ACOUSTIC COMFORT IN CHURCH AUDITORIA

A case of CITAM Church designs at Ngong and Parklands, Nairobi, Kenya.

By:

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Declaration

This thesis is original and has not been submitted to any other University or institution for a Master of Architecture degree. The content in this thesis is either my own work or a synthesis of work by other authors, which has been duly cited.

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I have read this thesis and certify that in my opinion, it is fully adequate as a thesis for the degree of Master of Architecture.

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Dedication

To Lilian my priceless wife, may Yahweh continually refresh you to inspire many more as you have always inspired me. I love you.

To Yannis, Hanzel and Enam our boys, may Yahweh grant you long life, health and wisdom. I hope you will critique this work some day!

To Alfred & Nancy our parents, no words can express my gratitude for your love and care since I was formed! May Yahweh grant you health and long life. I honour you.

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List of abbreviations and acronyms

CITAM	Christ is the Answer Ministries.
ISO	International Organization for Standardization.
RT_{60}	Reverberation Time.
D	Definition Index.
C80	Clarity.
EDT	Early Decay Time.
STI	Speech Transmission Index.
dB	Decibel.
RASTI	Rapid Speech Transmission Index.
STIPA	Speech Transmission Index for Public Address Systems.

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Abstract

Church auditoria are an extreme example of multipurpose rooms. A good speech intelligibility is necessary for understanding the spoken word, and an adequate reverberation is desirable for music. On the other hand, the acoustical features that make a space suitable for speech are frequently the same as those that make the space unsuitable for music, and vice versa. Room volumes and reverberation times should be kept low for optimum speech intelligibility. Rooms intended for music, on the other hand, demand high volumes and longer reverberation times. A compromise is therefore necessary for the best musical ambient without affecting speech intelligibility.

Given the foregoing, acoustic requirements for church auditoriums should always be considered from the start of the design process. Although changes can be made at mid and end stages of design, changing form, room heights, and adjacencies within structures is usually quite difficult once spatial relationships and budgets have been established. Defects in completed spaces, likewise, are often difficult and costly to fix. For instance, the addition of an electronic sound-reinforcing system in an excessively reverberant church auditorium may accentuate deficiencies rather than enhance the listening conditions. These acoustic problems are avoidable if designers understand the basic principles of church auditorium acoustics.

A successful design is one that provides spatial relationships, cubic volumes, and appropriate geometry for church buildings maintain design quality while best serving their intended purposes.

The primary goal of this study is to provide a tool for designers and church leaders to understand the critical issues associated with evangelical auditorium acoustics. This information can be used to either evaluate and make improvements to existing spaces or in the design of new spaces. The CITAM church auditoria at Ngong and Parklands are selected as representative case studies of Pentecostal church auditoria in Nairobi.

To achieve the primary goal as stated above, the author first examines the history of church building acoustics, room acoustics principles for auditoriums, and architectural design considerations for good church auditoria acoustics. Secondly, the author examines the primary parameter for acoustic characterization of church auditoria, as well as methods for its calculation and measurement. Although various factors influence the acoustic performance of church auditoriums, the most critical and obvious one for congregants is the RT60 (Reverberation time). As the most vital measure of a room's acoustic properties, RT60 can help investigate the suitability of an auditorium as a contemporary Pentecostal worship space. Thirdly, an architectural design survey and measurement of the reverberation time (RT60) of both CITAM church auditoria are undertaken. Finally, both auditoria designs and the measured acoustic results are analysed and a proposal for acoustic correction presented.

CHAPTER ONE – INTRODUCTION

1.1. BACKGROUND OF THE STUDY

Acoustics is a science that deals with sound waves, including their generation/creation, transmission/propagation and effects/perception (Harris, 2006). It is concerned with sound production, sound propagation between the source and the receiver, sound detection, and sound perception. (Rossing, 2007). In practice, Architectural acoustics comprises the fields of building acoustics and room acoustics. Building acoustics is concerned with the transfer of sound between rooms or from the exterior of a room to the interior (and vice-versa) through building elements such as walls, floors, doors and windows. Room acoustics deals with the behaviour of sound inside a room when the source of sound is in the same space (Ginn, 1978). According to Harris (2006), room acoustics is the behaviour of sound waves in a room including how the waves are generated, transmitted and their effects. In other words, it is the entirety of the geometrical and surface characteristics of a room (such as the shape and size of sound scattering elements on surfaces, the overall sound absorption, and level of noise in the room), which influence how a listener perceives and judges the quality of music and speech generated in the room.

According to Fernandez, Recuero, & Cruz, (2002), church acoustics has not been studied well enough in its historic evolution. Forces other than acoustics shaped the design of church buildings, including the different functions of the church, traditions, rituals and the search for architectural splendour.

According to Carvalho, (1994), one of the first authors to write on acoustics in places of worship was Sir Christopher Wren, a British architect (1632-1723). In the late 19th century, some scholars undertook elementary research studies on the subject of church building acoustics. Earlier studies (1875-1928) provided simple guidelines about acoustics in churches for specific Christian denominations including Methodist, Episcopal, and Evangelical.

In the 20th century, the study of acoustics in churches and worship places gained more and more prominence in the scientific community. Volumetric complexity, material usage, and multiplicity of sound sources (loudspeakers, musical instruments, mechanical installations, and people singing, talking and moving) make church buildings completely different from concert halls or theatres. In 1953, Raes and Sacerdotal published one of the earliest studies on the acoustic features of churches, analysing two Roman basilicas. Following systematic investigations on churches in Switzerland, Portugal, Germany, Italy, Spain, Serbia, and Poland, various research teams have published on the issue since then. Reverberation time was the sole acoustic parameter measured in all of the churches since it is the most representative and easiest to measure. Its considerable uniformity even in churches, which in some cases were very complicated in terms of volumetric articulation, allowed simple and direct comparisons (Martellotta & Cirillo, 2014).

Acoustic characterization of a room is the use of architectural, objective and subjective acoustic parameters to evaluate a room's acoustic quality. Architectural parameters are purely physical factors such as site selection and planning, room geometry, room size, surface finishes, and number of seats. Objective parameters measure quantifiable physical attributes dependent on the architectural features of the space. These include early decay time (EDT), reverberation time (RT60), definition (D50), clarity (C50), loudness (G), centre time (Ts), bass ratio (BR) and rapid speech transmission index (STI). Subjective parameters relate to a listener's subjective identification of acoustic attributes and include reverberance, clarity, loudness, directionality, envelopment, intimacy, echoes, balance, overall impression and background noise (Carvalho, 1995).

The physical methodologies used in room acoustic analysis consist of measurement, calculation, as well as modelling techniques for approximation of the impulsive response of a room (Vodopija, Fajt, & Krhen, 2010). Reverberation Time (RT60) is the primary objective parameter in room acoustics. It is the amount of time it takes for the level of sound in a room to drop by sixty decibels (60dB) after a continuous sound source is switched off. It is closely linked to other room acoustic parameters and is the primary parameter used in legislation and standards for room acoustics (Gade, 2007). According to Harris (2006), Optimum RT_{60} values are determined based on the use of the room, its volume, and may depend on frequency. The acoustics quality of a room, however, does not only depend on the reverberation time but also on the shape, volume, and size of the enclosure, the positioning and amount of the sound absorbing materials, and the positioning of the sound source and the audience (Ginn, 1978).

1.1.1. Acoustic comfort in church buildings

Acoustic comfort is a psychophysical condition achieved for a specific activity in a space through the absence or reduction of unwanted sounds (noise) combined with the adequate level and quality of desired sounds (Vardaxis, Bard, & Persson, 2017).

The acoustical situation in a church has three parts: source, path, and receiver. Sometimes the source can be made louder or quieter. The path (air and building materials) can be made to transmit more or less sound. The receiver (Building occupants) will hear better, or be more comfortable, if design achieves a suitable reverberation time and distracting noise systems are adequately controlled, isolated or removed (Egan, 2007).

Acoustics significantly affects the wellbeing (comfort) and productivity of the users in a building and architectural acoustics is therefore an important factor in the life cycle of many buildings - design, construction and operation (World GBC, 2014). Similar to lighting and the thermal environment, room acoustics is an environmental science that in the past century has become a recognized discipline (Egan, 2007).

Acoustic comfort in a building is determined by the acoustic properties of the building fabric in terms of transmission and absorption. A range of acoustic and architectural aspects must be considered when designing for acoustic comfort in a church. These include the activities in the building, the types of sound to be managed (internal and external), the frequency spectrum of the sound, the building's construction structure and materials, as well as background noise generated by electronic devices, ventilation systems, and appliances. (Saint-Gobain, 2020)

Acoustic comfort in a church building is realized when the design achieves a reverberation time suitable for both music and speech since the single most important purpose for any worship service is to unite the congregation in sung worship, and communicate the spoken word. According to Long (2014), this is one of the most dominant and current issues on church acoustics design. It is not easy to satisfy the acoustical requirements for both environments at the same time and ideally, none should be sacrificed for the other. One common solution for this issue in contemporary churches is generating sufficient reverberation time for music and installing sound reinforcement systems and hard surfaces near the speaker to improve speech intelligibility. However, this requires expensive and highly sophisticated sound systems. (Riedel,1983 as cited in Lee, 2003).

1.1.2. Acoustic comfort needs for different churches

Church acoustic comfort needs are denomination specific. The liturgy of a church determines its program (a list of the different functions for a space and their percentage distribution), which in turn determines the room geometry and aesthetics. (Long, 2014)

The acceptance of any specific sound is influenced by a range of variables, including the denomination, the type of church building, the nature of activity being conducted, and the inhabitants' social and cultural norms. The impact of noise on an individual is determined by a variety of factors. These include the sound's predictability and familiarity, its controllability, personal attitudes and sensitivities, knowledge about the sound's contents, and the sound's necessity.(Saint-Gobain, 2020).

Long (2014) observes that traditional Catholic churches are modelled after Middle Ages cathedrals, with lofty ceilings and extended reverberation time associated with the Gregorian chant. Following Vatican II in 1969, when the saying of Mass in languages other than Latin was allowed, church architecture has shifted toward an emphasis on communication and breaking down barriers between the priests and the congregation. As a result, designs have prioritized shorter reverberation time, smaller room volume, cushioned pews, and more treatment for absorption.

Episcopal churches are typically cruciform in design, with a double row of columns, reflecting their Anglican-Catholic ancestry. Pews are hardly ever padded, and room volumes are typically lower than in Catholic churches. An elevated pulpit with a steep wooden stair access is a frequent feature. The choir is typically found behind the altar, in a deep apse.

A majority of Protestant churches prioritize oral communication and have padded pews and lower ceilings. Their worship rooms, which originated from the Reformation's northern European churches, are cruciform, fan-shaped or rectangular, with a raised podium in front. Electronic systems play an important role in worship especially among Pentecostal groups. Many Pentecostal churches hold numerous services on the same day, necessitating different space arrangements and musical configurations.

Large churches with seating capacities of between 2500 to 5000 people have special acoustic design requirements. These churches typically rely on electronic sound reinforcement systems and have screens that display projected pictures from recorded sources or television cameras. They have elaborate audio, lighting, and projection systems and are built as both theatrical and sacred spaces. High-energy music, dancing, and pre-recorded visual pictures are a common feature in most services. The room's natural acoustics do not add much to the audience experience. Given the large size of the rooms, reverberation times should be low, and the ceiling designed to reinforce congregational singing. The seating arrangement is typically fan-shaped and frequently includes a large balcony. Due to sight line constraints, an included angle of no more than 160 degrees is recommended. Balconies should be robust enough to sustain the congregation's rhythmic movement while minimizing resonance vibration. The ideal option is to build a canopy over the platform to house the loudspeakers, video displays, and lighting equipment.

1.1.3. Acoustic design challenges in church buildings

The biggest cause of acoustic discomfort in churches is the presence of acoustical defects. These are acoustic problems which impair quality, function, or utility because of improper design or from construction limitations. (Long, 2014).

The most common defects include excessive reverberation, flutter echoes, room resonance, frequency imbalance and poor sound isolation. By avoiding or addressing these problems, it is possible to achieve clear and intelligible sound in any church building. (Haverstick, 2018).

1.1.4. Church design in Kenya.

European and American missionaries introduced Christianity to Kenya in the 19th and 20th centuries, which later underwent a process of indigenization and numerous transformations after the country won independence. (Bariu, 2017). As a result, churches in Kenya can be divided into three major categories, and the worship needs of each denomination dictate the architectural design of their worship buildings. The three categories are mainstream churches, indigenous African churches and charismatic Pentecostal churches (Gechiko and Nkonge, 2014).

The oldest mainstream church cathedrals have their design modelled after the British gothic style characterized by cruciform plans, construction using masonry, carved stone ornamentation, vertical proportions, bell towers, pointed windows and arches, and stained glass. The Nairobi All Saints Cathedral falls in this category (Teckla, Gerryshom, & Njuguna, 2016). Mainstream local parish church buildings are mostly simple rectangular structures with single hall like rooms, laid out longitudinally with the altar situated at one narrow end. The oldest local church structures were mostly small since it was difficult to achieve large spans without columns. Larger structures with extensive spans and polygonal, circular, or free shapes are now possible because of advancement in technology and improved building materials.

Some Africans founded indigenous churches after independence, such as "Akorino and Anaabii," to protest perceived oppression by missionaries, while others are splinter groups from mainstream churches. For example, in 1914, the Nomiya Luo Church broke away from Anglicanism, and in 1962, the Legio Maria of Africa broke away from Roman Catholicism. (Bariu, 2017). Indigenous church structures are mostly rectangular and vary in construction depending on the congregation's ability to raise finances. Walls are built using natural stone, rammed earth or iron sheets, with roofs mostly made of corrugated iron sheets. Some congregations meet in tents or sheds made of posts and iron sheets as roof cover.

Kenya's Charismatic Pentecostal churches began in the cities and have now spread to the countryside. Majority of charismatic Pentecostal church members came from mainstream denominations. This indicates that charismatic denominations provide something that mainstream churches do not. (Gechiko & Nkonge, 2014).

The charismatic Pentecostal main church (headquarter) designs do not follow any existing styles but mostly depend on the user needs and the Architects creativity. They are mostly designed as multipurpose auditoriums within larger complexes housing offices, classrooms, meeting rooms and restaurants. Most of the affiliate local church buildings are either simple rectangular forms or temporary tent structures, though some are similar to or larger and more complex than the headquarters depending on congregation size and capacity to raise finances.

1.1.5. Church acoustic design challenges in the current Kenyan context

Whereas acoustics is arguably the single most important consideration for new worship buildings, the design of many church auditoria in Kenya centres primarily on the architectural form for iconic value and on spatial accommodation requirements, with no adequate consideration of the resultant acoustic climate, and with little or no input from acoustic experts. As a result, critical acoustical requirements are overlooked during design. In some cases, designers rely on oversimplified and misleading advertisements and incomplete technical data from manufacturers and suppliers, leading to poor acoustic outcomes when the interiors are completed and sound systems commissioned.

1.1.6. Christ is the Answer Ministries (CITAM)

CITAM is the largest Pentecostal church institutions in Kenya with 18 branches countrywide situated in Nairobi – [Valley road (1959), Woodley (1994), Karen (1997), Parklands (1998), Buruburu (2005), Thika road (2008), Embakasi (2016) and Clay city(2018)], Kisumu (2000), Ngong (2003), Nakuru (2011), Eldoret (2013), Athi river (2013), Kapsabet (2015), Thika town (2016), Rongai (2016), Nyeri (2018) and Meru (2018).

The church also has interests in broadcast media, education, health, and hospitality. In 2018, CITAM had a total income of Kes 1.964 Billion and total assets valued at Kes 12.33 Billion (CITAM Agm Report, 2019).

From the above, it is evident that CITAM occupies a strategic position among the Pentecostal churches in Kenya and has played significant roles in the country through social and political engagement (Parsitau, 2014).

By April 2011, only the congregations at valley road, Woodley, Karen and Kisumu were meeting in permanent church auditoria. CITAM then embarked on an initiative dubbed “Moving the Ark (MTA)” a special purpose vehicle for raising funds to build permanent structures for congregations that were meeting in tents. This study evaluates the first two auditoria commissioned so far under the initiative – CITAM Parklands in 2014 and CITAM Ngong in 2017. CITAM Ngong has a capacity of 2900 and CITAM Parklands a capacity of 540.

The primary goal of this study is to provide a simple reference for practicing architects, students of architecture, interior designers, church leaders, and contractors in Kenya by methodically documenting the key design considerations for acoustic comfort in church auditoria. These include acoustic design principles, architectural design considerations, and the primary parameter for acoustic characterization as well as methods for its calculation and measurement. To illustrate a methodology for applying the above principles, acoustic evaluation of the CITAM church auditoria at Ngong and Parklands is undertaken through an architectural survey, acoustic measurement, and analysis of the drawings, surface finishes as well as the measured results. This methodology can be used to evaluate existing spaces or in the design of new spaces.

1.2. PROBLEM STATEMENT

More often than not, the acoustical environment in church auditoria is not factored in at project inception, planning and design. Designers and owners focus primarily on spatial requirements, iconic value and aesthetics. In the process, crucial aspects that contribute to the psychophysical well-being of worshippers are overlooked. Comfort in a church building is a combination of indoor environmental quality factors that include acoustics, air quality, natural lighting, artificial lighting, and temperature. Acoustic discomfort can result from factors within or outside the space because of poor sound control within the space, excessive noise from outside into the space, and noise from adjacent spaces (Paradis, 2016).

In April 2011, Christ is the Answer Ministries (CITAM) embarked on an initiative dubbed "Moving the Ark (MTA)" a special purpose vehicle for raising funds to build permanent structures for congregations that were meeting in tents. CITAM Parklands and Ngong are the only auditoria commissioned under the initiative so far.

Whereas acoustics should be the top consideration for worship buildings, the design of the CITAM Ngong and Parklands church auditoria was undertaken with no input from acoustic experts during design. When the auditoriums were completed, there were obvious acoustic defects and the development committees hired specialist acoustic panel suppliers to evaluate the problems and recommend possible solutions. The problem with this approach is that by this point, the acoustics of the church auditorium are substantially set because a room's acoustic performance mainly depends on geometry and size. Throughout the design process, these two elements must be carefully considered and incorporated. Surface finishes have a little impact on room acoustics once the construction is completed. (Breshears, 2020).

The CITAM church auditorium at Parklands was completed and commissioned in January 2014. It is rectangular with perforated acoustic panels lined with mineral wool on all the walls, ceramic tiles flooring in the audience hall, carpet on the stage floor, acoustic panel ceilings, and upholstered seats. The auditorium at Ngong was completed and commissioned in October 2017. It is fan shaped with plastered walls, terrazzo flooring in the audience hall, acoustic panel ceilings, carpet on the stage floor, and upholstered seats. The hall at parklands functions very well for speech but is very dry for music. After commissioning, the auditorium at Ngong had excessive echo and various acoustic corrections helped remedy the problem including mounting of upholstered and perforated panels on sections of the plastered walls, drapery on the rear stage wall, mounting perforated panels on the balcony front wall, installation of carpet on the stage floor, and replacement of plastic chairs with upholstered seats. The result was a hall that functions well for speech but not as live for music.

Both auditoria still have various acoustic design defects in relation to site selection and planning, auditorium proportions, room geometry, sight lines, surface finishes and sound isolation. The defects include low reverberation times due to excessive absorption, sound shadows, insufficient sound volume due to poor stage geometry, and high background noise.

The acoustic environment in a church auditorium, whether good or bad is the result of design. For acoustic comfort and functional performance, it is crucial to undertake acoustic design throughout the process of design and construction. (Cape, 2016). Poor acoustics in church structures are often blamed on the sound equipment, and many church leaders respond by purchasing bigger and/or newer sound systems hoping to improve the sound quality. Even with the best sound system, the quality of sound depends on the physical space in which the system is used. The equipment will only be as good as the acoustic environment in which it is placed (Haverstick, 2018).

The design of a church auditorium should be a team effort involving the church leadership / development committees, project managers, architects, structural engineers, MEP engineers, acousticians, sound engineers, interior designers, and project managers (BAP-Acoustics, 2019). Acoustic and sound consultants should coordinate with other consultants from the onset to align architectural, structural, mechanical and electrical design requirements for optimized acoustic performance of the church building (BAP-Acoustics, 2019).

In advocating for acoustic comfort in church auditoria, this study documents the key considerations for acoustic design. The CITAM church auditoria at Ngong and Parklands are evaluated in order to demonstrate a methodology for applying the above principles. Finally, a proposal is made for architectural and acoustic design improvements for optimized acoustics in both auditoriums.

1.3. OBJECTIVES

The primary goal of this research is to look at primary acoustic design requirements for optimal reverberation time (RT60) in Pentecostal church auditoriums and to present the findings in a format that is easy to follow for architects, church leaders, and building contractors in Kenya. Reverberation time (RT60), being the primary acoustic performance index, is central in the research. In order to achieve the aim stated above, the study objectives are structured as follows:

1. To study and document the design criteria for optimal RT60 values in church auditoria.
2. To evaluate the design and RT60 values for CITAM Ngong and Parklands church auditoria.
3. To recommend design improvements for optimized RT60 values.

1.4. RESEARCH QUESTIONS

1. What consists the design criteria for optimal RT60 values in church auditoria?
2. What are the design features and RT60 values for CITAM Ngong and Parklands church auditoria?
3. What design improvements will optimize RT60 values for improved acoustic performance?

1.5. RESEARCH PROPOSITION

Pentecostal church auditoriums in Nairobi are designed with an emphasis on architectural form and spatial accommodation, with little or no input from room acoustic experts. As a result, crucial acoustical requirements are overlooked during the design process, resulting in poor acoustics when the auditoriums are finished and commissioned.

1.6. JUSTIFICATION & SIGNIFICANCE

The aim of architectural acoustics is to create rooms that have good or appropriate acoustical qualities for the function (or functions) in particular spaces. Many scholars have looked at acoustic design and measurement methods for concert halls and multipurpose auditoriums, but this has not been the case for church buildings. There is a need to consider church buildings as a set of structures with unique acoustic needs and characteristics. (Carvalho, 1995).

The coexistence and interaction of speech and music in churches, as well as the various locations and types of sound sources involved, make church buildings completely different from concert halls or theatres. This gives church acoustics a unique place in the field of architectural acoustics, justifying this study.

In Kenya, there is generally little or no attention to the acoustical environment in church auditoria during project planning and design. The outcome is worship spaces with varying acoustic defects such as excessive reverberation, excessive absorption, echoes, sound focussing, dead spots, sound shadows, insufficient sound volume and high background noise.

By documenting the key design principles for acoustic comfort in church auditoria and illustrating a methodology for their application, this study will be of value to architects, students of architecture, interior designers, church leaders, and contractors in Kenya. It will also serve as a resource for those conducting research on a similar or related topic.

1.7. SCOPE

The selected auditoriums for this study – CITAM Ngong and Parklands, are located in Kajiado and Nairobi counties respectively in the republic of Kenya.

CITAM is one of the largest Pentecostal church institutions in Kenya with 18 branches countrywide. Eight of the assemblies are located in Nairobi and the other eight distributed across various counties. The selected CITAM church auditoriums are representative of other Pentecostal church auditoria in Nairobi and countrywide which are designed as rectangular, fan shaped, polygonal, circular or free form multipurpose auditoriums within larger complexes. CITAM occupies a strategic position among the Pentecostal churches in Kenya. It has the highest income among the

Pentecostal churches, has a very well organized leadership structure, and is among the few Pentecostal church institutions with very clear strategic plans. In 2011, CITAM embarked on an initiative to build permanent structures for congregations that were meeting in tents. This study evaluates the first two auditoria commissioned so far under the initiative – CITAM Parklands in 2014 and CITAM Ngong in 2017.

Since this is an architectural research on room acoustics, the literature study focuses on basic room acoustics theory, the behaviour of sound in enclosed spaces, architectural design considerations and parameters for acoustic characterization of church auditoria.

Apart from Reverberation Time, the prediction and evaluation of other room acoustics parameters is almost entirely done by computer software. Other parameters are Rapid Speech Transmission Index (RASTI), Clarity (C80), Early Decay Time (EDT) Sound Strength (G), and Definition (D50). The Reverberation Time (RT60) effectiveness as a key acoustical parameter is because of its association with perceived subjective quality, its suitability for evaluating a whole space and, most importantly, its predictability using certain simple formulas. RT_{60} is chosen for its undisputed importance as the primary acoustical quality index. The RT_{60} of the two church auditoria is evaluated to characterize their acoustic environment. The acoustics quality of a room including the reverberation time depend on the shape, volume, and size of the enclosure, the positioning and amount of the sound absorbing materials, and the positioning of the sound source and the audience. Architectural features of both auditoriums are surveyed including the site selection and planning, room geometry, room size, surface finishes, and number of seats.

1.8. LIMITATIONS

First, this master thesis is limited to a case study of two CITAM church auditoria which are representative of other Pentecostal church auditoria in Nairobi and countrywide.

Second, Reverberation Time (RT_{60}) is the only objective parameter investigated because: (1) It is the most representative acoustic parameter and the simplest one to calculate / measure, and (2) The equipment and computer software required for evaluation of the other objective parameters are not available.

Third, although the acoustic response of church auditoriums varies with occupancy, RT60 measurements were taken in an empty condition since this approach provides a normalized sound environment that can be easily compared amongst churches. Furthermore, the majority of available bibliographic data is for unoccupied situations. It is also possible to account for the presence of audience when processing data.

Fourth, architectural acoustics comprises the fields of building acoustics and room acoustics. This study is limited to room acoustics, i.e. the behaviour of sound inside the room when the source of sound is in the same space

1.9. BREAKDOWN OF CHAPTERS

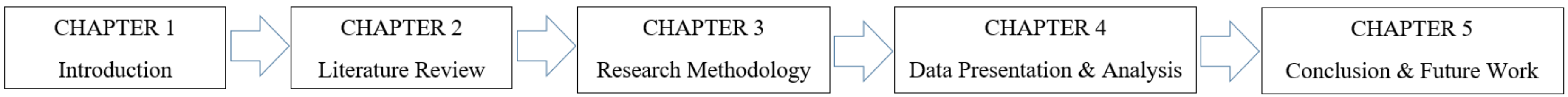

Figure 1. Breakdown of Chapters
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This research is divided into five chapters. Chapter 1 consists of the background, the problem, research objectives and questions, justification, significance and limitations of the study.

Chapter 2 is a review of existing published, unpublished and internet literature on church building acoustics. The areas reviewed include the development and history of church building acoustics, general concepts of acoustics and the relationships between these concepts, and the geometric and acoustic parameters for characterization of church buildings.

Chapter 3 gives an account of the research process and the procedures followed in meeting the objectives of the research as well as the instruments used to gather the data.

Chapter 4 presents the data gathered during the study and the results of geometric, acoustic and statistical analysis of the data as well as interpretation of the results.

Conclusions and recommendations for further study in church auditorium acoustics are presented in Chapter 5.

CHAPTER TWO – LITERATURE REVIEW

2.0. INTRODUCTION

This section provides a survey of existing published, unpublished, and online material on church building acoustics. The areas reviewed include the history of architectural acoustics, development and history of church building acoustics, general concepts of room acoustics and the relationships between these concepts, and the geometric and acoustic parameters for acoustic characterization of church buildings.

2.1. INDOOR COMFORT

Within the built environment, comfort is a state of physical ease and well-being for occupants as they carry out the specific tasks for which a space was designed. (Saint-Gobain, 2016).

According to Bluyssen (2009), the interior environment is composed of four main variables that have a direct impact on how inhabitants experience the indoor environment through their senses. These include thermal comfort/indoor climate, indoor air quality, lighting or visual quality, and acoustic quality. Indoor climate is determined by temperature, humidity, and air velocity. Visual quality is determined by factors such as illuminance, view, reflection, and luminance ratios. Indoor air quality comprises of factors such as internal air pollution, odour and fresh air supply. Acoustic quality is determined by outdoor sounds, indoor sound, and vibrations. These factors also have an effect on the occupants' mental and physical state (health and comfort).

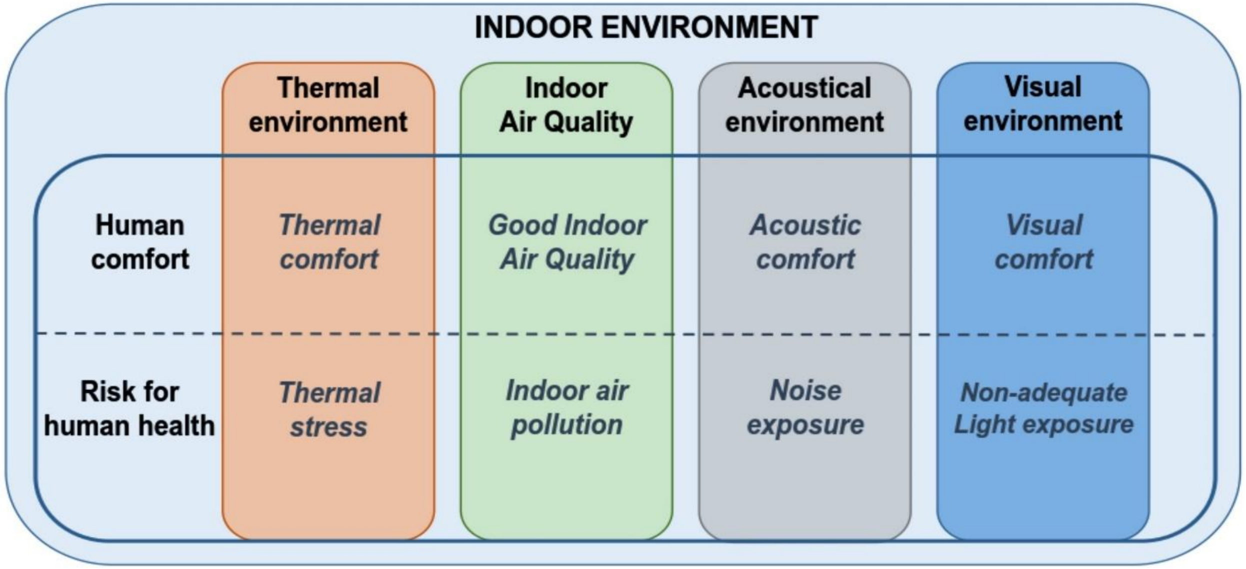

Figure 2. Main aspects related to the comfort and to the risk for human health for the four indoor environmental quality factors.

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2.1.1. Acoustics in the built environment

Acoustics in the built environment comprises the fields of environmental acoustics and architectural acoustics. Environmental acoustics, also known as architectural sound control, seeks to create environments that offer optimal hearing conditions in both enclosed and open spaces by shielding inhabitants of indoor and outdoor architectural spaces from unwanted noise and vibrations. The primary focus of environmental acoustics is outdoor vibration and noise originating from traffic, industry, transportation, exposed mechanical equipment in buildings, construction sites, road repairs, advertising, sports and other human activities (Doelle, 1972).

Architectural acoustics comprises of building acoustics and room acoustics. The primary focus of building acoustics is the transfer of sound between rooms or from the exterior of a room to the interior (and vice-versa) through building elements such as walls, floors, doors and windows. Room acoustics deals with the behaviour of sound inside a room when the source of sound is in the same space (Ginn, 1978).

2.1.2. Indoor Acoustic comfort

It is important to define the concept of acoustic comfort since it is often erroneously interpreted as the absence of, low levels of, or acceptable levels of noise in a place (Vardaxis et al., 2017).

According to Acoustic Lab (2018), Acoustic comfort is a psycho-physical state in which an individual enjoys a sense of well-being in relation to the specific activity that they are performing in a given place. It is the outcome of an appropriate balance of acoustic characteristics in a setting, and not a total absence of noise.

According to Vardaxis, Bard, & Persson, (2017), acoustic comfort is a psychophysical condition achieved for a specific activity in a space by providing the adequate level and quality of desired sounds, combined with isolating or reducing unwanted sounds (noise).

A space and its acoustic quality should benefit individuals and their activities within the space. Room acoustic comfort is achieved by creating the proper acoustic circumstances. Three elements are crucial: the people, the room, and the type of activity that will take place in the room. Good room acoustics entails tailoring the acoustics to the activities in the space. (Svenssonv & Nilsson, 2008).

2.2. RESEARCH IN ACOUSTICS AND ACOUSTIC COMFORT

2.2.1. Introduction

According to (Carvalho, 1994), acoustics in church buildings as a scientific field does not have a precise date or place of origin and church acoustics has not been studied well enough in its historic evolution. The British architect Sir Christopher Wren wrote about a program for 50 new churches in London, stating that the average parish preacher was not intelligible farther than about 15 m to his front, 9 m to either side and 6 m to his back. Later, in 1984, Lewers and Anderson backed the 15-meter distance, suggesting that a listener should be 17 meters or fewer from the pulpit for articulation loss to be less than 30%, as per Peutz formula.

According to Knudsen & Harris as cited in Carvalho (1994), almost all forms of church buildings have developed from the oblong, the circle, or the Greek or Latin cross. Forces other than acoustics shaped the design of church buildings, such as the different functions of the church, traditions, rituals and the search for architectural splendour.

Carvalho (1994) further states that since the late 19th century, some scholars undertook elementary research studies on the subject of church building acoustics. Earlier studies (1875-1928) provided simple guidelines about acoustics in churches for specific Christian denominations including Methodist, Episcopal, and Evangelical (Carvalho, 1994). Beginning in the early 1950's Parkin and Taylor began measuring reverberation times in St. Paul's Cathedral while and Raes and Sacerdote began measuring reverberation times in Roman basilicas. More researchers measured reverberation times in places of worship in the following years including McCandless and Lane 1963; Shanldand and

Shankland 1971; Fitzroy 1973; Tzekakis 1975/79/81; Angelini, Daumas and Santon 1975; Fearn 1975; Popescu 1980; Lewers and Anderson 1984; Lopez and Gonzalez 1987; Marshal, Day and Elliot 1987; Abdelazeez, Hammad and Mustafa 1991; Lubman and Wetherill 1985.

Researchers have proposed several additional subjective and objective acoustical parameters since 1950. However, their application has almost exclusively been in the acoustical analysis of concert halls and auditoria. (Beranek, 2005)

2.2.2. The Ten Books on Architecture - Vitruvius

According to Raichel (2006), architectural acoustics began about 20 BC, when the Roman engineer and architect Vitruvius published an essay on the acoustic features of theatres. He portrayed sound as a wave similar to a water wave expanded in three dimension, which, when interrupted by obstacles, would flow back and break up subsequent waves. He characterized rising seats in antique theatres as being designed to limit sound deterioration.

2.2.3. From Sabine to Fitzroy

The work of W.C. Sabine in early 1900s on reverberation and other topics marked the beginning of scientific room acoustics. (Niemas, Sadowski, & Engel, 1998). Sabine established that after a source generated sound waves in a space, listeners heard both the direct sound waves from the source as well as multiple reflections from walls, floor, and ceiling. The reverberant sound was created by these reflections. After the source was turned off, the reverberant sound could be heard for some time before becoming weaker. Sabine observed that the reverberation time of an auditorium, as he termed it, was connected to the auditorium's volume as well as the ability of the walls, ceiling, floor, and occupants to absorb sound. Using the assumptions stated above, he created an empirical relationship that could be used to calculate the reverberation time.

Sabine chose a 512Hz note as his reference point. He then timed how long it took for the sound to drop down by 60 decibels, or to become completely inaudible. Sabine published his equation for determining a room's reverberation time in October 1898.

Sabine had to make numerous simplifying assumptions in order to arrive at the equation. These were as follows: (1) the sound field in the room was completely diffuse; (2) absorption was uniformly distributed across the room; and (3) the reverberation time measured for a 512Hz tone would be indicative of all frequencies in the room. (Whealy, 2018).

Sabine's work was so important to scientists that his equation became the starting point for acoustic calculations for more than a century, and his reference frequency of 512Hz (later, 500Hz) became the accepted reference for quoting reverberation time. Sabine's original assumption, on the other hand, had significant ramifications. He had to assume a perfectly uniform distribution of sound energy throughout the space since he was using a statistical technique to calculate reverberation time. As a result, using Sabine's equation to predict the reverberation time of a space with a non diffuse sound field was inappropriate. Misapplication of Sabine's equation (or any other statistically based reverberation time equation) resulted in a significant difference between predicted and measured and reverberation times in non-diffuse rooms, leading to erroneous conclusions about the general usefulness of predicting both RT_{60} and the surface treatment requirements in the room. (Whealy, 2018).

For a long time, the reverberation time of rooms was the most important factor of room acoustic estimation and design as calculated with reasonable accuracy from room data using the Sabine's formula (Niemas et al., 1998).

Since Sabine’s formula overestimated the reverberation time for high absorption coefficients, Eyring developed a formula in 1930 that established a slightly different relationship between the same parameters as in the Sabine’s formula. Sabine's formula was more accurate in larger rooms with uniform absorbing material distribution, whereas Eyring's formula produced better results in small rooms with a wide range of surface treatments. (Valente, Dunn & Roeser as cited in Gonzalez, 2009).

In 1950, Stephens and Bate suggested a simple empirical formula for the optimum reverberation time (Hassan, 2009). In 1956, E. Mayer and R. Thiele undertook acoustical measurements in 31 different rooms with volumes ranging from $550m^3$ to $22000m^3$) as follows:

a) Measuring reverberation time as a function of frequency,

b) Recording of reverberation curves using the "impulse glide method"

c) Measuring sound pressure as a function of frequency and calculating the frequency irregularity,

d) Recording of the directional distribution of the sound at 2 kHz and calculating "directional diffusiveness", and

e) Recording reflections of a short pulse and measuring the "50% energy part".

Results of the above measurements showed that only the methods d and e, developed according to the geometrical conception of room acoustics, gave more information for judgement of the hearing conditions of a certain place in the room than reverberation time did.(Niemas et al., 1998).

In 1959, Fitzroy observed that when the average absorption was approximately the same in all the directions, reverberation times according to Sabine’s and Eyring’s formulas were quite close. However, when the distribution of absorption was unequal in terms of direction and in the average absorption per square metre, the reverberation time measured by Fitzroy was much longer than the Sabine’s and Eyring’s formulas predict. Fitzroy gave a reverberation time formula, which in the case of non-uniform distribution of absorption seems to be more accurate than the Sabine’s and Eyring’s formulas (Knudsen as Cited in Niemas et al., 1998).

2.3. HISTORY OF ACOUSTIC COMFORT CONSIDERATIONS IN CHURCH AUDITORIA

In any church, two categories of acoustic issues play an important role, namely the protection of the building interiors against external noise and vibrations, and the acoustics of the church interiors. The evolution and formulation of these issues over centuries was specific to circumstances of a given period in reference to site planning needs, culture of the society, building style of the period, structural and material solutions, decorative art, and availability of financial means. Another major influence was historical events such as invasions, war, and discrimination in the different periods of the world history. All these factors influenced the status of church structures, including their acoustics. Protection of church buildings against noise has developed over ages and resulted from functional, structural and material solutions of these structures. The acoustics of interiors, however, resulted not only from functional solutions but also from styles governing in particular periods and lack of sound amplification devices (Niemas et al., 1998).

2.3.1. Acoustics in the bible?

Exodus 26:7 may include the earliest documented mention of acoustical specifications to weave eleven curtains made from goat hair to cover over the tabernacle, with specific instructions for each curtain to be four cubits wide and thirty cubits long, and all curtains to be equal in size. The story goes into detail about the fabrication and hanging of these curtains over the tabernacle walls to ensure that they hang in sound-absorbing folds. More specifics on the tabernacle's construction followed. No substitution of materials or deviation from the prescribed procedure was permitted. (Raichel, 2006).

2.3.2. Speech Communication in the Synagogue

The synagogue service has always emphasized a spoken liturgy. In Hebrew religion, the spoken word was fundamental in the form of the "Shema," a standing prayer with the command to "Hear, O Israel." The ancient synagogue was used for prayer, learning, and community gatherings. The term synagogue refers to a "meeting place." The synagogue's acoustic communication route most likely favored discourse, while there was enough reverberation to permit communal singing. The liturgy of the synagogue was altered for early Christian worship. Synagogues or house churches were common places of worship in the first Christian centuries. A lector read Old and New Testament lessons, which were followed by a sermon delivered by the presiding officer, who sat in a prominent position. A cantor would sing a short recital in inflected monotonees, as is customary in synagogue traditions. (Lubman & Kiser, 2002).

2.3.3. Home Gatherings

Before the middle of the first century, Christians congregated at predetermined times in the evening to eat together and for companionship (Stewart, 2011). Twenty years after Jesus' death, Christians began to have structured periodic assemblies. These regular gatherings were held on Sundays at various places, with the majority taking place in private homes. Because they were held in small flats, house churches had a capacity of 15 to 20 people. The great majority of people lived in one- or two-room flats above or behind shops. When a house church got larger, it simply started another house church nearby. A house church often gathered in the largest room of a private household, often the dining room. (Comiskey, 2015). For special gatherings people came together in much larger numbers in public lecture halls or market places (Ediae et al. 2017)

2.3.4. Conversion of homes to Churches

Prior to the year 313 C.E. when Emperor Constantine recognized Christianity with the Edict of Milan, Christian worship took place in homes, at the graves of saints and relatives, and even outside. Dura Europos, a Roman outpost in Syria, has one of the earliest remaining churches (about 254 C.E.). This modest church was created by converting a typical Roman house with a square form and a courtyard in the centre. Members of the church demolished one of the walls to make more room for teaching and Eucharistic celebrations. One of the chambers was converted into a baptistery, which has some of the oldest Christian paintings still in existence. (Freeman, 2017).

2.3.5. Post Constantinian Era – From Speech to Music

Until Emperor Constantine Christianized the Roman Empire, Christianity and the construction of churches were mainly prohibited. In 313 CE, the Emperor issued the Edict of Milan, which provided legal status to Christianity as well as most other religions. This edict, together with the establishment of a Christian empire, heralded the first significant movement in church architectural design(Schroeder, 2016). Previously, Christians were a tiny society, but after 313 CE, Christianity became the official faith of the Roman Empire. As a result, churches were constructed on a grander scale than before. The creation of the Constantinian church marked a significant milestone in the Christian narrative, with ramifications that continue to this day. (Bess, 2003).

Shortly after his conversion and subsequent legalization of Christianity, Constantine launched a large building drive in key cities such as Rome, Jerusalem, and Constantinople to establish his new official religion. To satisfy the space demands of the rising Christian liturgy (such as larger crowds and complicated processions), Constantine modified the basilica which was previously utilized solely as a municipal facility. (Freeman, 2017)

Basilicas in Rome were lengthy, rectangular structures having a nave, a broad central aisle and two aisles on the side. The magistrates sat in at least one semi-circular apse, usually at one end of the basilica, and heard their cases there. In many respects, the basilica was the ideal structure to convert to a church since it did not have the pagan overtones associated with Roman temples. It was also large enough to serve the growing population of Christians. (Freeman, 2017).

