 kg/m3		0.53	0.92	1.00	1.00	1.00	1.00
Glass wool 50mm, 48 kg/m3		0.30	0.80	1.00	1.00	1.00	1.00
Glass wool 75mm, 48 kg/m3		0.43	0.97	1.00	1.00	1.00	1.00
Glass wool 100mm, 48 kg/m3		0.65	1.00	1.00	1.00	1.00	1.00
Rock wool 50mm, 33 kg/m3 direct to masonry	17	0.15	0.60	0.90	0.90	0.90	0.85
Rock wool 100mm, 33 kg/m3 direct to masonry	17	0.35	0.95	0.98	0.92	0.90	0.85
Rock wool 50mm, 60 kg/m3 direct to masonry	17	0.11	0.60	0.96	0.94	0.92	0.82
Rock wool 75mm, 60 kg/m3 direct to masonry	17	0.34	0.95	0.98	0.82	0.87	0.86
Rock wool 30mm, 100 kg/m3 direct to masonry	17	0.10	0.40	0.80	0.90	0.90	0.90
Rock wool 30mm, 200 kg/m3 over 300mm air gap	17	0.40	0.75	0.90	0.80	0.90	0.85
Glass wool or mineral wool on solid backing	25mm	0.20	0.00	0.70	0.00	0.90	0.80
Glass wool or mineral wool on solid backing	50mm	0.30	0.00	0.80	0.00	0.95	0.90
Glass wool or mineral wool over air space on solid backing	25mm	0.40	0.00	0.80	0.00	0.90	0.80
Fibreglass super fine mat	50mm	0.15	0.40	0.75	0.85	0.80	0.85
Fibreglass scrim-covered sewn sheet	40mm	0.40	0.80	0.95	0.95	0.80	0.85
Fibreglass bitumen bonded mat	25mm	0.10	0.35	0.50	0.55	0.70	0.70
Fibreglass bitumen bonded mat	50mm	0.30	0.55	0.80	0.85	0.75	0.80
Fibreglass resin-bonded mat	25mm	0.10	0.35	0.55	0.65	0.75	0.80

Fibreglass resin-bonded mat	50mm	0.20	0.50	0.70	0.80	0.75	0.80
Fibreglass resin-bonded board	25mm	0.10	0.25	0.55	0.70	0.80	0.85
Flexible polyurethane foam 50mm		0.25	0.50	0.85	0.95	0.90	0.90
Rigid polyurethane foam 50mm		0.20	0.40	0.65	0.55	0.70	0.70
12mm expanded polystyrene on 45mm battens		0.05	0.15	0.40	0.35	0.20	0.20
25mm expanded polystyrene on 50mm battens		0.10	0.25	0.55	0.20	0.10	0.15
WALL TREATMENTS							
Cork tiles 25mm on solid backing		0.05	0.10	0.20	0.55	0.60	0.55
Cork board, 25mm on solid backing	25mm	0.03	0.05	0.17	0.52	0.50	0.52
Cork board, 25mm, 2.9kg/m2, on battens	25mm	0.15	0.40	0.65	0.35	0.35	0.30
Glass blocks or glazed tiles as wall finish		0.01	0.00	0.01	0.00	0.01	0.01
Muslin covered cotton felt	25mm	0.15	0.45	0.70	0.85	0.95	0.85
Pin up boarding- medium hardboard on solid backing		0.05	0.00	0.10	0.00	0.10	0.10
Fibreboard on solid backing	12mm	0.05	0.10	0.15	0.25	0.30	0.30
25mm thick hair felt, covered by scrim cloth on solid backing	25mm	0.10	0.00	0.70	0.00	0.80	0.80
Fibreboard on solid backing	soft 12mm	0.05	0.00	0.15	0.00	0.30	0.30
Fibreboard on solid backing - painted		0.05	0.00	0.10	0.00	0.15	0.15
Fibreboard over airspace on solid wall	12mm	0.30	0.00	0.30	0.00	0.30	0.30
Fibreboard over airspace on solid wall - painted		0.30	0.00	0.15	0.00	0.10	0.10
Plaster on lath, deep air space		0.20	0.15	0.10	0.05	0.05	0.05
Plaster decorative panels, walls		0.20	0.15	0.10	0.08	0.04	0.02
Acoustic plaster to solid backing	25mm	0.03	0.15	0.50	0.80	0.85	0.80
