Stadiums as Widespan Structures in Cameroon Case Study: Ahmadou Ahidjo Stadium and Olembe Paul Biya Stadium

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ABSTRACT

Cameroon’s notable second generation stadium Ahmadou Ahidjo Stadium and the newly built Category 4 Olembe Paul Biya Stadium, are remarkable widespan constructions of cultural and architectural significance. This thesis examines widespan structures in the context of Cameroonian stadiums, providing insight into their structural system in relation to overall design with a particular focus on the structural system of their roofs.

Widespan structures differ in forms and sizes, displaying a variety of complexities. Among them, stadiums, feature tiered seating and intended for extensive spectator viewing of sporting events, competitions, and public gatherings. Given the significance of stadium architecture as a landmark in Cameroon and its broader impact on the country, this thesis explores stadium constructions. It examines the development of stadiums from ancient Greek and Roman empires to modern arenas globally, incorporating the latest technological advancements. Acknowledging a notable gap in the existing literature on this subject, this thesis concentrates its research on two specific cases of stadiums in Cameroon. The ultimate goal is to formulate a comprehensive technical guideline or recommendation specifically tailored for structures in stadium construction.

The research questions cover a critical topic, including the structural and architectural components of Cameroonian stadiums, the evolution of stadium design and construction over time, the cultural significance of widespan constructions, their contemporary relevance, and their impact on Cameroon's architectural landscape.

The research employs a methodical approach that combines architectural analysis, historical research, and case study assessments. Our findings illustrate the multiple advantages of widespan buildings, ranging from cost-effectiveness to architectural flexibility and aesthetic appeal. Simultaneously, the significance paying attention to maintenance and safety problems. The case studies underscore the essential role that context plays in stadium design and construction.

Finally, this study gives important information to architects and builders, allowing them to create cost-effective, long-lasting, and visually beautiful stadiums not just in Cameroon, but also as a global reference. It highlights the long-term usage of wide-span structures in stadium design and construction, acting as a model for future infrastructure projects and lastly contributes significantly to the stadium design body of knowledge which, is extremely important for Cameroonian architects as they navigate the stadium building landscape in the future.

Keywords: Widespan Constructions, Widespan Structures, Structural System, Roof Structure, Stadiums, Technological Advancements, Construction, Technical Guidelines, Cost-effectiveness, Architectural Flexibility, Stadium Design.

ÖZ

Kamerun'un dikkat çeken ikinci nesil stadyumları olan Ahmadou Ahidjo Stadyumu ve yeni inşa edilen Kategori 4 Olembe Paul Biya Stadyumu, kültürel ve mimari öneme sahip önemli geniş açıklıklı yapılar olarak durmaktadır. Bu tez, Kamerun stadyumlarının bağlamında geniş açıklıklı yapıları inceleyerek, tasarımın genel yapısına ilişkin yapısal sistemlerine dair içgörüler sunar, özellikle de çatı yapılarının yapısal sistemlerine odaklanır.

Geniş açıklıklı yapılar çeşitli şekil ve boyutlarda gelir ve genellikle farklı karmaşıklıklar sergilerler. Stadyumlar, genellikle büyük ölçekli seyirci etkinliklerine, spor karşılaşmalarına ve halk toplantılarına ev sahipliği yapacak şekilde tasarlanmış olan geniş açıklıklı yapıların en yaygın türünü temsil ederler. Kamerun'da stadyum mimarisinin anıtsal önemi ve ülke çapındaki daha geniş önemi göz önüne alındığında, bu tez, geniş açıklıklı yapıları keşfetmeye yola çıkarak Kamerun'da eski Yunan ve Roma imparatorluklarından günümüzün dünya genelindeki arenalara kadar stadyumların evrimini izlerken en son teknolojik gelişmeleri de inceler.

Bu alandaki mevcut literatürde önemli bir boşluğun farkında olarak, bu tez, Kamerun'daki iki farklı stadyum örneğine odaklanarak araştırma çabalarını yoğunlaştırır. Ayrıca, Kamerun'daki beş önemli stadyumu değerlendiren bir tartışma sunar, değerli teknik bilgiler ve öneriler sunar ve nihayetinde kapsamlı bir teknik kılavuzun geliştirilmesine yol açar.

Araştırma, Kamerun stadyumlarının yapısal ve mimari bileşenleri, stadyum tasarımı ve inşaatının tarihsel gelişimi, geniş açıklıklı yapıların kültürel önemi, çağdaş önemi ve Kamerun'un mimari manzarasına etkisi gibi çeşitli konuları kapsar. Mimarlık analizi, tarih araştırması ve vaka incelemesi değerlendirmelerini birleştiren sistemli bir yaklaşımı kullanarak, bu çalışma, geniş açıklıklı yapıların maliyet etkinliği, mimari esneklik ve estetik çekicilik gibi bir dizi avantajını aydınlatırken, bakım ve güvenlik konularının son derece önemli olduğunu vurgular.

Stadyum tasarımı ve inşaatında bağlam faktörlerinin incelenmesiyle, bu araştırma sadece Kamerun'da ekonomik, dayanıklı ve görsel olarak etkileyici stadyumlar oluşturmak için mimarlara ve inşaatçılara önemli bilgi sağlamakla kalmaz, aynı zamanda küresel bir referans sunar. Stadyum geliştirme sürecinde geniş açıklıklı yapıların uzun vadeli kullanımının önemini vurgular ve gelecekteki altyapı projeleri için bir model olarak hizmet eder ve son olarak gelecekte Kamerunlu mimarların stadyum inşaat manzarasını gezinirken son derece önemli bir kaynağa katkıda bulunur.