Paleochristian church structures had harmonic proportions with cross-shaped plans, brick walls, and low flat wooden ceilings with no vaults. These factors in fact enabled good acoustics (Fernandez et al., 2002).

2.3.6. Early Christian basilicas

The Roman basilica's basic structure was maintained in early Christian basilicas, with an addition of distinct Christian features. The bema was retained as was in the synagogue and served as an elevated platform from which priests spoke (towards the end of the Middle Ages, the bema was was often affixed to a pillar in the nave near the central aisle). In many churches the ambo was added - a higher platform accessible through steps, from where sermons were proclaimed. In these churches, the bema was used for reciting prayers and reading of the scripture. The transept, which was added towards the apse end of the building to make a cross-shape and give extra room, was another distinctly Christian architectural element. (Freeman, 2017). These church buildings were large, roofed, and very reverberant (Lubman & Kiser, 2002).

Large Roman Catholic churches featured extremely reverberant acoustic conditions for liturgical music and chanting from the Middle Ages and the Renaissance (Lee, 2003). During this period, it appears that the Christian church largely favoured musical liturgy over spoken liturgy. The musical liturgy took advantage of the new cathedrals' time dispersive qualities in new and creative ways. (Lubman & Kiser, 2002).

2.3.7. Byzantine Church Buildings

For almost a thousand years, Byzantine architecture inspired church construction in Greece, Italy, and beyond. It was distinguished by stone construction, shallow domes supported by pendentives, round arches, and extensive use of beautiful paintings, coloured glass mosaics, and marble cladding covering whole interiors. (Ching, 1995). Hagia Sophia, a greek orthodox church built in the 530s is one of the most impressive surviving example of Byzantine architecture (Craven, 2019).

2.3.8. Romanesque Church Buildings

The Romanesque architectural style was the first to dominate Central and Western Europe. The style first appeared in Italy and Western Europe in the ninth century and flourished until the 12th century, when Gothic architecture gained dominance. (Ching, 1995). It incorporated a number of related regional styles, such as semicircular arches (for arcades, doors, and windows), groin or barrel vaults supporting the nave's roof, large plain stone piers and few windows, galleries above side aisles , a massive tower above the nave and transept crossing, small towers at the western end of the church, balanced articulation of volumes and surfaces, and decorative arcades. (Fernie, 2014). These features generated cave acoustics characterized by such high reverberation times that resulted in poor intelligibility and sound focalization (Ampel, 2017).

2.3.9. Gothic Church Buildings

The Gothic architectural style was born in France in the 12th century and lasted until the middle of the 16th century throughout the western half of Europe. The pointed (Gothic) arch, rib vault, and flying buttress, offered a solution to the difficulty of constructing very tall structures while allowing sufficient natural light in. (Ching, 1995). Large volumes were the dominant feature of church buildings and cathedrals. The vaults' excessive heights and the pronounced reflective parallel walls resulted in cavernous spaces with high reverberation and echoes. However, other elements played a role to improve the acoustics, such as big stained glass windows that aided bass sound absorption, and deep side chapels that acted as bass sound diffusors (Ampel, 2017). The expanse of walls was also broken up by richly decorated fenestrations (Ching, 1995).

2.3.10. Renaissance Church Buildings

Renaissance architecture refers to several architectural styles that developed in Italy in the 15th and 16th centuries and spread over Europe until the 16th and 17th centuries, when the Baroque style emerged. The symmetry, precise mathematical relationships between pieces and overall simplicity were the main characteristics of the style. (Ching, 1995). Renaissance churches had flat wood ceilings and harmonic proportions with non-cross shaped plans. Rich ornamentation diffused treble sounds and side chapels aided bass sounds diffusion (Fernandez et al., 2002).

2.3.11. Baroque Church Buildings

Baroque architectural style was a richly decorative and dramatic style that originated in Italy at the beginning of the 17th century and expanded throughout Europe. It was first used by the Catholic Church, specifically the Jesuits, to resist the Protestant Reformation with a new style of architecture that evoked amazement and awe. Italy, Spain, Portugal, France, and Austria all embraced it in their churches and palaces. Baroque era architects made basic elements of Renaissance style such as colonnades and domes bigger, higher, and more ornate. (Bailey, 2003).

Baroque era church buildings had more side chapels, dense decoration, tapestries, plaster works, carpets, and alternate convex and concave shapes which helped to reduce focalization and spread bass and mid sounds. Circular plans were common in this era (Fernandez et al., 2002).

2.3.12. Neoclassicism Church Buildings

Neoclassicism brought back the spirit of Renaissance and turned away from circular plans (Fernandez et al., 2002). The style dominated architecture in America, Europe, and several European colonies in the transition between the 18^{th} and 19^{th} centuries. Church buildings were grand in scale with features such as renaissance style domes, extensive use of Roman and Greek orders and decorative patterns, simple details with strong geometric compositions, dramatic columns and blank walls (Ching, 1995).

2.3.13. Back to speech with Reformation

Protestant Reformation began in 1517, fractured the unity of the Western Europe church as an institution, and birthed a third branch of Christianity. The reformation church acoustics were intended meet the doctrinal need to understand sermons spoken in the vernacular. To improve speech clarity, Reformation church architects decreased reverberation. The old music written for more reverberant rooms, did not work with the new acoustics, which was an unforeseen consequence. This necessitated the creation of a new musical liturgy to meet the doctrinal demands of Protestantism. Liturgy was the engine for architectural and acoustic design. Luther popularized chorale music with simple, catchy melodies. (Lubman & Kiser, 2002).

2.3.14. Modern Age Church Buildings

Depending on the liturgical style, modern worship buildings had a variety of functions. The organ and Gregorian chants were ideally suited to the cathedral's reverberant acoustics. However, for cathedral-style churches, the requirement for good speech intelligibility was equally important. Evangelical churches, on the other hand, had cathedral-like volumes, but played contemporary popular music using electronic organs. (Lubman & Kiser, 2002).

Many countries, including Korea and Japan, needed to reconstruct church venues after WWII, and they began to adopt sound reinforcement systems. As the number of people attending grew, larger pipe organs and larger rooms became necessary, and church architecture began to shift. At the same time, classic instruments such as pianos and pipe organs were used alongside mechanical equipment and new musical equipment such as synthesizers and electronic organs. These changes necessitated attention to the acoustic quality of churches and established the need for acoustic

acoustic professionals to help achieve natural acoustics by guiding architectural design, and advising on proper sound reinforcement system installation (Din, Yong, & Razak, 2016).

2.3.15. Church auditoria in the 21st century

Many contemporary churches use electronic sound reinforcement to distribute speech and music throughout the auditorium. Worship leaders sing popular music accompanied by electronic equipment. The acoustic resembles a theatre or sound and television studio (Lubman & Kiser, 2001). Contemporary church auditoriums serve various functions such as worship, music concerts, classes, meetings, and recreation. Each of these functions requires specific acoustic conditions (Din et al., 2016)

In the modern and contemporary era, there is evidence of acoustical considerations to some extent in the design of church buildings. Modern churches are not excessively over-elaborate. They have plain plastered walls and panelled diffusors as well as appropriate ceiling shapes (Fernandez et al., 2002)

2.4. ACOUSTIC DESIGN CONSIDERATION IN CHURCH AUDITORIA

2.4.1. Church Acoustic Design Goals

The same acoustic qualities that make a church auditorium good for speech also make it bad for music, and vice versa. The needs of speech and music must be balanced in rooms designed for mixed use. (Long, 2014).

According to Barron as cited in Gou & Lau (2017), the acoustical design goals for a church auditorium should include the following respects:

a) The auditorium volume and floor area to be at a practical minimum to shorten sound paths and for adequate loudness in every part of the auditorium.

b) Providing optimum reverberation characteristics in the auditorium to facilitate speech and music.

c) Uniform distribution of the sound energy within the room.

d) The room to be free from acoustical defects.

Table 2.1 below lists Volume per seat values for auditoriums according to Egan.

Auditorium Type	Minimum	Optimum	Maximum
Rooms of Speech	2.3	3.1	4.3
Concert Halls	6.2	7.8	10.8
Opera Houses	4.5	5.7	7.4
Catholic Churches	5.7	8.5	12
Other Churches	5.1	7.2	9.1
Multipurpose Halls	5.1	7.1	8.5
Cinemas	2.8	3.5	5.6

Table 1. Volume per seat values for auditoriums.

Copyright. Egan as cited in Gou & Lau, 2017

V.O. Knudsen (1932) divided church buildings into three groups as country churches, village churches and city churches and proposed optimal reverberation times for church auditoriums according to their volumes.

Reverberation time for churches	Volume (m^3)					
	1000	2000	4000	8000	16000	32000
Roman Catholic churches	1.5	1.6	1.7	1.8	1.9	2.1
Protestant and Jewish churches	1.3	1.4	1.5	1.6	1.7	1.8
Christian Science churches	1.1	1.2	1.3	1.4	1.5	1.6

Table 2. Optimal values of reverberation times for church auditoriums

Copyright. Knudsen as Cited in Niemas et al., 1998.

2.4.2. Church Types And Sizes

Churches resemble multiuse auditoriums in that both require good acoustics for speech and music. Adjustable acoustic systems are not an option during services since speech and music acoustics must coexist. In almost every worship space, speech intelligibility is vital, but the ideal environment for worship music will vary depending on the type of music played.

A gospel choir that is amplified requires a short reverberation time and high definition. The choir requires a rather long reverberation time without amplification. Size is also an important factor to consider. The acoustics of a cathedral in a small church will sound unnatural, just as the acoustics of a lecture hall will be dry in a large cathedral. The degree of difference in the acoustical designs of worship spaces is highlighted by variations in church architectural styles. (Gonzalez, 2009).

2.4.2.1. Cathedrals

Big pipe organs and large choirs are central features in large cathedral-like worship spaces. The music portion of worship requires long reverberation times, but speech must also be intelligible. The common modern approach to reconcile these seemingly opposite acoustic needs is designing:-

a. A large spacious room with hard sound-reflective surfaces for effective distribution of music across the entire space, and
b. A sound reinforcement system to direct amplified speech energy to the congregational sitting area without directing large amounts of amplified energy towards the ceiling and wall surfaces (Gonzalez, 2009).

2.4.2.2. Small churches

Music is important but due to the small size, a long reverberation time is not possible. Because of the short distances, speech may be intelligible without the need of electronic amplification. Small and medium-sized churches can easily extend their music acoustic range using electronic surround systems (Gonzalez, 2009).

2.4.2.3. Medium-sized churches

Many churches are in the middle of the scale between cathedrals and small churches. Although cathedral acoustics are unlikely in such spaces, good concert hall acoustics are feasible. Hard and sound-reflective surfaces should be used. Pew cushions can significantly reduce the acoustic difference between full and empty conditions. A pipe organ of moderate to large size can be installed. A relatively simple central cluster sound system will ensure good speech intelligibility (Gonzalez, 2009).

2.4.2.4. Large Evangelical churches

In a large evangelical church, an electronic organ, a piano, and an amplified choir are the main music sound sources, playing contemporary popular music. Preachers employ a wide dynamic range of voice levels, the worship service is televised, and the entire church is like a large TV sound studio. The acoustic design of these large evangelical churches is similar to that of a large speech auditorium, with reverberation times in the 1.0 to 1.5 sec range. Rear walls should be sound absorbing and ceilings arranged so that reflections reach the listeners' ears within 30ms of the direct sound. The sound amplification systems often resemble the portable systems used for contemporary popular music concerts.

(Lee as cited in Gonzalez, 2009).

2.5. ROOM ACOUSTICS TECHNICAL BASICS

Fay, (2013) defines sound as a push and pull molecular chain reaction that begins with an oscillation or vibration and moves at a relatively slow rate. If the vibrations stimulate the neighbouring air molecules with enough energy for the ear to perceive, they form a sound we can hear. There is no sound produced by the air molecules themselves.

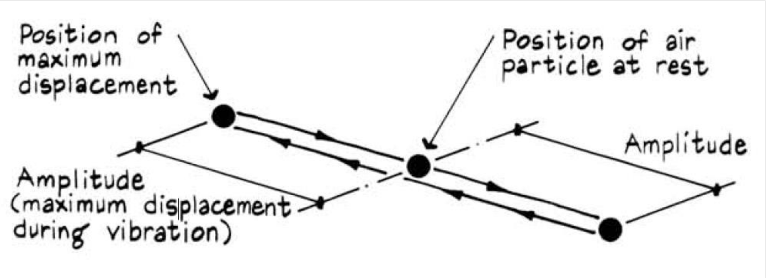

Figure 3. A complete cycle of a displaced air particle

Copyright. Egan, 2007

As illustrated in Figure 7, when an object vibrates, it causes the neighbouring air molecules to vibrate in a longitudinal motion, creating regions of high and low air pressure. Air particles are compressed together in the high pressure regions and spread apart in the low pressure regions. These regions are known as compressions and rarefactions respectively (Henderson, 2018).

Sound moves through air in all directions, can be easily controlled and directed into relatively defined zones, and with proper management, sound is responsive and adaptable to human demands. (Fay, 2013).

2.5.1. Pure Tones & Complex Sounds

A vibration that is produced at a single frequency is a pure tone. (Egan, 2007) i.e. a tone with a single frequency and no harmonics as illustrated in Figure 4. A sine wave is a pure tone (Gracey & Associates, 2019). It is characterised by its frequency (number of cycles per second) or its wavelength (distance it travels within a period) and the amplitude (maximum displacement). When a tuning fork is struck, nearby air molecules vibrate producing a nearly pure tone. (Egan, 2007).

A complex sound is one sound that is not a simple oscillation (Gracey & Associates, 2019). Most everyday sounds are complex, comprising a range of pressures that vary through time as illustrated in Figure 5 (Egan, 2007).

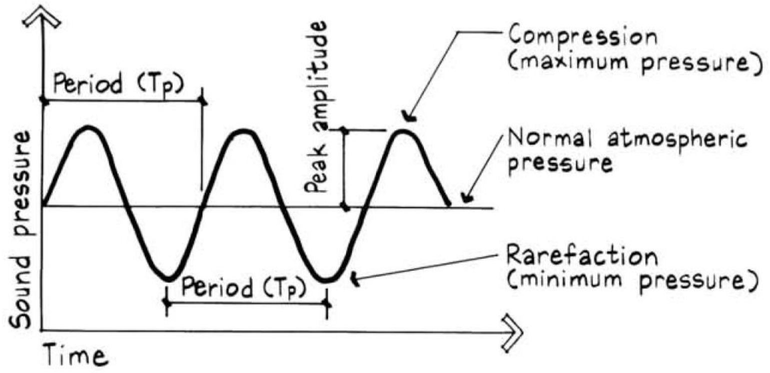

Figure 4. Variation in pressure caused by striking a tuning fork. Copyright. Egan, 2007.

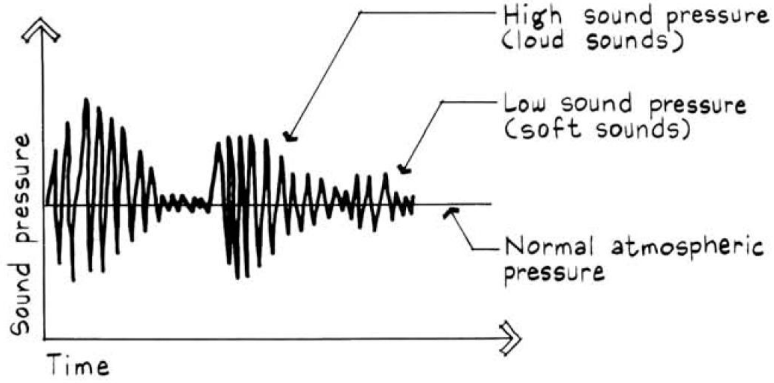

Figure 5. Variation in pressure caused by speech, music, or noise. Copyright. Egan, 2007.

The physics of sound can be described in three ways: Frequency - or tone, pitch, & wavelength; Sound level - or strength, energy, loudness & amplitude; and propagation - or elapsed time & path.(Barron, 2009).

2.5.2. Amplitude, Frequency, Wavelength & Speed of Sound

The amplitude of a sound wave refers to the maximum amount of displacement of an air particle from its rest position (Henderson, 2018). The magnitude of the pressure difference determines the amplitude of a sound wave. The range of pressures to which our ears can respond, however, exceeds a million to one, and the response is non-linear. (Barron, 2009). For this reason, sound pressure measurements are represented on a logarithmic scale. The decibel scale is the most widely used logarithmic scale for expressing sound levels. (Ginn, 1978).

When sound travels through a medium, the particles of the medium vibrate in a push and pull (back and forth) motion at a specific frequency, regardless of what is producing the sound waves by vibrating. When a wave passes through a medium, the wave frequency is the number of complete vibrations (cycles) made back-and-forth by a particle of the medium per unit of time. The Hertz (abbreviated Hz) is the unit of frequency, with 1 Hertz equalling one vibration per second. The higher the frequency, the more complete cycles there are. The human ears' perception of frequency is known as pitch. Low frequencies are perceived to be "boomy," whereas high frequencies are perceived to be "screechy" or "hissy." The human ear detects frequencies from 20Hz and 20kHz, but the latter diminishes as one becomes older (Barron, 2009). Most sound sources, as shown in Figure 6, contain energy at a wide range of frequencies. The frequency range is split into segments (called bands) for sound specification, analysis and measurement. The mid frequencies of octave bands include 31.5, 63, 125, 250, 500, 1000, 2000, 4000, 8000, and 16,000 Hertz. In sound analysis, an octave band represents a frequency ratio of 2:1 (Egan, 2007).

As seen in Figure 7, wavelength is the length between successive pressure maxima or minima. The speed of sound is equal to frequency x wavelength. A sound in the centre of the 1000 Hz frequency band therefore has a wavelength of 0.343 m. Audible sounds have a wavelength range of 17 metres at 20 Hz to 17 millimetres at 20,000Hz. This suggests that sound wavelengths are comparable to ordinary object sizes and dimensions of surfaces in a room. Sound waves typically bend around objects at low frequencies and long wavelengths. At High frequency on the other hand, object dimensions are often larger than wavelengths and sound waves are similar to light waves, propagating as straight lines and generating shadows. (Barron, 2009).

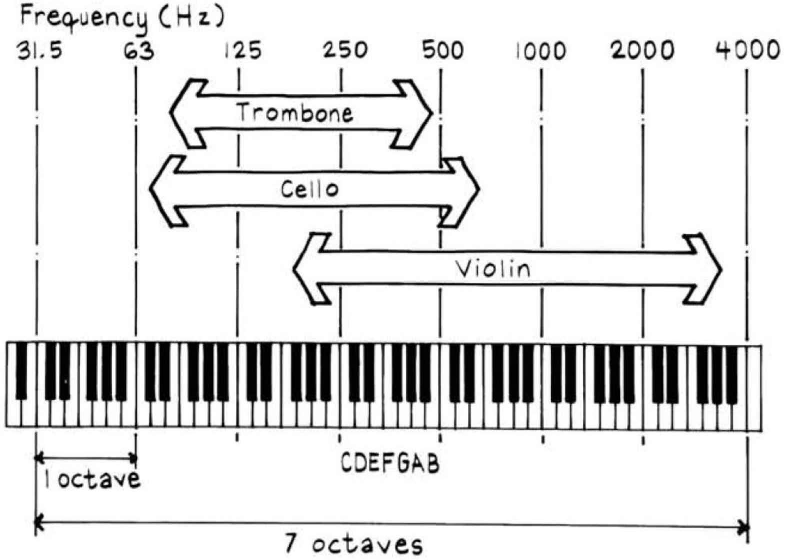

Figure 6. Octave Band ranges for various instruments

Copyright. Egan, 2007.

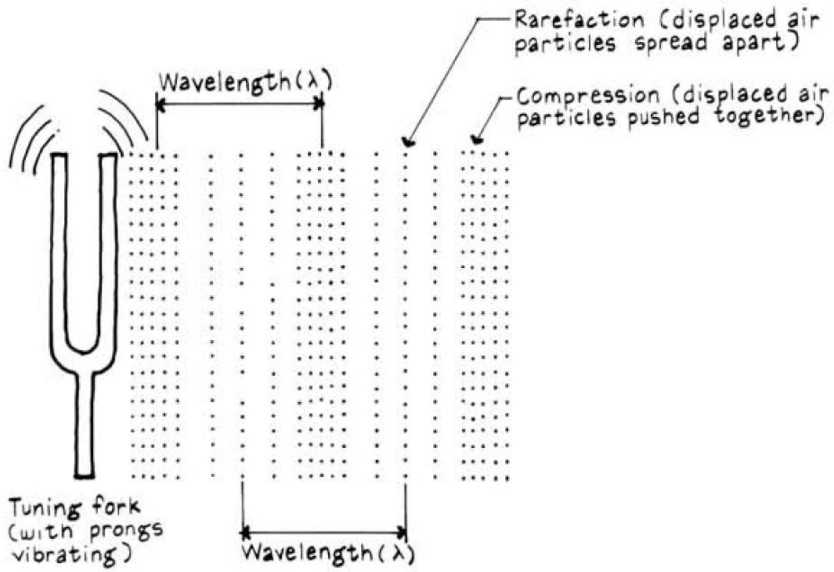

Figure 7. Wavelength of a vibrating fork.

Copyright. Egan, 2007.

For a sound wave, speed is the rate at which a vibration is transmitted from one particle to the next. Speed is the distance travelled by a disturbance per unit of time, whereas frequency is the number of vibrations made by a particular particle per unit of time. It is important to differentiate the two frequently confused metrics of frequency (how often) and speed (how fast). The speed of sound is defined as the distance travelled per unit of time by a point on the wave (such as a rarefaction or compression). The unit for speed is meters/second (abbreviated m/s), where **Speed = Distance/Time.** In general, all rarefaction and compression regions travel at a constant speed of 343 m/s at 20°C. This is the speed of sound. (Barron, 2009).

Wave velocity (v), wavelength (λ), frequency (f), and time (T) are related by the equations $f = 1/T$ and $\lambda = v/f$ (Gracey & Associates, 2019).

2.5.3. The Audible Range, Sensitivity of Hearing & Sound Spectrum

A vibration capable of creating a hearing experience is referred to as an audible sound. The human ear can respond to vibrations in air in the frequency range of 20 Hz to 20000Hz, with corresponding wavelengths of between 0.017 mm and 17m. (Gracey & Associates, 2019). This is the audible range as shown in Figure 8 and Figure 10. The threshold of hearing is the sound level below which a person's ear is unable to detect any sound. The measurement of sound levels in decibels is referenced to a standardized threshold of hearing equal to 2 x 10^{-5} Newtons/m^2 at 1000Hz. This value, which corresponds to 0 decibels, is widely accepted as a standard threshold. Hearing thresholds vary with frequency and low frequencies are strongly discriminated against by the ear for very quiet noises approaching the hearing threshold. As shown in Figure 9, at 1000Hz, about 0dB is required for a sound to be audible, while at 30Hz, about 60dB is required for a sound to be audible (Nave, 2019).

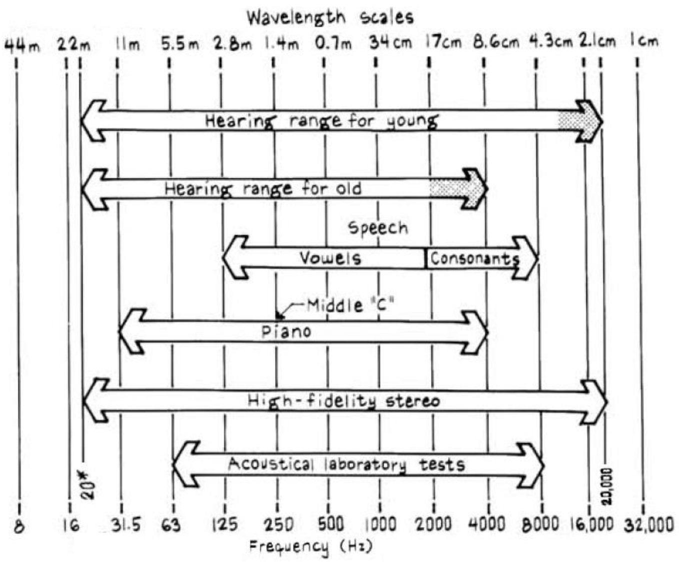

Figure 8. Frequency range of audible sounds

Copyright. Egan, 2007

For mid-range sounds around 60 dB, the discrimination is not so pronounced and for very loud sounds around 120 dB, the hearing response is nearly flat. The maximum sensitivity of the human ear is at about 3500 to 4000 Hz due to the resonance of the auditory canal (Nave, 2019).

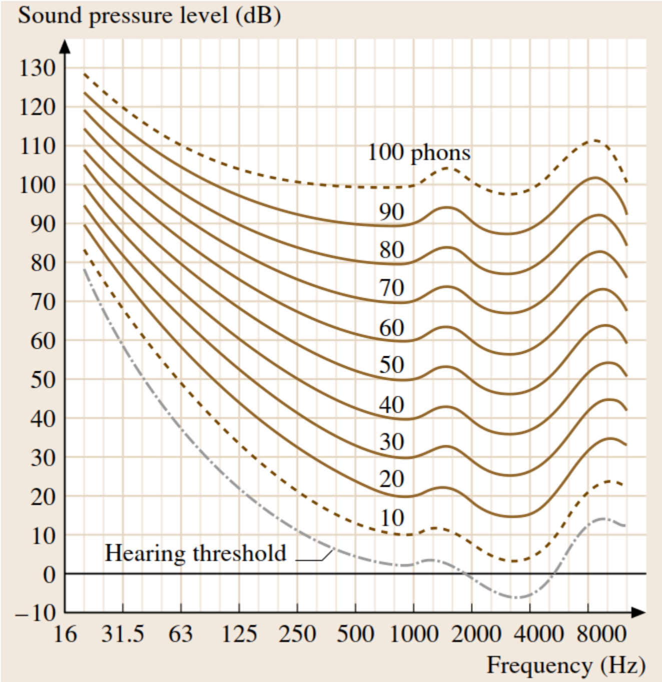

Figure 9. Equal loudness contours

Copyright. (Moore, 2007).

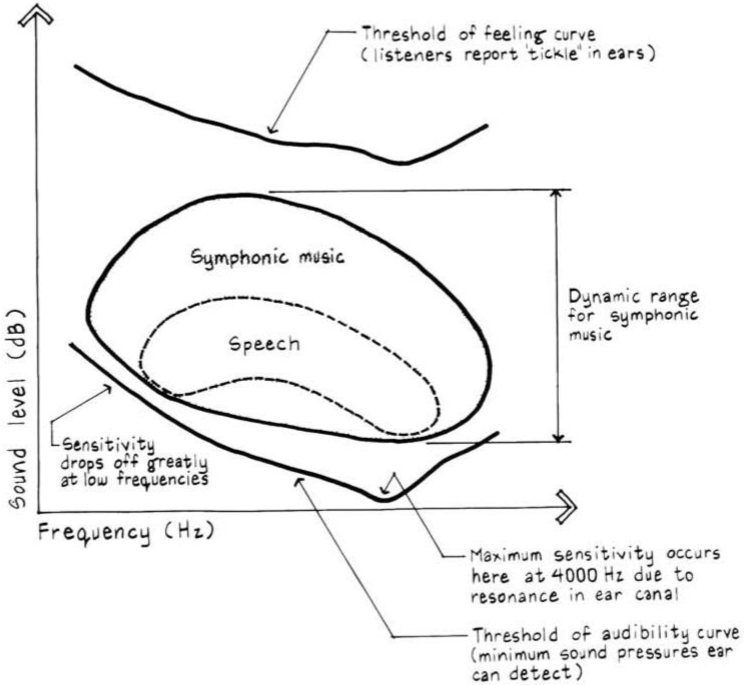

Figure 10. Audible Range

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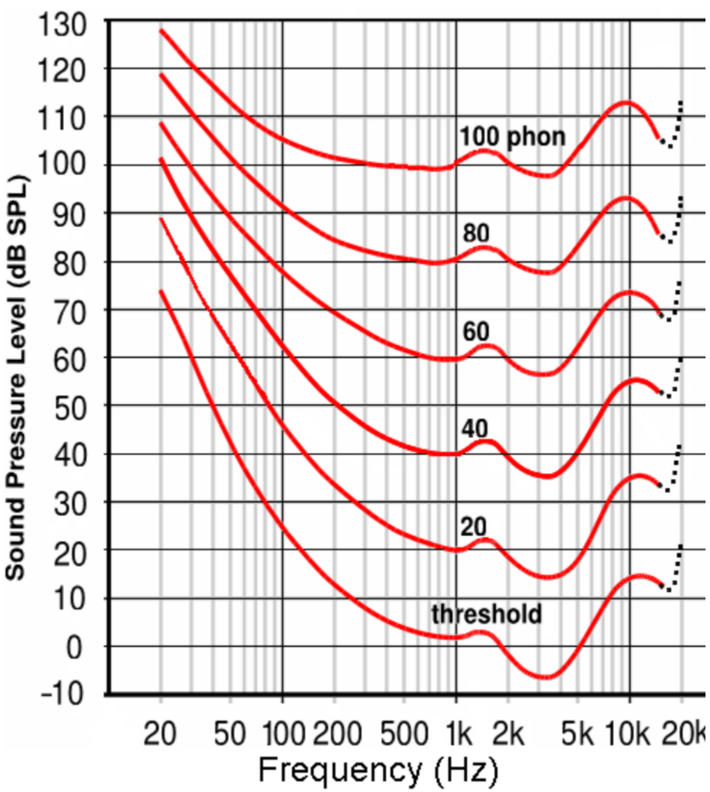

Figure 11. Normal equal-loudness level contours

Copyright. Sengpiel Audio, 2005.

Figure 11 shows Equal-loudness contours. They are a measure of sound pressure across the frequency range that is perceived as constant loudness by the listener. The unit of measurement for loudness is the phon. Sine waves with equivalent phons have equal loudness. (Sengpiel Audio, 2005)

The point at which a sound perception becomes painful is the threshold of pain.. The dynamic spectrum of human hearing extends from the threshold of hearing to the threshold of pain. (Nave, 2019). The pain threshold is subjective, ranging from 120 dBA to 140 dBA in literature, although 120 dBA is the most prevalent. (Gracey & Associates, 2019). However, many factors influence an individual's hearing sensitivity, including age, gender, ethnicity, and past exposure to high noise levels. Younger people are often more tolerant of loud noises than older people, but this does not mean that they are immune to the damaging consequences of loud sounds. (Nave, 2019)

A sound spectrum is a depiction of the magnitudes of complex sound components as a function of frequency, as seen in Figure 12 and Figure 13. Majority of sounds are complex, with varying levels of pressure, frequency, and level (Gracey & Associates, 2019).

Sound spectrum is data plotted to show the relationship between frequency and sound pressure level for meaningful analysis. The magnitude of sound energy at different frequencies is described by sound spectra. The breadth/width of octave bands is geometric (Egan, 2007).

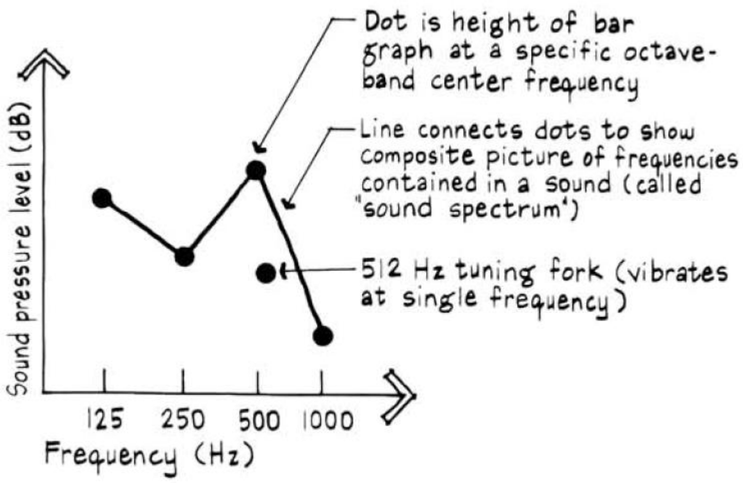

Figure 12. Line Graph Sound Spectrum.

Copyright. (Egan, 2007).

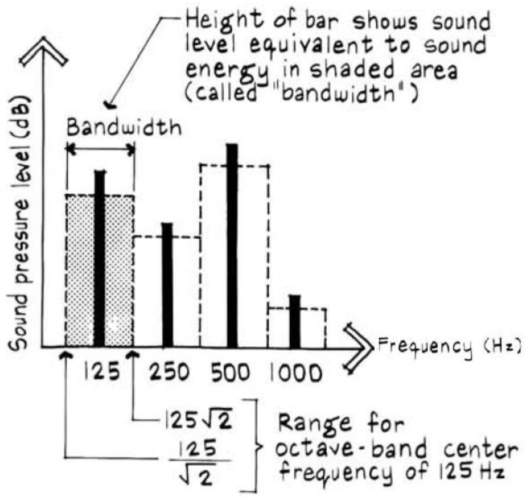

Figure 13. Bar Graph Sound Spectrum.

Copyright. (Egan, 2007).

2.5.4. Architectural Vs Room Acoustics

According to Trikustik GesmbH, 2015, architectural acoustics comprises the fields of building acoustics and room acoustics as shown in Figure 14. The focus of building acoustics is sound transmission between adjacent spaces or from the inside to the outside of a space (and vice-versa) through building elements such as walls, floors, doors and windows, whereas the focus of room acoustics is sound behaviour inside a room when the sound source is within the room. (Ginn, 1978). The key differences between building and room acoustics are summarized in Table 4.

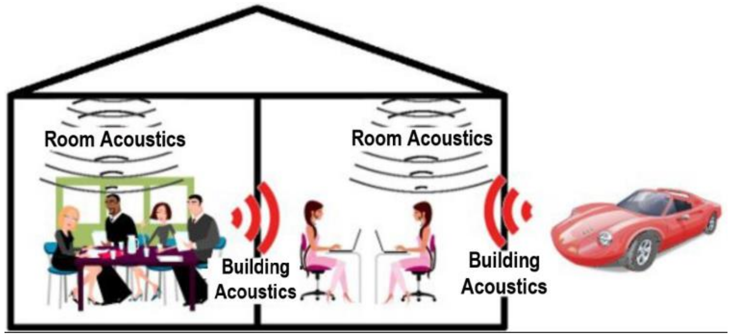

Figure 14. Architectural and Room Acoustics

Copyright. Trikustik GesmbH, 2015

In the dictionary of architecture and construction (2006), Harris defines room acoustics as the behaviour of sound waves in a room including how the waves are generated, transmitted and their effects. In other words, it is the entirety of the geometrical and surface characteristics of a room (such as the shape and size of sound scattering elements on surfaces, the overall sound absorption, and level of noise in the room), which influence how a listener perceives and judges the quality of music and speech generated in the room.

Acoustics significantly affect the wellbeing and productivity of the users in a building and architectural acoustics is therefore an important factor in the life cycle of many buildings - design, construction and operation (World GBC, 2014). Similar to lighting and the thermal environment, room acoustics is an environmental science that in the past century has become a recognized discipline (Egan, 2007).

Table ***3*** below shows the various elements of architectural acoustics.

Room acoustics	Mechanical vibration / noise	Isolation of sound	Electronic sound Systems
a) Cubic volume. b) Geometry and proportions – (Length : width) & (height : width) c) Selection and placement of finishes. d) Audience seating - Floor profile and distance from the speaker to the listener. e) Seats & Furnishing generally f) Other acoustic installations such as suspended reflectors, resonant absorbers & quadratic residue diffusers.	a) Noise from equipment b) Mechanical equipment placement. c) Vibration isolation using pads and springs. d) Treatment of air ducts and / or pipes using laggings, linings, and mufflers. e) Air outlets background noise.	a) Site characteristics - Noise Level, interval, and character. b) Nearby barriers (outside) in the form of structures, plants and berms. c) Layout of activities in buildings (In various zones including buffer zones). d) Construction - Walls, Floors, & ceilings. e) Background noise criteria - HVAC system & electronic noise. f) Coordination with room acoustics	a) System compatibility with room acoustics. b) Loudspeakers - Type, position & placement angle. c) System constituents & operation method. d) Sound masking - Loudspeaker arrangement & spectrum of sound.

Table 3. Essential elements for architectural acoustics

Copyright. (Egan, 2007)

	Building Acoustics	**Room Acoustics**
Major difference	Sound generation, transmission and reception between two or more separate rooms	Sound generation, transmission and reception within one room
Source of the sound	External – From outside	Internal – In the room
Construction requirements	Insulation to effectively reduce sound transmission	Precision in calculating the total sound absorption.
Measurement unit for structural elements	Decibel - primarily depends on frequency	**αw** (weighted coefficient of sound absorption) - primarily depends on frequency
Evaluation parameters	Sound transmission loss (STL) and corresponding sound insulation measures in dB.	Reverberation time – The most important indicator

Table 4. Key differences between building and room acoustics.

Copyright. Trikustik GesmbH, 2015

2.5.5. Acoustical approximation methods

Room acoustics is concerned with the prediction and measurement of the sound field produced by a particular distribution of sources, as well as how a listener perceives this sound field. Two major approaches to room acoustics prediction / approximation are geometrical room acoustics and statistical room acoustics (Vigran, 2008).

2.5.5.1. Geometrical Acoustics

Geometrical Acoustics uses optical principles to model specular reflection behavior. In geometrical acoustics, sound rays regarded as straight lines along which acoustic energy is propagated similar to light rays. This is illustrated in Figure 15 and Figure ***16***. Geometric acoustics equations are essentially the same as geometric optics equations. Sound beams follow the same rules of reflection and refraction as light rays. (Vigran, 2008). The methods of geometric acoustics are approximations - the shorter the wavelength, the more accurately they depict reality. The concept of rays is only appropriate for situations when the direction and amplitude and of a wave vary minimally across distances on the order of a sound wave length. The size of the rooms or obstructions in the sound path must be several times bigger than the wavelength when utilizing geometric acoustics. The reflecting surface must be hard and smooth surface.

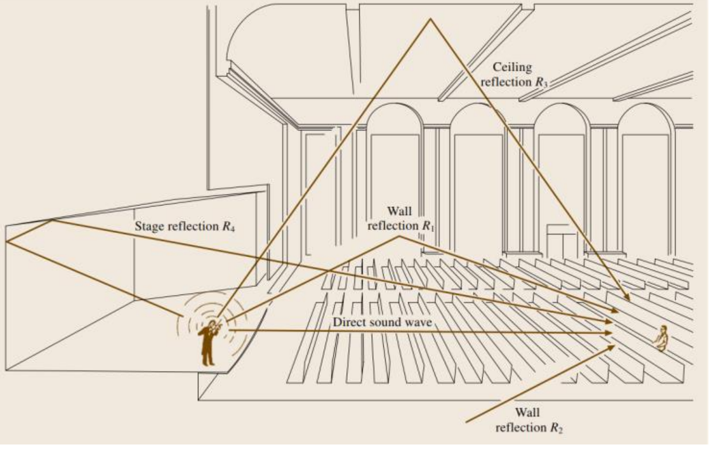

Figure 15. Arrival of direct sound and reflections to the receiver.

Copyright. Gade, 2007.

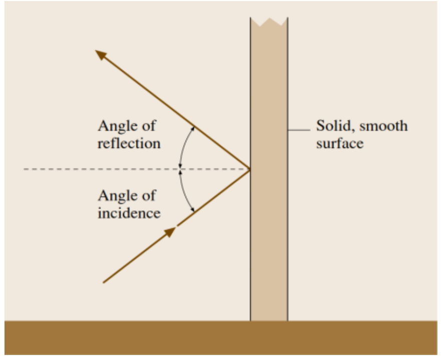

Figure 16. Specular reflection of a sound wave off a hard, smooth surface.

Copyright. Cowan, 2007.

Whenever the above conditions are not fulfilled, other phenomena take place. Sound waves travel past a surface and continue to propagate as if an obstacle does not exist if its dimensions are smaller or similar to the sound wavelength. This phenomenon is diffraction. If the surface, on the other hand, has irregularities that are equivalent to the sound wavelength, reflection occurs in various directions, resulting in diffusion.

Another phenomena is absorption, which occurs when the surfaces absorb some of the incident sound wave energy. The absorption coefficient (α) is the key determinant of absorption (Gonzalez, 2009). These phenomena are illustrated in Figure 17.

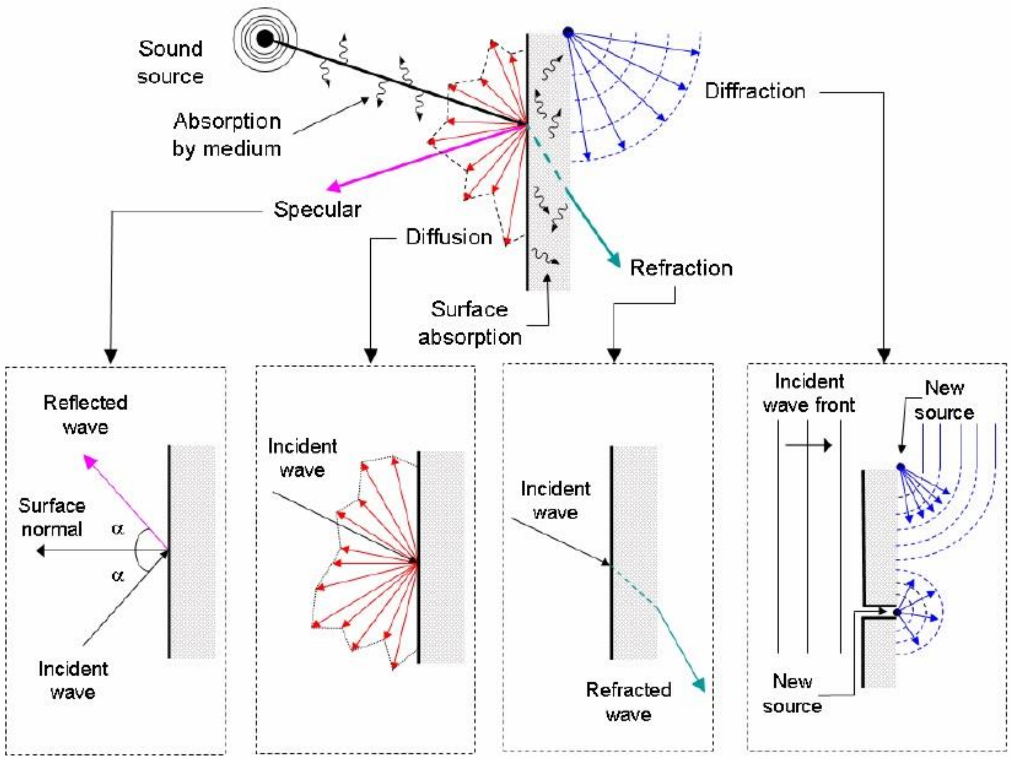

Figure 17. Acoustical phenomena: Reflection (specular and diffuse) Refraction, and diffraction.
Copyright. (Kapralos, Jenkin, & Milios, 2008).