9mm acoustic plaster to solid backing	9mm	0.02	0.08	0.30	0.60	0.80	0.90
9mm acoustic plaster on plasterboard, 75mm airspace	9mm	0.30	0.30	0.60	0.8	0.75	0.75
12.5mm acoustic plaster on plaster backing over 75mm air space	12.5mm	0.35	0.35	0.40	0.55	0.70	0.70
Woodwool slabs, unplastered on solid backing	25mm	0.10	0.00	0.40	0.00	0.60	0.60
Woodwool slabs, unplastered on solid backing	50mm	0.10	0.20	0.45	0.80	0.60	0.75
Woodwool slabs, unplastered on solid backing	75mm	0.20	0.00	0.80	0.00	0.80	0.80
Woodwool slabs, unplastered over 20mm airspace on solid backing	25mm	0.15	0.00	0.60	0.00	0.60	0.70
Plasterboard backed with 25mm thick bitumen-bonded fibre glass on 50mm battens	10mm	0.30	0.20	0.15	0.05	0.05	0.05
Curtains hung in folds against solid wall		0.05	0.15	0.35	0.40	0.50	0.50
Cotton Curtains (0.5kg/m2),draped to 75% area approx. 130mm from wall		0.30	0.45	0.65	0.56	0.59	0.71

Lightweight curtains (0.2 kg/m2) hung 90mm from wall		0.05	0.06	0.39	0.63	0.70	0.73
Curtains of close-woven glass mat hung 50mm from wall		0.03	0.03	0.15	0.40	0.50	0.50
Curtains, medium velour, 50% gather, over solid backing		0.05	0.25	0.40	0.50	0.60	0.50
Curtains (medium fabrics) hung straight and close to wall		0.05	0.00	0.25	0.00	0.30	0.40
Curtains in folds against wall		0.05	0.15	0.35	0.40	0.50	0.50
Curtains (medium fabrics) double widths in folds spaced away from wall		0.10	0.00	0.40	0.00	0.50	0.60
Acoustic banner, 0.5 kg/m2 wool serge, 100mm from wall		0.11	0.40	0.70	0.74	0.88	0.89
FLOORS							
Smooth marble or terrazzo slabs		0.01	0.01	0.01	0.01	0.02	0.02
Raised computer floor, steel-faced 45mm chipboard 800mm above concrete floor, no carpet		0.08	0.07	0.06	0.07	0.08	0.08
Raised computer floor, steel-faced 45mm chipboard 800mm above concrete floor, office-grade carpet tiles		0.27	0.26	0.52	0.43	0.51	0.58
Wooden floor on joists		0.15	0.11	0.10	0.07	0.06	0.07
Parquet fixed in asphalt, on concrete		0.04	0.04	0.07	0.06	0.06	0.07
Parquet on counter floor		0.20	0.15	0.10	0.10	0.05	0.10
Linoleum or vinyl stuck to concrete		0.02	0.02	0.03	0.04	0.04	0.05
Layer of rubber, cork, linoleum + underlay, or vinyl + underlay stuck to concrete		0.02	0.02	0.04	0.05	0.05	0.10
5mm needle-felt stuck to concrete	5mm	0.01	0.02	0.05	0.15	0.30	0.40
6mm pile carpet bonded to closed-cell foam underlay	6mm	0.03	0.09	0.25	0.31	0.33	0.44
6mm pile carpet bonded to open-cell foam underlay	6mm	0.03	0.09	0.20	0.54	0.70	0.72
9mm pile carpet, tufted on felt underlay	9mm	0.08	0.08	0.30	0.60	0.75	0.80
Composition flooring		0.05	0.05	0.05	0.05	0.05	0.05
Hair cord carpet on felt underlay	6mm	0.05	0.05	0.10	0.20	0.45	0.65
Medium pile carpet on sponge rubber underlay	10mm	0.50	0.10	0.30	0.50	0.65	0.70
Thick pile carpet on sponge rubber underlay	15mm	0.15	0.25	0.50	0.60	0.70	0.70