Anahtar Kelimeler: Geniş Açıklıklı Yapılar, Geniş Açıklıklı Yapılar, Yapısal Sistem, Çatı Yapısı, Stadyumlar, Teknolojik Gelişmeler, İnşaat, Teknik Kılavuzlar, Maliyet Etkinliği, Mimari Esneklik, Stadyum Tasarımı

DEDICATION

I dedicate my thesis to Ngo Manga Martine-Marie, my beloved mother, who raised me with patience and unwavering love. To my late father, who watches over me. To my siblings Aurelie, Crepin, and Marcus. Manga Marc Marcelin, My niece and nephew Karl and Melia. To my unborn kids and husband. Jeremiah 29:19.

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LIST OF ABBREVIATIONS

AFCON	African Cup Of Nations.
BIM	Building Information Modeling
CAF	Confederation of African Football
ETFE	Ethylene Tetra Fluoro Ethylene.
FECAFOOT	Cameroonian Football Federation.
FIFA	International Federation of Association football
MEP	Mechanical, Electrical and Plumbing.
PTFE	Polytetrafluoroethylene.
PVC	Polyvinyl chloride.
RC	Reinforced concrete.
UEFA	Union of European Football Associations

Chapter 1

INTRODUCTION

1.1 Background and Rationale

The first appearances of widespan structures can be identified in Ancient Greek and Roman societies. Facilities that resembled stadiums first appeared around 776 BC with the inauguration of the Olympics. While there may not have been much physical structure involved, these facilities were still regarded as engineering accomplishments. (Yaroni, 2012, p.13). The Ancient Greeks and Romans attributed great significance to the spectacle and rivalry of sports, elevating playing grounds into an interconnected array of stadiums crafted to pay homage to the gods and assert their divine authority.

However over time, widespan structures have gotten bolder and more distinctive as building designs have evolved to meet society's ever-changing demands, expectations and regulations. In architecture, wide span structures are constructions that envelop enormous areas without any intermediary support. Its use is very desirable in certain architectural plans such as conference halls and sports stadiums, where huge open areas free of structural components are required to facilitate specialized activities. While widespan structure’s form has remained the same its applications and construction methods have evolved dramatically over time.

Widespan structural systems particularly stadiums, have to be designed correctly following guidelines given to architects. As a result, while the overall form has remained unchanged, the application itself has changed significantly due to modifications and adaptations and technological advancements Stadiums as widespan structures have long been an important part of the cultural and architectural fabric of nations across the world. These massive structures are more than just sports stadiums; they symbolize a country's cultural character, exhibit its technical superiority, and serve as a hub for social and cultural activities.

Therefore, it is important that you read and understand the guidelines before in this context two Cameroonian stadiums are chosen which are: the second generation Ahmadou Ahidjo Stadium and the recently constructed category 4 Olembe Paul Biya Stadium, which stand out as outstanding examples of widespan structures that give tribute to the country's rich past and persistent dedication to modernity. These stadiums are not only serve as settings for sporting events, but also as visible representations of Cameroonian goals and architectural development. Given their importance to society, the importance of widespan design and construction cannot be emphasized. Understanding the history of stadiums, the evolution, design, construction and their structural systems can help plan and create a contemporary stadium with superior designs and utility for widespan stadium designs in other contexts too.

1.2 Problem Statement

There is an easily identifiable gap in the literature concerning the complete investigation of widespan constructions within Cameroonian stadiums.The lack of a comprehensive body of knowledge in this area not only limits the ability of Cameroonian architects and builders to accurately practice in widespan structure design and construction. As a result, the primary issue addressed by this research is to therefore this research aims at bridging this gap in the literature.

1.3 Main Objectives and Research Questions

The core objectives and inquiries of this thesis, address various aspects of widespan stadium structures, their historical context, design considerations, construction challenges, and broader implications for architectural and infrastructural development. The primary objectives of this research are as follows;

1. To examine the historical development of stadium design and construction, from ancient civilizations to modern worldwide standards, with a focus on technical improvements.
2. How has stadium design and construction developed through time, both internationally and in the Cameroonian context, and what technical developments have played a key part in this evolution?
3. To thoroughly explore the two case studies within Cameroonian stadiums, with a particular emphasis on structural systems and architectural features, particularly roof systems.
4. What is the significance of contemporary widespan structures and their impacts on the architecture of Cameroon?
5. To evaluate the cultural value of widespan constructions in Cameroonian stadium design, as well as how they adapt to the local setting, adding to the nation's identity.
6. What cultural relevance do widespan constructions have in Cameroonian stadium design, and how do these structures change to and reflect local cultural and contextual factors?
7. What are the essential structural and architectural components of Cameroonian stadium widespan structures, with a concentration on roof systems?

8. Can an in-depth examination of 2 notable Cameroonian stadiums provide useful technical insights and recommendations for future stadium construction, with a focus on cost-effectiveness, durability, and aesthetic appeal?

1.4 Research Methodology

An analytical Research Methodology approach is used to investigate stadiums as widespan structures in Cameroon, specifically focusing on the second-generation Ahmadou Ahidjo Stadium and the Category 4 Olembe Paul Biya Stadium. It involves a systematic approach to dissect and comprehend the topic by combining both qualitative and quantitative methods, this research will employ surveys, observation, on-site observations, and historical document analysis to gather primary and secondary data.

The qualitative analysis will delve into the cultural significance and contextual adaptability of widespan stadium structures, while quantitative analysis will assess technical aspects such as load-bearing capacity and structural integrity. Ethical considerations will be prioritized throughout the research process, ensuring participant consent and data confidentiality.

The utilization of case studies will provide in-depth insights into architectural and technical components, building techniques, technological advancements, and cultural importance. Despite certain limitations, such as the focus on specific stadiums in Yaoundé, this research methodology aims to offer a holistic and reliable exploration of widespan stadium structures in Cameroon, contributing to the understanding of their historical evolution and contemporary relevance. In the exploration of this the methodology can be explained as follows:

a) Literature Review

- Gain insights into theories and trends spanning historical to contemporary perspectives.
- Collect quantitative data.
- Engage in comprehensive background reading.
- Review existing research within the relevant fields and explore theories applicable to the research topic.
- Provide a comprehensive conclusion summarizing the findings.

b) Data Analysis:

- Develop graphical representations of collected information.
- Present findings through tables and charts.
- Organize data within a structured framework

c) Case Study:

- Identify a selection of standout projects analyzing the structural system, roof and façade

d) Synthesis:

- Summarize overall results and draw generalizations from the findings.