2.5.5.2. Statistical Acoustics

The statistical method of room acoustics analysis involves the use of reverberation time (RT) equations. Geometrical acoustics do not apply for the calculation of reverberation time, which, as will be discussed further in section 2.5, is due to late reflections.

A high concentration of reflections occurs at every receiving point because the increase in temporal density at any point of an enclosed facility with time is quadratic. At all receiving points, these reflections are nearly identical. for this reason , the study of reverberation uses statistical acoustics criteria, which considers not only the direct rays produced by the source, but also any other rays still present in the room. (Gonzalez, 2009).

2.5.6. Behaviour of sound in a room

2.5.6.1. Sound Propagation

Sound propagates, or travels through air, in waves. The waves form when the air molecules closest to the vibration source are pushed against the adjacent molecules, and those adjacent molecules push against their neighbours, and so on. The movement of the air particles is forward and backward, parallel to the wave direction. In reality, individual air molecules hardly move. Each molecule is pressed and compressed just enough to bump its neighbour and start or continue a chain reaction (Fay, 2013).

Since sound travels at around 345 meters per second, direct sound from a source in a large space will ordinarily reach a listener in 0.01 to 0.2 seconds.

2.5.6.2. Sound Fields & Boundary Behaviour of Sound waves

Sound field refers to any region of a room containing sound waves. Near Field is the zone within about two wavelengths of the sound source. In this zone, there is no simple relationship between distance and sound level. The sound pressure and particle velocity are not in phase, and the instantaneous sound pressure does not follow the inverse square law.

The Direct Sound Field is the area where the sound measured may be ascribed only to the source without any reflections. A sound field region with no surrounding reflecting surfaces is known as a free sound field. A free sound field occurs in practice when the direct sound is 6 dB or better (about 10dB) than the reverberant or reflected sound.

The Far Sound Field is a zone at a distance from the source of sound where the level of sound upholds the inverse square law (intensity of sound declines by 6 decibels for every doubling of source to listener distance). In this zone sound wave pressure and particle velocity are in phase.

Initial reflections that arrive at the listener within 50 milliseconds blend in with the direct sound and increase clarity of speech. Late reflections may have a detrimental impact on the clarity of speech. Reverberant sound field refers to the zone in a room where reflected sound is dominant. (Gracey & Associates, 2019). Figure 18 below illustrates the sound fields in a room.

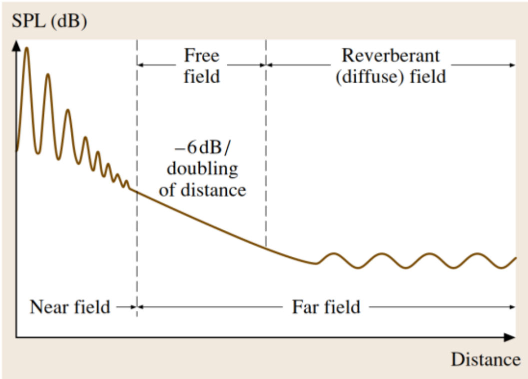

Figure 18. Sound fields in rooms.

Copyright. Cowan, 2007

The Diffuse sound field is the zone in which the direct sound pressure is equal to the reverberant sound pressure in the room where the source is located.

At a certain distance from the sound source, direct and reverberant sound levels are equal. This is the direct sound distance/critical distance. Measured sound levels at the critical distance will be 3 dB higher than the sum of the direct and reverberant sound levels (Gracey & Associates, 2019).

When sound waves are generated, they travel away from the source until they reach a room boundary, where part of sound the energy is absorbed, some reflected back around and within the space and some transmitted, as illustrated in *Figure 19 and Figure 20.*

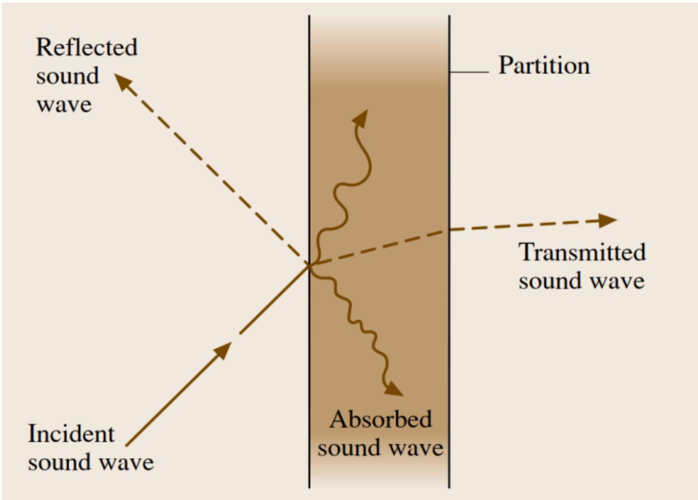

Figure 19. The interaction of a sound wave with a partition

Copyright. Cowan, 2007

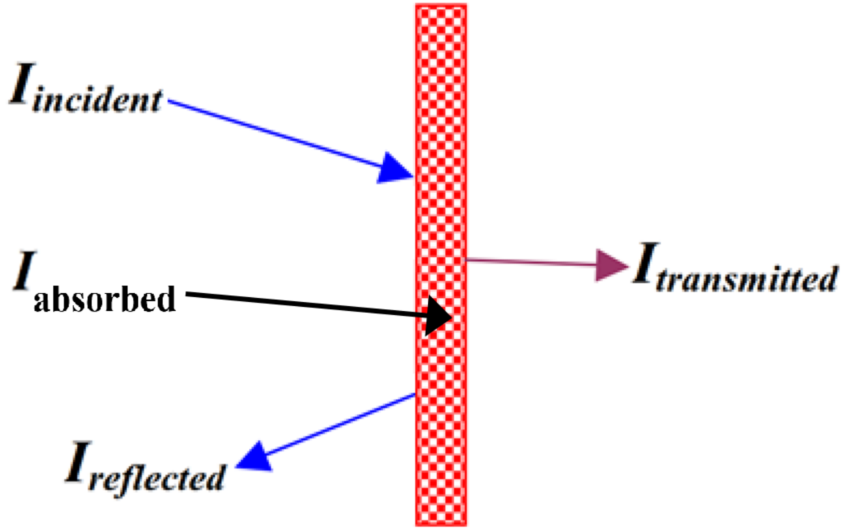

Figure 20. Boundary behaviour for sound waves.

Copyright. (Lamancusa, 2000)

There are two parts to the sound that arrives at a certain point within a space. The sound that travels direct from the sound source to the receiver is the first part. This forms the direct sound field is not affected by room geometry or surface finishes. It is affected by the source and the distance from source to the receiver.

After the direct sound has arrived, reflections from room surfaces begin to reach the receiver position. Reflections can arrive almost immediately or with a considerable delay if the initial reflecting surfaces are far from the source and receiver. The indirect sound field, which is independent of the source to receiver distance but is highly dependent on room characteristics, is formed by subsequent reflections off any number of surfaces. Sound waves can be controlled by absorption, reflection or diffusion. Each of these control methods is determined by the type and composition of the material with which the sound waves make contact. These are acoustic "tools" that may be used to control how sound behaves inside rooms (Fay, 2013).

2.5.6.3. Sound Absorption

Absorption is the process of dissipating sound energy by converting it to heat (Harris, 2006). It is what happens when sound waves strike an absorbent wall, panel, boundary or barrier of some type. If the surface is a soft and/or porous material, some of the mid and high frequency waves will become absorbed or trapped inside the fibres, pores or pockets of that material or structure. Most materials that absorb sound are only partially effective. The absorption (α) coefficient α is a measure of absorption, calculated as shown in Equation 1.

Each type of material has a different absorption coefficient, implying that the material is able to absorb more, or less, sound at various frequencies. Examples of mid and high frequency wave absorbers include mineral wool, spun glass, and semi-rigid fiberglass panels (Fay, 2013).

Low frequency waves can be absorbed too, but not as easily as high frequency waves. There are various low frequency wave absorption materials, devices and techniques. One method is to construct a limp mass assembly consisting of materials that have size, weight, and a freedom of movement. Other methods include the use of damped-vibration panels and perforated panels. For proper performance, perforated panels should always be mounted with airspace behind them, and the airspace should be lined or filled with mineral wool or spun glass insulation.

Materials and techniques that are most effective at absorbing mid and high frequency waves are generally least effective at absorbing low frequency waves. The inverse relationship is true (Fay, 2013).

$$\alpha = \frac{I_{absorbed}}{I_{incident}} = \frac{I_{incident} - I_{reflected}}{I_{incident}}$$

$\alpha = 1$ if totally absorptive

$\alpha = 0$ if totally reflective

Equation 1. The Absorption Coefficient.

Copyright. (Lamancusa, 2000)

There are three basic types of absorbents namely porous absorbers, discrete absorbers, and resonant absorbers.

a) Porous Absorbers

Natural fibers (like wood and cotton), mineral fibers (like mineral wool and glass fiber), acoustical foams, sprayed and trowel applied coatings, draperies, carpets, and acoustic tiling are all examples of porous absorbers.

Frictional losses transform some of the sound energy into heat energy when sound waves make air particles to vibrate down in the depths of porous materials. The quantity of loss is determined by the density of the material. Frictional loss is less when the fibres are loosely packed. There is limited penetration and increased reflection from the surface when the fibres are compressed into a compact board, resulting in less absorption.(Szymanski, 2008).

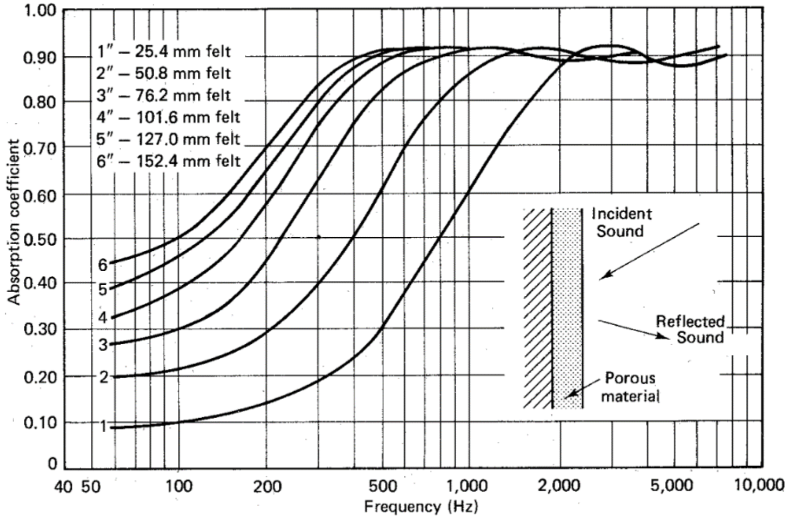

Figure 21. Absorption coefficient vs frequency for felt (porous fabric)
Copyright. Lamancusa, 2000

As Figure 21 shows, high-frequency sounds are absorbed more effectively by porous materials. The efficacy is determined by the porous material's thickness in relation to the sound wavelength. The material thickness should be at least a quarter (1/4) of a wavelength to be effective (almost anechoic) at a particular frequency, i.e. the lowest frequency that will be successfully absorbed by a porous material should have a wavelength 4 times the thickness of the absorbing material. Low frequency absorption is difficult to achieve with porous materials because they must be very thick (Lamancusa, 2000).

b) Discrete Absorbers

Discrete absorbers include people and seats, acoustical baffles and banners, and any other furnishing or objects within the room. People and the chairs they sit on will be the largest acoustic treatment in most large rooms. People should therefore be included in any acoustic calculations for suitably large indoor spaces.

In very large rooms, reverberant sound can be reduced by positioning absorbers high on the ceiling. Prefabricated acoustic baffles and banners hanging from the ceiling are frequently used as a solution. A hard or semi-rigid mineral fibre, such as glass fibre, is commonly used as the core material, with a coating layer made of polyester, PVC or rip stop nylon. Baffles are also often made in the form of acoustic foam panels and other porous absorbing panels. Finally, all furnishings or objects have a bearing on the behaviour of sound in a room.

c) Resonant Absorbers

Special materials are required to absorb frequencies below 250 Hz. For increased absorption, these materials have air gaps behind open or light surfaces. Helmholtz resonators, membrane/diaphragm absorbers, perforated membrane absorbers, and slat absorbers are widely used for this purpose. Figure 22 shows general design criteria for absorptive wood-slat ceilings.

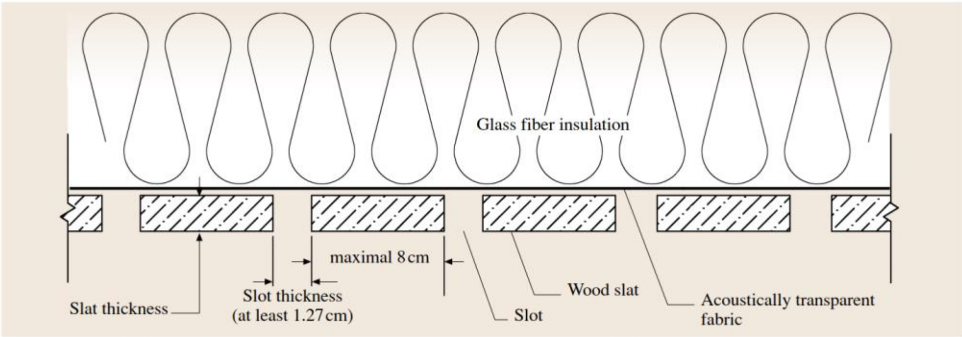

Figure 22. General design guidelines for absorptive wood-slat ceilings.

Copyright. Cowan, 2007.

A Helmholtz Resonator is a cavity type resonator consisting of a relatively large volume and a small opening, and vibrates at specific frequency. An empty bottle is a good example: when one blows over the top, the air within vibrates.(Gracey & Associates, 2019)

Helmholtz resonators have special properties for absorption in acoustical treatments. Absorption is very high at the frequency of resonance, and the frequency range of the absorption is extremely narrow – ordinarily only a few Hertz wide. The effective frequency range can be widened by partially filling the Helmholtz resonator with an absorptive material like loosely packed mineral fibre. Sound-absorbing concrete masonry units (CMU) are one of the most prevalent commercial products that use Helmholtz resonator theory. See Figure 23 (Szymanski, 2008).

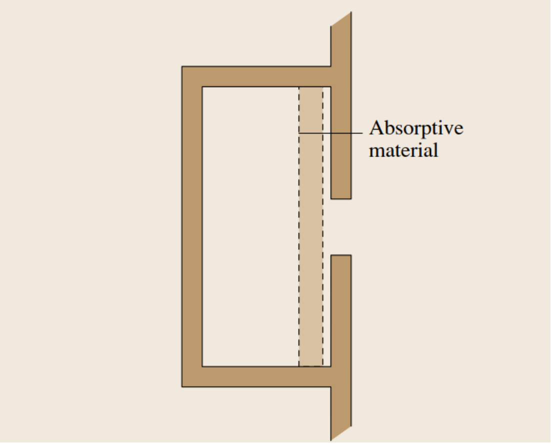

Figure 23. Cross section of a Helmholtz resonator CMU.

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The functioning of Helmholtz resonators and Membrane absorbers depends on the size of their cavity/air space. Cutting or drilling perforations in the membrane's face can be used to transform Membrane absorbers into the Helmholtz resonators. A Helmholtz resonator is created by tuning the cavity of a membrane absorber. A perforated absorber is created when round holes are utilized for the apertures in the face. (Szymanski, 2008). Spaced slats over an air gap (with or without absorptive fill) can also be used to make Helmholtz resonators, as shown in Figure 24. Similar to the perforated panel type, the air mass in the gaps between the slats reacts with the springiness of the air in the cavity to generate a resonant system. If all other conditions stay constant, randomly arranged slats (resulting in randomly sized slots) will reduce overall absorption while increasing bandwidth. (Szymanski, 2008).

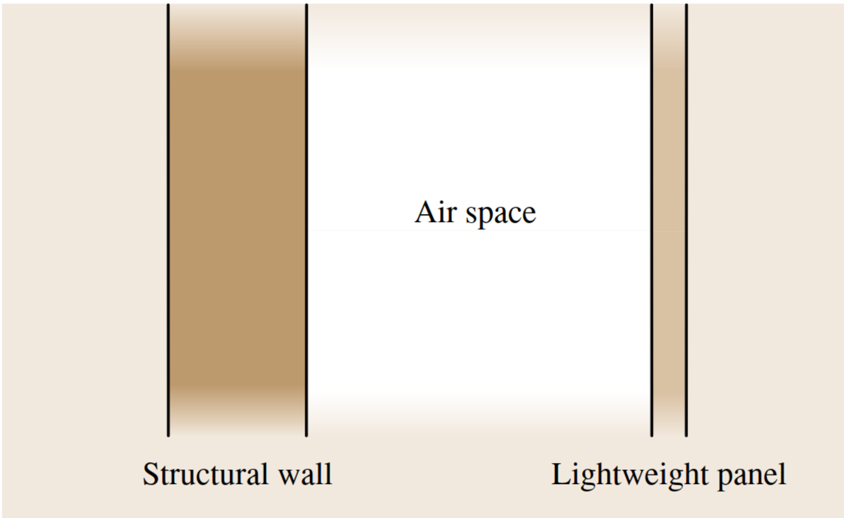


Figure 24. Cross section of a generalized membrane absorber

Copyright. Cowan, 2007.

2.5.7. Acoustical Defects

Acoustical defects in spaces result in poor speech intelligibility and general discomfort. The basic defects attributable to room geometry include long-delayed or multiple reflections, echoes, flutter echo, high amplitude zones, room resonance, coloration and focusing of sound. Large spaces can have coupled spaces having inconsistent RT_{60} characteristics and sound shadows below balconies, as well as excess sound attenuation caused by grazing incidence. Some of these defects may be present without compromising primary use of the room, and not all will be of concern in every room. (Long, 2014).

Table 5 and Figure 25 below present a summary of common acoustical defects in auditoriums.

Defect	Cause	Solution(s)
Excessive Reverberation	Insufficient absorption	Add Absorbents to give optimum reverberation
Echoes	Unsuitable shape	Avoid unsuitable shapes or alter geometry of offending surface
	Remote reflecting surfaces	Make offending surface highly absorbent
	Note: In an auditorium, echo refers to a reflected sound that significantly stands from the auditorium's normal reverberant sound. Often called a 'slap-back' echo, it is caused by prominent reflections from a reflective flat back wall.	
Flutter Echo	Parallel surfaces reflecting sound back and forth	Treat offending zones to absorb and diffuse
Sound Focussing	Concave reflecting interior surfaces	Avoid curvilinear interiors, Alter shape of the surface, or treat surface with absorbers or diffusers
Dead Spots	Irregular distribution of sound	Provide even diffusion of sound
Sound Shadowing	Protrusions that do not contribute to the reflected sound component	Get rid of the protrusion or redesign the protruding surface to provide reflected sound to affected seats
Insufficient Sound Volume	Lack of reflections close to source of sound	Treat surfaces around the source of sound to reflect
	Excessive absorption	Adjust absorption to give optimum reverberation
Distortions (Colouring of sound quality)	Selective absorption	Use combination of absorbents to obtain uniform absorption coefficient over the required frequency range
	Uncontrolled resonance	Use large sound diffusers on offending surfaces
High Background Noise and vibrations	Poor sound insulation and Vibration Isolation	Select construction with requisite sound insulation and vibration isolation
	Poorly fitted doors and windows	Provide proper fitting of doors and windows with requisite sound insulation.
	Noisy mechanical systems	Reduce noise from mechanical equipment by Isolation or treating the plant rooms

Table 5. Summary of common acoustical defects in auditoriums

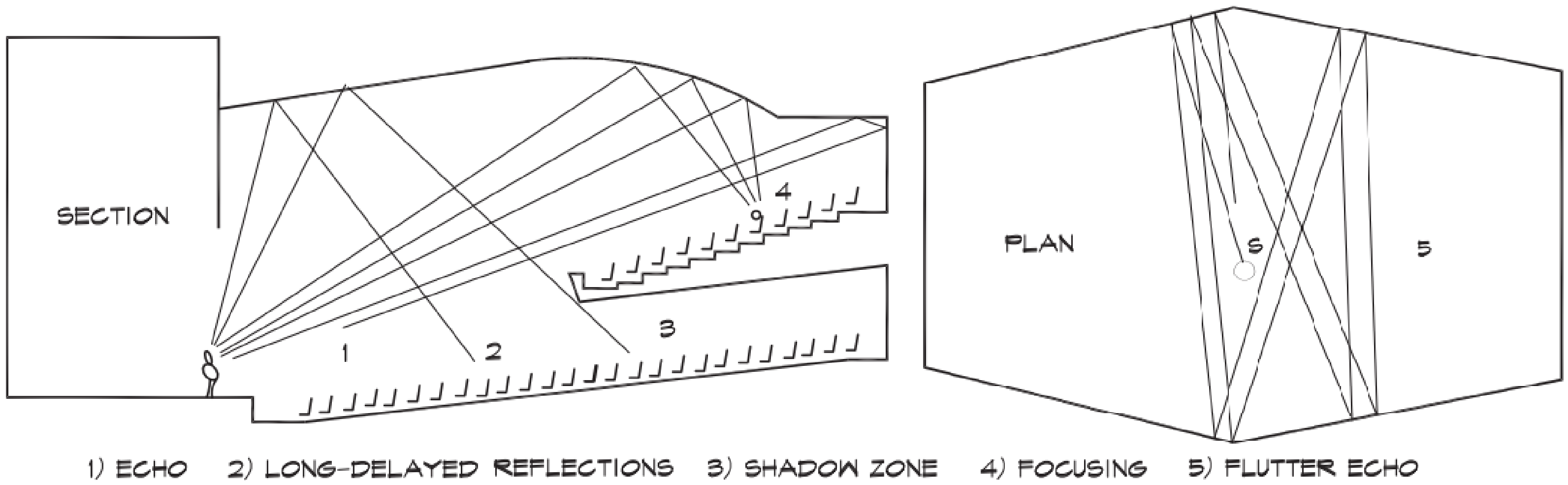


Figure 25. Acoustical Defects Examples

Copyright. Long, 2014

2.6. PARAMETERS FOR ACOUSTIC CHARACTERIZATION OF CHURCH AUDITORIA

Room acoustic characterization refers to the use of objective and subjective acoustic parameters to evaluate a room's acoustic quality. Objective parameters measure quantifiable physical attributes dependent on the architectural features of the space, while subjective parameters relate to a listener's subjective identification of acoustic attributes. The physical methodologies used in room acoustic analysis consist of measurement, calculation, as well as modelling techniques for approximation of the impulsive response of a room. Through analysis of the impulse response, it is possible to retrieve the relevant parameters for acoustic characterization of the room. (Vodopija et al., 2010).

Meeting the criteria of the acoustic parameters that define the quality of sound fields and listener perception is fundamental for good acoustics. Clement Sabine's Reverberation Time (RT60), Definition (D50), Clarity (C80), and Early Decay Time (EDT), and Sound Strength (G) are the main parameters as defined by ISO 3382(2009).

In a broader sense, the parameters for acoustic evaluation of church buildings can be broken down into architectural parameters, objective parameters and subjective parameters.

2.6.1. Architectural Parameters / Variables

These are purely architectural factors such as shape, dimensions, orientation of boundary surfaces, materials used, seating arrangement and audience capacity (Pereira, 2010). According to Carvalho (1995), the effects of the architectural features including length, width, height, volume, number of seats and total absorption may explain the acoustical behaviour of a church.

Architectural factors refer to both the design of the sound sending end (stage area) well as the sound receiving end (audience area). Poor design of either will compromise the acoustic performance of the church auditorium (Wenger Corporation, 2008). The section below details important architectural parameters for design and evaluation of contemporary evangelical church auditoriums as recommended by various authors.

2.6.1.1. Site Selection and Planning

a) Depending on the ambient noise level of the site, use orientation, layout and structural design to provide necessary noise reduction, so that the background noise level of not more than 40 to 45 dB is achieved within the hall as measured on 'A' scale of a sound level meter (Bureau of Indian Standards, 1998).
b) Whenever possible, selected sites should be away from noisy industries, highways, and flight paths. When optimal site selection is not possible, design to reduce the noise impact of the offending source (Everest & Pohlmann, 2009). The auditorium can be isolated from noise using buffer spaces such as storage rooms and corridors (Egan, 2007).
c) All enclosed spaces adjacent to the auditorium should be isolated from the main hall by appropriate (well fitting) doors and windows to avoid any influence on the hall acoustics. The door and window rebates should be lined with draught strip rubber or felt (Bureau of Indian Standards, 1998).

2.6.1.2. Main Construction elements

Noise reduction requires use of dense or heavy structural components during construction like concrete and thick masonry to increase the structural mass of walls, floors or ceilings, as well as using double-glazed windows and door sweeps / seals (BAUX, 2020).

2.6.1.3. Program

The term "program" refers to a space's intended uses and the percentage distribution of each. For a church, this depends on the liturgy. Defining the program at the onset helps guide the design with music as the dominant activity, speech as the dominant activity, or music and speech distributed equally (Long, 2014).

2.6.1.4. Room Size

a) The size is determined in relation to the number of audience seats. The floor area should be 0.6 to 0.9 m^2 per person with the stage excluded and gangways included (Bureau of Indian Standards, 1998).

b) Volume is calculated based on specified volume per seat. This may range from $5.7m^3$ to $11.3m^3$ per seat (Long, 2014). For church buildings, the volume per seat ratio should be $5.1m^3$ to $8.5m^3$ per person for churches where speech is the most important part of the service and $5.7m^3$ to $11m^3$ per person for churches where music is the most important part (Egan, 2007).

c) The required overall room volume determines ceiling height. In general, the ceiling height should be one-third to two-thirds of the width of the space. For big spaces, the lower ratio is employed, and the higher ratio is used for small spaces. (Everest & Pohlmann, 2009)

d) In an ideal scenario, the furthest seat should not be more than 30 m from the stage (Long, 2014).

e) The width of a seat should be between 45 cm and 56 cm (Bureau of Indian Standards, 1998).

2.6.1.5. Room Geometry

a) Floor plans can be Rectangular, Fan and Horse-shoe shaped (Bureau of Indian Standards, 1998). As the number of people in the room increases, the room's lateral dimensions must increase as well. To effectively reflect sound energy to the rear of the hall, the side walls should be splayed. (Everest & Pohlmann, 2009). The fan-shaped layout is the best choice for achieving good results without complicating the hall's acoustical treatment (Bureau of Indian Standards, 1998). A sidewall splay should range from 30° to 60° due to the directionality of speech (Everest & Pohlmann, 2009).

b) Sidewalls must avoid parallelism. Splayed or tilted wall surfaces can help direct reflected sound to the audience sitting area while also providing diffusion (Everest & Pohlmann, 2009).

c) Although the ceiling can be level, it is desirable to have a slight rise in height in the centre of the hall. Avoid ceilings with concave shapes, such as barrels or domes. (Bureau of Indian Standards, 1998). Reflected sound should be directed throughout the hall by the ceiling geometry. The size and angle of several ceiling portions may be adjusted to reflect sound to specific seating sections in the hall (Everest & Pohlmann, 2009).

d) Spaces with high ceilings should have a canopy above the stage for early reflection of sound and to eliminate late reflections from the ceiling. (Egan, 2007).

e) A smooth ceiling should not be parallel to the floor to avoid flutter echoes. (Everest & Pohlmann, 2009).

f) Shape the stage such that strong early reflections and diffusion are evenly distributed. The stage's reverberation time should be nearly equal to that of the auditorium (Egan, 2007).

g) The rear wall(s) of the auditorium should be either flat or convex in design. Avoid Concave rear walls. Where a concave back wall is unavoidable, the wall surface should be splayed or convex corrugations introduced to prevent sound from focusing into the hall (Bureau of Indian Standards, 1998).

h) A ceiling splay between the ceiling and the rear wall will avoid echoes and produce useful short-delayed reflections (Egan, 2007)

i) To eliminate long-delayed reflections and echoes, balcony faces and back walls should have convex features, sizeable splays, or be treated for moderate absorption. (Egan, 2007).

j) The false ceiling at the proscenium should be angled appropriately to allow reflections from the stage to reach the hall's rear seats. (Bureau of Indian Standards, 1998).

k) The floor level should rise towards the back as successive rows of chairs are elevated over the previous ones. The elevation is based on the premise that each listener should be elevated in relation to the person directly in front such that their head is roughly 12 cm above the head of the person in front. If the chairs are staggered, this can be lowered to 8 cm. (Bureau of Indian Standards, 1998). A sloping (raked) floor is desirable especially in large halls because it improves sight lines, and the listener receives more direct sound than would be available on a flat floor. In both cases, the stage should be raised (Egan, 2007).

l) The chosen APS (arrival point of sight) will have a significant impact on the slope of the floor. Generally, a high APS goes with lower raking. The stage floor heights should however be low for a spectator in the first row to see the feet of those on stage, and high enough so that the APS will not necessitate a steep rake on the floor. A seated person's average eye height is about 1120mm and 1220mm for adult females and males. The stage heights are set at 1.02–1.07m above the floor. (Long, 2014).

m) As rule of thumb, the elevation angle of the inclined auditorium floor should be 8 degrees or more. (Bureau of Indian Standards, 1998).

n) The line of sight for balcony seating should not incline by more than 30 degrees measured from a horizontal plane (Bureau of Indian Standards, 1998).

o) The slope of balcony floors should not exceed 26°and the top most floor level in the balcony should not exceed 19.8m from the stage level to prevent vertigo - a sensation of whirling and loss of balance (Egan, 2007).

p) The balcony overhang into the hall should be less than double the open height of the balcony recess opening (Bureau of Indian Standards, 1998).

q) The under balcony soffit should be sloped (downwards from the opening towards the rear) for useful reflection to seats beneath and to link the volume of the main hall and that of under-balcony seamlessly (Egan, 2007).

r) The balcony parapet front should be shaped to avoid undesirable reflections that could affect sound quality in the seating areas in the front of the hall (Everest & Pohlmann, 2009).

s) Seats should be laid out in concentric arcs, with the center of the arcs as far behind the curtain line as the distance between the curtain line and the auditorium back wall. The angle subtended with the horizontal at the front most observer by the highest object on stage should not exceed 30 degrees. The Minimum distance of front seats should be determined by the highest point required to be seen on the stage which is usually raised by about 75 cm or more (Bureau of Indian Standards, 1998).

t) The back-to-back distance of chairs in successive rows of seats should be at least 85 cm. If extra comfort is required, the spacing can vary between 85 cm and 106 cm (Bureau of Indian Standards, 1998).

2.6.1.6. Sight lines

a) Sight lines should converge at the arrival point of sight (APS) - a point along the front edge of the stage apron, so that seated audience have a view of entire performance area on stage with no obstruction (Egan, 2007).

b) Sight lines are set so that a listener can see the APS over the head of a person sitting in front of them. This method however yields very steep floor slopes. In practice therefore, most auditoriums are designed for every-other-row visibility and seats arranged so that a person's line of sight is between the two people seated in the next row (Long, 2014).

f) Sight lines from the side should be within a 30° view angle, measured perpendicular from the end of the proscenium opening (Egan, 2007). The furthest seat should not be more than 30 degrees from the nearest side of the proscenium opening (Long, 2014).

c) The balcony audience should have a view of the first few seating rows in the main hall for a sense of community/congregation. The bottom 2.1m of the back stage wall should be visible from the balcony, without obstruction by the proscenium arch.(Egan, 2007).

2.6.1.7. Surface finishes

a) In small halls, the audience provides the majority of absorption. Therefore, the room's surfaces can be reflective. Larger halls, with more room volume per seat, necessitate a higher level of room absorption. Reflective surfaces in the stage area and front of the hall should be used, with absorption in the sitting area and back of the hall if needed. (Everest & Pohlmann, 2009).

b) Wall and ceiling surfaces should be used for useful reflection of sound as well as for diffusion. Useful reflections have a path difference of less than 8.5 metres (Egan, 2007).

c) Sidewalls should have bumps, splays and large-scale irregularities to enhance lateral reflections, reverberance, and diffusion. Materials that preferentially absorb low-frequency sound energy should be avoided on side walls (Egan, 2007).

d) Ordinarily, a large hall's back wall should be absorbing, but when absorption is undesirable, the wall should have a diffusing surface with large-scale irregularities. (Everest & Pohlmann, 2009).

e) If sound absorption is not necessary due to other factors, non-parallel sidewalls may remain reflective and be aesthetically treated in any manner required. If the sides are parallel, they can be left untreated for up to 7.5 meters from the proscenium. (Bureau of Indian Standards, 1998).

f) Sound absorbing material should be applied to any wall surfaces that are likely to create a delayed or flutter echo. The distance between the direct and reflected sound paths from sidewalls should not be more than 15 meters. (Bureau of Indian Standards, 1998).

g) Provide for a false ceiling below the roof structure. To reflect sound, ceiling surfaces should be made of concrete, thick wood, or thick gypsum board. If reverberation control is required, sound-absorbing materials can be utilized around the perimeter on both sides and rear (about one-third to half of the ceiling area in a horseshoe design), or a checker pattern with alternate areas of sound absorbing and reflecting materials can be employed. A reflecting false ceiling is necessary near the proscenium (Egan, 2007).

h) To avoid echoes, cover the front of the balcony parapet with sound diffusing materials (or an absorbing material) (Egan, 2007).

i) To supplement direct sound, the balcony's underside should be reflective (Everest & Pohlmann, 2009).

2.6.1.8. Sound reinforcement

a) Provide a cluster of loudspeakers slightly in front of and centrally above the proscenium opening with the audience having a direct line of sight to the cluster's high frequency speakers (Egan, 2007).
b) Use central and highly directional electronic sound-amplification system in reverberant rooms to focus amplified speech over the audience area and for the sound to originate from the pulpit direction. (Egan, 2007).
c) Even if there are no auxiliary inputs, a sound reinforcement system is required for rooms with capacities exceeding 100-150 seats, volumes exceeding $425m^3$, or listener-to- speaker distances of more than 12 metres (Long, 2014).

2.6.2. Objective Variables/Parameters

These are physical parameters/variables can be quantified/measured and are closely related to a room's architectural qualities (Pereira, 2010). Measurement of acoustical parameters is typically based on impulse responses (Carvalho, 1995). The key objective parameters for characterization of church building acoustics include reverberation time, early decay time, clarity, definition, centre time, loudness, bass ratio and rapid speech transmission index (Carvalho, 2010). The ISO 3382 series of standards details most of these parameters.

a) Reverberation Time (RT60): Proposed by Wallace Clement Sabine in the late 1890s. It is typically measured from a 30 dB decay (-5dB to -35 dB) which is also called RT30, then multiplied by 2.
b) Early Decay Time (EDT): Proposed by Vilhelm L.Jordan in 1965, it is measured from a 10 dB decay (0dB to -10 dB) which is also called RT10, then multiplied by 6.
c) Clarity Index (C80): It measures how clear a listener perceives music and is a logarithmic ratio of the sound energy reaching a point within the first 80milliseconds to sound energy reaching the point after 80 milliseconds.

d) Definition (D): It measures how clear a listener perceives speech and a ratio of the sound energy reaching a point within the first 50milliseconds to the overall energy reaching the point thereafter. It is measured from 0-1. The higher the value, the clearer the sound is perceived to be.

e) Center Time (TS) is a moment in time at which the sound energy received before and after this point is equal. It has values between 140 and 180ms in the frequency range 250-2000 Hz and the lower the value of TS, the clearer the sound is perceived to be.

f) Loudness (L) is a ratio of the total energy reaching a specific point in the room to the energy reaching that point from direct sound only (with measurements taken 10m away from the source inside an anechoic chamber). Its application is in verifying sound field uniformity and analysis of the transmitted energy for deficiencies at some frequencies. It has values between 3dB and 9 dB.

g) Bass Ratio (BR_RT) a ratio of the reverberation time in the 125 Hz and 250 Hz frequencies to the reverberation time in the 500 Hz and 1000 Hz frequencies. Its application is in evaluating balance by comparing reverberation times for low frequencies to reverberation times for high frequencies.

h) Speech intelligibility is the Percentage of correctly received units of speech units out of all the transmitted units. Different Speech Transmission Indices are used to evaluate the intelligibility of speech. RASTI, STI, STIPA are the most common indices.

i) Methods for depicting acceptable levels of background noise are known as background noise criteria. The balanced noise criterion (NCB), room criterion (RC) and noise criterion (NC) curves are commonly used to assess background sound levels within spaces.

2.6.2.1. The Reverberation Time (RT60)

RT60 is the time it takes for the level of sound in a room to drop by sixty decibels (60dB) after a continuous sound source is switched off.

RT_{60} has a direct relationship with room volume and an inverse relationship with absorption of the materials in the room (Cowan, 2007).

The figures below (Figure 26, Figure 27 , and Figure 28) illustrate the concept of RT_{60} concept and other aspects associated with its measurement.

The direct sound travels directly from the loudspeaker to the test microphone or listener.

The lag in milliseconds between when direct sound arrives and when the first strongest reflection arrives at the centre of the audience sitting area is known as the initial delay time.

A sequence of semi-distinct reflections from various surfaces will reach the listener shortly after the direct sound arrives. These early reflections usually happen in the range of 50 to 80 milliseconds (Long, 2014).

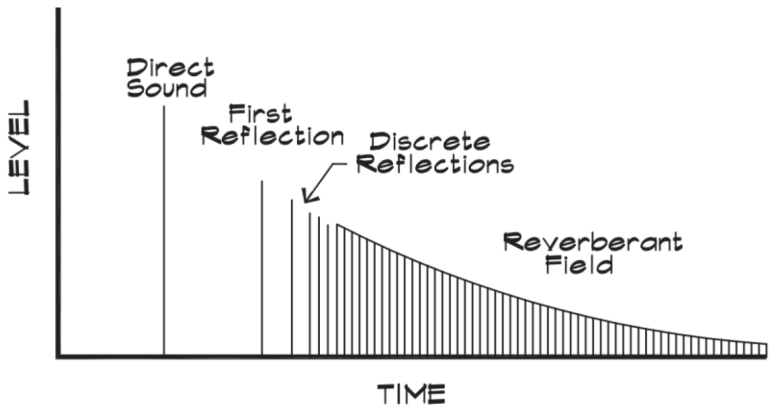


Figure 26. Energy vs Time graph for an Impulsive Source.
Copyright. Long, 2014

The reflections reaching a listener position after early reflections are of lower amplitude and at very close time intervals. These reflections combine to form the late reflections or reverberant sound. (Scavone, 2019).

If the sound emitting source is continuous, reverberant sound will build up in the room until an equilibrium level is reached. When the emitting source is stopped, the sound level will decrease at a constant rate until it is inaudible. For an impulse sound, decay of the reverberant sound begins immediately. (Scavone, 2019). This is illustrated in Figure 26 above, Figure 27 and Figure 28 below.

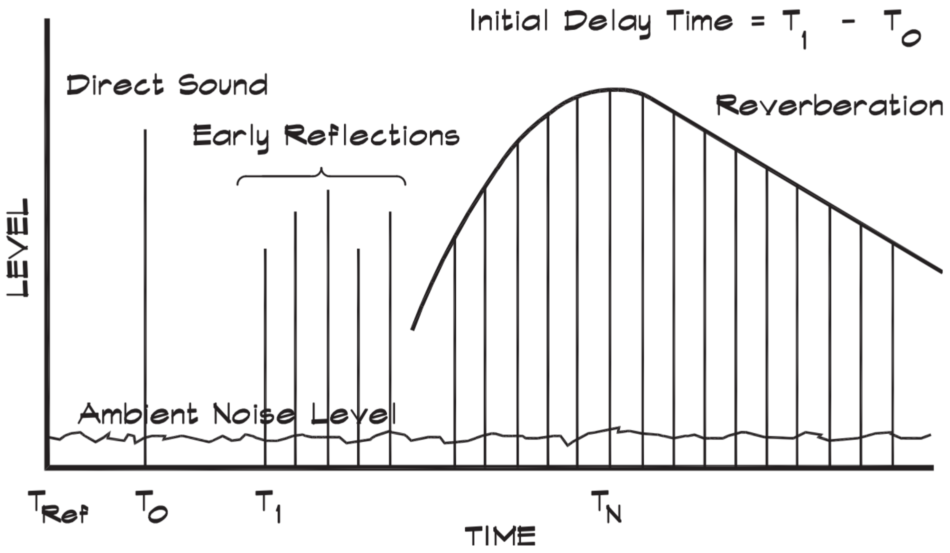


Figure 27. Idealized Acoustic Response of a Room

Copyright. Long, 2014

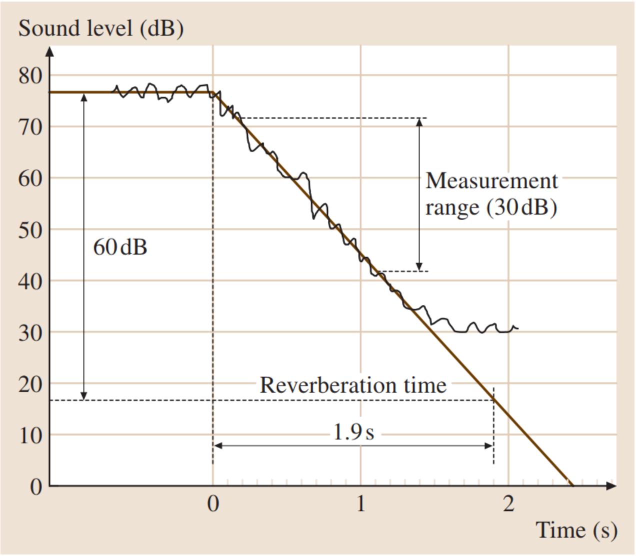


Figure 28. Illustration of reverberation time.

Copyright. Gade, 2007.

In an existing space, RT60 can be calculated by measuring the time it takes for sound to decay by 20 dB then multiply with a factor of 3 and the Sabine Equation used to predict RT60. The reverberation time is lengthened by highly reflective surfaces and shortened by absorbent surfaces

(Gracey & Associates, 2019). Reverberation time at 500 or 1000 Hz is typically used as a single quantity to characterize a space's acoustic performance.