Rubber floor tiles	6mm	0.05	0.05	0.10	0.10	0.05	0.05
Carpet, thin, over thin felt on concrete		0.10	0.15	0.25	0.30	0.30	0.30
Carpet, thin, over thin felt on wood floor		0.20	0.25	0.30	0.30	0.30	0.30
Carpet, needle punch	5mm	0.03	0.05	0.05	0.25	0.35	0.50
Stone floor, plain or tooled or granolithic finish		0.02	0.00	0.02	0.00	0.05	0.05
Cork floor tiles	14mm	0.00	0.05	0.15	0.25	0.25	0.00
Sheet rubber (hard)	6mm	0.00	0.05	0.05	0.10	0.05	0.00

Woodblock/linoleum/rubber/cork tiles (thin) on solid floor (or wall)		0.02	0.04	0.05	0.05	0.10	0.05
Floor tiles, plastic or linoleum		0.03	0.00	0.03	0.00	0.05	0.05
Steel decking		0.13	0.09	0.08	0.09	0.11	0.11
PANEL AND DOORS							
Wood hollow core door		0.30	0.25	0.15	0.10	0.10	0.07
Solid timber door		0.14	0.10	0.06	0.08	0.10	0.10
Acoustic door, steel frame, double seals, absorbent in airspace, Double sheet steel skin.		0.35	0.39	0.44	0.49	0.54	0.57
CEILINGS							
Mineral wool tiles, 180mm airspace		0.42	0.72	0.83	0.88	0.89	0.80
Mineral wool tiles, glued/screwed to soffit		0.06	0.40	0.75	0.95	0.96	0.83
Gypsum plaster tiles, 17% perforated, 22mm		0.45	0.70	0.80	0.80	0.65	0.45
Metal ceiling, 32.5% perforated, backed by 30mm rockwool		0.12	0.45	0.87	0.98	1.00	1.00
Perforated underside of structural steel decking (typical, depends on perforations)		0.30	0.70	0.85	0.90	0.70	0.65
12% perforated plaster tiles, absorbent felt glued to back, 200mm ceiling void		0.45	0.70	0.88	0.52	0.42	0.35
100mm woodwool slabs on 25mm cavity, pre-screeded surface facing cavity		0.50	0.75	0.85	0.65	0.70	0.70
50mm woodwool slabs on 25mm cavity, pre-screeded surface facing cavity		0.30	0.40	0.50	0.85	0.50	0.65
100mm woodwool fixed directly to concrete, pre-screeded surface facing backing		0.25	0.80	0.85	0.65	0.70	0.75
75mm woodwool fixed directly to concrete, pre-screeded surface facing backing		0.15	0.40	0.95	0.60	0.70	0.60
Plasterboard 10mm thick backed with 25mm thick bitumen	10mm	0.30	0.20	0.15	0.05	0.05	0.05
Plasterboard 10mm thick, perforated 8mm diameter holes 2755m2 14% open area backed with 25mm thick bitumen- bonded fibreglass on 90mm battens	10mm	0.25	0.70	0.85	0.55	0.40	0.30
Plywood, 5mm, on battens 50mm airspace filled with glass wool	5mm	0.40	0.35	0.20	0.15	0.05	0.05
Plywood, 12mm, with 30mm thick fibreglass backing between 30 mm battens		0.40	0.20	0.15	0.10	0.10	0.05
Plywood 12mm thick perforated 5mm diameter holes 6200 m2 11% open area with 60mm deep air space behind		0.20	0.35	0.55	0.30	0.25	0.30

Plywood 12mm thick perforated 5mm diameter holes 6200 m2 11% open area backed with 60mm thick fibreglass between mounting battens		0.40	0.90	0.80	0.50	0.40	0.30
Hardboard, 25% perforated over 50mm mineral wool		0.27	0.87	1.00	1.00	0.98	0.96