1.5 Limitations

Clearly defining the limitations of the thesis has helped to establish the boundaries of this research hence avoiding generalization of findings while providing direction on what the research did not cover for future research. These limitations will inevitably provide suggestions for potential avenues for future scholars to explore. And are as follows:

It should be noted that there are various types of widespan structures but this thesis primarily focuses on the analysis of stadiums as widespan structures with emphasis on the structural systems of the roofs as the roofing systems are distinctive and unique for each case.

To begin, it is crucial to understand that the structural system classification provided in this study is based on a specific 2 author's methodology and terminology Engel (2007). Structure Systems focusing on structural systems and Hürol & Baydu(2016). The Tectonics of Structural Systems an Architectural Approach to backup.

While this system of classification is comprehensive, it is crucial to recognize that other categorization of structural systems may exist, and their exclusion from this study may result in a more restricted perspective of structural systems.

- This thesis will focus on contemporary structural systems.
- FIFA and UEFA design requirements will be considered as evaluation Criteria.

As they are the unanimously accepted and worldwide used regulations, factors affecting widespan in stadiums will be looked into.

Additionally, the criteria for selecting case studies in this research were based on specific considerations, such stadium categories and historical significance.
There are 5 stadiums according to FIFA standards out of which two stadiums chosen are within the Cameroonian context. These are the Ahmadou Ahdjio stadium and Olembe Paul Biya stadium chosen due to; their difference in time of construction, structural features, and structural system difference in roofs, Architectural era.

It should be highlighting; the second-generation Ahmadou Ahdjio stadium (1976) was renovated over the years to fit to specific standards (new FIFA standards) Ahmadou Ahidjo Stadium (Roure, 2016) and the recently constructed Category 4 Olembe Paul

Biya Stadium this most importantly enables us to see a significant evolution in our context.

These selections were made to represent contrasting categories of stadiums: one built during the 1970s mostly focused on engineering aspects and one conforming to contemporary structure standards by a more elaborate team focusing on adaptation of structural system, technological advancements an aesthetic. It is vital to note that this choice of case studies may limit the generalizability of the findings to stadiums outside these categories or with different historical contexts.

In the literature review, the evolution of stadiums over time has undergone significant changes, and several studies contribute valuable insights to this discourse. The pertinent studies are as follows:

- **Gürer, & Arslan (2020).** *Stadyum Çanağının Yapısı Üzerine Notlar* (*Notes on the Structure of the Stadium Bowl.)* Offers noteworthy observations and analysis concerning the structural aspects of stadium bowls.
- **Jenaway (2013).** Evolution of stadiums: A study in the design and construction of ancient and modern stadia. Contributes to the discourse in "Evolution of Stadiums: A Study in Design," delving into the structural evolution of stadiums from historical origins to their contemporary forms.
- **Miller (2000).** *Structural Roof Systems for Athletic Stadia.* Meticulously examines the diverse roof systems employed in stadium structures.
- **Orhon & Altın (2014).** *Sustainable Roofs and Facades in Sports Buildings.* Provide insights into sustainable practices with their study "Sustainable Roofs and Facades in Sports Buildings," offering a description of sustainable roofs and innovative materials utilized in sports facilities.

- **Sartori & Nienhoff (2013**). *A Blueprint for Successful Stadium.* Offers a comprehensive exploration of the developmental processes integral to creating a successful stadium.

In the studies mentioned above, the general architecture of stadium structures was mostly examined. And changes in this regard are discussed. In this thesis; Stadium structure, roof and façade will be examined.

Another limitation relates to the capacity, span limits of structure and materials of the selected stadiums, as it directly impacts their structural systems. This study primarily focuses on stadiums with varying capacities, and the findings may not be directly applicable to stadiums with significantly different seating capacities.

- The City of Yaoundé is the selected study area due to time constraint in the data collection process. In addition, the structures of this buildings have striking characteristics which are similar and contracts and serve a different architectural purpose and functional purpose due to their capacity and amenities.

1.6 Thesis Outline

The structure of the thesis is designed to systematically present and set the stage for the study, following a logical flow as illustrated in Table 1.1. The format explanation outlines the research process, providing a step-by-step guide for the development of the thesis.

The thesis will begin with an introduction that providing a summary of the study, its aims, objectives, and methods, while also identifying its limits. A detailed literature study will be conducted in Chapter 2 to investigate the concept of structural systems, their major components, features, functions, classification techniques, and their unique significance to stadium design and widespan structures.

Chapter 3 explores the evolution of stadium design and widespan constructions, charting their historical growth and present relevance. Case studies will be analyzed in Chapter 4 to assess individual stadiums based on criteria such as architectural and technical components, building techniques, technology advancements, and cultural importance. Chapter 5 will provide conclusions, summarizing major results, highlighting the importance of the researched stadiums in Cameroon's, analyzing lessons learned, and making recommendations for future stadium roof construction. A thorough list of technical recommendation or guidelines will be included at the end of the thesis. To conclude Chapter 6: Recommendation and Conclusion Conclusions and suggestions for further study are presented.