2.6.2.1.1. Optimal RT_{60} values for Church Auditoria

Achieving an optimum RT60 requires a balance between clarity which requires short reverberation times, sound intensity which requires high reverberant levels, and liveness which requires long reverberation times. The intended usage of an auditorium will determine the optimal reverberation time.

In a room with more reflection, sound will take longer to decay, and the room will be regarded as acoustically "live" whereas in a room with more absorption, sound will decay quickly and the room regarded as "dead" acoustically (Gonzalez, 2009).

Reverberation time can be determined based on hall dimensions and the intended use. Stephens and Bates (1950) developed the formula in Equation 2 below for calculating the “optimum” reverberation time. The formula is an approximation best suited to frequencies of 500Hz. It is recommended to add 40% to the resulting T from the Stephens and Bates equation in low frequencies (Lamancusa, 2000).

$$RT_{60} = K(0.0118\,V^{1/3} + 0.1070)\ \text{s}$$

$$\begin{aligned} \text{where: } & V = \text{room volume } (m^3) \\ & K = 4 \text{ for speech} \\ & \quad = 5 \text{ for orchestra} \\ & \quad = 6 \text{ for choir} \end{aligned}$$

Equation 2. Stephens & Bates Formula

Copyright. Lamancusa, 2000.

Table 6 and Figure 29 below present generally accepted optimum mid-frequency (500–1000 Hz) RT_{60} values for various occupied facilities (Cowan, 2007).

Type of facility	Optimum mid-frequency RT_{60} (s)
Broadcast studio	0.5
Classroom	1.0
Lecture/conference room	1.0
Movie/drama theater	1.0
Multipurpose auditorium	1.3 to 1.5
Contemporary church	1.4 to 1.6
Rock concert hall	1.5
Opera house	1.4 to 1.6
Symphony hall	1.8 to 2.0
Cathedral	3.0 or higher

Figure 29. Optimal RT60 values for various facilities (occupied) at mid frequency.

Copyright. Gade, 2007.

<table>
<tr><td>Optimum RT60 (s)</td><td>Implications</td></tr>
<tr><td>0.5</td><td>“Dead sound”,</td></tr>
<tr><td>1.0</td><td rowspan="3">Clear Intelligibility of speech. Desirable for lecture halls speech only. Loss of richness and fullness. Not desirable for music</td></tr>
<tr><td>1.0</td></tr>
<tr><td>1.0</td></tr>
<tr><td>1.3 to 1.5</td><td rowspan="5">Desirable for halls with both speech and music, provided other important acoustical needs are fulfilled</td></tr>
<tr><td>1.4 to 1.6</td></tr>
<tr><td>1.5</td></tr>
<tr><td>1.4 to 1.6</td></tr>
<tr><td>1.8 to 2.0</td></tr>
<tr><td>3.0 or higher</td><td>Full, rich music sound. Some loss of intelligibility. More difficulty in understanding speech</td></tr>
</table>

Table 6. Optimum mid-frequency RT60 values for various occupied facilities

Copyright. Gade, 2007.

The graph in Figure 30 below presents recommended RT_{60} values for different church room volumes according to Harris as cited in Othman & Mohamed, (2012). Table 7 shows recommended RT_{60} values for different church room sizes (Doelle as cited in Lee, 2003). Small volume churches usually have seating capacities of less than 400 or 500 people. The medium size of churches have a seating capacity of between 500 and 1000, and large churches have a seating capacity of over 1500 (Lee, 2003).

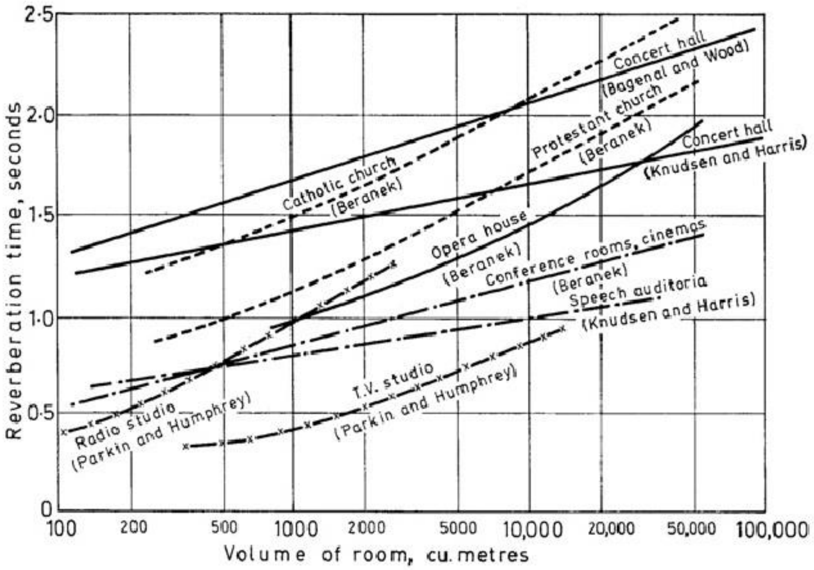


Figure 30. Optimal RT60 for different hall volumes.

Copyright. Othman & Mohamed, (2012)

Church Size	**Optimum RT_{60} (Mid Frequency)**	
	Roman Catholic	**Protestant**
Small	1.7	1.2
Medium	1.9	1.3
Large	2.0 – 2.6	1.4 – 1.6

Table 7. Optimal RT60 values for various church sizes.

Copyright. Lee, 2003

The bar graph in Figure 31 below gives recommended mid frequency RT60 levels for a various room types (shaded). The RT60 range for each room is extended using dashed lines beyond the shaded bars to indicate the extreme acceptable limits of short and long reverberation times for each room type.

If other critical acoustical demands are met, satisfactory listening conditions can be achieved in auditoriums with varying reverberation times within the recommended range. Large rooms should on average, be closer to the top end of the RT60 range than similar small rooms. (Egan, 2007)

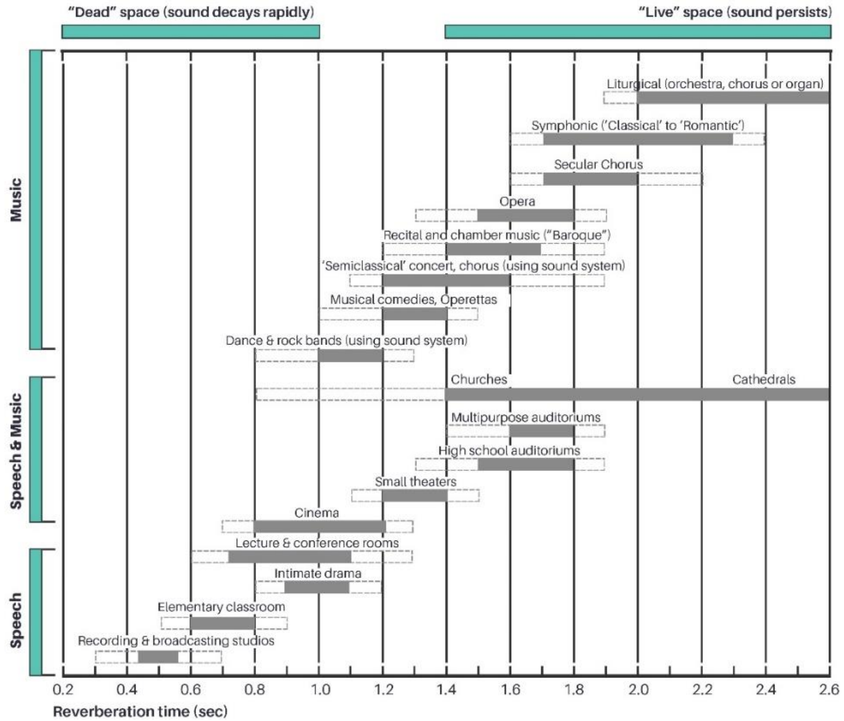


Figure 31. Recommended mid frequency RT60 levels for a various room types.

Copyright. Egan, 2007.

2.6.2.1.2. RT_{60} Formulas

Several formulae for reverberation time are available and have different applications. The most commonly used in practice are the Sabine and Eyring-Norris formulas.

<u>The Sabine Equation</u>:

The Sabine equation is the classical and oldest RT_{60} equation developed by W.C. Sabine at the turn of the 20th century. The equation is based on the assumption that the room has a diffuse sound field, meaning that sound arrives at any listener point from any direction and that the sound field is the same in the entire space. This assumption is inconsistent with the situation in actual rooms and the equation yields erroneous results in highly absorbent spaces. The equation is accurate in highly reverberant rooms with the averaged coefficient of absorption less than 0.25. In this respect the effect air absorption is neglected above 4 kHz (where it becomes dominant). In addition, the Sabine equation will yield accurate results in rooms with simple geometry and with an even distribution of absorbent materials. In spaces with all the absorption material on only one surface, the equation will yield a reverberation time shorter than the actual (Remes, 2015).

$$RT_{60} = 0{\cdot}161\frac{V}{A}$$

$$A = \alpha_1 S_1 + \alpha_2 S_2 + \ldots + \alpha_n S_n = \sum_{i=1}^{n} \alpha_i S_i$$

Where,

RT_{60} = Reverberation Time (sec)

V = Volume of the room (m^3)

A = total room absorption (metric sabins)

S_i = total surface area of each material in the room (m^2)

α_i = absorption coefficient at a given frequency for each material in the room (decimal percent)

Equation 3. The Sabine RT60 Equation

Copyright. Everest & Pohlman, 2009.

Eyring-Norris equation:

The Sabine equation is not appropriate for rooms with extremely high ratios of absorption to room volume such as recording studios or anechoic chambers. The Eyring-Norris equation is used when the average absorption coefficient greater than 0.25 and for frequencies below 4 kHz.

$$RT_{60} = 0.161 \frac{V}{-S \ln(1-\alpha_{average})}$$

Where,

RT_{60} = Reverberation Time (sec)

V = Volume of the room (m^3)

S = Total Surface Area of the room (m^2)

ln = natural logarithm (to base "e")

$\alpha_{average}$ = average absorption coefficient $= (\Sigma S_i \alpha_i / \Sigma S_i)$

S_i = total surface area of each material in the room (m^2)

α_i = absorption coefficient at a given frequency for each material in the room (decimal percent)

Equation 4. The Eyring - Norris RT60 Equation

Copyright. Long, 2014

The commonly available and published absorption coefficients by materials manufacturers are Sabine coefficients (measured in a reverberation chamber and calculated using Sabine equation) and can be applied directly in the Sabine equation. (Remes, 2015)

For this reason, Sabine equation is the usual choice in acoustical design and is used in this thesis.

2.6.2.1.3. Air Absorption

In large spaces with long travel paths for sound, air absorption effectively lowers reverberation time for frequencies above 2kHz. In small rooms, air absorption can be ignored since it is not a significant factor. To account for air absorption, the denominator of the reverberation time equation is multiplied by 4mV. 4m is the air attenuation coefficient in sabins/m and V is the room volume in m^3. Some values of *4m* in sabins per metre are: *4m* = 0.009 at 2 kHz; *4m* = 0.025 at 4 kHz; *4m* = 0.080 at 8 kHz), measured at a temperature of 20^0C, normal atmospheric pressure of 101.325 kPa, and relative humidity between 40% and 60%. The level of relative humidity affects the value of 4m. It is higher with low humidity and lower with high humidity (Everest & Pohlmann, 2009).

Taking account of air absorption, the Sabine and Eyring-Norris equations will be as follows: (Remes, 2015)

$$RT_{60} = 0{\cdot}161 \frac{V}{A + 4mV}$$

Equation 5. Sabine equation modified for air absorption.

Copyright. Everest & Pohlmann, (2009)

$$RT_{60} = 0{\cdot}161 \frac{V}{-S \ln\left(1 - \alpha_{average}\right) + 4mV}$$

Equation 6. Eyring-Norris equation modified for air absorption.

Copyright. Everest & Pohlmann, (2009)

2.6.2.1.4. Sound Absorption coefficients

Absorption coefficients rate by using a fraction, how effective a material is in absorbing incident sound energy at a certain frequency. In theory, it varies from 0 to 1. At 0, there is no absorption and at 1, there is 100% absorption. (Egan, 2007)

Suppose 44% of sound energy (at a certain frequency) incident on a surface was absorbed, the absorption coefficient (α) of that material at the particular frequency is 0.44. For a perfect sound absorber α be 1.0 because of 100% absorption, whereas for a perfect reflector α will be 0.0. (Everest & Pohlmann, 2009).

Building materials have absorption coefficients ranging from 0.01 - 0.99. Those with absorption coefficients above 0.5 are absorbers and those below 0.20) are sound reflectors (Egan, 2007).

When an absorbing material is placed on top of a surface, the loss of absorption attributable to the first surface must be taken into account. To calculate the net increase in absorption, the absorption coefficient of the first material should be deducted from the absorption coefficient of the new material (Everest & Pohlmann, 2009).

A material's absorption coefficient varies with frequency. Manufacturers measure and publish absorption coefficients for commercially available materials. Published coefficients cover the 125, 250, 500, 1000, 2000, and 4000 Hz frequencies. Sometimes the absorption of a material is published as NRC - Noise Reduction coefficient, derived by averaging absorption coefficients at 2kHz, 1kHz, 500 Hz, and 250 Hz frequencies. It is therefore more applicable in halls for speech because it is based on absorption coefficients at middle frequencies . For music applications, individual coefficients spread over the relevant frequency range should be used (Everest & Pohlmann, 2009).

$$NRC = (\alpha_{250} + \alpha_{500} + \alpha_{1000} + \alpha_{2000})/4$$

Equation 7. Noise reduction coefficient

Material	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	NRC
Painted drywall	0.10	0.08	0.05	0.03	0.03	0.03	0.05
Plaster	0.02	0.03	0.04	0.05	0.04	0.03	0.05
Smooth concrete	0.10	0.05	0.06	0.07	0.09	0.08	0.05
Coarse concrete	0.36	0.44	0.31	0.29	0.39	0.25	0.35
Smooth brick	0.03	0.03	0.03	0.04	0.05	0.07	0.05
Glass	0.05	0.03	0.02	0.02	0.03	0.02	0.05
Plywood	0.58	0.22	0.07	0.04	0.03	0.07	0.10
Metal blinds	0.06	0.05	0.07	0.15	0.13	0.17	0.10
Thick panel	0.25	0.47	0.71	0.79	0.81	0.78	0.70
Light drapery	0.03	0.04	0.11	0.17	0.24	0.35	0.15
Heavy drapery	0.14	0.35	0.55	0.72	0.70	0.65	0.60
Helmholtz resonator	0.20	0.95	0.85	0.49	0.53	0.50	0.70
Ceramic tile	0.01	0.01	0.01	0.01	0.02	0.02	0.00
Linoleum	0.02	0.03	0.03	0.03	0.03	0.02	0.05
Carpet	0.05	0.05	0.10	0.20	0.30	0.40	0.15
Carpet on concrete	0.05	0.10	0.15	0.30	0.50	0.55	0.25
Carpet on rubber	0.05	0.15	0.13	0.40	0.50	0.60	0.30
Upholstered seats	0.19	0.37	0.56	0.67	0.61	0.59	0.55
Occupied seats	0.39	0.57	0.80	0.94	0.92	0.87	0.80
Water surface	0.01	0.01	0.01	0.01	0.02	0.03	0.00
Soil	0.15	0.25	0.40	0.55	0.60	0.60	0.45
Grass	0.11	0.26	0.60	0.69	0.92	0.99	0.60
Cellulose spray (1″)	0.08	0.29	0.75	0.98	0.93	0.76	0.75

Table 8. Absorption coefficients and NRC values for common building materials and finishes

2.6.2.2. Speech Intelligibility Indices

Speech intelligibility is the Percentage of correctly received units of speech units out of all the transmitted units. It is a high design priority for any hall intended for spoken word, as is the case in church auditoriums. It is influenced directly by background noise levels, reverberation time and the room geometry.

Different Speech Transmission Indices are used to evaluate the intelligibility of speech. RASTI, STI, STIPA are the most common indices.

To evaluate intelligibility units of speech such as single-syllable words, sentences, and nonsense syllables are read for listeners to identify with varying difficulty levels of understanding due to presence of background noise. (Long, 2014)

2.6.2.3. Background Noise Criterion for Church Auditoria

In the built environment, there is no perfect silence. Background Noise Level is defined as the lowest recurrent noise level measured before the noise (or sound) under investigation is induced, and in the absence of any other brief noises - traffic, insects, foliage, etc. (AAAC, 2019).

Acceptable background sound levels depend on the sound frequency.

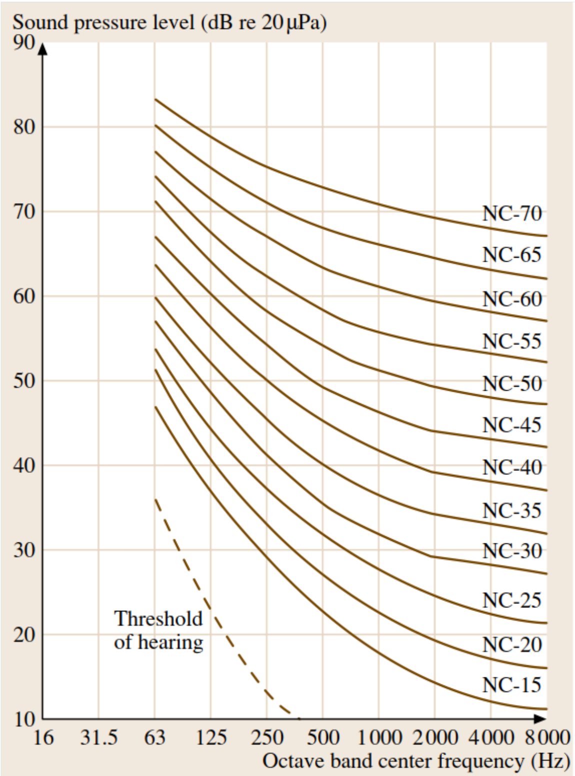
The balanced noise criterion (NCB), room criterion (RC) and noise criterion (NC) curves are commonly used to assess background sound levels within spaces. (Cowan, 2007).The Noise Criterion (NC) was created in the 1950s and was widely used in the United States to show the allowable range of background noise in spaces. It is measured between 63Hz and 8 kHz. NC has a flaw in that it allows for dB values that are uncomfortable at extremely low or very high frequencies, such as HVAC equipment rumbling or hissing (Archtoolbox, 2019).

Room Criterion (RC) is a 1980s-era alternative range of allowed background noise in a room. It is measured between 16Hz and 4 kHz. To accommodate for rumbling HVAC equipment, RC examines sounds at considerably lower frequency levels. Straight lines of constant slope are used to represent RC, which was reported to be the average spectrum as observed in office buildings in the 1980s (Archtoolbox, 2019).

The Balanced Noise Criterion curves (NCB) take into account sound frequencies as low as 16 Hz. This takes care of concerns caused by the low frequency hum of energy-efficient HVAC systems. NCB also suppresses higher frequency levels, so eliminating hisses.

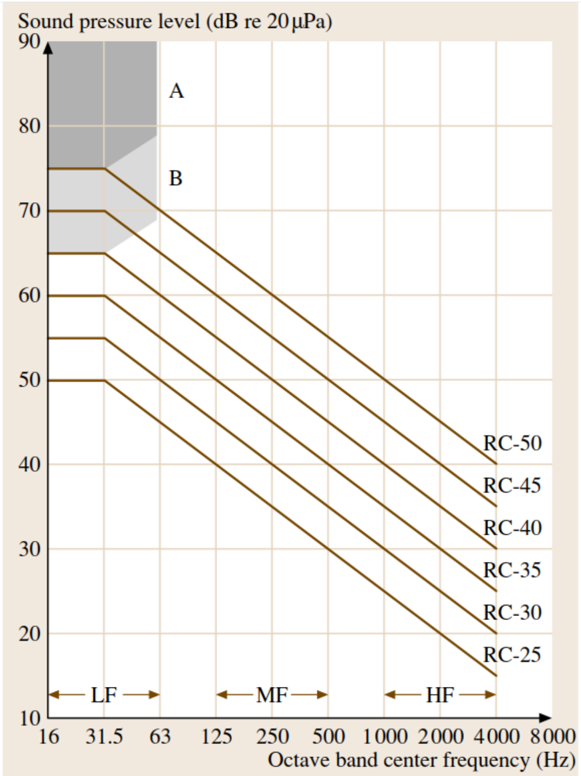
In Figure 32 below, Sound in the A area can create audible vibration induced by noise. Examples include rattling fixtures, windows and doors. Low levels of noise-induced vibrations may be generated by sound in the zone labelled B.

The abbreviations HF, MF and LF denote high frequency, medium frequency, and Low frequency ranges respectively.



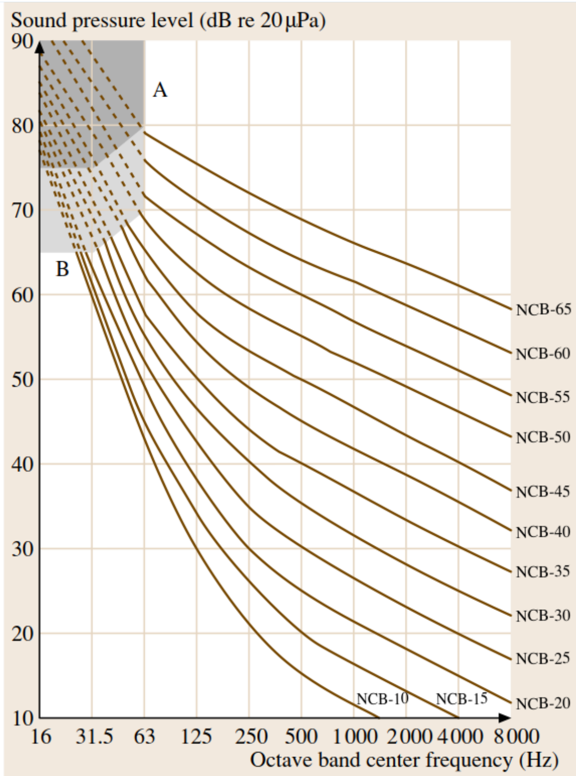
Noise Criterion (NC) Curves

Source: Beranek as cited in Cowan, 2014



Room Criterion (RC) Curves

Source: Blazier as cited in Cowan, 2014



Balanced Noise Criterion (NCB) Curves

Source: Beranek as cited in Cowan, 2014

Figure 32. Noise Ratings for Steady Background Sound Levels.

Copyright: As indicated

Category of space	Specific uses	NC, NCB or RC(N) range	dBA limit
Sensitive listening spaces	Broadcast and recording studios, concert halls	15 to 20	25 dBA
Performance spaces	Theaters, churches, video and teleconferencing	20 to 25	30 dBA
Presentation spaces	Large conference rooms, small auditoriums, movie theaters, courtrooms, meeting and banquet rooms, executive offices	25 to 30	35 dBA
Private spaces	Offices, small conference rooms, classrooms, private residences, hospitals, hotels, libraries	30 to 35	40 dBA
Public spaces	Restaurants, lobbies, open-plan offices, clinics	35 to 40	45 dBA
Service and support spaces	Computer equipment rooms, public circulation areas, arenas, convention centers	40 to 45	50 dBA

Table 9. Recommended background noise criteria for common spaces.

Copyright. Cowan, 2014

2.6.3. Subjective Variables/ Parameters in Acoustics

According to Carvalho, (1995) these are acoustic attributes subjectively identified by a listener described below;

a) Loudness - Overall strength/loudness of sound.

b) Clarity - Degree to which music notes are clearly heard and separated distinctly in time and.

c) Reverberance – Sound persistence in space.

d) Intimacy - Auditory impression that the sound source is close.

e) Directionality - Auditory impression of sound coming from the sound source axis because of the amount of direct sound received.

f) Envelopment - Sense of immersion in sound or surrounding by sound because of the amount of reverberant sound received.

g) Balance – Balance between treble frequencies and bass levels.

h) Echoes - Clearly audible, long delayed reflections.

i) Background Noise – Any other sound perceived beside the sound from the intended source on stage.

j) Overall Acoustic Impression – A person’s overall impression on a room’s acoustic quality.

2.6.4. Correlation of Objective Parameters and Subjective Descriptors

Objective parameters and subjective characteristics are correlated and there exists acoustic quality criteria well defined for different types of spaces, in particular performance halls and auditoriums (Pereira, 2010).

Objective Parameter	**Subjective Measure**
Reverberation Time (RT60)	Reverberance - Perceived persistence of sound in an enclosed space after the sound source has stopped.
Early Decay Time (EDT)	Perception of improved speech and music clarity. Early reflections that reach the listener within 50 to 80 milliseconds integrate with the direct sound and can improve speech clarity
Clarity (C_{50}) & (C_{80})	The degree to which details of the speech or music are perceived to be distinctly separated in time and clearly heard
Definition (D_{50})	Perception of speech intelligibility
Sound Strength (G)	Perception of how loud / clear a sound appears to a listener

Table 10. Correlation between subjective descriptors and objective parameters.

Copyright. Pereira, 2010.

2.6.5. Classification of Parameters by Their Acoustic Quality

Quality	Description	Parameters
Energy Parameters	Parameters that determine the degree to which tones are distinctly separated in time and how clear a sound appears to a listener.	Definition, Clarity, Strength, Centre Time,
Time Parameters	Parameters that quantify persistence of sound in a room after the source of a continuous sound is turned off.	Reverberation Time, Initial Time Delay Gap, Early Decay Time, Bass Ratio Reverberance
Spatial Parameters	Parameters that define the space impression such as feeling of being surrounded by the sound and the impression of being near the sound source or in a small room	Overall impression, envelopment, Intimacy
Speech Parameters	Parameters that determine speech intelligibility	Definition, Alcons, Clarity, RASTI,

Table 11. Classification of parameters by their acoustic quality.

Copyright. Lacatis et al., 2008

2.6.6. Summary

In the Christian tradition, there is a long history of the interaction between liturgy and architecture - between worship and the space in which it takes place. With Constantine's establishment of a Christian empire, churches were able to express Christianity's dominance on the landscape. Christians have worshiped in a variety of locations since then, including early Christian home churches, Roman basilicas, Gothic cathedrals, and modern worship places. Church architecture has evolved in tandem with architectural styles, and vice versa.

Church structures always reflect the character and demands of the congregation. Often, the character of the structure will identify the Church denomination as Pentecostal, Catholic, or Anglican.

Several factors affect church auditoria acoustics. The geometry and size of the auditorium, the type of furniture, the general fabric of the walls, floors and ceilings, background noise, and most importantly, the primary use of the auditorium.

An important consideration for optimal acoustic design of church auditoriums is to engage an acoustic expert from the onset of the planning and design process. It is very important to establish the room geometry according to its intended use and capacity. RT60 should be determined once the intended use is clearly defined. The optimal RT60 value depends on the program and the room size.

It is critical to distinguish between classical and contemporary modern church architecture. The size and iconic significance of classical rooms dictate their room-acoustical properties such as extended reverberation period and extraordinary spaciousness. In such a setting, short reverberation times will sound deficient.

Modern church structures, in many ways, have the acoustic characteristics of multipurpose halls. Appropriately built acoustics, as well as the use of sound reinforcement technologies, allow the structures to host religious services as well as conferences and concerts.

Finally, the science of acoustics continues to evolve with more refined measuring and modelling techniques and an ever-expanding variety of treatment methods and materials. This advancement is spurred by the current digital revolution, which is expected to result in more precise measuring tools and prediction software, the use of augmented and virtual reality in auditory simulation, and more efficient acoustic materials.

CHAPTER THREE - RESEARCH METHODOLOGY

3.1. INTRODUCTION

As earlier stated in chapter 1, the aim of this research are to investigate the primary acoustic design requirements for optimal reverberation time (RT60) in Pentecostal church auditoriums, evaluate two existing auditoriums, recommend possible acoustic design improvements and present the findings in a format that is easy to follow for architects, church leaders, and building contractors in Kenya.

In order to achieve the aim stated above, the research objectives were structured as follows:

1. To study the design criteria for optimal RT_{60} values in church auditoria.
2. To evaluate the design and RT_{60} values for CITAM Ngong and Parklands church auditoria.
3. To recommend design improvements for optimized RT_{60} values.

This chapter introduces and describes the research design and methodology used to carry out the study. It outlines the methods, techniques and tools used to collect and analyse data. This study relies on data obtained from the church auditoria at CITAM Ngong and Parklands, as well as published data where required for calculations.

3.2. RESEARCH DESIGN

This design of this research aims to investigate the research problem by realizing the three objectives as listed above. It has elements of quantitative, descriptive, analytical, empirical, and applied research types.

The first objective identifies planning, geometric and surface design factors that influence the reverberation time and acoustic performance of Pentecostal church auditoriums. To document the architectural design considerations as well as the objective parameters for acoustic characterization of church auditoriums, a detailed literature review was undertaken.

The second objective is realized by determining the sample size, collecting data, processing data, analysing data and presenting the results. Templates for data recording, processing and analysis were developed in reference to the design criteria established from the first objective. Techniques adopted include participant observation, measurement, recording notes and sketching. The main instruments used for data collection include a digital acoustic analyser, a 1/2" omnidirectional microphone, a laser distance meter, a self-retracting metal tape measure, a digital camera and a notebook. The main instruments used for data processing and analysis include ArchiCAD, Microsoft Word and Microsoft Excel computer applications.

The third objective is accomplished by checking evaluation results against the established design criteria to determine the extent to which the evaluated auditoriums meet or fall short of the recommended design criteria.

3.3. REVIEW OF RELEVANT LITERATURE

This entailed a survey of books, journals, scholarly articles, and other sources relevant to church auditoria acoustics to explore existing research on the subject and help tie this study to a larger body of related research.

3.4. POPULATION AND SAMPLE

Pentecostal churches have proliferated throughout Kenya since the 1980s, but more significantly since the 1990s till present. CITAM, Deliverance Church, Neno Evangelism Ministries, Maximum Miracles Ministries, Jesus is Alive Ministries, Faith Evangelistic Ministries, Redeemed Gospel churches, and Winners Chapel International Ministries are examples of Pentecostal churches in Kenya. These Pentecostal and charismatic organizations today comprise a sizable Christian constituency with millions of followers.

CITAM was established in 1952 and as such is one of the oldest Pentecostal ministries in the county. It is also the largest Pentecostal church institutions in Kenya with 18 branches countrywide situated in Nairobi – [Valley road (1959), Woodley (1994), Karen (1997), Parklands (1998), Buruburu (2005), Thika road (2008), Embakasi (2016) and Clay city(2018)], Kisumu (2000), Ngong (2003), Nakuru (2011), Eldoret (2013), Athi river (2013), Kapsabet (2015), Thika town (2016), Rongai (2016), Nyeri (2018) and Meru (2018). The church also has interests in broadcast media, education, health, and hospitality. In 2018, CITAM had a total income of Kes 1.964 Billion and total assets valued at Kes 12.33 Billion (CITAM Agm Report, 2019).

For the reasons cited above, the author settled for CITAM because it occupies a strategic position among the Pentecostal churches in Kenya and has both financial and leadership capacity to influence how Pentecostal church auditorium design in Kenya is undertaken.

As of April 2011, only the CITAM congregations at valley road, Woodley, Karen and Kisumu were meeting in permanent church auditoria. CITAM then embarked on an initiative dubbed “Moving the Ark (MTA)” a special purpose vehicle for raising funds to build permanent structures for congregations that were meeting in tents. This study evaluates the first two auditoria commissioned so far under the initiative – CITAM

Parklands in 2014 and CITAM Ngong in 2017. The findings will be shared with the presiding bishop, accompanied by a proposal for the church to consider developing a standard template with guidelines for incorporation of acoustic requirements during design.

Since the population does not constitute a homogeneous group, stratified sampling technique was used to obtain a representative sample. The population of 18 branches is narrowed down to the six branches with permanent church auditoria. These are Valley road, Woodley, Parklands, Karen, Kisumu and Ngong. The other congregations meet either in tent structures or leased halls and godowns.

Purposive (non-probability) sampling was used to select the church auditoria at Ngong and Parklands for a detailed acoustical evaluation because they were the first sanctuaries under the "move the ark" initiative.

3.5. DATA COLLECTION

This study utilizes both Primary and Secondary data sources. (Kothari, 2004). First, the architectural features of both auditoriums are surveyed including the geometry, dimensions, surface areas, volume, seating capacity, and the general fabric of the walls, floors, ceilings and furniture. Second, the main objective acoustic parameter - RT_{60} is measured to characterize the physical response of each auditorium. The measurements are taken at several receiver locations using an interrupted noise signal through the existing PA systems and a handheld AL1 acoustic analyser by NTI audio.

The research instruments adopted for data collection are measurement and scaling techniques, personal observation and desk review as explained below.

3.5.1. Measurement and scaling

The author used various instruments to obtain relevant information or data on particular acoustical elements.

a) The AL1 Acoustilyzer by NTI audio - a handheld sound level meter and acoustic analyser used to measure sound pressure level and various room acoustics parameters including RT_{60}.

b) MiniSPL microphone by NTI audio – A class 2 omnidirectional 1/2" microphone with a built in impedance converter, pre-amplifier and power supply. It is battery powered with balanced XLR-output. The Acoustilyzer in (a) above in combination with the MiniSPL forms a comprehensive class 2 acoustical analyser.

c) A Self-retracting metal tape measure & a Leica Disto E7400x Laser Distance Meter by Leica geosystems for measuring length, width and heights of the church auditoria for calculation of the room areas, volumes and length to width ratios.

3.5.2. Architectural Measurements

This involved architectural survey of the auditoriums to establish the shape, dimensions, surface areas, volume, and orientation of surfaces for further analysis.

3.5.3. Acoustic Measurements

This involved acoustic survey in order to evaluate the main acoustic parameter RT_{60} as defined by ISO 3382. The test signal source was the PA system speakers as currently positioned in each auditorium. The receiver (MiniSPL microphone) positions were in the front, middle and rear of each seating segment within the main halls and balconies.

At each receiver position, the microphone was placed at a height of 1.20 m (ears height in sitting position) facing the stage. The procedures employed are those established in the ISO 3382- 2 standard, and all measurements were undertaken in an unoccupied state.

3.5.3.1. Acoustic Measurement Procedure

The International Standard cited above describes two different methods for Reverberation Time measurement: “interrupted noise” method and the “integrated response to the impulse” method. Because of the instruments available, the measurements in this study were taken using the interrupted noise method as described below.

a) A measurement of the actual sound pressure level (background noise level) in the room is undertaken without a test signal present.

b) The room under test is injected with a gated pink noise signal with an on/off cycle of 2 seconds through auditoria speakers. 2 seconds was sufficient time for the sound to reflect off all surfaces.

c) After each cycle, the AL1 recognizes the interruption, the room response (decay time) is measured and the RT60 test result is automatically calculated at each octave band from 125 Hz to 8000 Hz for all the receiver positions. Three test cycles are taken at each receiver position to obtain an averaged test result.

d) The test results are transferred to Microsoft excel software for analysis.

3.5.4. Observation

This involved observation, photography and notes taking to document the surface materials used, seating arrangement, audience capacity, and PA system setting. Aerial images from Google earth show the context of the church auditoria, building orientation and sources of external noise.

3.6. DATA RECORDING TEMPLATES

3.6.1. General design data

The following categories were used to organize general design data for further analysis.

i) Location – To record the immediate context within which the church auditorium was located.

ii) Floor plan shape - To record the shape and profile of the floor plan – rectangular, fan shaped, circular, or polygonal.

iii) Structure - To record the construction materials of the main building elements such as walls, floors, roofs, windows and doors.

iv) Program - To record the various uses and percentage distribution of each activity.

v) Floor area – To record the overall auditorium floor area in square metres

vi) Ceiling area - To record the overall auditorium ceiling area in square metres.

vii) Seating capacity - To record the auditorium seating capacity

viii) Volume - To record the overall auditorium volume in cubic metres.

ix) Surface finishes – To record the various surface finishes of floors, walls and ceilings.

x) Reverberation time (RT60) - To record measured and calculated RT60 values respectively.

3.6.2. Quantitative design data template

The template in ***Table 12*** below was used to record quantitative survey data for further analysis.

Variable		**Quantity**
Seats		Pieces
Volume	Main Hall	m^3
	Below balcony	
	Balcony	
	Stage	
Floor areas	Terrazzo	m^2
	Ceramic tiles	m^2
	Carpet	m^2
Ceiling areas	Acoustic fibre tiles	m^2
	Plaster and paint	m^2
	Gypsum board	m^2
	Light fittings with diffusers	m^2
	Panel light fittings	m^2
	Air-conditioning grilles	m^2
	Perforated sheet metal	m^2
Wall, column and other surface areas	Plaster & paint	m^2
	Perforated gypsum panels	m^2
	Fabric covered Foam Panels	m^2
	Gypsum board	m^2
	Ceramic tiles	m^2
	Terrazzo	m^2
	Laminated glass	m^2
	Solid wood	m^2

	Laminated Mdf panels	m^2
	Perforated Mdf panels	m^2
	Slatted Mdf panels	m^2
	Plain Mdf panels (solid)	m^2
	Drapery	m^2
	Carpet	m^2
	Mild steel	m^2
	Powder coated aluminium	m^2
	Plain aluminium	m^2
	AC outlets	m^2
	Vinyl banners	m^2
	LCD display screens	
	LED display screens	
	Granite	m^2

Table 12. Quantitative data recording template.
Source. Author, 2020.

3.6.3. Measured RT60 values template

The template in ***Table 13*** below was used to record measured RT60 values for further analysis.

Zone	Frequency bands (Hz) & measured RT60 (s)					
	125 Hz	250 Hz	500Hz	1kHz	2kHz	4kHz
Zone 1						
Zone 2						
Zone - - -n						
Average RT60 value per frequency band						

Table 13. Measured RT60 values

Source. Author, 2020.

3.6.4. RT60 Calculation - Template 1

The template in ***Table 14*** below was used to calculate RT60 using coefficients of absorption for frequencies between 125Hz and 4KHz.

	Surface area (m²), Absorption coefficients and Sabins Sabins = Area x respective absorption coefficient (α) at the specific frequency band.												
		125 Hz		**250 Hz**		**500 Hz**		**1 kHz**		**2 kHz**		**4 kHz**	
Material	**Area m²**	α	**Sabins**	α	**Sabins**	α	**Sabins**	α	**Sabins**	α	**Sabins**	α	**Sabins**
Material 1													
Material 2													
Material . . . . n													
Total Absorption (Summation of sabins)													
Auditorium Volume													
RT60 – Unoccupied (calculated using Sabine formula)													

Table 14. RT60 calculation template 1

Source. Author, 2020.

3.6.5. RT60 Calculation - Template 2

The template in ***Table 15*** below was used to calculate RT60 using the Noise Reduction Coefficient (NRC) for each material.

Material	**Area (m^2)**	**NRC**	**Sabins**
Material 1			
Material 2			
Material . . . . n			
Total Absorption (summation of Sabins)			
Auditorium Volume			
RT60 – Unoccupied (calculated using Sabine formula)			

Table 15. RT60 calculation template 2
Source. Author, 2020.

3.6.6. Acoustic design evaluation template

In reference to 2.6.1 and 2.6.2, the categories below and the associated recommended design criteria were used to evaluate the acoustic design and properties of the two auditoriums.

i) Site selection

ii) Site layout and external noise isolation

iii) Main Construction

iv) Auditorium size: Hall Capacity, floor area, volume, and ceiling height

v) Room Geometry: Hall shape and profile, stage shape and profile, side & rear walls geometry, balcony projection and profile, ceiling geometry, and sight lines

vi) Surface finishes: Floors, Walls, ceilings and seats

vii) Sound reinforcement

i) Reverberation time (RT60)

ii) Noise Pollution

3.7. DATA PROCESSING TECHNIQUES

The collected data was processed and organised for analysis in the form of photographs, illustrated drawings, tables, graphs and charts. The computer applications for processing included ArchiCAD, Microsoft Word and Microsoft Excel.

The field measurement data was keyed into ArchiCAD to generate a digital 3D model of the auditorium from which drawings and other architectural quantities were derived.

CHAPTER FOUR - ACOUSTIC ANALYSIS OF THE CITAM CHURCH AUDITORIUMS AT NGONG AND PARKLANDS, NAIROBI.

4.1. INTRODUCTION

The purpose of this chapter is to evaluate a successful case study, as well as presentation, analysis and interpretation of the data collected from a surveying the CITAM auditoria at Ngong and Parklands. Photographs, illustrated drawings, and tables are used for presentation and analysis of general auditoria information, immediate context, form, room volume, surface areas, surface treatment, number and type of seats, and RT60 values.

4.2. CASE STUDY – CALVARY CHURCH CENTRE, KUALA LUMPUR, MALAYSIA

4.3. Case Study - Introduction

The Calvary church auditorium was chosen as a case study due to its success in incorporating most of the design requirements for acoustic comfort in a Pentecostal church auditorium, as detailed previously in chapter 2.

The Calvary Church Centre is located on a 4.9 acre piece of land in the southern part of Wilayah Persekutuan, Kuala Lumpur.

Designed by T.R. Hamzah & Yeang Architects, it has facilities that are unique and dedicated to enhancing worship, convention and educational requirements.

The entire complex has a built-up area measuring 55,000 square meters, spreading across 4.9 acres of prime land close to the heart of Kuala Lumpur, with the 5,000-seat (4,515 sqm) auditorium as the main focal point. Past events held in the Auditorium include church services, Pentecostal conferences, praise concerts, TEDx Conferences, and award ceremonies.

4.3.1. Case Study – Architectural Details

The Site – The complex is located Within the Bukit Jalil International zone in Kuala Lumpur, Malaysia, at the junction of two busy roads – Jalan Jalil Way and Bukit Jalil Highway. The immediate context has a golf course, a recreational park, a mixed-use complex and residential estates.