0.8mm unperforated metal panels backed with 25mm thick resin bonded fibreglass, mounted on 22mm diameter pipes 135mm from wall.	0.8mm	0.50	0.35	0.15	0.05	0.05	0.00
0.8mm perforated metal tiles 2mm diameter holes 29440/m2. 13% open area backed with 25mm thick resin-bonded fibreglass slab. No airspace.	0.8mm	0.10	0.30	0.60	0.75	0.80	0.80
50mm mineral wool (96 kg/m3) behind 25% open area perforated steel.	50mm	0.20	0.35	0.65	0.85	0.90	0.80
Wood panels, 18mm alternate 15mm slot & 35mm wooden slat 25mm rockwool backing, 32mm airspace behind	18mm	0.10	0.36	0.74	0.91	0.61	0.50
Plaster decorative panels, ceilings		0.20	0.22	0.18	0.15	0.15	0.16
AUDIENCE AND SEATING							
Children, standing (per child) in m2 units		0.12	0.22	0.37	0.40	0.42	0.37
Children, seated in plastic or metal chairs (per child) in m2 units		0.28	0.00	0.33	0.00	0.37	0.37
Students seated in tablet arm chairs		0.30	0.41	0.49	0.84	0.87	0.84
Adults per person seated		0.33	0.40	0.44	0.45	0.45	0.45
Adults per person standing		0.15	0.38	0.42	0.43	0.45	0.45
Empty plastic or metal chairs (per chair) in m2 units		0.07	0.00	0.14	0.00	0.14	0.14
Seats, leather covers, per m2		0.40	0.50	0.58	0.61	0.58	0.50
Cloth-upholstered seats, per m2		0.44	0.60	0.77	0.89	0.82	0.70
Floor and cloth-upholstered seats, per m2		0.49	0.66	0.80	0.88	0.82	0.70
Adults in plastic and metal chairs in m2 units		0.30	0.00	0.40	0.00	0.43	0.40
Adults in wooden or padded chairs or seats (per item) in m2		0.16	0.00	0.40	0.00	0.44	0.40
Adults on timber seats, 1 per m2 per item		0.16	0.24	0.56	0.69	0.81	0.78
Adults on timber seats, 2 per m2 per item		0.24	0.40	0.78	0.98	0.96	0.87
Wooden or padded chairs or seats (per item) in m2		0.08	0.00	0.15	0.00	0.18	0.20
Seating, slightly upholstered, unoccupied		0.07	0.12	0.26	0.42	0.50	0.55
Seating, slightly upholstered, occupied		0.32	0.62	0.74	0.76	0.81	0.90
Fully upholstered seats (per item) in m2		0.12	0.00	0.28	0.00	0.32	0.37
Upholstered tip-up theatre seats, empty		0.33	0.51	0.64	0.71	0.77	0.81

Areas with audience, orchestra, or seats, including narrow aisles		0.60	0.74	0.88	0.96	0.93	0.85
Auditorium seat, unoccupied		0.13	0.33	0.59	0.58	0.61	0.62
Auditorium seat, occupied		0.37	0.48	0.68	0.73	0.77	0.74
Orchestra with instruments on podium, 1.5 m2 per person		0.27	0.53	0.67	0.93	0.87	0.80
Orchestral player with instrument (average) per person		0.37	0.80	1.00	1.00	1.00	1.00
Proscenium opening with average stage set per m2 of opening		0.20	0.00	0.30	0.00	0.40	0.50
Wood platform with large space beneath		0.40	0.30	0.20	0.17	0.15	0.10
Adult office furniture per desk		0.50	0.40	0.45	0.45	0.60	0.70
OTHER							
Water surface, i.e. swimming pool		0.01	0.01	0.01	0.01	0.02	0.02
Ventilation grille per m2		0.60	0.60	0.60	0.60	0.60	0.60