Table 1.1: Outline of Thesis

INTRODUCTION			
Background	**Aims & Objectives**	**Research question & Methodology**	**Limitation of thesis**

↓

LITERATURE REVIEW/ STRUCTURALSYSTEMS		
STRUCTURAL SYSTEMS	**CLASSIFICATION**	**STADIUMS AS WIDESPAN STRUCTURES**
• Terminology and key concepts • Characteristics • Functions	• Classification methodology • Factors of classifications	• Evolution of stadium design • Contemporary relevance

↓

ANALYSIS CASE STUDIES; AHMADOU AHIDJO STADIUM AND OLEMBE STADIUM		
• selection criteria	• structural analysis • design evaluation	• stadiums as widespan structures

↓

COMPARATIVE ANALYSIS, FINDINGS, AND DISCUSSIONS, IMPLICATIONS AND RECOMMENDATIONS, TECHNICAL RECOOMEDATION

↓

CONCLUSION

1.7 Key definitions

2D (Two-Dimensional): Objects or images that exist in two dimensions, typically represented on a flat surface.

3D (Three-Dimensional): Refers to objects or spaces that have three dimensions: length, width, and height, providing a more realistic representation of the physical world.

Adaptations: Adjustments or modifications made to a design to suit specific requirements or conditions.

Aesthetic: visual and artistic qualities of the outside design of a structure.

Application (in the context of architecture): The use or practical implementation of design concepts and principles.

Architectural Design: The process of creating and planning the layout and form of buildings and structures.

Architectural Features: Distinctive elements or characteristics of a building or structure, often contributing to its aesthetic or functional qualities.

Assemblage: The act of assembling or putting together various components to create a whole architectural structure.

Axial Forces: Forces acting along the axis of a structural element, such as tension or compression.

Axial Forces: Forces that act along the axis of a structural element, such as tension or compression. Axial forces are critical in understanding the behavior of columns, beams, and other load-bearing members.

Beam: A structural member designed primarily to counteract bending moments.

Braces: These components contribute to effectively stiffening the framework.

Building Skin: The exterior surface or envelope of a building, which includes elements like walls, windows, and cladding.

Cantilevers: structural component that is anchored at one end and extends horizontally into space without requiring extra support at its open end.

Cladding: application of one material over another to provide a protective, decorative, or insulating layer.

Column: A structural member primarily designed to resist axial force. Component (of vector): One of several vectors combined to form a resultant vector.

Compression Flanges: The parts of a structural element (such as a beam) that experience compression forces.

Compression forces: internal forces within a structure that act to shorten or compress the material.

Compression: A force that tends to shorten or crush a member or material.

Concentrated load: An external force concentrated at a specific point (point load).

C**oncrete:** A material composed mainly of cement, crushed rock or gravel, sand, and water.

Connection: Joins members to transfer forces or moments from one to another.

Constraint: Limitations or restrictions that influence the design or construction process.

Construction Methods: Techniques and processes used in building or assembling architectural structures.

Construction Processes: The series of steps and activities involved in building a structure.

Construction: The process or act of building or assembling something. In the context of structures, it involves the creation and assembly of various elements to form a complete and functional entity.

Contextual Adaptability: The ability of a design to adjust and respond to the specific context or surroundings.

Cultural Character: The distinctive features and elements that reflect the cultural identity, history, or values associated with a particular society or community. In architecture, cultural character influences design choices and aesthetics.

Cultural Character: The distinctive qualities or characteristics of a design that reflect the culture it belongs to.

Cultural Significance: The importance or meaning of a structure within a cultural context.

Dead load: The weight of a structure or anything permanently attached to it.

Deflection: Vertical deformation under gravity load in beams, for example, while lateral movement under wind or seismic load is called drift.

Distributed load: An external force acting over a length or an area.

Drift: Lateral deflection of a structure due to lateral wind or seismic load.

Durability: The ability of a material, element, or structure to perform its intended function for its required life without the need for replacement or significant repair, subject to normal maintenance.

Dynamic stiffeners resist dynamic loads, which are loads that change rapidly or have a time-dependent nature.

Dynamic: In the context of architecture, it simply means "time-varying."

Elastic limit: The point on a stress/strain graph beyond which material deformation becomes plastic, i.e., remains permanently deformed.

Elastic: A material or structure is elastic if it returns to its original geometry upon unloading.

Elastic/plastic: Materials having both an elastic zone and a plastic zone (e.g., steel).

Energy: The effort required to move an object a certain distance; energy is the result of forces multiplied by distance.

Equilibrium: An object is in equilibrium when the resultant of all acting forces has zero magnitude.

External force: A force acting on an object; these forces are also referred to as applied forces.

Façade; exterior face or front elevation of a building. It is the part of a building that is visible from the outside can include a variety of elements such as windows, doors, architectural details, and surface materials, all contributing to the overall aesthetic and visual appeal of the structure.

Facilities: The physical structures or amenities designed to serve a particular function.

Facility: A building, structure, or place designed for a particular purpose. It can refer to a wide range of structures, including industrial facilities, recreational facilities, or educational facilities.

Fixed connection: A connection resisting axial, shear forces, and bending moments.

Flexible Design: A design approach that allows for adaptability and modification.

Flexure: Bending deformation characterized by increasing curvature.

Force: The result of stress distribution over a prescribed area or an action changing the shape, position, or motion of an object.

Form: The shape, configuration, or visual appearance of a structure.

Form: The shape, configuration, or overall appearance of a structure.

Foundations: There are two basic types: 'shallow,' including pad footing, strip footings, and rafts; and 'deep,' i.e., piles. The choice depends on the underlying strata's strength and stiffness and the load to be carried.

Funicular: The shape of a chain or string suspended from two points under any load.

Girders: Horizontal support beams in a structure, often used to support the load of a floor or roof.

Gravity: The attractive force between objects; each object accelerates based on the force divided by its mass.

Horizontal Forces: Forces acting parallel to the ground or a horizontal plane.

Instability: disruption in loads or geometry leads to substantial displacements, marking a critical limit state

Integrity: The quality of being whole, undivided, or unimpaired. In the context of structures, it refers to the soundness and completeness of the construction, ensuring that all parts are functioning as intended.

Internal force: inherent force within an object, opposing external forces and alternatively termed resisting force.

Joint: Area where two or more ends, surfaces, or edges are attached, categorized by the type of fastener, weld, and method of force transfer.