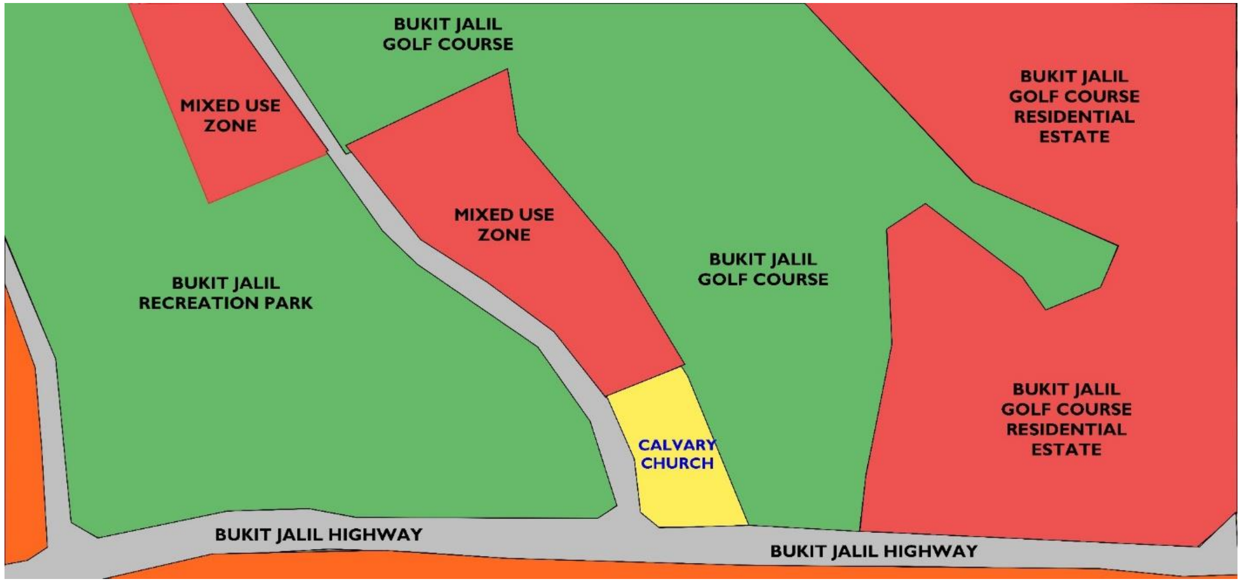


Figure 33. Calvary Church Immediate Context

Copyright. Author

Figure 34. Calvary Church Immediate Context

Copyright. Calvary Church, 2020

Form – The complex is symbolically shaped like a dove, with wings of an angel (cherubim). The plan of the building is shaped like a fish. The built form consists of two blocks separated by a day-lit semi-enclosed all-weather covered plaza. The larger block comprises the auditorium and its supporting facilities while the opposite block is the institutional block with teaching classrooms, hostel/guest apartments and administrative offices (TR Hamzah & Yeang Sdn Bhd, 2021).

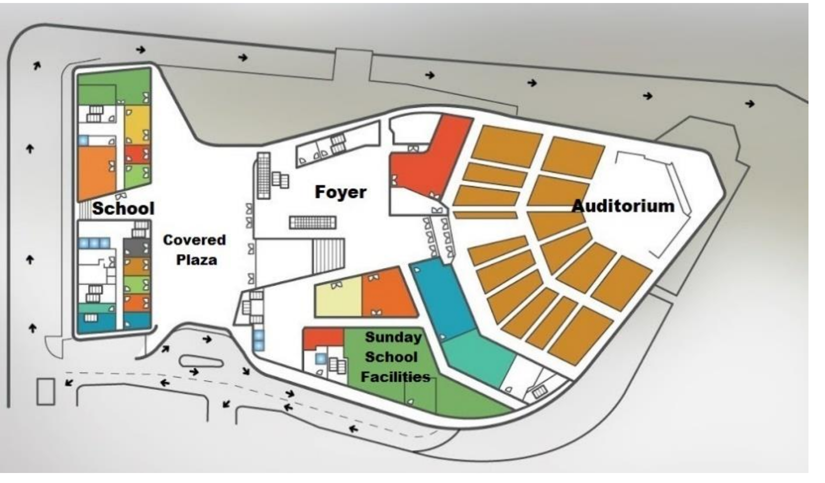


Figure 35. Calvary Church Space Layout

Copyright. Emey, 2020

The Auditorium - The auditorium has a column-free span of 60m. Its roof is supported by 2 main trusses spanning from the back to the front of the hall on 4 mega columns. It is designed to be sub-dividable into 3 smaller halls, and has built-in structures in the ceiling for future installation of foldable ceiling mounted 'Sky-fold' partitions, up to 10m in height. The front of the sub-dividable halls has retractable seats to convert the space into a speaker area when needed. The stage is designed to accommodate theatrical and musical productions, including a fly tower, orchestra pit, stage proscenium, changing rooms, rehearsal rooms, and a green room (TR Hamzah & Yeang Sdn Bhd, 2021).

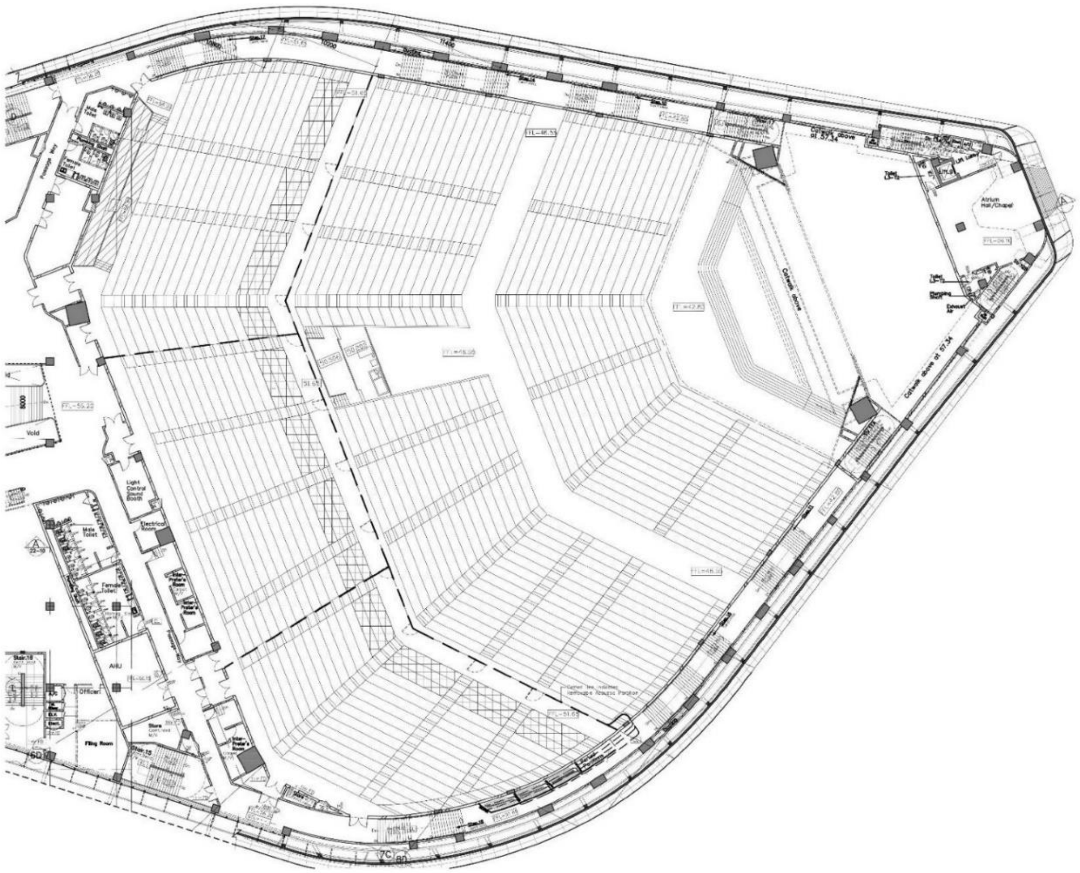


Figure 36. Calvary Church: Fan-shaped floor plan.

Copyright. TR Hamzah & Yeang Sdn Bhd, 2021

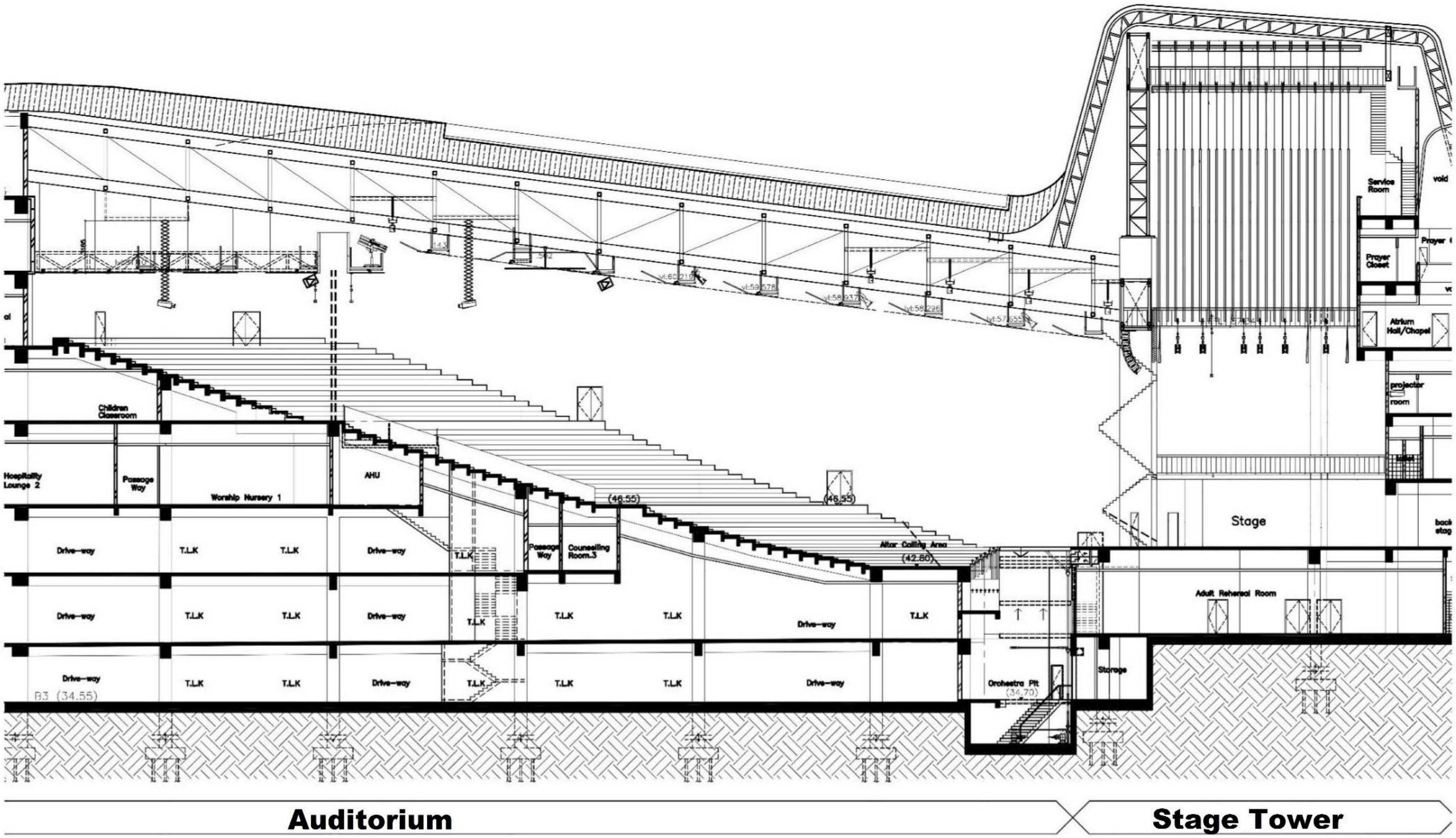


Figure 37. Calvary Church:Auditorium Longitudinal Cross Section

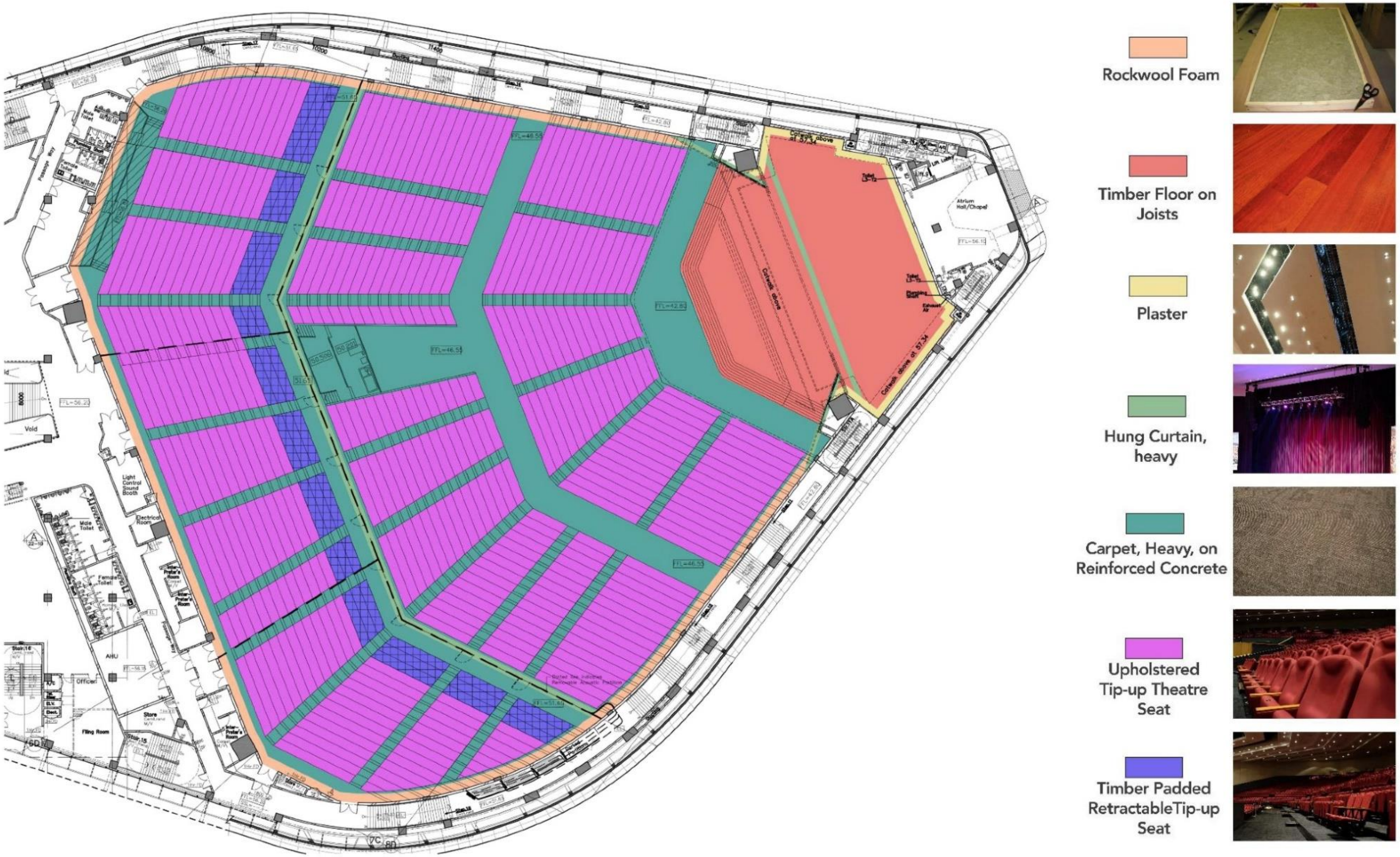


Figure 38. Calvary Church: Surface Finishes.

Copyright. (Xiang et al., 2017).

4.3.2. General design data

i) **Location** - The Calvary Church Centre is located on a 4.9 acre piece of land in the southern part of Wilayah Persekutuan, Kuala Lumpur. The complex is located Within the Bukit Jalil International zone in Kuala Lumpur, Malaysia, at the junction of two busy roads – Jalan Jalil Way and Bukit Jalil Highway. The immediate context has a golf course, a recreational park, a mixed-use complex and residential estates.

ii) **Floor plan shape -** The auditorium floor plan is fan shaped and raked towards the rear. Raking angles vary between 15 to 18 degrees. The auditorium sidewalls have a 30 degrees splay. Stage walls at either side of the proscenium have a 140 degrees splay – measured from the proscenium line. The rear wall is flat with 140 degrees splays at the ends.

iii) **Structure -** The main building components consist of a reinforced concrete frame structure, solid block infill walls, reinforced concrete floor, solid timber entrance doors, thick clear glass window panes, and metal roofing deck with rock wool layer underside.

iv) **Program -** The Calvary Church Centre is a distinctive convention centre dedicated to the pursuit of holistic activities including the hosting of worship services, international and local conventions, seminars and creative arts productions.

v) **Floor area -** The auditorium has a cumulative floor area of 4,515 square metres including the main hall and stage (isles included in the area).

vi) **Seating capacity -** The auditorium has a cumulative seating capacity of 5,000 consisting of fabric and leather upholstered seats.

vii) **Volume –** The overall auditorium volume is 39,136 cubic metres including the main hall and stage.

viii) **Surface finishes** – The main finishes consist of rock wool sandwich panels to side walls, plasterboard panels to stage walls, laminated timber and carpet floors, angled gypsum panels on ceilings, heavy curtain at proscenium opening, and upholstered tip up theatre seats. Some wall sections have heavy curtain hung in fold, 6mm thick glass in aluminium frames, plywood over a 25mm air gap, and Plasterboard on battens with 18mm Airspace.

ix) **Reverberation time (RT60)** – The design of the Calvary Convention Centre achieved a reverberation time of 0.92s at 500Hz.

4.3.3. Quantitative Design Data

Variable		**Quantity**
Floor Area		4515 m^2
Volume		39,136.6 m^3
No. of Seats (Current occupancy)	Upholstered = 2965	3,385
	Timber padded = 420	
Heavy thick Piled Carpet on Reinforced Concrete		3295 m^2
Timber Floor on Joists		115 m^2
Heavy Curtain, Hung in Fold Against Solid Wall		465 m^2
Rock Wool 30mm, 200 kg/m3 over 300mm Air Gap		1675 m^2
Acoustic Timber Board		2480 m^2
Plywood Panels over 25mm Airspace		220 m^2
Plasterboard on Battens with18mm Airspace		2480 m^2

6mm thick Pane Glass	100 m^2
Upholstered Tip-Up Theatre Seat	2965 m^2
Timber Padded Retractable Tip-Up Seat	420 m^2

Table 16. Calvary Church: Quantitative Data.

Copyright. (Xiang et al., 2017).

4.3.4. RT60 Calculation – NRC

Material	**Area (m^2)**	**NRC**	**Absorption of Surface(m^2 Sabins)**
Heavy thick Piled Carpet on Reinforced Concrete	3295 m^2	0.50	1647.50
Timber Floor on Joists	115 m^2	0.10	11.50
Heavy Curtain, Hung in Fold Against Solid Wall	465 m^2	0.55	255.75
Rock Wool 30mm, 200 kg/m3 over 300mm Air Gap	1675 m^2	0.85	1507.50
Acoustic Timber Board	2480 m^2	0.42	1041.60
Plywood Panels over 25mm Airspace	220 m^2	0.15	33
Plasterboard on Battens with18mm Airspace	2480 m^2	0.15	372
6mm thick Pane Glass	100 m^2	0.03	3

Upholstered Tip-Up Theatre Seat	2965 m^2	0.64	1897.60
Timber Padded Retractable Tip-Up Seat	420 m^2	0.15	63
Total Room Absorption, (m^2 Sabins)			**6832.45**
Auditorium Volume			**39136.6**
Sabine RT60 - Unoccupied			**0.92s**

Table 17. Calvary Church: Calculated RT60 using coefficients of absorption.

Copyright. (Xiang et al., 2017).

4.3.5. Calvary Church Centre – Acoustic design evaluation

This section is an evaluation of the extent to which the Calvary Church auditorium meets the recommended design criteria for acoustic comfort based on the template in section 3.6.6.

i). **Site Selection** - As noted earlier, the Calvary Church Centre is located at the junction of two busy roads, one of which is a major highway. This proximity to vehicular noise sources necessitates certain design solutions as discussed more under site layout below.

ii). **Site layout & External noise isolation –** The design at Calvary Church isolates the auditorium from external noise as follows:

a. A circulation buffer around the auditorium hall doubles up as an air barrier to isolate the hall from external noise sources. All auditorium entry points have air gaps.

b. Sunday school facilities separate the hall and the foyer.

c. The roofing comprises of a metal roofing deck with rock wool underlay (to reduce rain noise impact) and substrate acoustic panels

d. Air conditioning equipment are beneath the auditorium floor for circulation of cool air from below.

e. A thick layer of insulation separates the basement carpark ceiling and the underside of the auditorium floor.

f. There is no vehicular circulation adjacent to the auditorium walls. A landscaped zone separates the hall and the nearest driveway. The basement parking also minimizes vehicular movement at hall level.

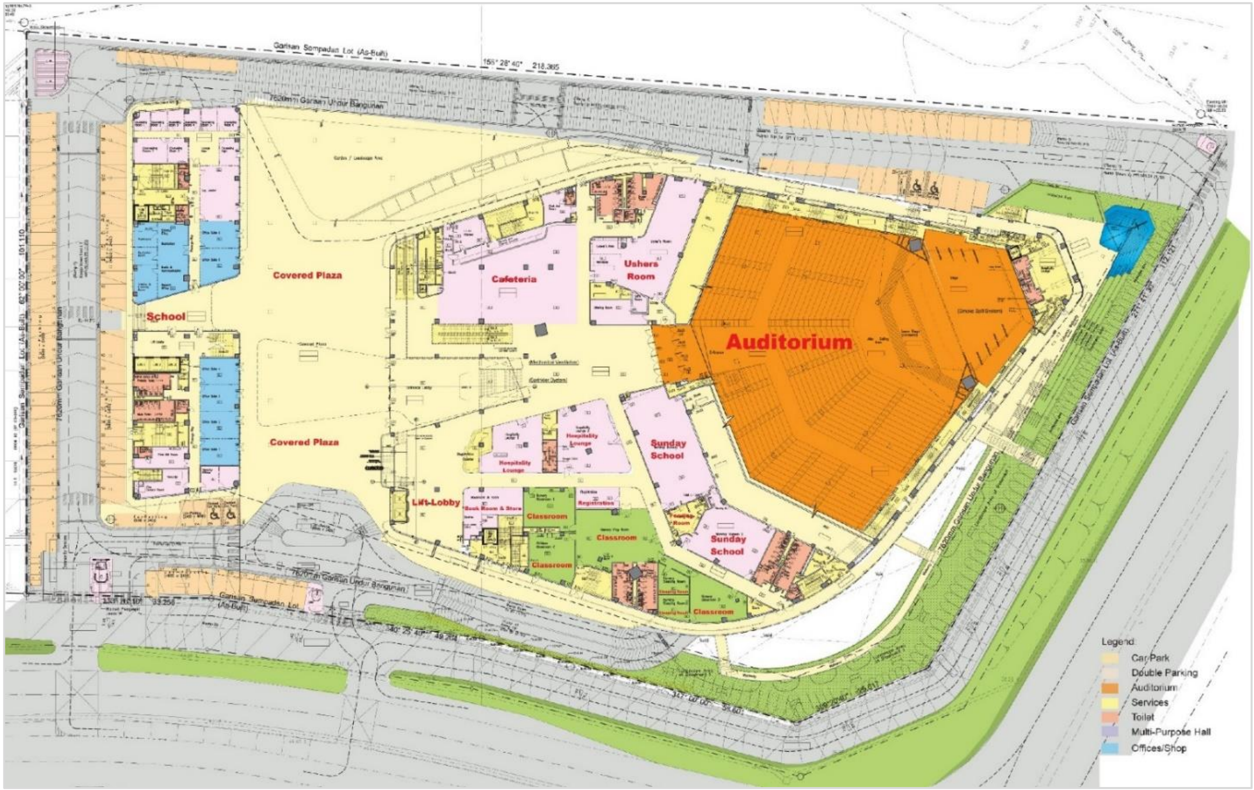


Figure 39. Calvary Church: Buffer spaces around Auditorium

***Figure 40*.** Calvary Church: External Noise Control

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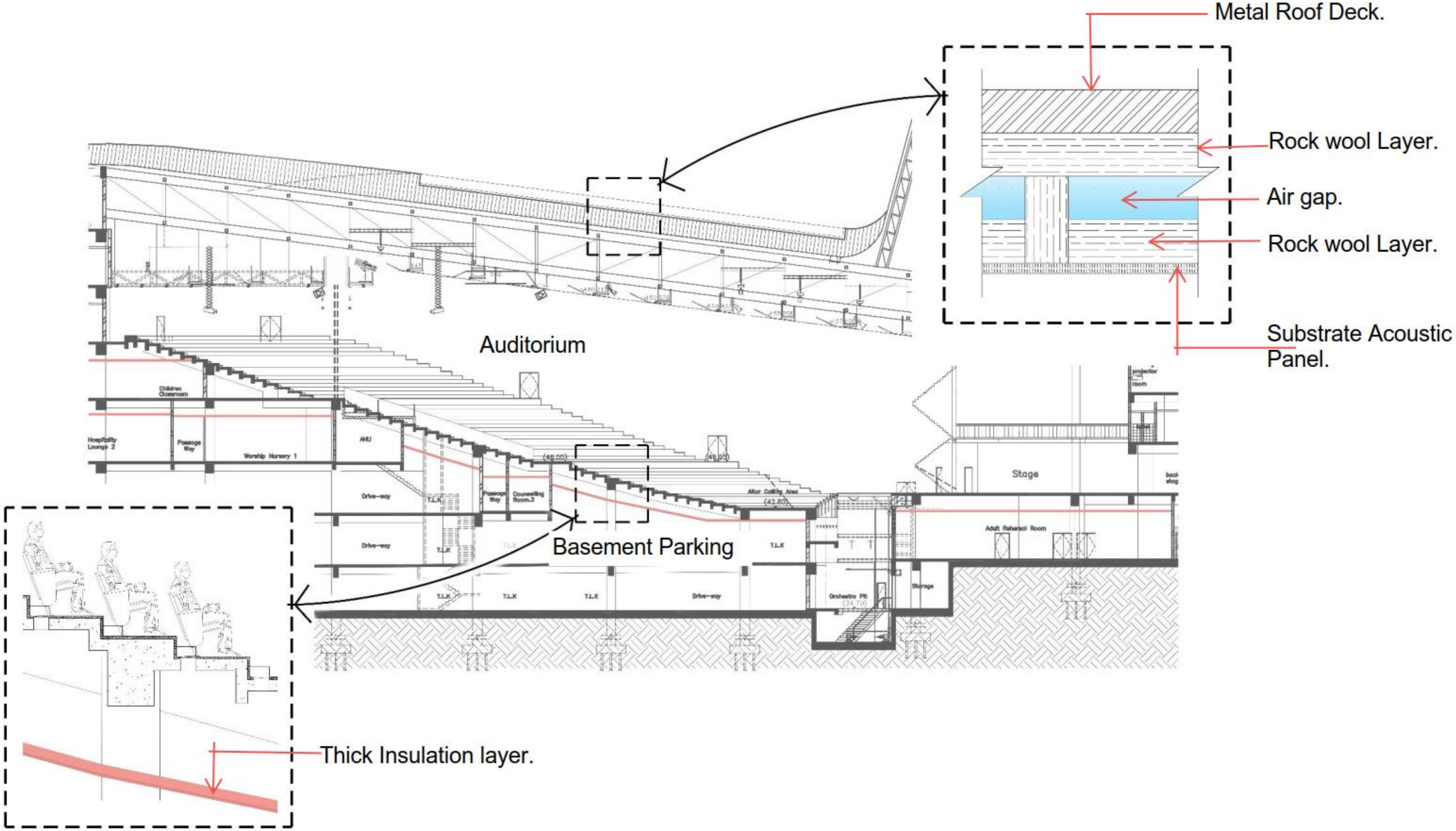

Figure 41. Calvary Church: Roof & Floor Sound Insulation.

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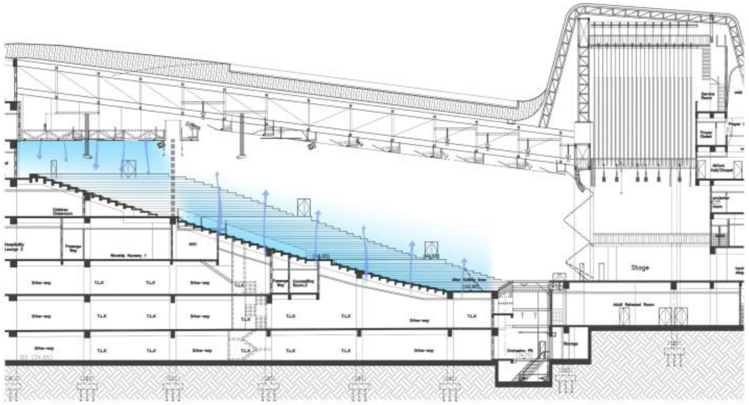

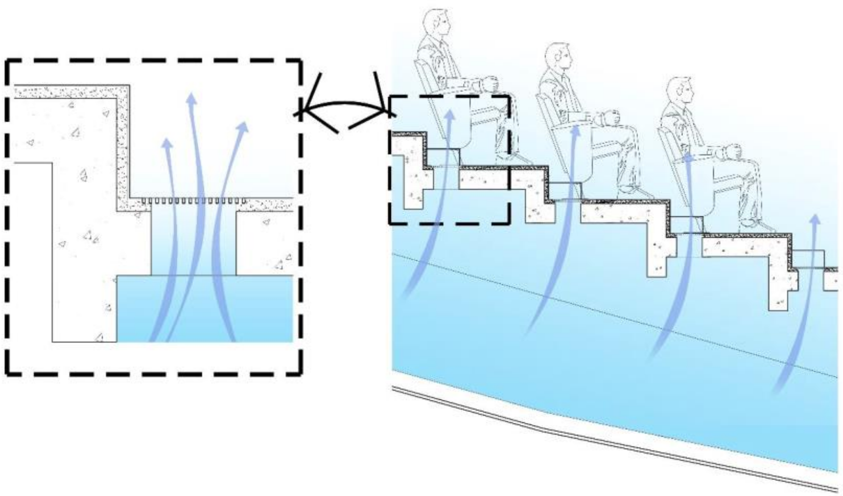

Figure 42**.** Calvary Church: Ventilation Beneath the seats.

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iii) **Structure -** The main building components consist of a reinforced concrete frame structure, solid block infill walls, reinforced concrete floor, solid timber entrance doors, 6mm thick glass window panes, and metal roofing deck with rock wool layer underside and substrate acoustic panels. Concrete, solid wall blocks, and solid timber are dense materials and efficient in blocking unwanted noise.

iv) **Room size: *Hall Capacity, floor area, volume, and ceiling height*** – The auditorium design capacity is 5000 seats with a floor area of 4515m^2 and an overall volume of 39,137m^3. This translates to an area of 0.9m^2 and a volume of 7.8m^3 per seat respectively. This is within the recommended design range of 0.6 m^2 to 0.9 m^2 and 5.1m^3 to 8.5m^3 per seat. This implies that with appropriate surface treatment, it is possible to attain an acceptable RT60 for the hall. The average ceiling height of the hall is 17m. The recommended ceiling height for a large hall is 1/3 of the width. With an average width of 67m, 1/3 translates to 22m. The auditorium ceiling height is therefore below the recommended height by 5m, implying that the current hall volume, though within the acceptable range, is below the optimal volume.

v) **Room Geometry: *Hall shape and profile, stage shape and profile, side & rear walls geometry, balcony projection and profile, ceiling geometry, and sight lines***: The Calvary Church auditorium meets the recommended design criteria

a) The auditorium floor plan is fan shaped and raked towards the rear. Raking angles vary between 15 to 18 degrees.
b) The forestage (apron) stage is 600mm above the lowest auditorium level, and the main stage 600mm above the apron.
c) The auditorium sidewalls have a 30 degrees splay.
d) Stage walls at either side of the proscenium have a 140 degrees splay – measured from the proscenium line.
e) The rear wall is flat with 140 degrees splays at the ends.

f) There are two ceiling surfaces. The heavily insulated first (upper) ceiling slopes from the back towards the stage. The second (lower) ceiling consists of stepped gypsum board panels, tilted at different angles to reflect sound to particular seating areas.
g) The gypsum panel ceiling above the stage has a tilt upwards towards the audience hall.

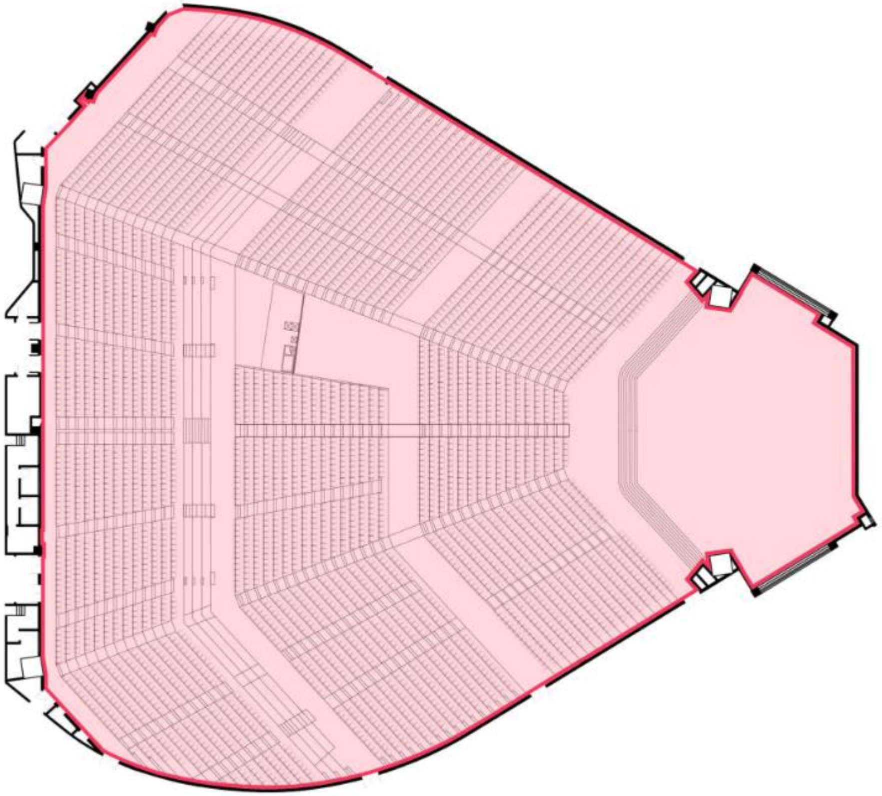

Figure 43. Calvary Church: Fan shaped floor

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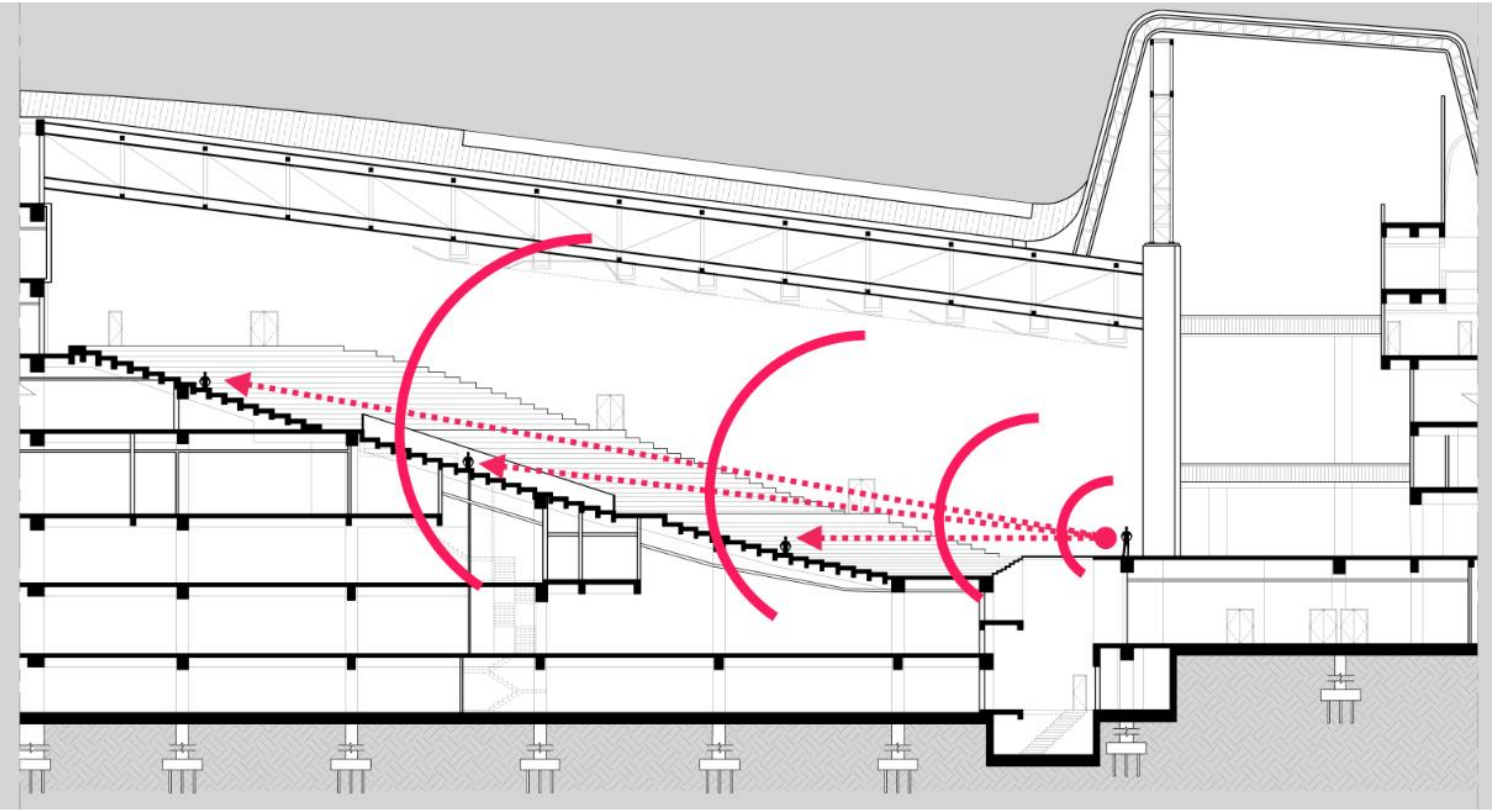

Figure 44. Calvary Church: Raked floor

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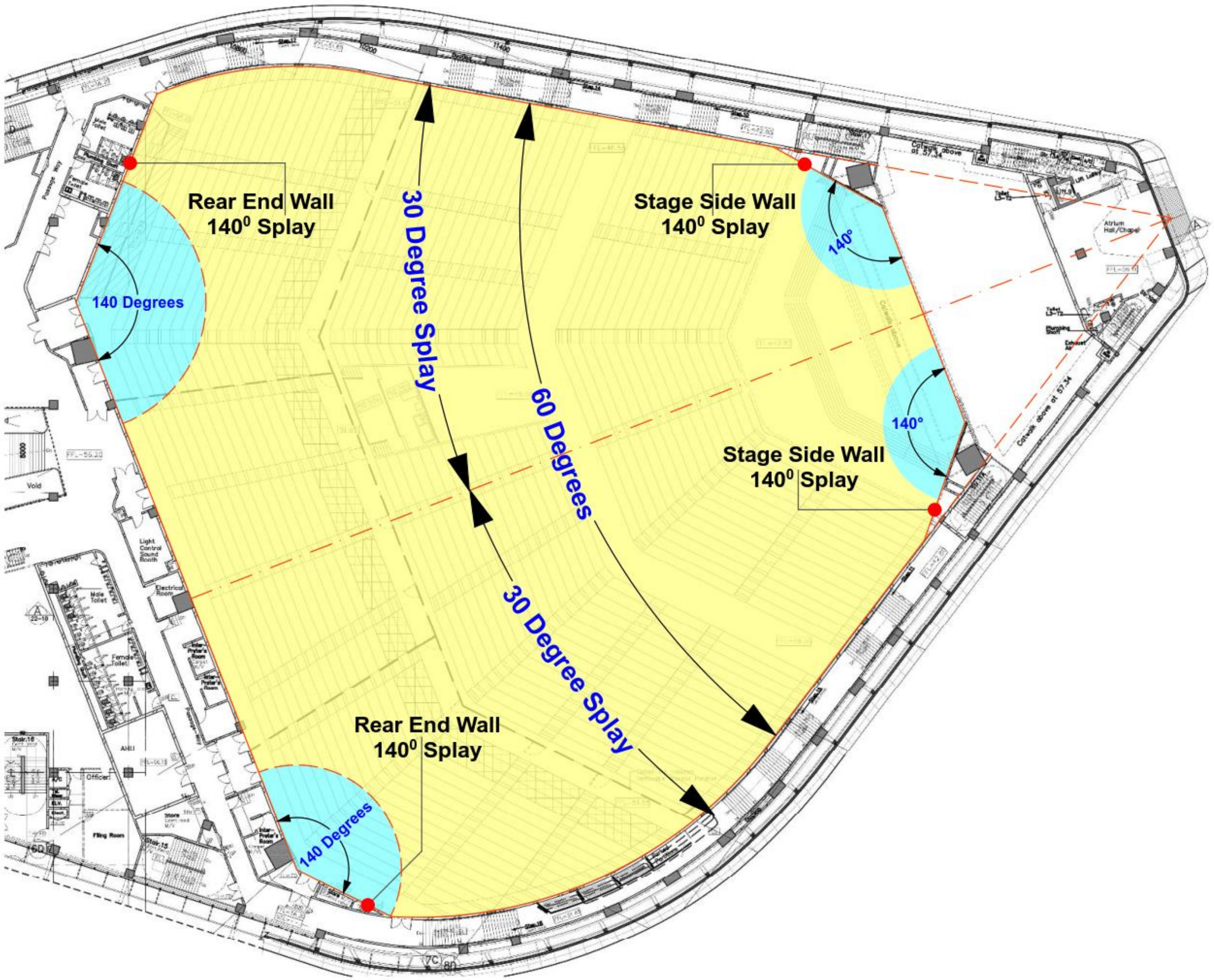

***Figure 45*.** Calvary Church: Various wall splays

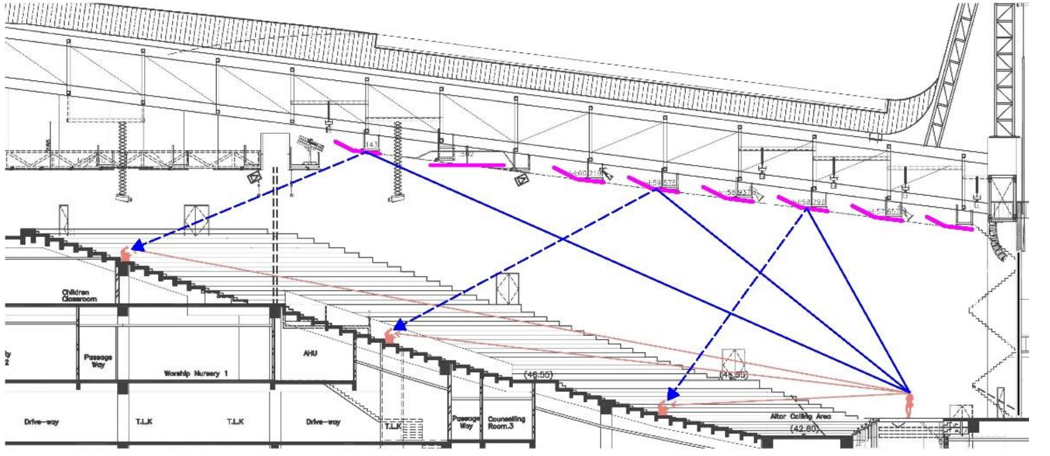

***Figure 46*.** Calvary Church: Ceiling Profile
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Figure 47. Calvary Church: Ceiling Profile

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***vi) Surface finishes: Floors, Walls, ceilings and seats* –** The Calvary Church auditorium incorporates the recommended criteria as described below:

a) Sidewalls consists of various materials with 200 kg/m3 rock wool sandwich panels, over a 300mm air gap as the outer finish. Beneath the air gap are fabric covered foam panels on the main wall surface and a layer of plywood over the foam panels.
b) The rear wall has absorptive wall panels.
c) The upper ceiling surface has thick insulation. The lower ceiling surface consists of stepped and angled gypsum board panels. The panels cover 70% of the ceiling area, with 30% as gaps opening up to the insulated upper ceiling for sound absorption.
d) The stage floor has laminated timber strips on joists. All isles have heavy carpet on concrete slab.

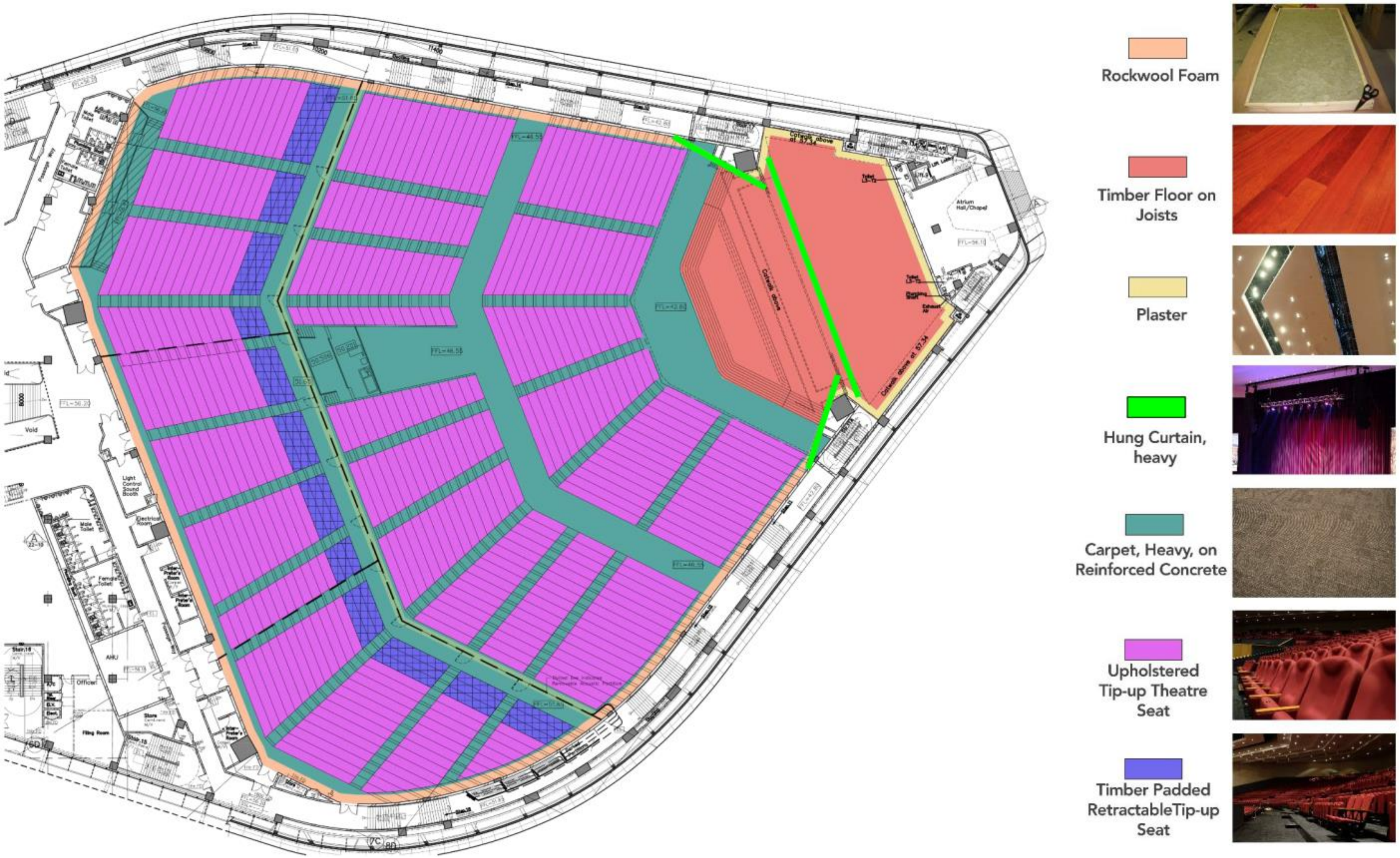

Figure 48. Calvary Church: Wall & ceiling surface finishes in plan.

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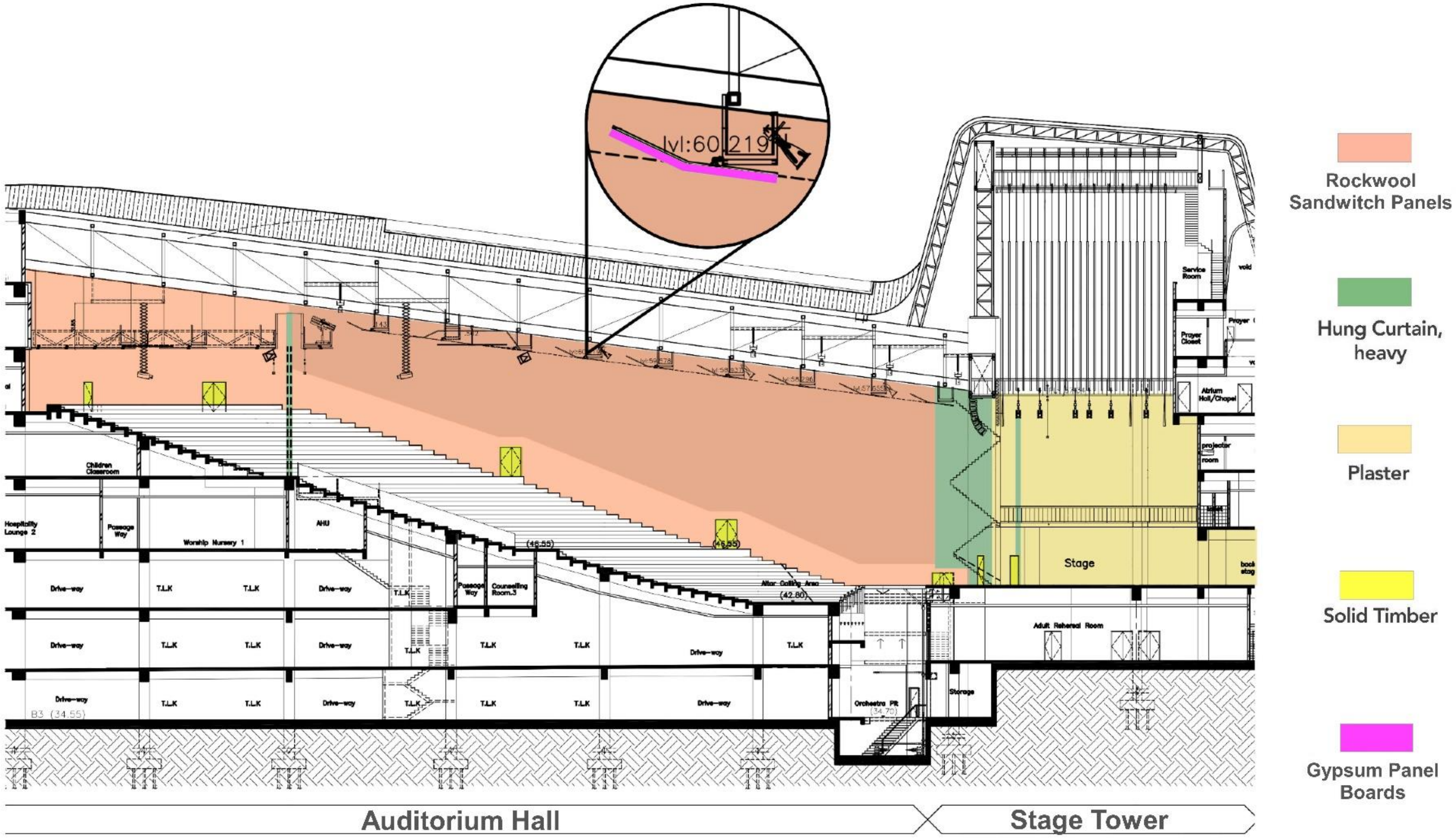

Figure 49. Calvary Church: Wall & ceiling surface finishes in section.

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Figure 50**.** Calvary Church. Internal surface finishes.

The photo shows undulated rock wool sandwich panels on sidewalls, angled gypsum panels on ceilings, heavy carpet on aisles, laminated timber strips on stage, and heavy curtain at proscenium opening.

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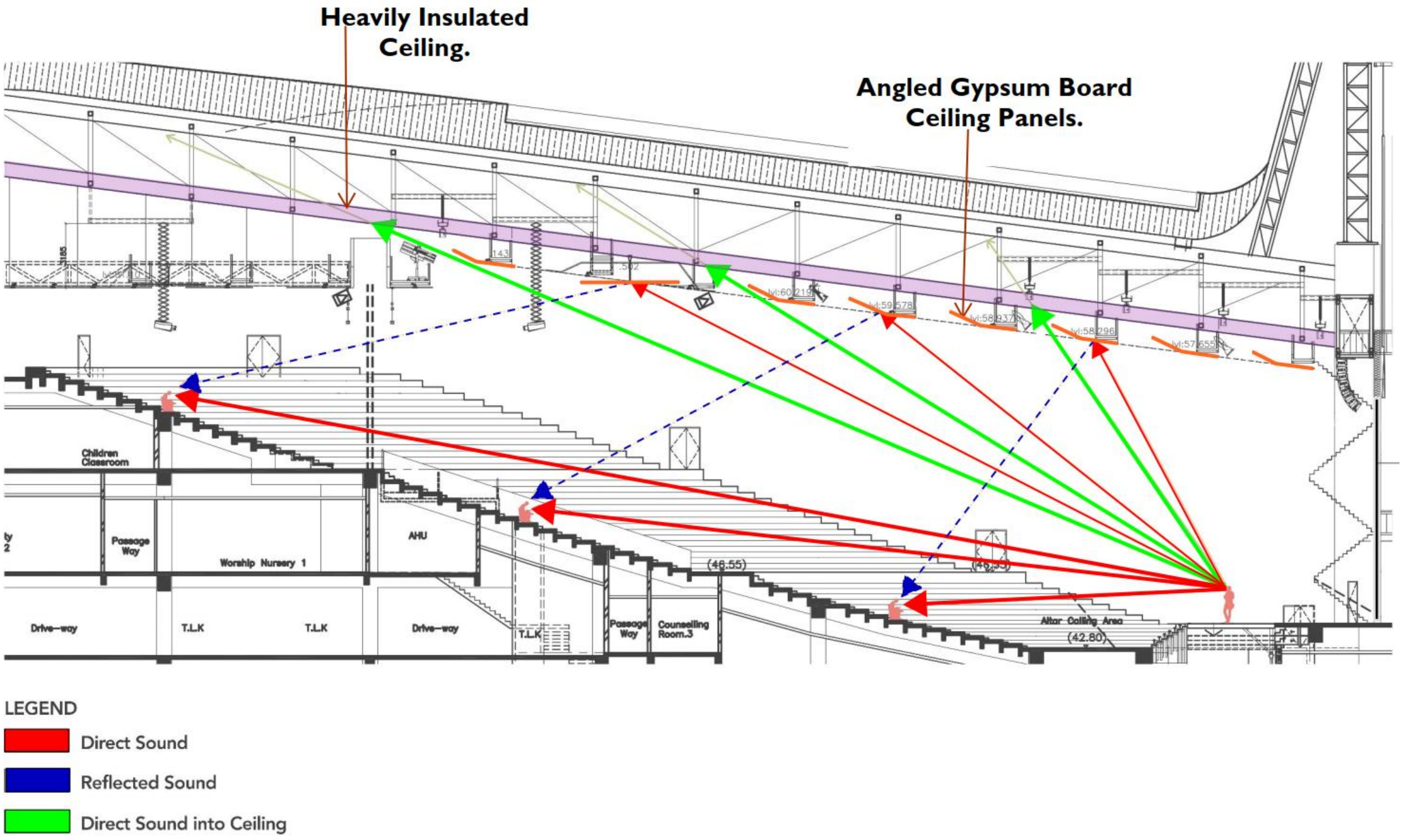

Figure 51. Calvary Church: Ceiling Finishes

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vii) **Sound *reinforcement* -** Three types of loud speakers are used in the auditorium. The first set is a line-array loudspeaker system anchored on the ceiling slightly in front of and above the proscenium opening, and positioned to project sound to the back of the auditorium. The next set of loud speakers is located in the flat area below the stage and positioned to project sound towards the front four (4) seating rows, which are not served by the line array loud speakers. The last set consists of stage monitors located on stage and positioned to project sound back to the performers and speakers. The various loud speakers and stage monitors as manufactured by L-Acoustics have a combined frequency range of between 50 Hz to 20 kHz which is ideal for both music and speech reproduction.

viii) **Reverberation time** - The calculated RT60 using coefficients of absorption was 0.91s at 500Hz (unoccupied). Under occupied conditions, these RT60 values will be lower due to audience absorption. With a volume of 39137m3, the ideal RT60 for the hall based on Stephen and Bates formula = $4(0.0118V^{1/3} + 0.1070) = 2.0s$, implying that the hall was treated for excessive absorption to suit both speech and music.

4.4. CITAM NGONG ANALYSIS

4.4.1. Architectural details

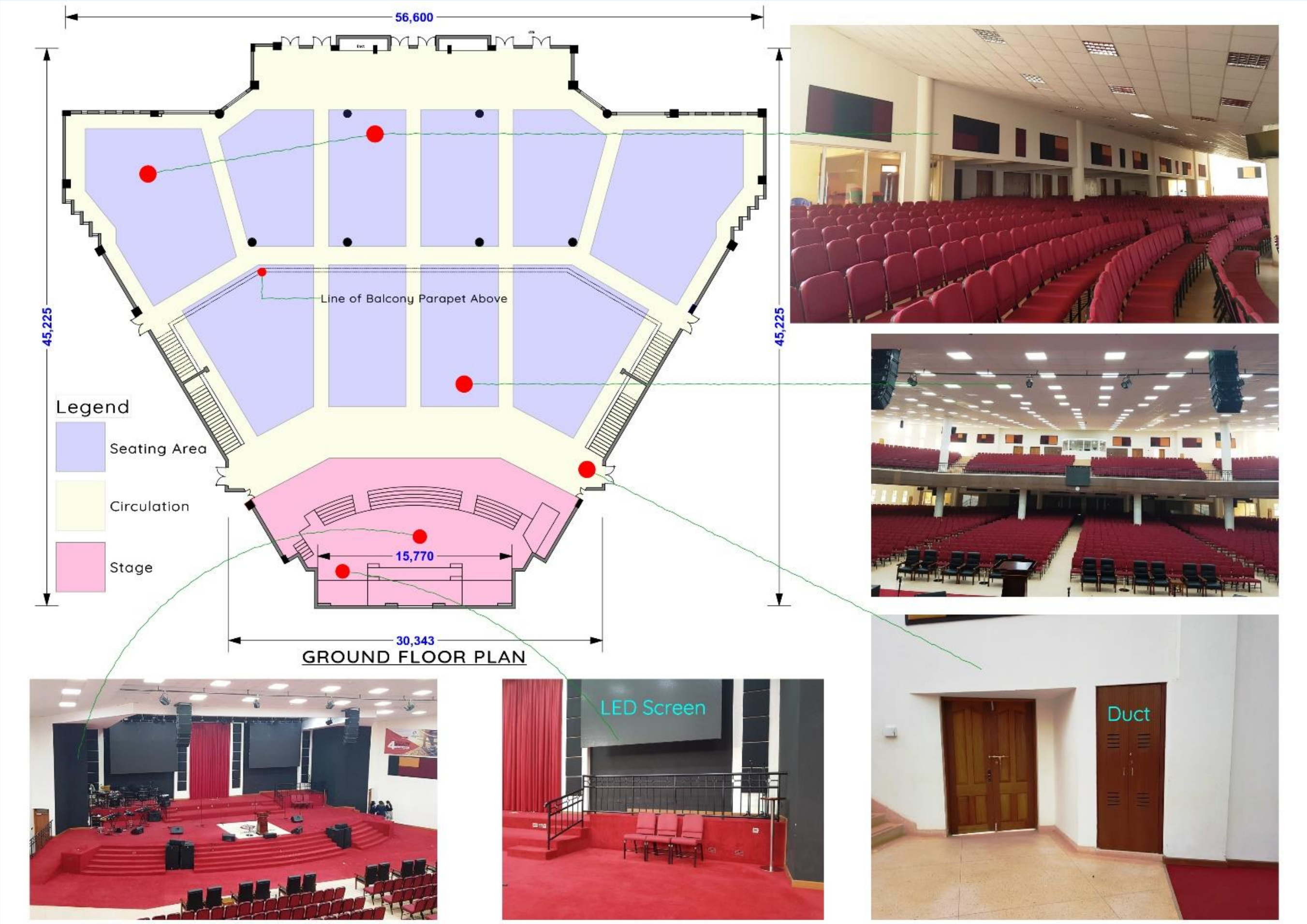

Figure 52. CITAM Ngong Ground Floor Plan & Internal photographs.

Copyright: Author

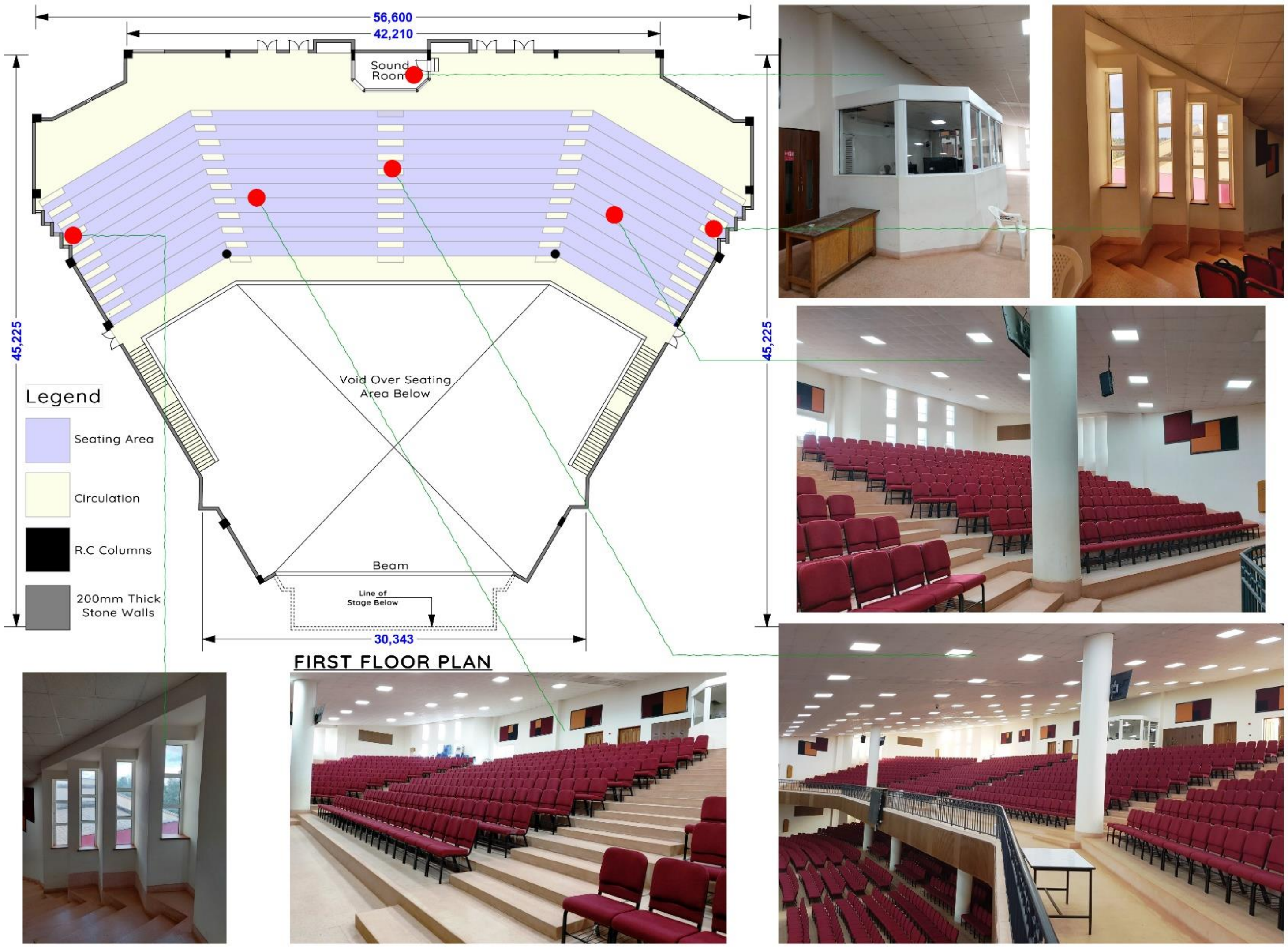

Figure 53. CITAM Ngong Balcony Floor Plan & Internal photographs.

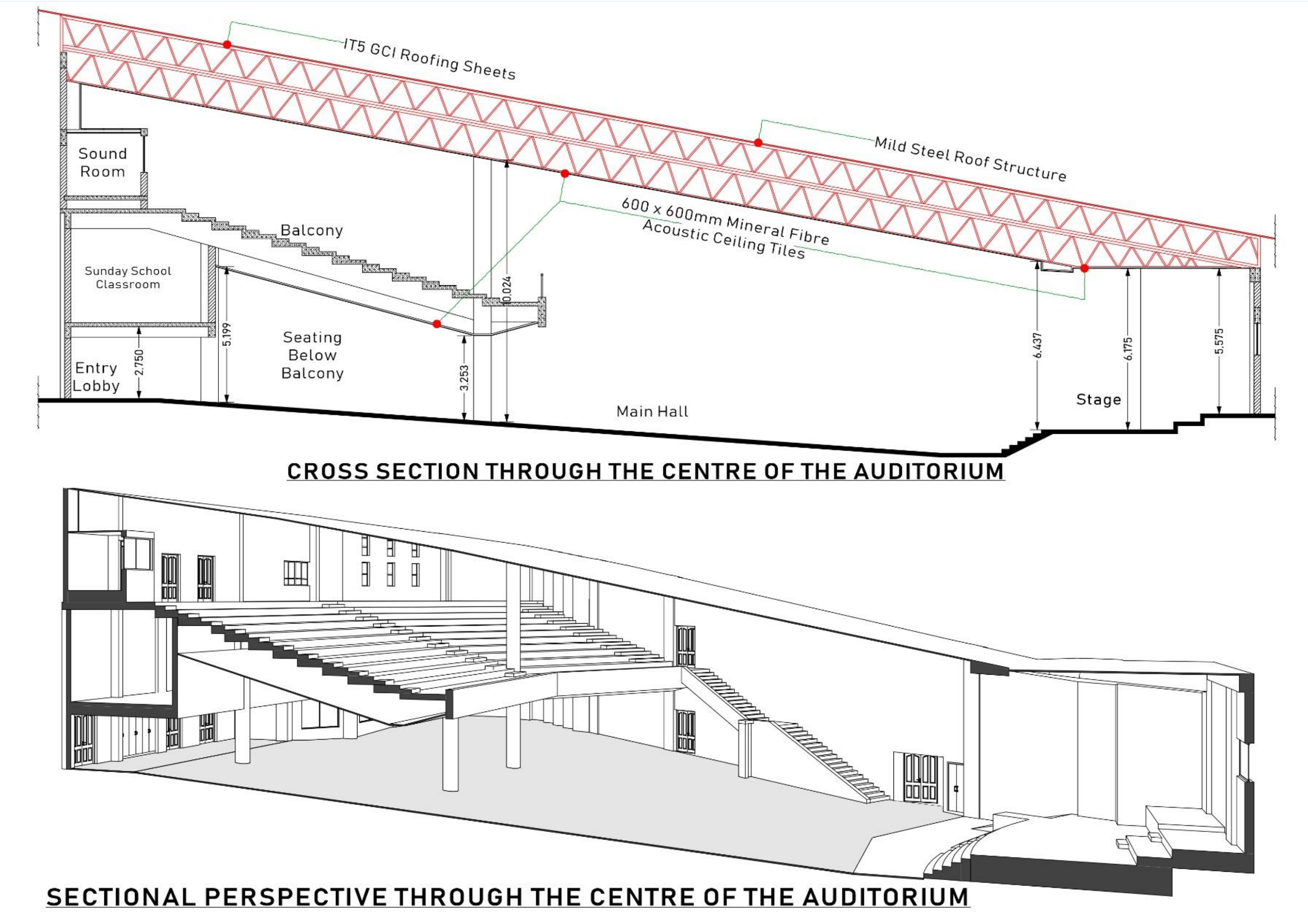

Figure 54. CITAM Ngong Longitudinal Cross-Sections.
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Figure 55. CITAM Ngong: Surface finishes
Copyright: Author

4.4.2. General design data

i) **Location -** The CITAM Ngong auditorium is part of a larger complex consisting of offices, meeting rooms, Sunday school classrooms, ablution facilities and a youth hall located along the Ngong-Kiserian road. The immediate neighbourhood has several church buildings, the Ngong stadium, residential flats and a school. The church complex and other associated facilities, including a primary school, sit on a 10-acre land parcel.

ii) **Floor plan shape -** The auditorium is fan shaped with a gently sloped ground floor (towards the back) and a raked balcony. Sidewalls have a 30 degrees splay.

iii) **Structure -** The main building components consist of 200mm thick natural stone walls, reinforced concrete floor, solid timber entrance doors, laminated glass window panes in aluminium frames, and IT5 roofing sheets with an aluminium coated underlay.

iv) **Program -** The main use of the auditorium is for Sunday worship services and Friday evening prayers, with a 75 % speech and 25% music program. Occasionally, it hosts other events such as weddings, conferences, and concerts.

v) **Floor area -** The auditorium has a cumulative floor area of 2704 square metres including the main hall, balcony and stage (isles included in the area).

vi) **Ceiling area -** The auditorium has a cumulative ceiling area of 2765 square metres including the main hall, under balcony, balcony and stage.

vii) **Seating capacity -** The auditorium has a cumulative seating capacity of 2900 consisting of fabric and leather upholstered seats.

viii) **Volume –** The overall auditorium volume is 15,250 cubic metres including the main hall, under balcony, balcony and stage.

ix) **Surface finishes –** The main finishes consist of plastered and painted walls, terrazzo and carpet floors, mineral fibre acoustic tile ceilings. Some wall sections have slatted Mdf panels, perforated Mdf panels and fabric covered foam panels, and drapery.

x) **Reverberation time (RT60)** – The measured average RT60 at 500Hz was 1.02s (unoccupied). The calculated RT60 at 500Hz was 1.08s (unoccupied). The calculated RT60 using NRC was 1.02s.

4.4.3. Quantitative design data

Variable		**Quantity**
No. of Seats		2,900
Volume	Main Hall (5,975m^3)	15,250m^3
	Below balcony (3,723m^3)	
	Balcony (4,804m^3)	
	Stage (748m^3)	
Floor areas	Terrazzo	2,462m^2
	Carpet	242m^2
Ceiling areas	Acoustic fibre tiles	2,330m^2
	Plaster and paint	164m^2
	Gypsum board	42m^2
	Light fittings with specular diffusers	12.6m^2
	Panel light fittings	46.8m^2
	Perforated sheet metal	78.12m^2
Wall, column and other surface areas	Plaster & paint	1276m^2
	Fabric covered Foam Panels	119.5m^2

	Gypsum board	48.4m^2
	Terrazzo	262m^2
	Laminated glass	65m^2
	Solid wood	93.5m^2
	Laminated Mdf panels	31.8m^2
	Perforated Mdf panels	16.8m^2
	Slatted Mdf panels with foam backing	5.46m^2
	Plain Mdf panels (solid)	36.15m^2
	Drapery	14.4m^2
	Carpet	36.13m^2
	Powder coated aluminium	19.6m^2
	Vinyl banners	m^2
	LED display screens	27 m^2

Table 18. CITAM Ngong measured RT60 values.

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4.4.4. RT60 measurement results

	125 Hz	250 Hz	500Hz	1kHz	2kHz	4kHz
MAIN HALL						
Stage	1.75	1.34	0.99	0.86	1.17	1.04
Front Left	1.62	1.2	1.06	1.05	1.13	1.11
Front Mid Left	1.4	1.46	1.1	1.05	1.19	1.17
Front Mid Right	1.47	1.05	1.06	1.01	1.16	1.13
Front Right	1.62	1.39	1.01	1.06	1.02	1.03
Centre Left	1.59	1.25	1.04	0.96	1.22	1.09
Centre Mid Left	1.31	1.3	0.96	1	1.23	1.09
Centre Mid Right	1.72	1.21	1.09	1.04	1.16	1.09

Centre Right	1.68	1.39	1.13	0.92	1.19	1.1
UNDER BALCONY						
Extreme Left (Front)	1.48	1.27	0.82	1.09	1.26	1.12
Extreme Left (Mid way)	1.38	1.2	0.97	1.13	1.55	1.29
Extreme Left (Rear)	1.62	1.08	1.03	1.22	1.46	1.45
Middle Left (Front)	1.6	1.07	1.01	1.09	1.34	1.09
Middle Left (Mid way)	1.37	1.26	0.86	1.11	1.34	1.26
Middle Left (Rear)	1.41	1.03	1.03	1.21	1.5	1.4
Middle (Front)	1.75	1.3	0.91	1.13	1.3	1.15
Middle (Mid way)	1.83	1.12	0.88	1.12	1.34	1.31
Middle (Rear)	1.46	1.18	1.03	1.21	1.47	1.4
Middle Right (Front)	1.58	1.29	1.03	1.09	1.35	1.15
Middle Right (Mid way)	1.61	0.95	1.02	1.08	1.32	1.32
Middle Right (Rear)	1.73	1.24	0.94	1.1	1.43	1.38
Extreme Right (Front)	1.46	1.2	0.95	1.21	1.45	1.33
Extreme Right (Mid way)	1.7	1.15	0.88	1.05	1.24	1.24
Extreme Right (Rear)	1.3	1.14	1.12	1.16	1.5	1.47
BALCONY						
Right (Front)	1.86	1.32	1.08	1.05	1.07	1.03
Right (Mid Way)	1.74	1.34	1.16	1.01	1.05	1.04
Right (Rear)	1.62	1.33	1.04	1.02	1.07	0.93
Middle (Front)	1.85	1.22	1.08	0.97	1.05	1.02
Middle (Mid way)	2.09	1.13	1.05	1.04	1.08	0.99
Middle (Rear)	1.58	1.3	1.01	0.92	1.04	1.02
Left (Front)	2.08	1.39	1.14	1.07	1.1	1.02
Left (Mid way)	1.67	1.29	1.06	0.98	0.97	0.9
Left (Rear)	2.37	1.27	1.11	1.02	0.95	0.72

Averaged RT60 Values (s)	1.65	1.23	1.02	1.06	1.23	1.15

Table 19. CITAM Ngong measured RT60 values.

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4.4.5. RT_{60} Calculation – Using coefficients of absorption (Template 1)

This template utilizes coefficients of absorption for frequencies between 125Hz and 4KHz

Material	Area m^2	125 Hz	Sabins	250 Hz	Sabins	500 Hz	Sabins	1 kHz	Sabins	2 kHz	Sabins	4 kHz	Sabins
Terrazzo	2,724	0.01	27.24	0.01	27.24	0.015	40.86	0.02	54.48	0.02	54.48	0.02	54.48
Solid Wood - Stained	93.5	0.15	14.03	0.11	10.29	0.1	9.35	0.07	6.55	0.06	5.61	0.07	6.55
Carpet on Concrete	278	0.05	13.91	0.1	27.81	0.15	41.72	0.3	83.44	0.5	139.07	0.55	152.97
Empty Seat- Fabric Upholstered	1450	0.19	275.50	0.37	536.50	0.56	812.00	0.67	971.50	0.61	884.50	0.59	855.50
Drapery (0.50 kg/m2), Pleated 50%	14.5	0.07	1.02	0.31	4.50	0.49	7.11	0.75	10.88	0.7	10.15	0.6	8.70
Fabric Covered Foam	124.96	0.06	7.50	0.25	31.24	0.56	69.98	0.81	101.22	0.9	112.46	0.91	113.71
Glass: window	65	0.1	6.50	0.05	3.25	0.04	2.60	0.03	1.95	0.03	1.95	0.03	1.95
Plaster: Smooth on Masonry	1,440	0.013	18.72	0.015	21.60	0.02	28.80	0.03	43.20	0.04	57.60	0.05	72.00
Gypsum Board - 12mm	90.4	0.29	26.22	0.1	9.04	0.05	4.52	0.04	3.62	0.07	6.33	0.09	8.14
Acoustic Ceiling Tiles	2,330	0.49	1141.70	0.53	1234.90	0.53	1234.90	0.75	1747.50	0.92	2143.60	0.99	2306.70
Powder coated Aluminium (Assumed to be same as glass)	19.6	0.1	1.96	0.05	0.98	0.04	0.78	0.03	0.59	0.03	0.59	0.03	0.59
Laminated Mdf (Assumed to be same as plywood)	32	0.58	18.56	0.22	7.04	0.07	2.24	0.04	1.28	0.03	0.96	0.07	2.24

Stained Mdf	36.15	0.28	10.12	0.21	7.59	0.15	5.42	0.12	4.34	0.11	3.98	0.09	3.25
Perforated Mdf - Assumed to work as a Helmholtz Resonator	17	0.4	6.80	0.9	15.30	0.8	13.60	0.5	8.50	0.4	6.80	0.3	5.10
Perforated Sheet Metal	78.12	0.06	4.69	0.06	4.69	0.07	5.47	0.09	7.03	0.14	10.94	0.16	12.50
LED Display – Assumed to be same as large glass panes	27	0.18	4.86	0.06	1.62	0.04	1.08	0.03	0.81	0.02	0.54	0.02	0.54
LED Panel Lights – Assumed to be same as Glass	46.8	0.1	4.68	0.05	2.34	0.04	1.87	0.03	1.40	0.03	1.40	0.03	1.40
Fluorescent Lights (Specular Diffusers)- Same as glass	12.6	0.1	1.26	0.05	0.63	0.04	0.50	0.03	0.38	0.03	0.38	0.03	0.38
Total Absorption		**1585.25**		**1946.55**		**2282.80**		**3048.65**		**3441.33**		**3606.70**	
Auditorium Volume		**15,250m^3**		**15,250m^3**		**15,250m^3**		**15,250m^3**		**15,250m^3**		**15,250m^3**	
Sabine RT60 – Unoccupied		**1.55s**		**1.26s**		**1.08s**		**0.81s**		**0.71s**		**0.68s**	

Table 20. CITAM Ngong calculated RT60 values using coefficients of absorption.

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4.4.6. RT60 Calculation – Using Noise reduction coefficients. (Template 2)

This template utilizes the Noise Reduction Coefficient (NRC) for each material.

Material	**Area m^2**	**NRC**	**Sabins**
Terrazzo	2,724	0	0
Solid Wood - Stained	93.5	0.1	9.35
Carpet on Concrete	278	0.1	27.81
Empty Seat- Fabric Upholstered	1450	0.55	797.50

Drapery (0.50 kg/m2), Pleated 50%	14.5	0.55	7.98
Fabric Covered Foam	124.96	0.4	49.98
Glass: window	65	0.05	3.25
Plaster: Smooth on Masonry	1,440	0.05	72.00
Gypsum Board - 12mm	90.4	0.05	4.52
Acoustic Ceiling Tiles	2,330	0.6	1,398.0
Powder coated Aluminium (Assumed to be same as glass)	19.6	0.05	0.98
Laminated Mdf (Assumed to be same as plywood)	32	0.1	3.20
Stained Mdf	36.15	0.15	5.42
Perforated Mdf - Assumed to work as a Helmholtz Resonator	17	0.65	11.05
Perforated Sheet Metal	78.12	0.1	7.81
LED Display – Assumed to be same as large glass panes	27	0.05	1.35
LED Panel Lights – Assumed to be same as Glass	46.8	0.05	2.34
Fluorescent Lights (Specular Diffusers)- Same as glass	12.6	0.05	0.63
Total Absorption			**2403.18**
Auditorium Volume			**15,250m^3**
Sabine - RT$_{60}$ - Unoccupied			**1.02s**

Table 21. CITAM Ngong calculated RT60 values using NRC.

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4.4.7. CITAM Ngong – Acoustic design evaluation

i) **Site selection -** The CITAM Ngong auditorium is adjacent to Ngong-Kiserian road and the CITAM Ngong school. The school play area fronts the main entrances to the balcony level. This adjacency to noise sources necessitates certain design solutions, which are discussed more under site layout below.

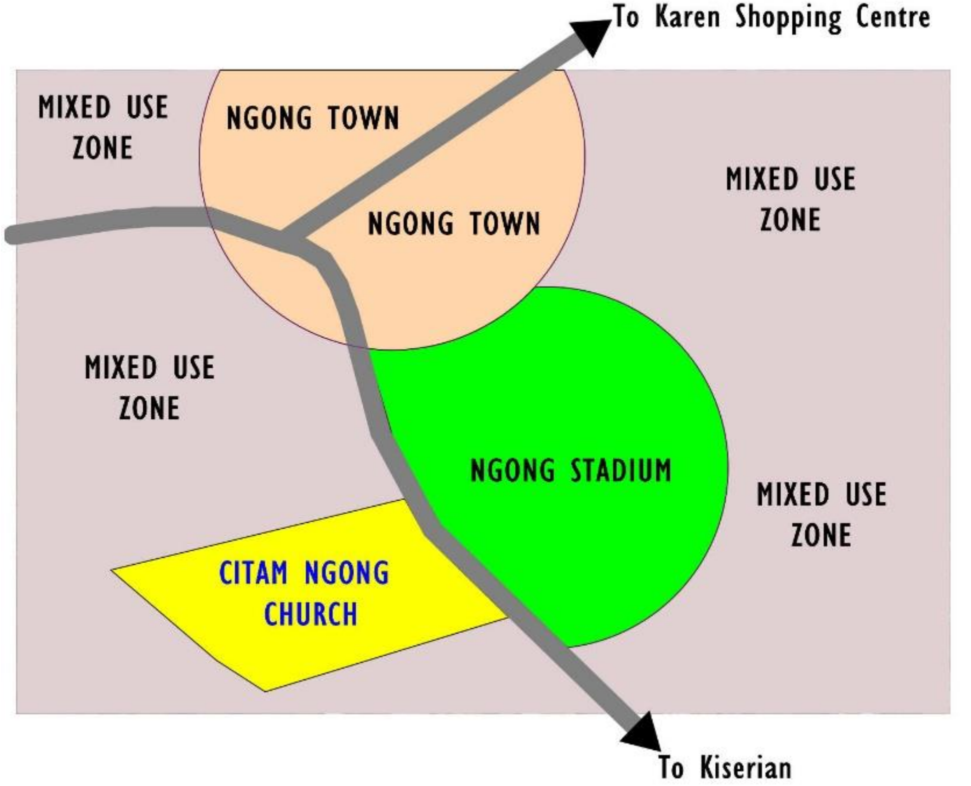

Figure 56. CITAM Ngong immediate context.

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ii) **Site layout & External noise isolation -** The staff parking and administration wing front Ngong-Kiserian road, thereby providing a buffer between the road and the auditorium. Dense landscaping between the building and the road helps further reduce vehicular noise. The staircase landing lobbies on either side of the auditorium provide a buffer against noise from the access road and the lower parking. The crèche spaces separate the entry landing stairs and the auditorium wall. There are however are certain omissions in the layout that allow intrusion of unwanted noise. First, there are no air gaps between the staircase landing lobbies and the auditorium. Second, the entry landings facing the games courts are not enclosed and there are no air-gaps transitioning to the auditorium.

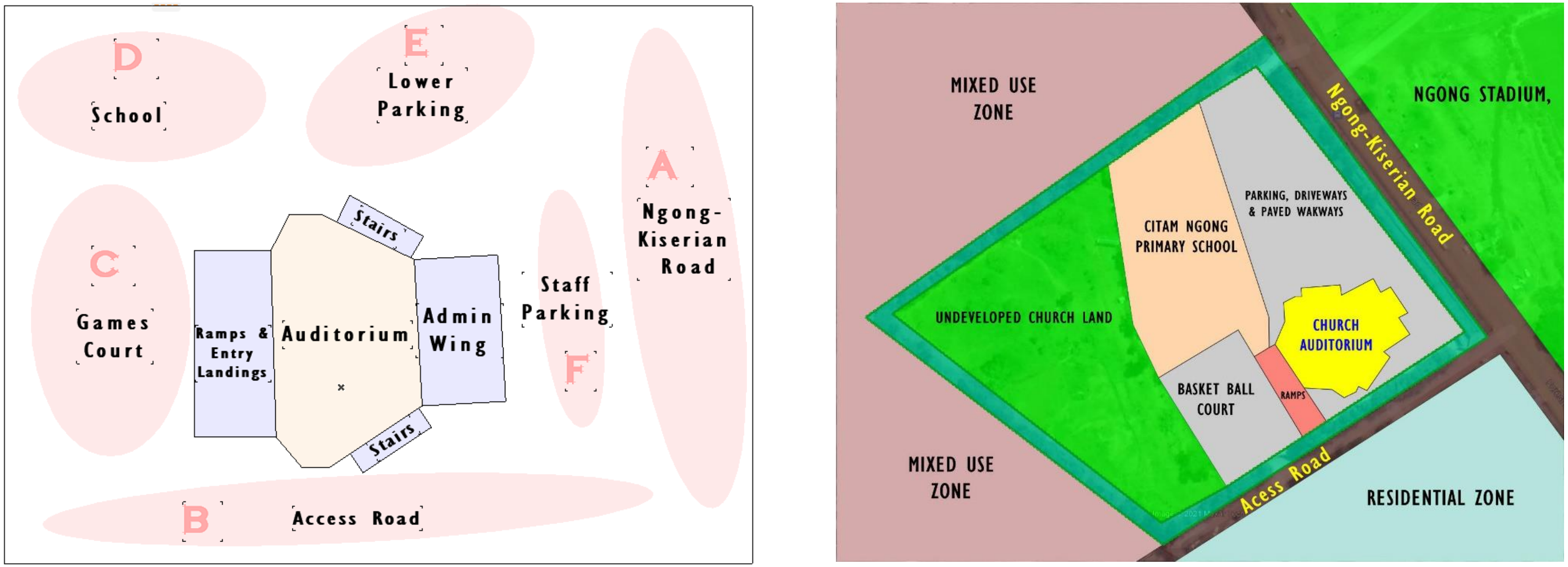

Figure 57. CITAM Ngong – Site Layout & Adjacent zones.