Joint: The point where two or more structural elements are joined together.

Lacing structural bracing or tying system. This involves the use of additional elements, such as rods or braces, to connect and strengthen structural members, providing stability and resisting lateral forces.

Lateral Buckling: The sideway deformation or bending of a structural element under load, which may affect its stability.

Lateral load resisting system: A structural system designed to resist lateral loads and provide overall stability.

Lateral load: Load, such as wind or earthquake effects, acting in a lateral direction.

Lateral Stability: The ability of a structure to resist sideways loads and remain stable.

Lightweight: Of relatively low weight, making it easy to carry, move, or handle.

Linear: Structural or material behavior is linear if deformation is directly proportional to loading.

Live load: Any load not permanently attached to the structure.

Load effect: Forces, stresses, and deformations produced in a structural component by applied loads.

Load: Force or action resulting from building materials' weight, occupants and their possessions, environmental effects, differential movement, or restrained dimensional changes.

Members: Individual structural components that make up a larger structure, such as beams, columns, or trusses.

Modifications: Changes or alterations made to a design or structure.

Modular structure: Construction approach where a building or structure is composed of individual modules or components. These modules are prefabricated or preassembled in a controlled environment (like a factory) and then transported to the construction site for assembly.

Moment: A force causing rotation without translation; defined as force time’s lever

One-Dimensional: Relating to measurements along a single axis, often used in the context of linear elements.

Overlapping: The act of extending over and covering part of the same space as something else. In structures, overlapping elements may provide reinforcement or support.

Permanent load: A load where variations over time are rare or of small magnitude; all other loads are variable loads.

Pin connection: Transfers axial and shear forces but no bending moment.

Pin support: Resists axial and shear forces but no bending moment.

Plastic: Material may be elastic or plastic; plastic deformation remains after the load is removed.

Pressure: Similar to stress, force intensity at a point, acting on the surface of an object.

Pressures: Forces applied uniformly over a surface, often measured per unit area. In structural terms, this could refer to external loads or stresses acting on a structure.

Reaction: The response of a structure to resist applied load.

Rehabilitation: restoring or renovating a building, structure, or system to a good state of repair. Involves repairing or updating existing elements while preserving the original character or functionality.

Rehabilitation: process of restoring or upgrading a building or infrastructure to a functional and often improved state.

Renovation making significant changes or improvements to the existing structure to enhance its appearance, functionality, or both.

Required strength: Forces, stresses, and deformations acting on the structural component, determined by structural analysis.

Rigid: Having a high resistance to deformation or flexibility.

Roller support: In two dimensions, restrains one translation degree of freedom.

Roofing Systems: The various components and structures used to create a building's roof.

Rotation: The act or process of turning around an axis.

Shear: A sliding force pushing and pulling in opposite directions.

Skeletal Structure: The internal framework that provides the basic support for a building or other structure. It typically includes the primary load-bearing elements.

Skeleton: The framework or internal structure of a building or object. It forms the essential support system for the rest of the structure.

Skeleton: The primary load-bearing framework or structure of a building.

Space: The physical extent in which objects exist and events occur. In architecture, consideration of space involves how it is organized and utilized within a structure.

Span: The distance between the centers of supports for a beam or truss.

Stability: A condition reached in the loading of a structural component, frame, or structure where a slight disturbance does not produce large displacements.

Stability: The ability of a structure to maintain its equilibrium or resist being displaced or overturned. A stable structure can withstand external forces without collapsing.

Stability: The ability of a structure to maintain equilibrium and resist deformation or collapse.

Standards: Established criteria or guidelines used to ensure quality and consistency in design and construction.

Static loads: that act on a structure in a stable and unchanging manner over time.

Static stiffeners; resist static loads, which are loads that act gradually and do not change with time.

Stiffness: The resistance of a structure to deformation or deflection.

Strength: The ability of a material or structure to withstand applied forces.

Strength: The capacity of a material to resist breaking.

Stress: Force per unit area caused by axial force, moment, shear, or torsion.

Structural component: A member, connector, connecting element, or assemblage.

Structural Components: Individual elements that make up the structure of a building.

Structural Loads: forces, deformations, or other actions that are applied to a structure.

Structural system: An assemblage of load-carrying components joined together to provide interaction or interdependence.

Structural Systems: The organization and arrangement of structural elements within a building.

Structure: A composition of elements defining form and resisting applied loads.

Technical Breakthroughs: Significant advancements or innovations in the technical aspects of architecture.

Technological Advancements: Progress in the use of technology within the field of architecture.

Torsion: A twisting moment.

Transmission: The process of conveying or transferring something from one place, person, or thing to another. In the context of structures, it may refer to the transmission of forces or loads through various components.

Truss: A linear support system consisting of triangular panels usually with pin joints.

Uneven load distribution: In a connection, a condition where the load is not distributed through the cross section of connected elements in a readily determinable manner.

Vibration: The cyclic motion of an object.

Visual aesthetics: perceived beauty, appeal, or attractiveness of a visual design or composition.

Wall: A vertical element resisting load and defining space; shear walls also resist lateral loads.

X-Bracing: A structural bracing system where diagonal members form an "X" shape to provide lateral stability and resist forces such as wind or seismic loads.

Chapter 2

STRUCTURAL SYSTEMS

Structural systems chapter focuses in the context of widespan structures, concentrating on their definition, important components, characteristics, functions, classifications, and significance in widespan in stadium architecture.

According to Azizi (2015), the past building structure was hidden and covered, with no traces of structure visible inside or outside the buildings. However, with the development of science and technology, the role and position of structures have changed hence making structural systems play a vital role in ensuring the stability, integrity, and functionality of widespan structures like stadiums. Throughout history and prehistory, buildings have consistently relied on various structural systems for their formation and existence.

According to Pershakov et al. (2020), in the context of construction, the term "structure" describes the overall design and composition of a building, which is made up of a number of interrelated structural components that guarantee the building's strength, stiffness, and stability.