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iii) **Main Construction -** The main building components consist of 200mm thick external walls, reinforced concrete floor, solid timber entrance doors, laminated glass window panes, and IT5 roofing sheets with an aluminium coated polyethylene underlay. Stone, concrete and solid timber are dense materials and efficient in blocking unwanted noise. However, the windows are not double-glazed and the laminated panes are not thick enough to block external noise. The solid door shutters no not have draught strips / sweeps and gaps at the bottom allow sound intrusion. The IT5 roof also allows easy intrusion of aircraft noise.

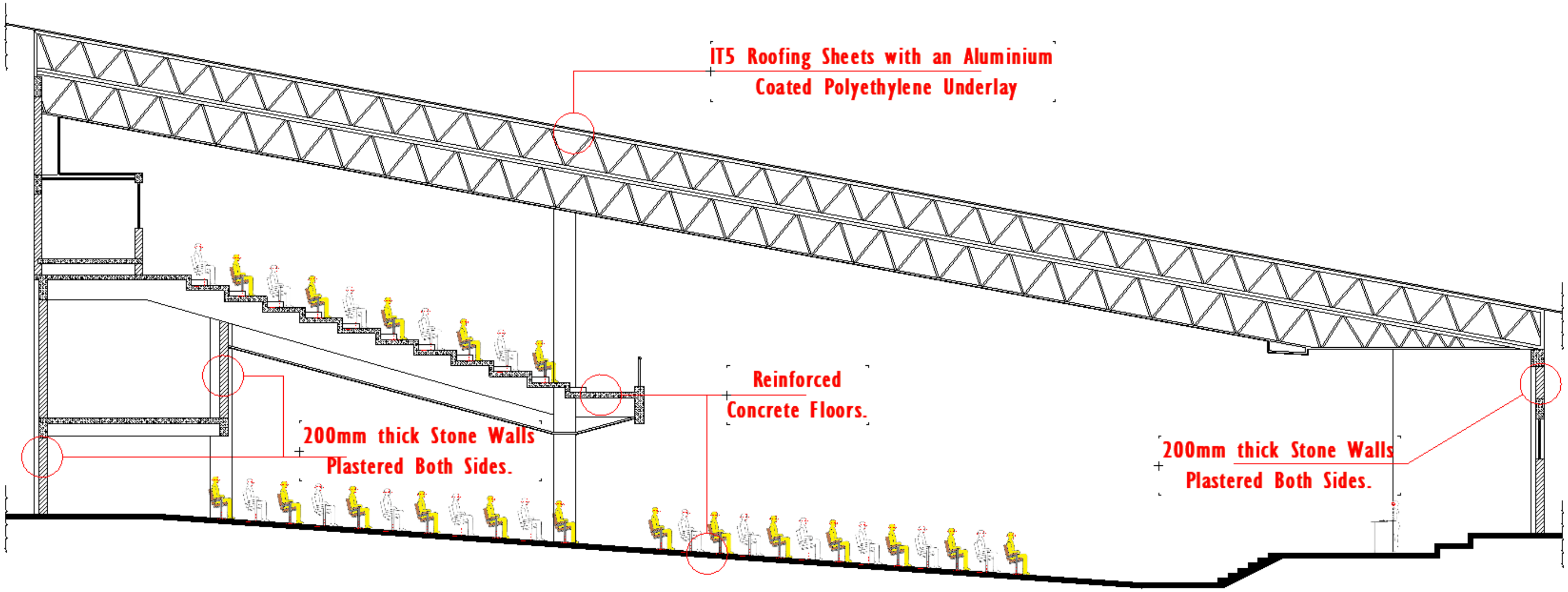

Figure 58. CITAM Ngong – Main Construction Elements.

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iv) **Room size: *Hall Capacity, floor area, volume, and ceiling height*** – The auditorium capacity is 2900 seats with a floor area of 2535m^2 in the audience hall and 155m^2 on stage, and an overall volume of 15,250m^3. This translates to an area of 0.87m^2 and a volume of 5.26m^3 per seat respectively. This within the recommended design range of 0.6 m^2 to 0.9 m^2 and 5.1m^3 to 8.5m^3 per seat, although the volume per seat is more towards the lower limit. This implies that with appropriate surface treatment, it is possible to attain an acceptable RT60 for the hall. The average ceiling height of the hall is 9.4m. The recommended ceiling height for a large hall is 1/3 of the width. With an average width of 34m, 1/3 translates to 11.4m.The current ceiling height is therefore below the recommended height by 2m, implying that the current hall volume, though within the acceptable range, is below the optimal volume by 5,380m^3 (2690 m^2 x 2m). The overall optimal volume should have been 20,630 m^3 (15,250m^3 + 5,380m^3), translating to 7.11m^3 per seat.

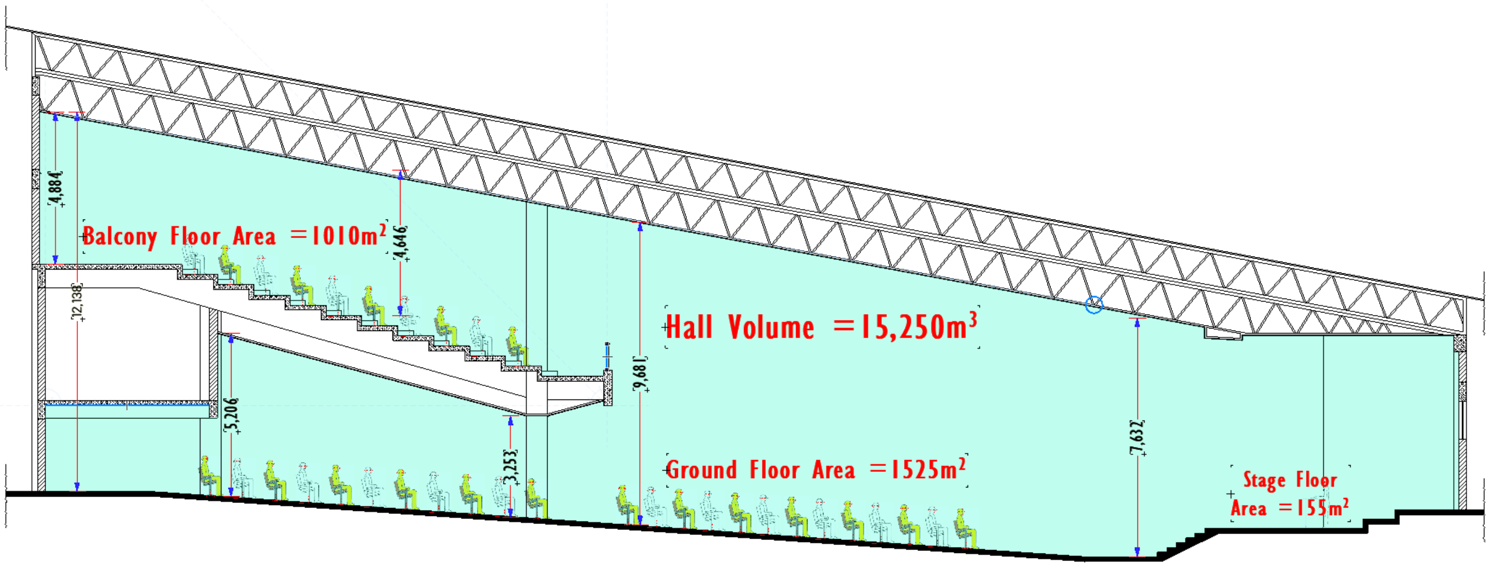


Figure 59. CITAM Ngong – Auditorium Size & Ceiling Heights.

Copyright: Author.

v) **Room Geometry:** ***Hall shape and profile, stage shape and profile, side & rear walls geometry, balcony projection and profile, ceiling geometry, and sight lines*** - The hall is fan shaped in plan, which is ideal for a large hall to allow for greater seating area close to the stage. The ground floor inclination of 4 degrees is below the minimum recommended incline of 8 degrees. The 30 degrees splay of stage sidewalls is within the recommended range of 30° to 60° for strong early reflections. The stage is elevated by 900mm, which is within the recommended range. The 30 degrees splay of the main hall sidewalls translates to a 60 degrees included angle, which is within the recommended range of 60° to 120°. The flat geometry of the rear wall is ideal for the hall. The balcony floor incline is 16 degrees, which is within the recommended range of less than 26 degrees. However, the balcony over hang into the hall is more than the recommended depth of less than twice the height of the balcony opening, which is likely to create sound shadows. A large portion of the balcony parapet wall is parallel to the stage back wall, creating the possibility of flutter echoes. The ceiling geometry of a mono-pitch slope towards the back of the hall is not ideal. The ceiling should be sloped and angled to reflect sound to particular seating areas in the hall. The under balcony ceiling slope is not ideal since it slopes upward from the balcony opening towards the rear. Ideally, it should be downward from the opening towards the rear to reflect sound toward the heads of the listeners seated underneath and to better connect the under-balcony volume with the volume of the main hall. The balcony ceiling at the rear is not splayed as recommended for useful short-delayed reflections. Both the main hall and balcony sight lines do not work if targeted to the recommended APS along the edge of the apron stage, implying that some audience will not have a full-unobstructed view of entire stage area and performers.

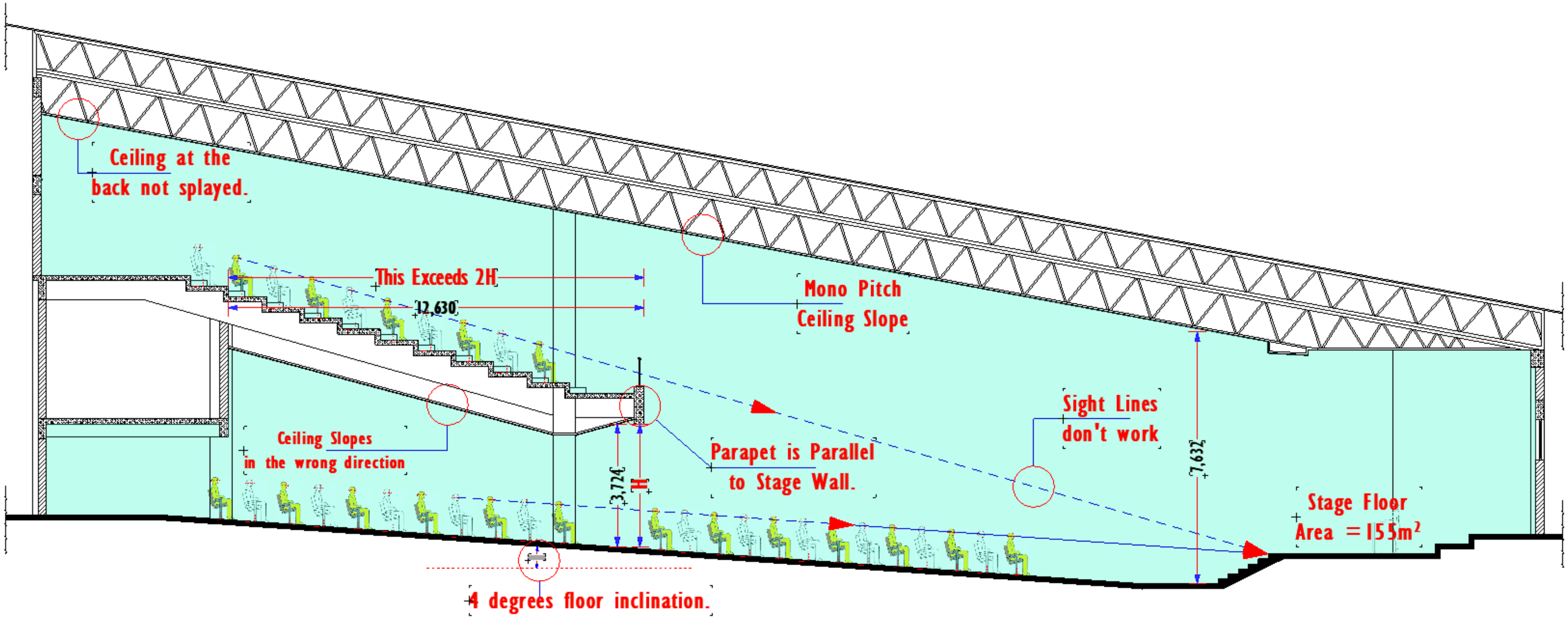


Figure 60. CITAM Ngong – Geometrical Acoustic design failures shown in section.

Copyright: Author.

vi) **Surface Finishes: Floors, *Walls, ceilings and seats* –** Stage and sidewall surfaces are generally finished in reflective plaster and paint with selected sections treated for absorption or diffusion using fabric covered foam panels and perforated Mdf panels respectively. The rear walls are mostly in reflective plaster and paint, which is not ideal since they should be absorbing or diffusing to avoid echoes. The balcony parapet wall is well treated for diffusion and absorption using slatted Mdf panels with foam backing. The entire main ceiling is absorbing. This is not ideal since the ceiling should be reflecting, with sections along the side and rear perimeter treated for absorption as required for reverberation control. All seats are fabric upholstered, which is ideal for stable reverberation conditions when the auditorium is partially occupied.

vii) **Sound reinforcement -** A cluster of line array loud speakers are anchored from the ceiling in the central space just above and slightly in front of the proscenium opening. The audience has a direct line of sight to the high-frequency speakers of the cluster, which is ideal for speech intelligibility. Additional loud speakers positioned in the flat area below the stage are positioned to direct sound to audience at front in the main hall. There is also a set of stage monitor speakers for projecting sound back to speakers / performers on stage. The various loud speakers and stage monitors as manufactured by dB Technologies have a combined frequency range of between 30 Hz to 20 kHz which is ideal for both music and speech reproduction.

viii) **Reverberation time -** The measured average RT60 was 1.02s at 500Hz and 1.06s at 1kHz (unoccupied). The calculated RT60 was 1.08s at 500Hz and 0.81s at 1kHz (unoccupied). The calculated RT60 using NRC was 1.02s. Under occupied conditions, these RT60 values will be lower due to audience absorption. With a volume of 15250m3, the ideal RT60 for the hall based on Stephen and Bates formula = 4(0.0118V1/3 + 0.1070) = 1.6s, implying that the hall as currently treated has excessive absorption.

ix) **Noise Pollution** – The auditorium is not a source of noise pollution for the following reasons:-

a) The site layout is such that the auditorium is located away from adjacent properties.

b) The openable auditorium windows are oriented facing the games court and the Ngong- Kiserian road.

c) The auditorium as currently treated has excessive absorption.

4.5. CITAM PARKLANDS ANALYSIS

4.5.1. Architectural details

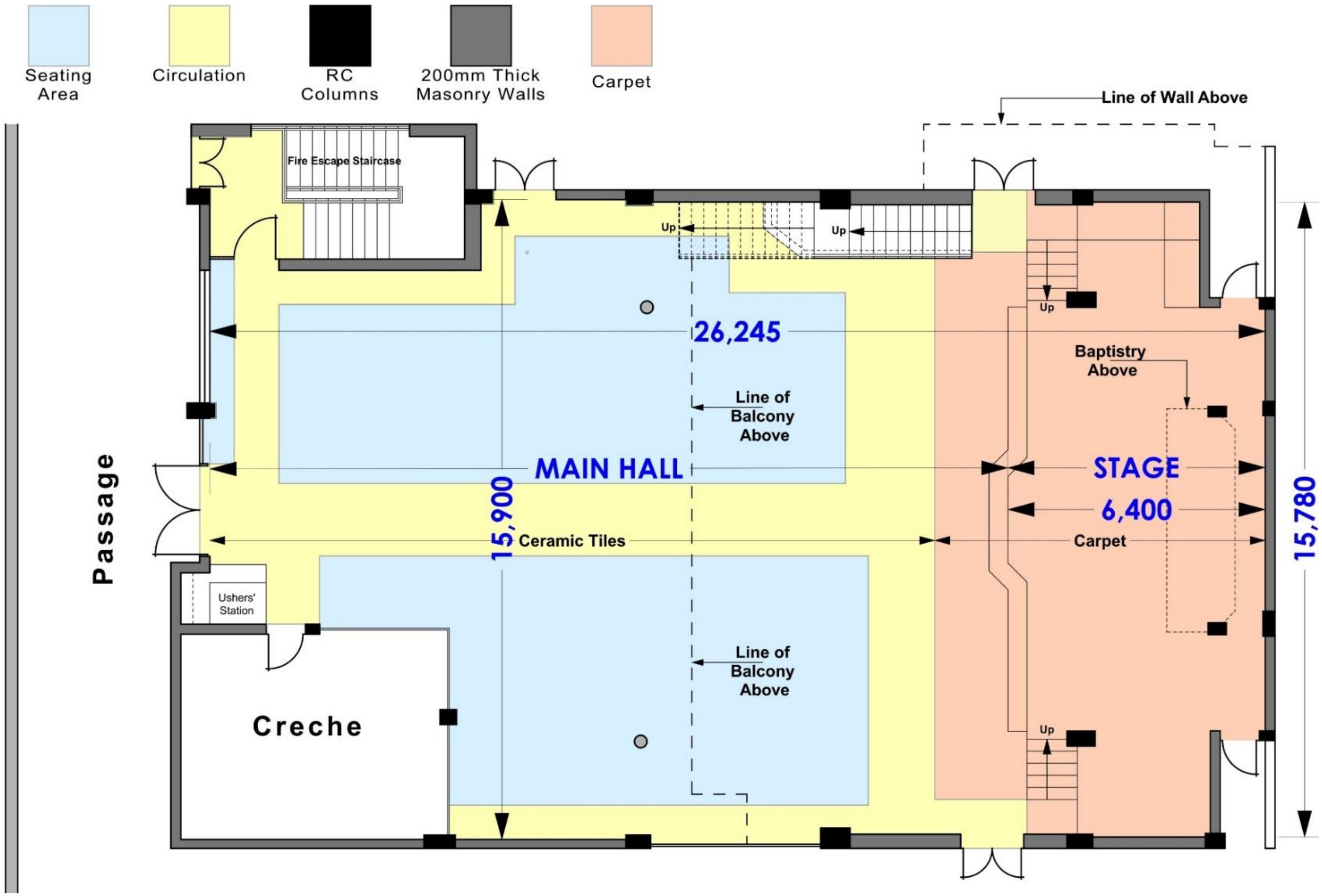
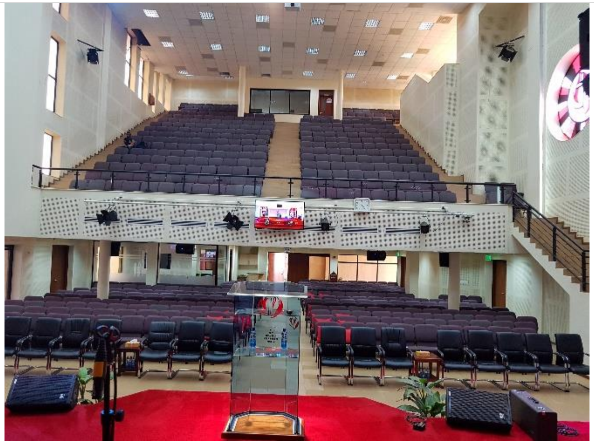


Figure 61. CITAM Parklands ground floor plan.
Copyright: Author.

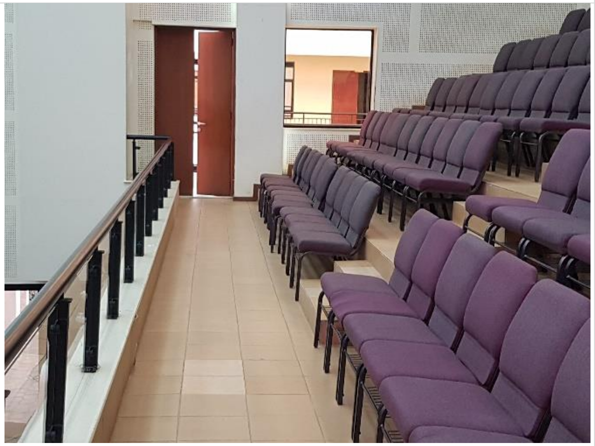


View of Auditorium from stage

Stage

Ground Floor Seating

View of stage from last balcony seat



Balcony

Ceiling Profile

Figure 62. CITAM Parklands - Internal photographs.

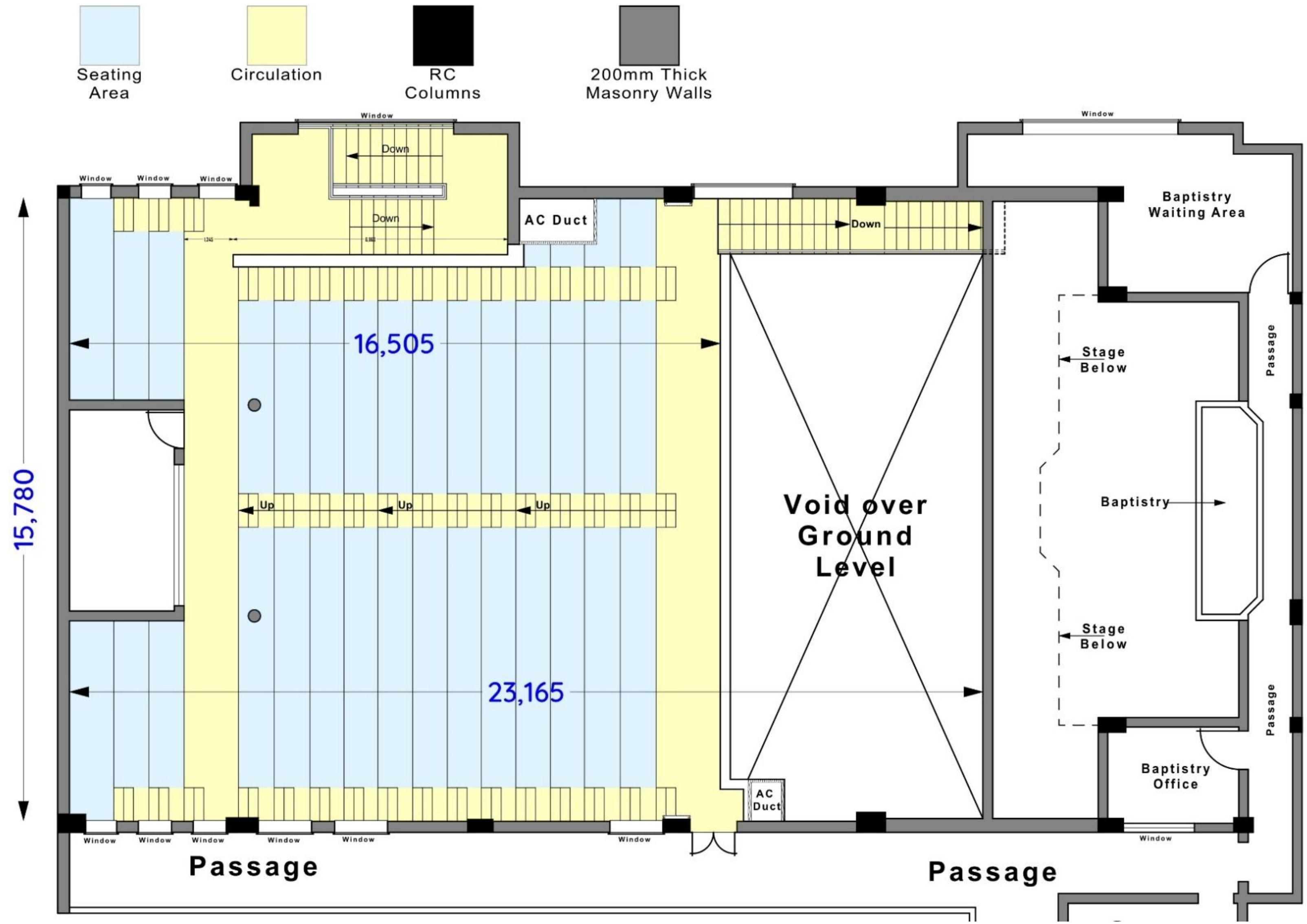


Figure 63. CITAM Parklands balcony floor plan.

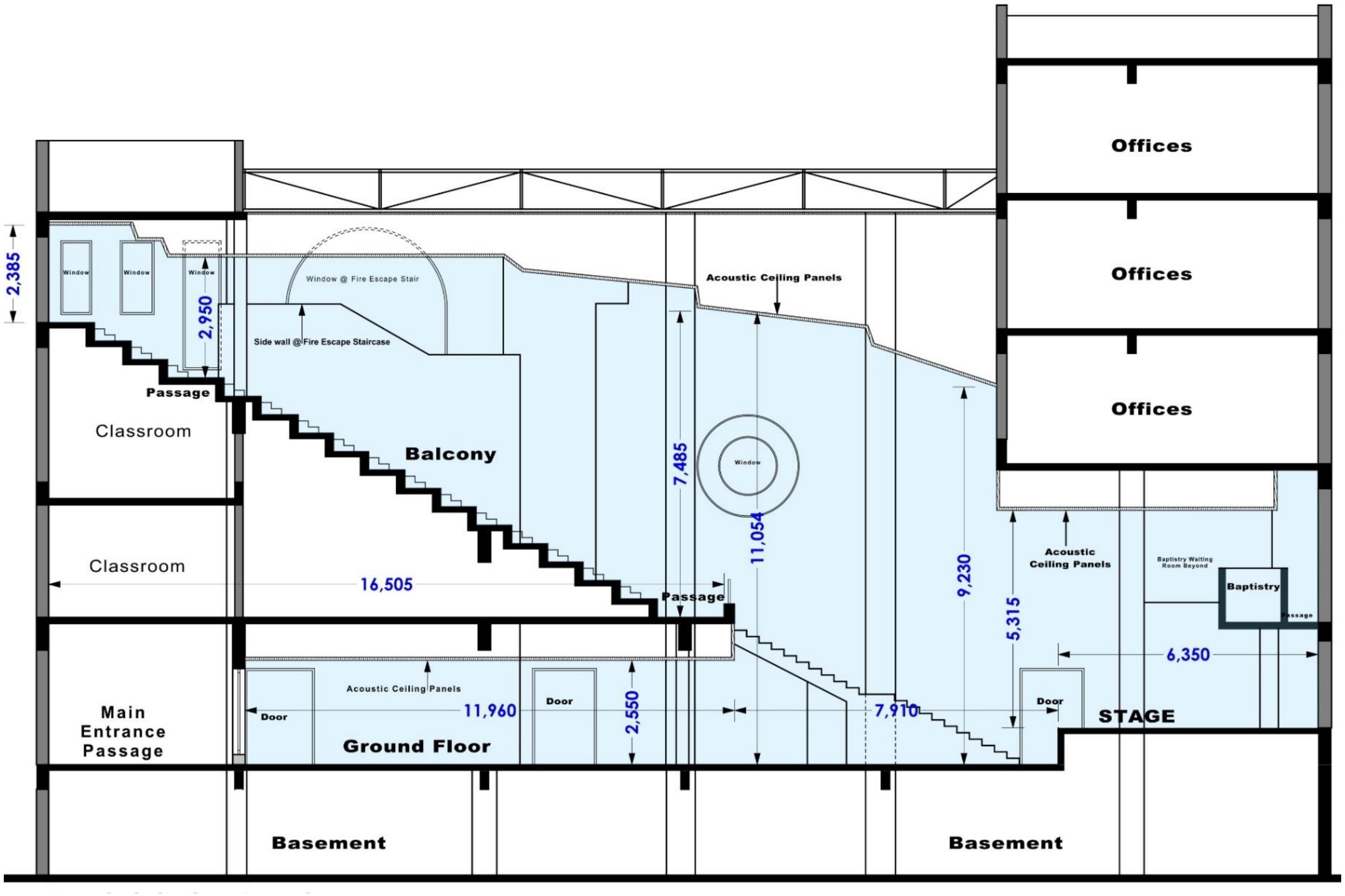
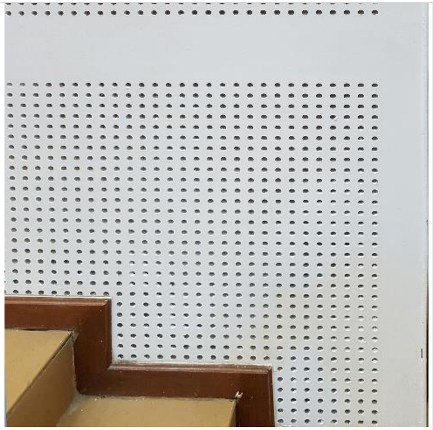


Figure 64. CITAM Parklands longitudinal cross-section.

Copyright: Author



Perforated Gypsum

Plaster & Paint

Timber

Laminated Glass Panes

Carpet

Ceramic Tiles

Acoustic Ceiling Tiles

AC Grilles

			
Fluorescent Fittings	Vinyl Banners	Upholstered Seats	Laminated mdf

Figure 65. CITAM Parklands surface finishes.

Copyright: Author

4.5.2. General design data

iii) **Location -** The CITAM Parklands auditorium is part of a larger complex consisting of offices, meeting rooms, Sunday school classrooms and ablution facilities located along Second Parklands Avenue in Nairobi. The church complex sits on a 0.7 acre plot. The immediate neighbourhood has commercial, residential and educational amenities.

iv) **Floor plan shape –** The hall is rectangular, which is ideal for a small auditorium. The ground floor is flat and the balcony raked.

xi) **Structure -** The main building components consist of 200mm thick natural stone walls, reinforced concrete floors, solid timber entrance doors, thick laminated glass window panes in aluminium frames, and IT5 roofing sheets with an aluminium coated underlay.

v) **Program -** The main use of the auditorium is for Sunday worship services and Friday evening prayers, with a 75 % speech and 25% music program. Occasionally, it hosts other events such as weddings, conferences, and concerts.

vi) **Floor area -** The auditorium has a cumulative floor area of 625 square metres including the main hall, balcony and stage (isles included in the area).

vii) **Ceiling area -** The auditorium has a cumulative ceiling area of 680 square metres including the main hall, under balcony, balcony and stage.

viii) **Seating capacity -** The auditorium has a cumulative seating capacity of 542 consisting of fabric and leather upholstered seats.

ix) **Volume –** The overall auditorium volume is 3318 cubic metres including the main hall, under balcony, balcony and stage.

xii) **Surface finishes –** The main finishes consist of perforated gypsum panels and plastered/painted walls, ceramic tile and carpet floors, and mineral fibre acoustic tile ceilings.

x) **Reverberation time (RT60)** – The measured average RT60 at 500Hz was 0.74s (unoccupied). The calculated RT60 using NRC was 0.72s.

4.5.3. Quantitative design data

Variable		Unit of measurement
Seats		542 Pieces
Volume	Main Hall & stage (2018m3)	3318m^3
	Balcony (1300m3)	
	Ceramic tiles	509.26m^2
	Carpet	115.79m^2
Ceiling areas	Acoustic fibre tiles	566.63m^2
	Plaster and paint	40.84m^2
	Gypsum board	19.28m^2
	Light fittings with specular diffusers	36.36m^2
	Air-conditioning grilles	16.92m^2
Wall, column and other surface areas	Plaster & paint	238.42m^2
	Perforated gypsum panels	398.52m^2
	Gypsum board	83.08m^2
	Ceramic tiles	115.53m^2
	Laminated glass	92.96m^2
	Solid wood	62.47m^2
	Laminated Mdf panels	7.61m^2
	Carpet	17.17m^2
	Mild steel	3.22m^2
	Powder coated aluminium	7.46m^2
	AC outlets	1.44m^2
	Vinyl banners	24.95m^2
	Granite	2.58m^2

Table 22. CITAM Parklands: Quantitative design data.

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4.5.4. RT60 measurement results.

	125 Hz	250 Hz	500Hz	1kHz	2kHz	4kHz
STAGE						
Mid Centre	0.93	0.78	0.76	0.82	0.77	0.71
Front Centre	0.79	1.02	0.78	0.76	0.76	0.68
MAIN HALL						
Rear Right	1.0	0.99	0.55	0.80	0.79	0.80
Rear Centre	0.99	0.77	0.66	0.53	0.81	0.77
Rear Left	0.99	0.88	0.71	0.73	0.72	0.68
Mid Right	0.78	0.81	0.83	0.77	0.65	0.60
Mid Centre	0.97	0.85	0.75	0.64	0.66	0.58
Mid Left	0.87	0.83	0.80	0.70	0.56	0.55
Front Right	0.85	0.82	0.73	0.73	0.64	0.66
Front Centre	0.97	0.81	0.68	0.71	0.71	0.60
Front Left	0.92	0.84	0.80	0.64	0.64	0.64
BALCONY						
Front Right	0.80	0.93	0.85	0.75	0.69	0.56
Front Centre	0.76	0.80	0.70	0.74	0.67	0.63
Front Left	0.90	0.97	0.77	0.71	0.66	0.61
Mid Right	0.90	0.94	0.73	0.77	0.70	0.47
Mid Centre	0.76	0.90	0.68	0.73	0.70	0.47
Mid Left	0.83	0.86	0.82	0.74	0.71	0.52
Mid landing Right	0.91	0.77	0.87	0.80	0.78	0.68
Mid landing Centre	0.96	0.92	0.70	0.77	0.72	0.62
Landing Left	1.13	0.80	0.77	0.78	0.66	0.64
Rear Right	0.92	0.81	0.70	0.78	0.65	0.62
Rear Left	0.97	0.74	0.68	0.64	0.61	0.54
Averaged RT_{60} Values	**0.90**	**0.86**	**0.74**	**0.73**	**0.69**	**0.62**

Table 23. CITAM Parklands RT60 measurement results

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4.5.5. RT_{60} Calculation – Using coefficients of absorption (Template 1)

Material	Area	125Hz	Sabins	250Hz	Sabins	500Hz	Sabins	1KHz	Sabins	2KHz	Sabins	4KHz	Sabins
Ceramic Tiles	624.79	0.01	6.25	0.01	6.25	0.015	9.37	0.02	12.50	0.02	12.50	0.02	12.50
Acoustic Ceiling Tiles	566.63	0.49	277.65	0.53	300.31	0.53	300.31	0.75	424.97	0.92	521.30	0.99	560.96
Perforated Gypsum Wall Panels(10 mm thick)	326.8	0.08	26.14	0.32	104.58	0.99	323.53	0.76	248.37	0.34	111.11	0.12	39.22
Plaster: Smooth on Masonry	279.26	0.013	3.63	0.015	4.19	0.02	5.59	0.03	8.38	0.04	11.17	0.05	13.96
Carpet on Concrete	132.96	0.05	6.65	0.1	13.30	0.15	19.94	0.3	39.89	0.5	66.48	0.55	73.13
Glass	92.96	0.1	9.30	0.05	4.65	0.04	3.72	0.03	2.79	0.03	2.79	0.03	2.79
Gypsum Board	174.1	0.29	50.48	0.1	17.41	0.05	8.70	0.04	6.96	0.07	12.19	0.09	15.67
Solid Wood - Stained	62.47	0.15	9.37	0.11	6.87	0.1	6.25	0.07	4.37	0.06	3.75	0.07	4.37
Flourescent Lights (Specular Diffusers)	36.36	0.1	3.64	0.05	1.82	0.04	1.45	0.03	1.09	0.03	1.09	0.03	1.09
Air Conditioning Grilles	18.36	0.3	5.51	0.4	7.34	0.5	9.18	0.5	9.18	0.5	9.18	0.4	7.34
Vinyl Banners	24.95	0.02	0.50	0.04	1.00	0.05	1.25	0.05	1.25	0.1	2.50	0.05	1.25
Laminated Mdf	7.61	0.58	4.41	0.22	1.67	0.07	0.53	0.04	0.30	0.03	0.23	0.07	0.53
Powder Coated Aluminium	7.46	0.1	0.75	0.05	0.37	0.04	0.30	0.03	0.22	0.03	0.22	0.03	0.22
Mild Steel (Painted)	3.22	0.05	0.16	0.1	0.32	0.1	0.32	0.1	0.32	0.07	0.23	0.02	0.06
Polished Granite Tops	2.58	0.01	0.03	0.01	0.03	0.01	0.03	0.01	0.03	0.02	0.05	0.02	0.05
Empty Seat- Fabric Upholstered	271	0.19	51.49	0.37	100.27	0.56	151.76	0.67	181.57	0.61	165.31	0.59	159.89
Total Absorption		**455.95**		**570.38**		**842.24**		**942.19**		**920.09**		**893.04**	
Auditorium Volume		**3,318m^3**		**3,318m^3**		**3,318m^3**		**3,318m^3**		**3,318m^3**		**3,318m^3**	
Sabine - RT60 per Frequency		**1.17s**		**0.94s**		**0.63s**		**0.57s**		**0.58s**		**0.60s**	

Table 24. CITAM Parklands calculated RT60 values using coefficients of absorption.

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4.5.6. RT60 Calculation – Using Noise reduction coefficients. (Template 2)

Material	Area (m^2)	NRC	Sabins
Ceramic Tiles	624.79	0	0
Acoustic Ceiling Tiles	566.63	0.6	339.98
Perforated Gypsum Wall Panels(10 mm thick)	326.80	0.6	196.08
Plaster: Smooth on Masonry	279.26	0.05	13.96
Carpet on Concrete	132.96	0.1	13.30
Glass	92.96	0.05	4.65
Gypsum Board	174.10	0.05	8.70
Solid Wood - Stained	62.47	0.1	6.25
Fluorescent Lights (Specular Diffusers)	36.36	0.05	1.82
Air Conditioning Grilles	18.36	0.45	8.26
Vinyl Banners	24.95	0.05	1.2
Laminated Mdf	7.61	0.1	0.76
Powder Coated Aluminium	7.46	0.05	0.37
Mild Steel (Painted)	3.22	0.1	0.32
Polished Granite Tops	2.58	0	0
Empty Seat- Fabric Upholstered	271	0.55	149.05
Total Absorption			**744.75**
Hall Volume			**3,318m^3**
Sabine RT_{60} - Unoccupied			**0.72s**

Table 25. CITAM Parklands calculated RT60 values using NRC.

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4.5.7. CITAM Parklands – Acoustic design evaluation

i) **Site selection -** The church is located along second parklands avenue in Nairobi. The immediate neighbourhood has commercial, residential and educational amenities. The proximity to a busy road and residential apartments necessitates certain design solutions, which are discussed more under site layout below.

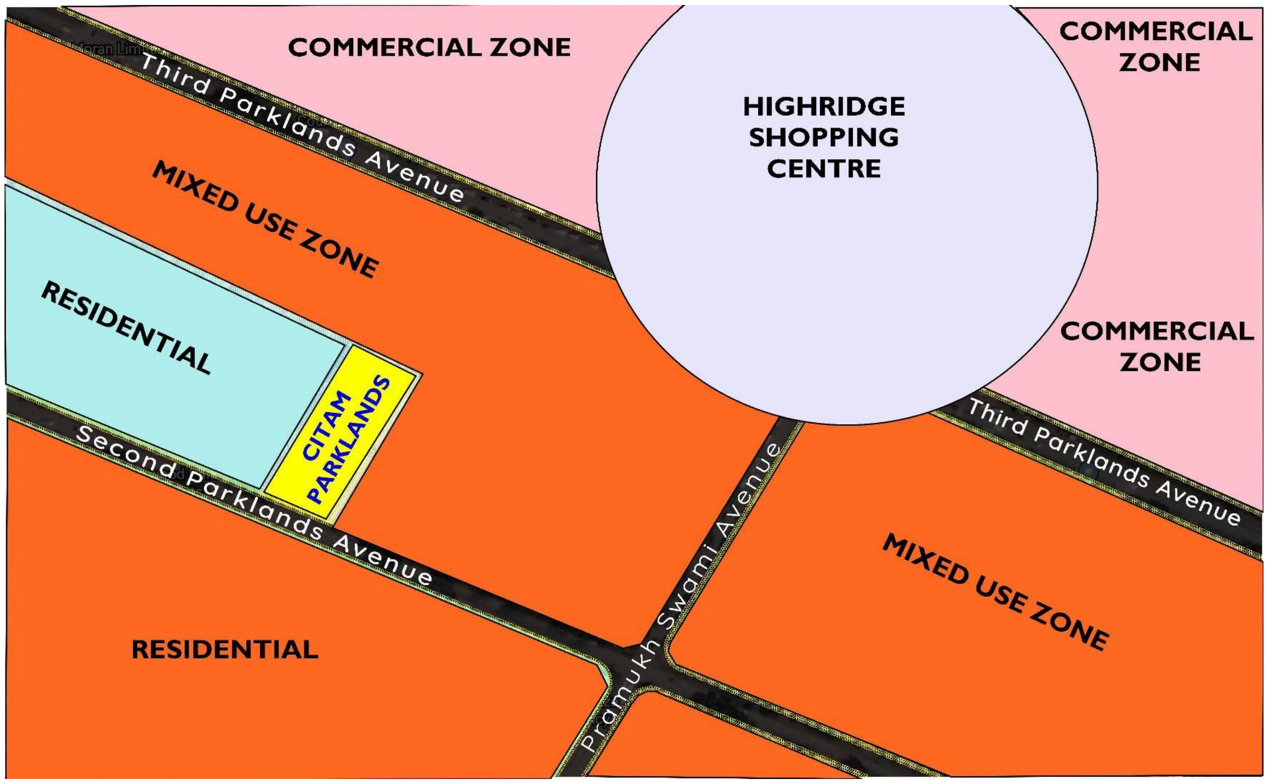

Figure 66. CITAM Parklands immediate context.