Structure is the underlying, physical or intangible concept of structure or framework of recognizable elements These elements include vertical components such as columns, walls, cores, and diaphragms, as well as horizontal elements such as slabs, roofs, beams, and lateral bracing systems.

Monroy (2021) defines structures as; "the skeleton" of the building in question, responsible for supporting all loads, both external and those generated by its own weight, without deforming or generating any damage to the people who may inhabit it. Hence we have structural systems that form parts of the building structures.

Sawant (2015) agree that Structures are components on which structural systems are constructed on. Structural systems are the ones factors of creation which can shape a part of a building’s form both to assist the complete constructing or different constructed assets, including a bridge or tunnel or simply part of it.

Furthermore, Falahat et al., (2007) defines structures as ‘the design of forms with different materials that provides various load bearing on horizontal parts or the roof.’As a result, architects, engineers, and designers looking to construct creative and efficient widespan stadium designs must have a thorough grasp of these systems and understand them as structure is a technical requirement. A building's structural system is an important part of its design and functioning. It includes the placement and configuration of all; structural components, materials, and elements that work together to carry loads and assure the structure's stability and integrity.

The selection of an appropriate structural system becomes even more crucial in the context of widespan buildings, which often comprise widespan roofs, bridges, and other expansive architectural forms, due to the specific constraints provided by such designs.

2.1 Structural System Definition

‘’ Structure is the primary and solitary instrument for generating form and space in architecture. Owing to this function, structure becomes essential means of shaping the material environment of man ‘’ (Engel, 1968, p.19).

Buildings are an assemblage method of various systems and structural systems so that they support and transmit applied loads safely to the ground without exceeding the allowable stresses in the members.

“Structures in nature and technique essentially serve the function of sustaining physical form. Preservation of form is perquisite to the performance of the systems; engine / house / tree / man + without structure no system.” (Engel, 1968, p. 19)

Structural systems hence are the elements of construction that creates a portion of a building's form, either to support the entire structure or other developed assets, such as a bridge or tunnel, or only a part of it. Any form consists of a structure (beams, columns, slabs) and non-structural (doors, partition walls, stairs) elements hence without no structure there no building. Structural systems can be classified into three categories: low-rise, high-rise, and widespan.

2.1.1 Key Terminology

Vibæk and Cinark (2011) explains that a considerable amount of the vocabulary used in architectural design and especially structural language can seem unfamiliar many terms are closely connected to each other and are gathered around a central key concepts or themes of structures.

Before going into the complex nature of structural systems, it is critical to define important concepts that will serve as the foundation of our discussion which will serve as a glossary. And also Engel's book of 'Structure system' will be used as a reference to address and define these terminologies. This vocabulary are elements of languages used and are connected to structural systems.

2.2 Key Components of a Structural System

The structural system is made up of many structural elements; Vertical force resisting elements, floor systems, and horizontal force resisting elements are the three subsystems of structural systems.

Structural members differ in numerous aspects, including material, size, and behavior. Foundations, floors, walls, beams, columns, roof, stairs, and other structural components contribute to the overall integrity and functionality of a building's structural systems (Figure 2.1).

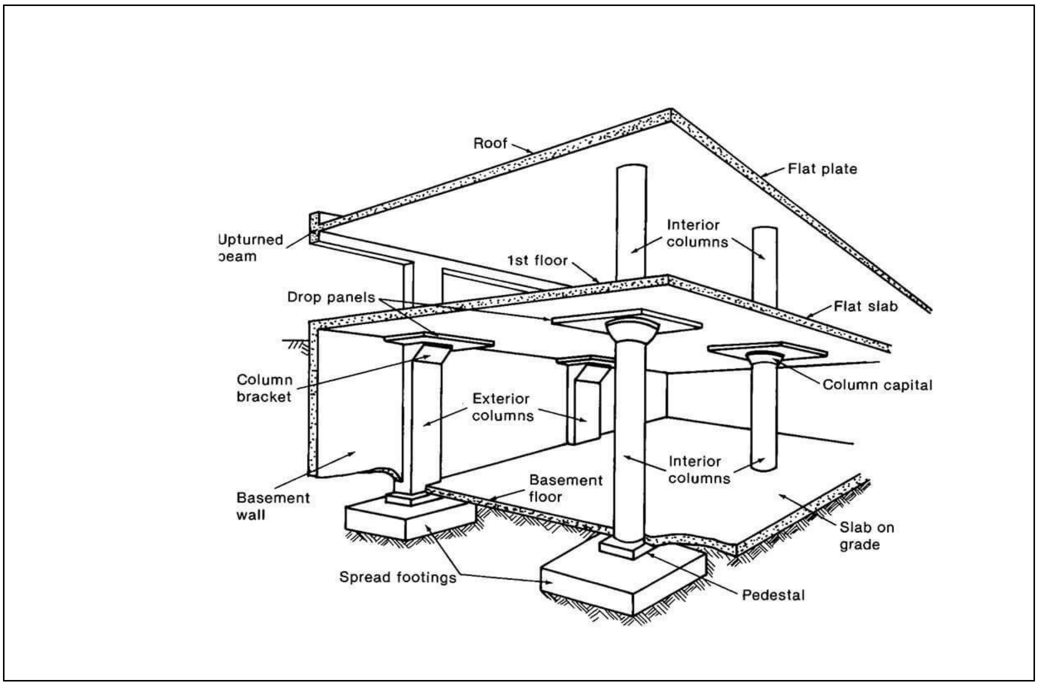


Figure 2.1: Building Components (URL 1, 2023)

These components are based on their roles and their functions within the system and can be categorized as; Primary load bearing components, secondary load bearing components, connections, support systems and materials (Table 2.1).

Table 2.1: Structural Systems Key Components (Mangaleu Toukam, 2023)

KEY COMPONENTS OF STRUCTURAL SYSTEM	
COMPONENT	**ELEMENT**
LOAD BEARING COMPONENTS	• Walls • Beam • Columns • Foundation • Slabs • Braces • Trusses
CONNECTION SYSTEMS	• Riveted • Bolted • Welded • Pinned
SUPPORTS	• Roller • Pined • Fixed • Simple

Primary components are the main load bearing elements, secondary components support and enhance the primary ones, connections ensure efficient load transfer, and support systems provide stability and support to the entire structure, materials are the substances used to build various components of the structure and explained as follows:

2.2.1 Load Bearing Components

According to Hossain (2021), the principal structural components that carry load are: walls, beams, columns, foundations, slab, braces, and trusses. Load bearing components transfers loads to the foundations. This component can be divided into primary and secondary load. The load bearing structures and it performs a range of functions from supporting loads, subdividing the space, providing thermal and acoustic insulation to structure, etc. Primary load bearing and Secondary Load-Bearing Components.

2.2.1.1 Walls

Hossain (2021) define a wall as; a structural element of a building that various functions, including; providing support, dividing spaces, and offering protection. It can be classified into different types based on its function and construction materials.

a) A load-bearing wall or bearing wall is an active structural element that bears the weight of the elements above it and conducts the weight to a foundation structure. It is typically constructed using materials such as concrete, block, or brick.

b) Curtain wall is a non-load-bearing wall that provides no significant structural support beyond bearing its own materials or conducting loads to a bearing wall.

Understanding the concept of walls is crucial in analyzing the load-bearing structures of a building. This analysis process involves determining the function of each structural element, calculating the forces acting on them, and identifying the forces transmitted by these elements.

2.2.1.2 Beams

The Editors of Encyclopedia Britannica (2023) define beams as a horizontal member spanning an opening and carrying a load that may be a brick or stone wall above the opening, in which case the beam is often called a lintel (post-and-lintel system). In a more structural way Beam structures are slender bodies that are loaded in the most general, three-dimensional, case by axial and shear forces as well as bending and torsion moments (D’Ottavio and Polit 2017, pp. 91-140).

According to Nandy (2023), beam is one kind of structural building block that transfers loads compelled along its axis to its supports like walls, columns, foundation, and much more. Bending is generally known as the mode of beam deflection. Types of beams can be classified into multiple types based on the type of support it provides, the load conditions, the cross-sectional shape, or the type of material it is made of. some examples of common beams are ; single double overhanging beam , simply supported beam, fixed end beam , continuous beam , cantilever beam , concrete beam, I beam , C beam , T beam.

2.2.1.3 Columns

Column is one of the most important elements in architecture and interior design that we can see through the history till now in different ways of expression, navigating between structural, functional, esthetics and symbolic need. (Shafiq 2013)

A structural column is an element which through compression, transfers the load from above lying structures to elements below i.e. an element subjected to axial loading (Christensen & Roug, 2014, p.1).

2.2.1.4 Foundations

Foundations are part of a structural system that supports and anchors the superstructure of a building and transmits its loads directly to the earth. (The Editors of Encyclopedia Britannica, 2009).

Magar et al. (2020) adds that foundations are an essential component of construction activities as they provide support and stability to structures. They are the first step in building any superstructure. Different types of foundations and footings are used based on specific requirements and weather conditions.

Foundations can be divided into two categories; deep and shallow foundations and each of these is further subdivided into several categories based on the specific type of structure to be implemented (Table 2.2).

Table 2.2: Categories Of Foundations (according to Magar et al. (2020))

Type of foundation	Category	Sub Category
Shallow foundation	Spread footing foundation	- Pad foundation - Strip foundation
	Combined foundation	- Rectangular foundation - Trapezoidal foundation - Strap foundation
	Mat foundation	
Deep foundation	Pile foundation Pier foundation Compensated foundation Caisson Foundation	

2.2.1.5 Slabs

Slabs are designed to distribute loads, such as the weight of the building itself, furniture, people, and other items, evenly across its surface and transfer those loads to the supporting columns, walls, or beams. They are an essential part of building construction and provide the foundation for various functional spaces within a structure.

A slab can be conceptualized as a shallow, laterally extended beam, spanning either between beams of normal depth or directly between walls.

To enhance its strength for spanning larger distances, simplifying assumptions can be applied with secondary bands in one or two ways (Mainstone, 1998). Slabs can be categorized into three types: simple, ribbed, or waffle. A ribbed slab is reinforced in one way, while a waffle slab is reinforced in two ways. The spanning capacity of a simple slab is up to 7 meters, a waffle slab spans between 7-15 meters, and a ribbed slab spans between 4-9 meters.

2.2.1.6 Bracing Systems

According to Patil and Sangle (2015) , bracing refers to the use of structural elements to provide additional support and stability to a building or structure. It is used to resist lateral forces such as wind or seismic activity, which can cause deformation or collapse.

Bracing systems ensures the enduring structural integrity and stability of buildings and bridges throughout their construction and lifespan. Different types of bracing systems exist, including diagonal braced frames, chevron braced frames, and eccentrically braced frames. Each system has its own characteristics, mechanisms, and improvements (Patil and Sangle ,2015, pp.282-305.).

2.2.1.7 Trusses

'*Trusses are referred to as structures for transferring loads from buildings to ground, which are able to simultaneously transfer horizontal and vertical loads.'*(Altan & Zamani, 2021).

Trusses are simple structures that, commonly used in homes and bridges, with stability provided by knots on truss plates. They are mostly used due to their low weight, high strength, and ability to cover large areas without the need for columns, while also possessing a simple and aesthetically pleasing triangular shape.

Trusses can be classified based on their structure and design each type of truss is used in different settings, such as sports stadiums, bridges, commercial buildings, and farm structures as follows;

- Simple trusses are triangular grids and are commonly used in gables. Examples include the King post truss.
- Compound trusses are created by combining simple trusses.
- Space trusses have a three-dimensional structure and are used in various applications.
- Standard trusses are commonly used and have a simple structure. Examples include commercial roof trusses, farm trusses, and attic trusses.