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ii) Site layout & External noise isolation – The parking block (with surface and basement parking) is closest to the road, thereby creating a distance between the road and auditorium. The auditorium is located next to the parking block, with offices, meeting rooms and facilities farthest from the road. Immediately adjacent to the offices is a residential block, hence the design decision to have the auditorium in the middle of the site plan between the office and the parking blocks. From a design point of view, this was a good compromise. Auditorium windows face the parking block and the atrium thereby minimizing the possibility of disturbance to or from the adjacent mixed use and residential zones.

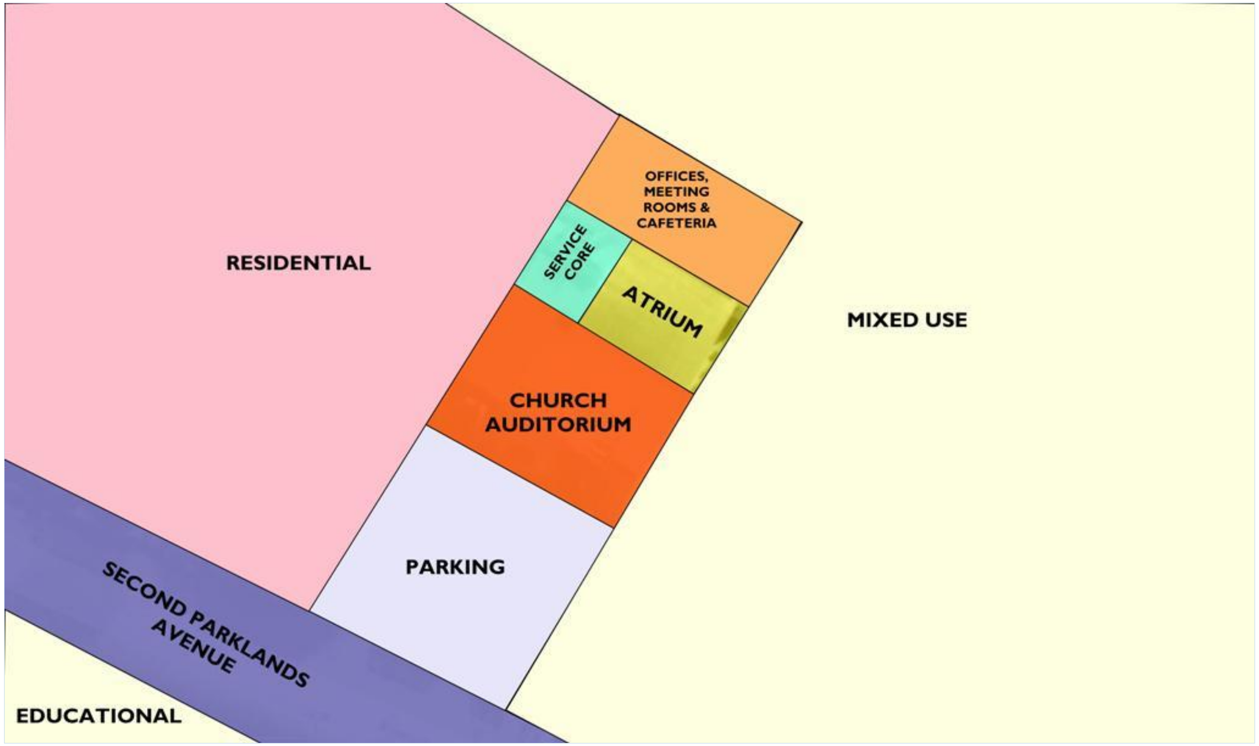

Figure 67. CITAM Parklands – Site Layout & Adjacent zones.

Copyright: Author.

iii) Main Construction – The main building components consist of 200mm thick natural stone walls, reinforced concrete floors, solid core flush doors, thick laminated glass window panes in aluminium frames, and IT5 roofing sheets with an aluminium coated underlay. Stone, concrete and solid timber are dense materials and efficient in blocking unwanted noise. The windows are not double-glazed but the laminated panes are thick enough and efficient in blocking external noise. The solid door shutters no not have draught strips / sweeps and gaps at the bottom allow sound intrusion. The IT5 roof also allows easy intrusion of aircraft noise. Internally, there are two levels of ceiling to reduce noise intrusion through the roof.

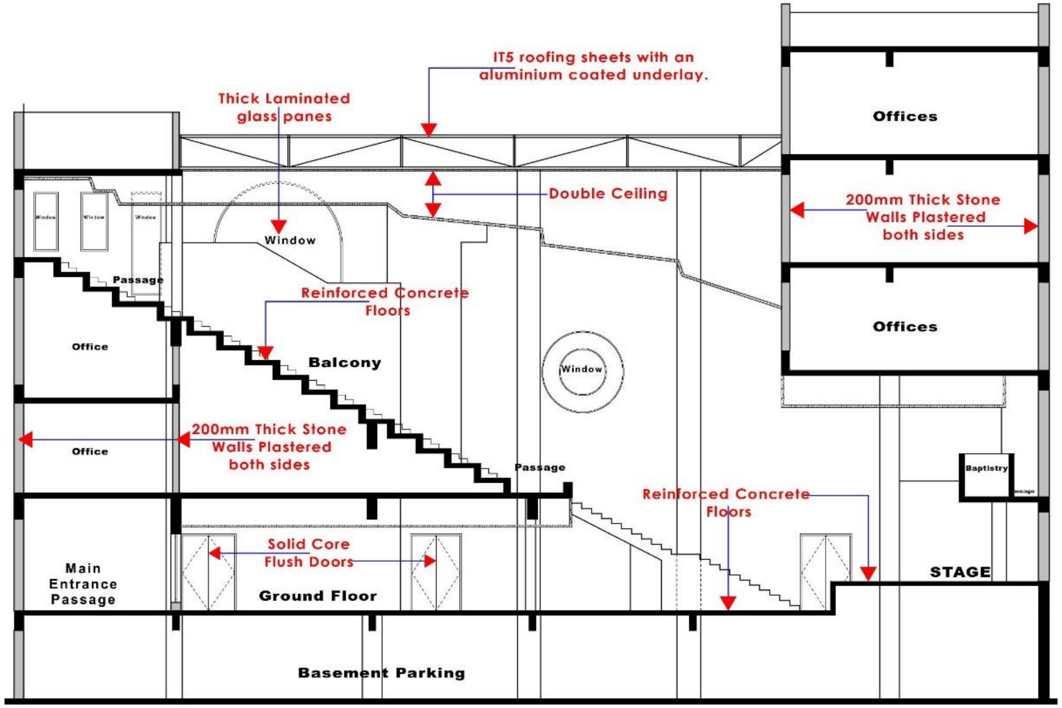

Figure 68. CITAM Parklands – Main Construction Elements.

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iv) **Room size: *Hall Capacity, floor area, volume, and ceiling height*** – The auditorium capacity is 542 seats with a floor area of 509m^2 in the audience hall and 116m^2 on stage, and an overall volume of 3,318m^3. This translates to an area of 0.96m^2 and a volume of 6.12m^3 per seat respectively. This within the recommended design range of 0.6 m^2 to 0.9 m^2 and 5.1m^3 to 8.5m^3 per seat. This implies that with appropriate surface treatment, it is possible to attain an acceptable RT60 for the hall.

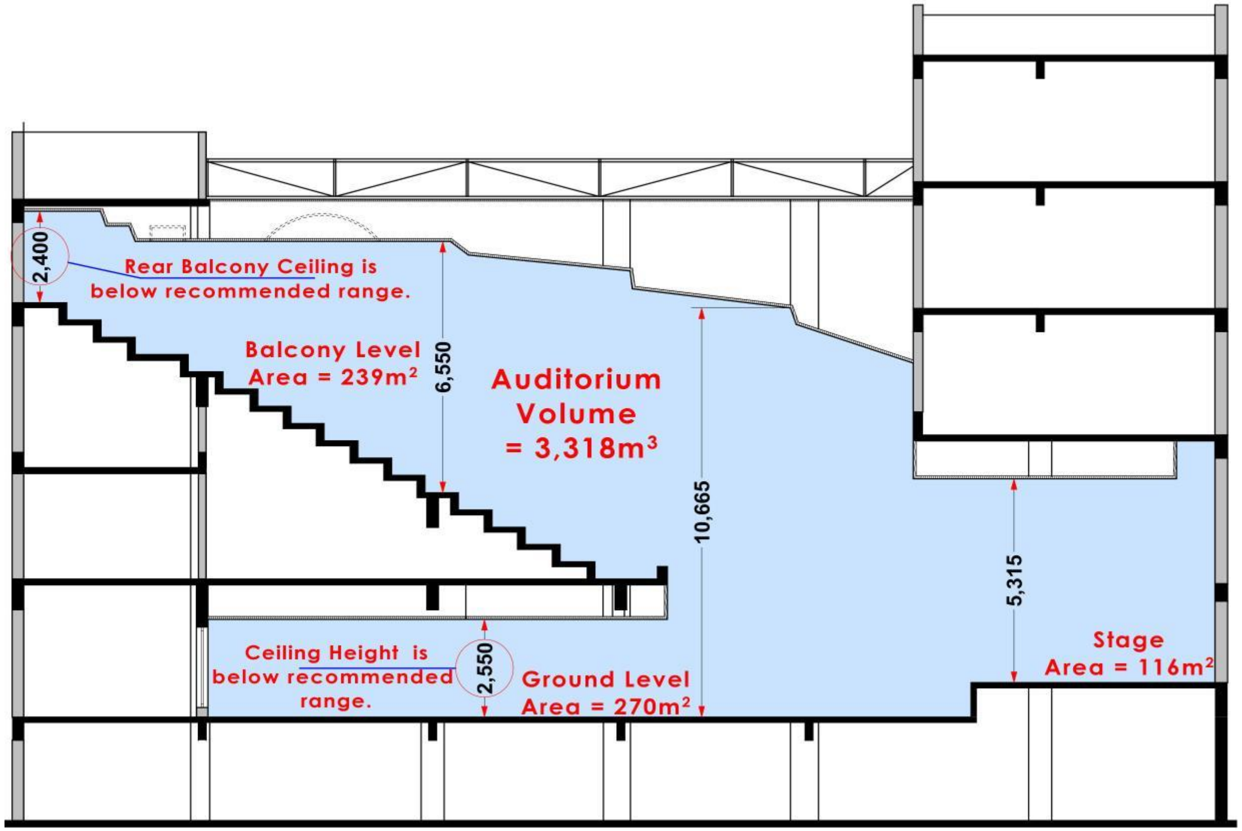

Figure 69. CITAM Parklands – Hall Size.
Copyright: Author.

The average ceiling height of the hall is 6.2m. The recommended average ceiling height should be about 1/3 to 2/3 of the hall width. With an average width of 15.78m, that translates to ceiling heights between 5.3m to 10.6m.The current average ceiling height is therefore within the recommended range. However, the ground floor and rear balcony ceiling heights at 2.55m and 2.4m respectively are too low for any useful reflection.

v) **Room Geometry:** ***Hall shape and profile, stage shape and profile, side & rear walls geometry, balcony projection and profile, ceiling geometry, and sight lines*** - The hall plan rectangular in plan, which is ideal for a medium size hall. The ground floor is flat which goes against the recommended design criteria to incline the floor by 8 degrees or more. The sidewalls are neither splayed nor undulated, creating a high possibility for flutter echoes. The stage is elevated by 900mm, which is within the recommended range. The stage sidewalls however are not splayed as recommended for strong early reflections. The flat geometry of the rear wall is ideal for the hall. The balcony floor incline is 27 degrees, which is slightly outside the recommended range of less than 26 degrees. A slope exceeding 26 degrees is likely to cause vertigo - a sensation of whirling and loss of balance. The balcony over hang into the hall is more than the recommended depth of less than twice the height of the balcony opening, creating the possibility of sound shadows. The balcony parapet wall is parallel to the stage back wall, creating the possibility of flutter echoes. The main hall ceiling is angled and stepped upwards from the stage towards the balcony rear wall. This helps to reflect sound to particular seating areas. However, the ceiling above the stage is flat, which is contrary to the recommended design criteria for an upward tilt to enhance early sound reflections. The under balcony ceiling is not ideal since is flat. Ideally, it should slope downward from the opening towards the rear to reflect sound toward the heads of the listeners seated underneath and to better connect the under-balcony volume with the volume of the main hall. The balcony ceiling at the rear is not splayed as recommended for useful short-delayed reflections. Finally, the balcony sight lines work well if targeted to the recommended APS along the edge of the apron stage, implying that the balcony audience will have a full-unobstructed view of entire stage area and performers. However, the main hall sight lines do not work since the floor is flat.

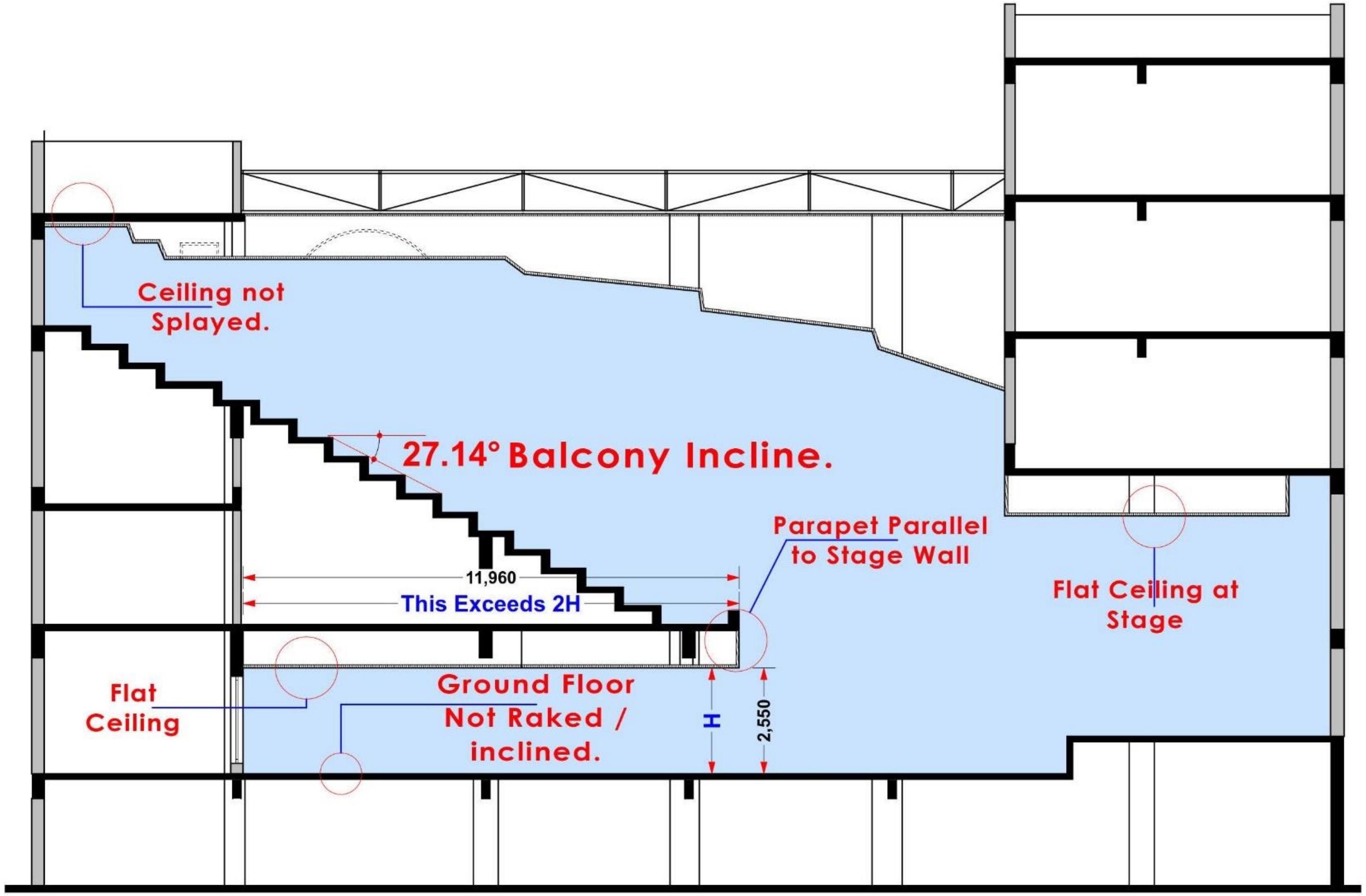

Figure 70. CITAM Parklands – Geometrical Acoustic design failures shown in section.
Copyright: Author.

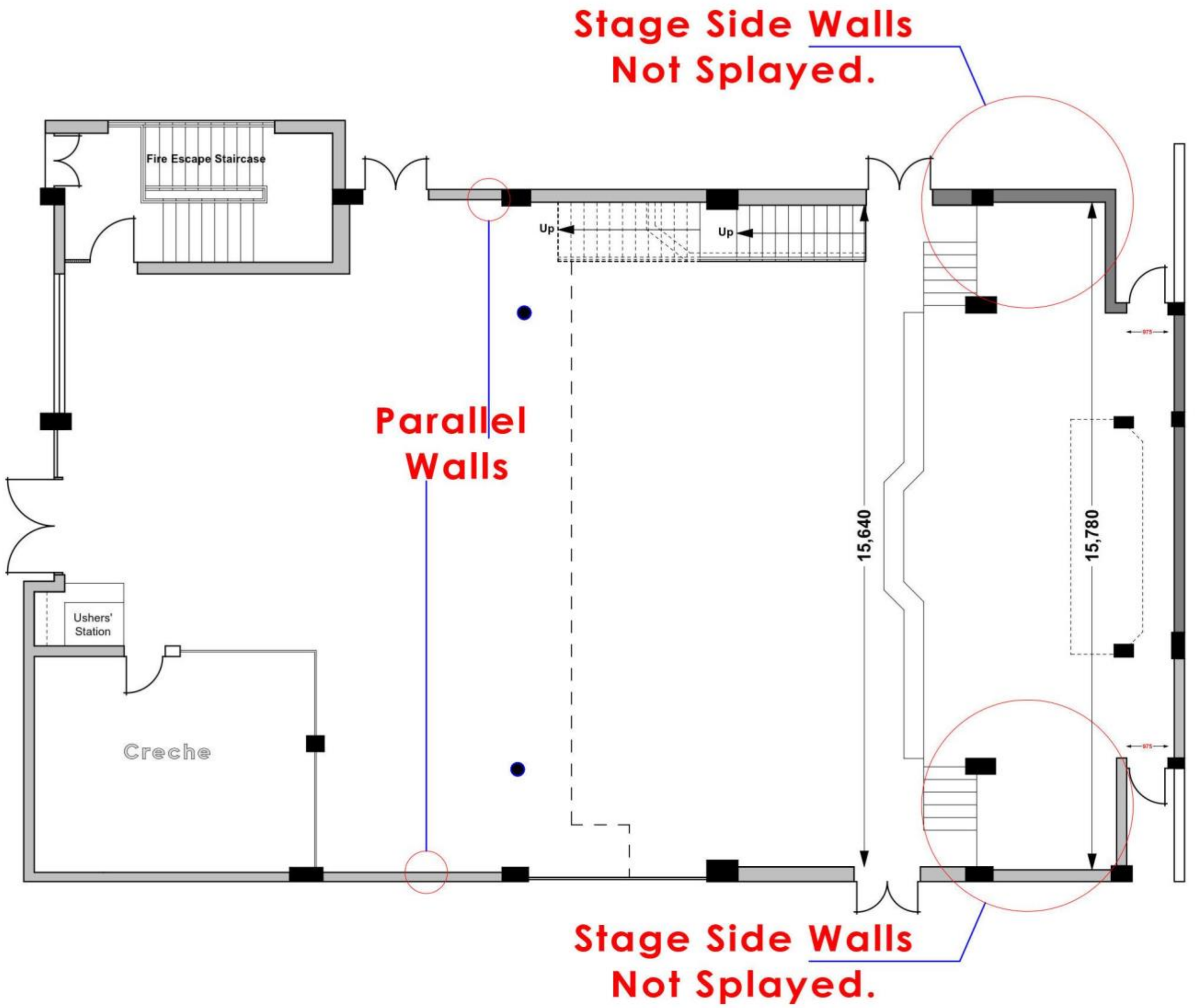

Figure 71. CITAM Parklands – Geometrical Acoustic design failures shown in plan.

x) **Surface finishes: Floors, *Walls, ceilings and seats* –** Apart from sections with doors and windows, all other areas of sidewall surfaces in the main hall and balcony are lined plain gypsum and perforated gypsum panels with mineral wool backing, which are ideal for absorption and diffusion. This was necessary to prevent flutter echoes since the sidewalls are parallel. A better solution would have been using mini splays or undulations to deal with the parallelism and eliminate the need for excessive absorption. Large absorbing wall areas in a small church are not ideal since in a small hall, the audience should provide most of the absorption. The stage walls are finished in plaster and paint, which is ideal to enhance reflection. The ground floor rear wall surface finishes consist of plaster & paint, stained timber, glass on aluminium frames, and perforated gypsum board panels. Ideally, this wall should be treated to absorb and diffuse to prevent long delayed reflections (echoes). The balcony rear and parapet walls surfaces have perforated gypsum board with mineral wool backing which is ideal for diffusion. Apart from sections with light fittings, AC grilles, and a small plastered section on stage, all other ceiling surfaces are finished in mineral fibre acoustic tiles. This is not ideal since the ceiling should be reflecting, with sections along the side and rear perimeter treated for absorption as required for reverberation control. All seats are fabric upholstered, which is ideal for stable reverberation conditions when the auditorium is partially occupied.

vi) **Sound reinforcement -** Clusters of loud speakers are anchored from the ceiling in the central space just above the proscenium opening, which is ideal for speech intelligibility. Point source loud speakers under the balcony cover the ground floor listeners who do not have a direct line of sight to the central clusters. Additional loud speakers positioned in the flat area below the stage are positioned to direct sound to audience at front in the main hall. There is also a set of stage monitor speakers for projecting sound back to speakers / performers on stage. The various loud speakers and stage monitors as manufactured by EV and AVSHK have a combined frequency range of between 30 Hz to 20 kHz which is ideal for both music and speech reproduction.

vii) **Reverberation time -** The measured average RT60 was 0.74s at 500Hz and 0.73s at 1kHz (unoccupied). The calculated RT60 was 0.63s at 500Hz and 0.57s at 1000Hz (unoccupied). The calculated RT60 using NRC was 0.72s. Under occupied conditions, these RT60 values will be lower due to audience absorption. With a volume of $3318m^3$, the ideal RT60 for the hall based on Stephen and Bates formula = 4(0.0118V1/3 + 0.1070) = 1.13s, implying that the hall as currently treated has excessive absorption. The recommended RT60 for a medium size church auditorium is between 1.2s to 1.3s.

viii) **Noise Pollution –** The Parklands auditorium is not a source of noise pollution for the following reasons:-

a. The walls shared with adjacent properties have no windows.

b. The openable auditorium windows are oriented facing atrium. Windows facing second Parklands Avenue are not openable.

c. The auditorium as currently treated has excessive absorption.

4.6. COMPARATIVE ANALYSIS OF THE CITAM NGONG & PARKLANDS AUDITORIUMS

PARAMETER	**CITAM NGONG**	**CITAM PARKLANDS**
Site selection	A large parcel of land in a low-density zone, and near a busy road.	An urban plot in a high-density zone, and near a busy road.
External noise isolation	Dense landscaping, staff parking, and administration block used as buffer spaces to isolate the auditorium from external noise.	Perimeter wall, parking block, and administration block used as buffer spaces to isolate the auditorium from external noise.
Construction Elements		
• Floors	Reinforced concrete	Reinforced concrete
• Walls	200mm thick external walls.	200mm thick external walls.
• doors	Solid wood panel doors.	Solid core flush doors.

• Windows	Laminated glass window panes in aluminium frames.	Thick laminated glass window panes in aluminium frames.
• Roof	IT5 roofing sheets with an aluminium coated polyethylene underlay.	IT5 roofing sheets with an aluminium coated underlay.
Auditorium Size		
• Capacity	2900 seats	542 seats
• Floor Area	2535m^2 in the audience hall and 155m^2 on stage.	509m^2 in the audience hall and 116m^2 on stage.
• Floor Area/seat	0.87m^2	0.96m^2
• Volume	15,250m^3	3,318m^3
• Volume/seat	5.26m^3	6.12m^3
Auditorium Geometry		
• Shape in plan	Fan shaped	Rectangular
• Floor Profile	Ground floor inclined by 4 degrees. Balcony raked with an incline of 16 degrees.	Ground floor is flat. Balcony raked with an incline of 27 degrees.
• Stage Layout	Splayed sidewalls and a flat back wall.	Rectangular
• Stage Elevation	900mm	900mm
• Side Walls	Splayed by 30 degrees	Flat.
• Rear Walls	Flat	Flat.
• Balcony opening	3.75m	2.55m
• Balcony Overhang	12.6m	11.9m
• Ceiling Profile	10.5-degrees mono-pitch sloping upwards from front to back.	Angled and stepped upwards towards the back.
Surface Finishes		
• Auditorium Floor	Terrazzo	Ceramic Tiles.
• Stage Floor	Carpet on concrete.	Carpet on concrete.
• Side walls	Plaster and paint, fabric covered foam panels and perforated Mdf panels.	Perforated gypsum panels with mineral wool backing.
• Rear walls	Plaster & paint, and glass panes.	Perforated gypsum panels with mineral wool backing
• Balcony parapet	Slatted Mdf panels with foam backing	

• Stage walls	Plaster & paint on sidewalls, fabric covered foam panels & heavy curtain hung in fold to stage back wall.	Plaster & paint.
• Auditorium ceiling	Mineral fibre acoustic tiles.	Mineral fibre acoustic tiles.
• Stage ceiling	Combination of mineral fibre acoustic tiles and gypsum panels.	Mineral fibre acoustic tiles.
Sound reinforcement	Clustered line array speakers, point source speakers, and stage monitors.	Clustered line array speakers, point source speakers, and stage monitors.
Reverberation time	1.02s	0.74s

4.7. PROPOSALS FOR IMPROVEMENT - CITAM NGONG

a) External noise control - The hall should be isolated from external noise by lining the door and window rebates with draught strip rubber or felt, adding insulation to the space between the ceiling and the roofing sheets, and creating air gaps at all entry lobbies by adding a second layer of entrance doors.

b) The ceiling above the pulpit should be appropriately tilted to effectively reflect sound towards the audience. The main ceiling should be angled and stepped for reflection of sound to particular seating areas. To improve reverberation, the middle section of the ceiling should be reflective, and the perimeter along both sides and rear can be sound absorbing. Alternatively, the entire ceiling surface can be finished in a checkerboard pattern consisting of alternate areas of sound absorbing and reflecting materials, to achieve 70% reflection and 30% absorption.

c) The front part of the auditorium should be reflective. The carpet floor on stage and front part of the auditorium should be replaced with a reflective material. The stage back wall should be diffusive. Currently is mainly treated for absorption.

d) The rear walls should be treated for absorption and diffusion. Currently the walls are mainly reflective with some sections treated for absorption. Side walls should be reflective. Currently the larger percentage of upholstered foam panels are placed on the side walls. These should be moved to the rear walls.

e) By adjusting the amount of absorption on floors, walls and ceilings, the target should be to tweak the RT_{60} (unoccupied) upwards to a value between 1.4s to 1.6s.

4.8. PROPOSALS FOR IMPROVEMENT - CITAM PARKLANDS

a) External noise control - The hall should be isolated from external noise by lining the door and window rebates with draught strip rubber or felt, adding insulation to the space between the upper ceiling and the roofing sheets, and creating air gaps at all entry lobbies by adding a second layer of entrance doors.

b) Sidewalls – To avoid parallelism, sinusoidal or serrated elements should be used to line the walls. This will make the walls diffusive and eliminate the need for the entire wall surfaces finished for absorption as is the case currently. This will help to increase reverberation and RT_{60}.

c) The entire front part of the auditorium should be improved for strong early reflections by introducing splayed walls on stage and an appropriately angled reflective ceiling to direct sound to the audience. The carpet floor on stage and front part of the auditorium should be replaced with a reflective material.

d) The middle section of the main ceiling should be reflective. Currently it is absorbing. The perimeter along both sides and rear can be sound absorbing or finished in a checkerboard pattern consisting of alternate areas of sound absorbing and reflecting materials to achieve the desired RT_{60}.

e) The ground floor rear wall should be treated for absorption and diffusion. Currently the wall is reflective.

f) By carefully adjusting the amount of absorption on floors, walls and ceilings the target should be to tweak the RT_{60} (unoccupied) upwards to a value between 1.2s to 1.3s.

4.9. SUMMARY

In this chapter, the CITAM church auditoriums at Ngong and Parklands are evaluated to establish their respective RT_{60} values and acoustic design considerations. The acoustic analysis revealed that the RT_{60} values for both auditoriums are below the recommended acceptable values based on the auditorium sizes and intended uses. The unoccupied mid frequency RT_{60} for Ngong is 1.02 seconds. This is below the ideal mid frequency range of 1.4 to 1.6 seconds for a large evangelical church auditorium. With a volume of 15,250m^3, the ideal value based on Stephen and Bates formula should be 1.6 seconds. The unoccupied mid frequency RT_{60} for Parklands is 0.74 seconds. This is below the recommended mid frequency value of 1.2 to 1.3 seconds for a medium size evangelical church auditorium. With a volume of 3,318m^3, the ideal value based on Stephen and Bates formula should be 1.13 seconds. From an acoustic point of view, the architectural design of both halls has mixed elements of both success and failure. Some architectural design aspects can be altered to improve acoustics and have been discussed under 0.

CHAPTER FIVE – CONCLUSION AND FUTURE WORK

5.1. CONCLUSION

The acoustic environment of church auditoriums is complex due to conflicting acoustic needs of music and speech, as well as multiplicity of the sound sources that contribute to the overall soundscape.

This study documents the key design principles for acoustic comfort in church auditoria and illustrates a methodology for their application in evaluating new designs as well as existing church auditoriums.

As detailed in chapter 2, the author conducted a detailed literature review to document the recommended design criteria and parameters for acoustic comfort in church auditoria.

The knowledge gained from the literature review was applied to design a methodology for undertaking data collection, analysis and evaluation of two existing church auditoriums as detailed in chapter 3.

In chapter 4, the overall acoustic character of the CITAM church auditoriums at Ngong and Parklands was discussed in detail. Using the recorded survey information and analysis results, suggestions were made on how to improve some of the negative aspects of the auditoria.

As a guideline, the following factors are essential for good acoustics in new Pentecostal church auditoriums:-

a) Because of the highly specialized nature of church acoustics, hiring an acoustics expert early in the process is essential. The consultant should be involved either from the onset of the design process or at the early stages of schematic design.

b) Where possible, select a quiet location away from noisy industries, flight paths and highways. For sites near such noise sources, use corridors, storage rooms, and other buffer spaces to isolate the auditorium from noise. Spaces adjacent to the auditorium should be isolated from the main hall by air gaps and acoustic doors.

c) Define the auditorium's intended uses and the percentage distribution of each activity from the onset – to help establish what is dominant between speech and music.

d) For planning purposes, provide a floor area of 0.8 to 0.9 m^2 per person in the audience hall (excluding stage) and an overall volume of $5.1m^3$ to $8.5m^3$ per seat.

e) Use dense or heavy construction components like concrete and thick masonry to increase the structural mass of walls, floors and ceilings, as well as laminated double-glazed windows.

f) Floor plans can be rectangular or fan shaped. For fan shaped halls, the sidewall splay should range from 30° to 60°. Sidewalls should not be parallel.

g) Floors in large halls should be raked to improve sight lines. The angle of elevation of the inclined floor should not be less than 8 degrees. Balcony floor slopes should not exceed 26°.

h) Some ceiling segments should be be sized and angled to reflect sound to particular seating areas in the hall.

i) The stage area and front of the hall should be reflective, and absorption placed in the seating area and rear of the hall. Side walls should generally be sound reflecting with large-scale irregularities, splays, or bumps.

j) A cluster of loudspeakers should be provided just above and slightly in front of the proscenium opening.

k) Depending on the auditorium volume, the target RT60 should range between 1.2s to 1.6s.

To improve acoustics in existing buildings the following steps should be undertaken:-

a) Compile a list of the acoustical problems in the auditorium based on feedback from users.
b) Hire an acoustics expert to assess the auditorium, document the reasons for poor acoustics, and propose possible solutions to achieve good acoustics.
c) Engage a specialist contractor to implement the recommended solutions under the supervision of the specialist.

5.2. RECOMMENDATIONS FOR FUTURE STUDY

The primary goal of this study was to provide a simple reference tool for practicing architects, students of architecture, interior designers, church leaders, and contractors in Kenya by methodically documenting the key design considerations for acoustic comfort in church auditoria. These include acoustic design principles, architectural design considerations, and the primary parameter for acoustic characterization as well as methods for its calculation and measurement. To illustrate a methodology for applying the above principles, acoustic evaluation of the CITAM church auditoria at Ngong and Parklands was undertaken through an architectural survey, acoustic measurement, and analysis of the drawings, surface finishes as well as the measured results. This methodology can be used to evaluate existing spaces or in the design of new spaces.

The analysis completed in the current study is just one of many research possibilities. By using the information already gathered, one can adapt and build on it to improve upon the acoustics of the auditoriums. One very realistic route for future work would be to validate the improvements highlighted in chapter 4. If the suggestions are actually implemented, the same measurements made for this study could be repeated. The results could then be compared with the current results to assess the success of the improvements. In the event that the results were unsuccessful, further investigation could then be made as to where calculations were misguided, improper assumptions made or installations done incorrectly.

Below are other possible areas of further investigation related to the subject of this research.

a) Acoustic simulations to evaluate the effects of the proposed improvements on the auditoriums' acoustic characteristics.

b) Evaluation of the auditoriums' acoustic characteristics when occupied. Data collected under occupied conditions will provide stronger validity in the conclusions drawn considering that audience absorption plays an important role in church acoustics.

c) Evaluation of other acoustic indices besides RT60 as defined in ISO 3382 including the Definition (D50), the Clarity (C80), the Early Decay Time (EDT) and the Speech Transmission Index (STI).

References

1. Bailey, G. A. (2003). *Between Renaissance and Baroque: Jesuit Art in Rome, 1565 -1610*. University of Toronto Press.
2. Bariu, M. R. (2017). Transformations of Christianity in Kenya: A Historical Survey. *The International Journal Of Humanities & Social Studies*, *5*(11), 307–311. Retrieved from www.theijhss.com
3. Barron, M. (2009). Auditorium Acoustics and Architectural Design. In *Auditorium Acoustics and Architectural Design* (2nd ed.). https://doi.org/10.4324/9780203874226
4. Beranek, L. L. (2005). Concert Halls and Opera Houses: Music, Acoustics, and Architecture (Second Edition). *The Journal of the Acoustical Society of America*, *117*(3), 987–988. https://doi.org/10.1121/1.1861061
5. Bluyssen, P. (2009). The Indoor Environment Handbook. In *The Indoor Environment Handbook*. https://doi.org/10.4324/9781849774611
6. Bureau of Indian Standards. (1998). *Code of Practice for Acoustical Design of Auditoriums and Conference Halls* (9th ed.). New Delhi: Bureau of Indian Standards.
7. Carvalho, A. P. O. (1994). *Influence of Architectural Features and Styles on Various Acoustical Measures in Churches*. University of Florida.
8. Carvalho, A. P. O. (1995). Influence of architectural features and styles on various acoustical measures in churches. *The Journal of the Acoustical Society of America*, *97*(4), 2608. https://doi.org/10.1121/1.411917
9. Ching, F. D. . (1995). *A Visual Dictionary of Architecture*. New York: John Wiley & Sons.
10. Cowan, J. (2007). Building Acoustics. In Thomas Rossing (Ed.), *Springer Handbook of Acoustics* (2nd ed.). New York: Springer-Verlag.
11. Doelle, L. L. (1972). *Environmental Acoustics*. New York: McGraw-Hill.
12. Ediae O.J, Enoma, E. P., Igbogbo, O. S., Ezema, I. C., & Ekhaese, E. N. (2017). A Study of the Effects of Architectural Forms on Sound

Quality in Church Buildings. *Nigerian Journal of Environmental Sciences and Technology March 2017*, *1*(1).

13. Egan, M. D. (2007). *Architectural acoustics*. New York: J. Ross Publishing.
14. Everest, F. A. (Frederick A., & Pohlmann, K. C. (2009). *Master handbook of acoustics* (5th ed.). New York: McGraw-Hill.
15. Fay, M. W. (2013). Acoustics 101 for architects. *The Journal of the Acoustical Society of America*, *134*(5), 4005. https://doi.org/10.1121/1.4830611
16. Fernie, E. (2014). *Romanesque Architecture: The First Style of the European Age* (Illustrate). London: Yale University Press.
17. Gade, A. (2007). Acoustics in Halls for Speech and Music. In T. D. Rossing (Ed.), *Springer Handbook of Acoustics* (Illustrate, pp. 301–350). https://doi.org/10.1007/978-0-387-30425-0_9
18. Gechiko, N. B., & Nkonge, K. D. (2014). Charismatic Pentecostal Churches in Kenya: Growth, Culture and Orality. *International Journal of Humanities Social Sciences and Education (IJHSSE)*, *1*(3), 27–33. Retrieved from www.arcjournals.org
19. Ginn, K. B. (1978). *Architectural Acoustics*. Retrieved from https://www.bksv.com/media/doc/bn1329.pdf
20. Gonzalez, V. G. (2009). *Acoustic study and conditioning for Kirche am Hohenzollernplatz in Berlin*. Technical University of Berlin.
21. Gou, Z., & Lau, S. (2017). Acoustic Design for an Auditorium Project. In M. A. Schnabel (Ed.), *51st International Conference of the Architectural Science Association (ANZAScA)* (pp. 167–176). Wellington: Architectural Science Association.
22. Harris, C. M. (2006). *Dictionary of Architecture & Construction* (4th ed.; Cyril M. Harris, Ed.). New York: McGraw-Hill.
23. Kothari, C. R. (2004). *Research methodology : Methods and Techniques* (2nd Revised Edition). New Age International (P) Ltd.
24. Lacatis, R., Giménez, A., Barba Sevillano, A., Cerdá, S., Romero, J., & Cibrián, R. (2008). Historical and chronological evolution of the concert hall acoustics parameters. *European Conference on Noise Control*. https://doi.org/10.1121/1.2933348
25. Lamancusa, J. S. (2000). Room acoustics. *Engineering Noise Control*, pp. 8.1-8.19. Pennsylvania: Penn State University.
26. Lee, S. (2003). Comparative Analysis Of Speech Intelligibility In Church Acoustics Using Computer Modeling (University of Florida). Retrieved from http://etd.fcla.edu/UF/UFE0000866/lee_s.pdf
27. Long, M. (2014). *Architectural Acoustics* (2nd ed.). Amsterdam: Academic Press.

28. Lubman, D., & Kiser, B. (2001). Acoustics of Worship Buildings. *17th International Congresses on Acoustics (Rome)*. Retrieved from https://www.icacommission.org/Proceedings/ICA2001Rome/5_02.pdf
29. Lubman, D., & Kiser, B. (2002). The History of Western Civilization Told Through the Acoustics of its Worship Spaces. *17th International Congress on Acoustics*, 12–13. Rome: ICA.
30. Martellotta, F., & Cirillo, E. (2014). Acoustics and architecture in Italian Catholic churches. *International Symposium on Room Acoustics*.
31. Moore, B. (2007). Psychoacoustics. In Thomas Rossing (Ed.), *Springer Handbook of Acoustics* (2nd ed., p. 468). https://doi.org/10.1007/978-0-387-30425-0_13
32. Niemas, M., Sadowski, J., & Engel, Z. (1998). Acoustics of Sacral Structures. *Archives of Acoustics*, *23*(1), 87–104.
33. Othman, A. R., & Mohamed, M. R. (2012). Influence of Proportion towards Speech Intelligibility in Mosque's Praying Hall. *Procedia - Social and Behavioral Sciences*, *35*, 321–329. https://doi.org/10.1016/J.SBSPRO.2012.02.094
34. Parsitau, D. S. (2014). *The Civic and Public Roles of Neo-Pentecostal Churches in Kenya (1970- 2010)*. Kenyatta University.
35. Raichel, D. R. (2006). *THE SCIENCE AND APPLICATION OF ACOUSTICS*. New York: Springer.
36. Rossing, Thomas. (2007). Introduction to Acoustics. In T Rossing (Ed.), *Springer Handbooks* (Illustrate, pp. 1–6). https://doi.org/10.1007/978-0-387-30425-0_2
37. Saint-Gobain. (2016). *Indoor Environment and Wellbeing - The Saint-Gobain Building Science Handbook*. Paris: Saint-Gobain.
38. Scavone, G. (2019). *Room Acoustics*. Montreal: McGill University.
39. Stewart, A. C. (2011). The Earliest History of the Christian Gathering: Origin, Development and Content of the Christian Gathering in the First to Third Centuries. By VALERIY A. ALIKIN. *The Journal of Theological Studies*. https://doi.org/10.1093/jts/flr062
40. Svenssonv, C., & Nilsson, E. (2008). Optimum Room Acoustic Comfort^{TM} (RAC^{TM}) can be achieved by using a selection of appropriate acoustic descriptors. *Proceedings - European Conference on Noise Control*, *123*(5), 3859–3863. https://doi.org/10.1121/1.2934365
41. Szymanski, J. (2008). Small Room Acoustics. In G. Ballou (Ed.), *Handbook for Sound Engineers* (Fourth, p. 111).

https://doi.org/10.4324/9780080927619

42. Teckla, M., Gerryshom, M., & Njuguna, M. (2016). Reflections on architectural morphology in Nairobi, Kenya: implications forconservation of the built heritage. *Conservation of Natural and Cultural Heritage in Kenya*.
43. Vardaxis, N.-G., Bard, D., & Persson, W. K. (2017). On the definition of acoustic comfort in residential buildings. *The Journal of the Acoustical Society of America*, *141*(5), 3540–3540. https://doi.org/10.1121/1.4987481
44. Vigran, T. . (2008). *Building Acoustics*. London: Taylor & Francis.
45. Vodopija, J., Fajt, S., & Krhen, M. (2010). Evaluation of Acoustic parameters of Churches. *10th French Congress of Acoustics*. Retrieved from https://hal.archives-ouvertes.fr/hal-00539758/document
46. Wenger Corporation. (2008). *Planning Guide for Performance Spaces*. Owatonna.