2.2.2 Connection Systems

A structural system is configured in such a manner that its three components intersect to establish connections. Each connection is specifically crafted to either transfer or support a particular type of load.

According to McMahon (2023), structural connections refer to points in a structure where components are joined together, presenting potential weak points that necessitate careful consideration in connection selection for the intended task.The design of connections plays a pivotal role in structural detailing, significantly influencing the behavior of systems.

As emphasized by Ribeiro et al. (2022), the design of elements and connections must occur concurrently and iteratively due to their interconnected impact on structural performance. Connectors serve to unite structural components, providing opportunities to transfer loads within the structure, thereby enhancing strength and support in the final construction. Connections become essential in various scenarios, including:

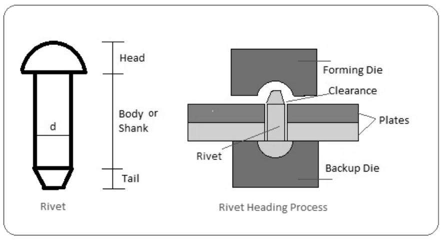
- Heavy loads and wider spans
- Various structural elements that need to be connected or joined at the end

2.2.2.1 Riveted Connections

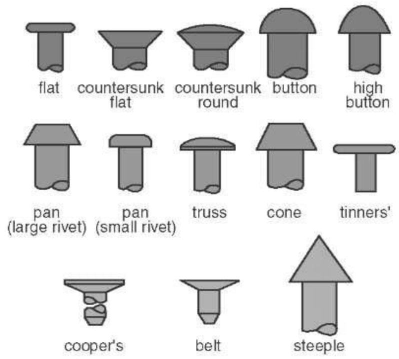
Francken (1910) defines rivet as a kind of nail with a cylindrical section and usually a round head, used to assemble sheets, and its end has been flattened and widened afterwards to form a second head “Le rivet est une sorte de clou à section cylindrique et à tête ordinairement ronde qui sert à assembler les tôles et dont l’extrémité a été aplatie et élargie après coup de façon à former une seconde tête.”.

The rivet is put through the rivet hole and a second rivet head is formed - the forged head - to pull the connecting elements towards each other, (figure 2.2).

Riveting is a specific technique used to join metal components. Riveting is the traditional method of joining steel members . This process involves inserting malleable metal pins, known as rivets (Figure 2.2) , into holes in the pieces to be joined. A head is then formed at one end of the rivet to secure the metal pieces together and prevent them from separating. The shank of the rivet comprises the length that extends through the various parts to be joined, with an additional length to allow for the creation of a second head at the opposite end.



Riveted joint (URL 2, 2023)



Types of rivets joints (URL 2, 2023)

Figure 2.2: Riveted Connection

Rivets are typically categorized into the following types: a)Hot-driven rivets: These are rivets that are installed under high-temperature conditions. b)Shop rivets: These rivets are installed in a workshop or manufacturing facility. c)Field rivets: These are rivets installed on-site or in the field during construction or assembly.) Cold-driven rivets: less common because it requires substantial pressure to form the head at room temperature.

2.2.2.2 Bolted Connections

A bolt connection serves various purposes, including functioning as end connections in both tension and compression members (Figure 2.3). Additionally, bolts can secure column bases, act as separators for purlins and beams in foundations, and play a crucial role in holding structural elements in position. Compared to rivets and pins, bolts offer several advantages: (a) they expedite the erection of structures, (b) require less skilled labor for installation, and (c) generally entail a lower overall cost for the connection.

However, according to BrainKart (2022) bolted connections come with certain drawbacks: (a) the cost of materials is higher, approximately double that of rivets, (b) the tensile strength of bolts may be compromised due to reduced thread root area and stress concentration, (c) loose-fit bolts typically experience strength reduction, and (d) bolts may loosen under vibrational forces.

Furthermore, bolted connections can be categorized based on various criteria, including: (a) resultant forces transferred, (b) type of force, and (c) force mechanism.

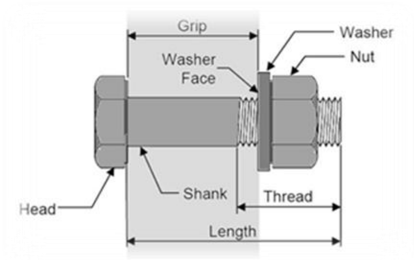
<table>
<tr><td>
</td><td></td></tr>
<tr><td>Bolt connection (URL 4,2023)</td><td>Bolt connection of steel fin plate (URL5 , 2023)</td></tr>
</table>

Figure 2.3: Bolted Connection

2.2.2.3 Welded Connections

Welding is the process of joining metals by heating the base materials to their melting points, with or without the addition of filler metals Bala (2022).

Ohi and Lin (1998) states that welded connections widely used in beam to column connection Similar to a bolt connection, a welded connection employs welding instead of bolts for fastening. However, the application of loads on the beam in this connection introduces eccentricities in the weld pattern, resulting in the generation of stress. Consequently, similar to welded framed connections, it is imperative to consider and address these stresses.

El-Reedy (2017), also agrees that connections rely on welds as the primary means of joining components together (Figure 2.4) .Welds can be categorized based on:

a) Types of welds, including; groove, fillet, plug, and slot welds.

b) Positions of the welds, such as; horizontal, vertical, overhead, and flat welds.

c) Types of joints, encompassing; butt, lap, corner, edge, and tee joints.

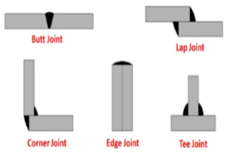
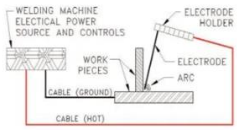
		
Basic Types of welding joints (URL 6,2023)	Basic welding circuit Bala (2022).	Example of welding connection in a building (URL 7,2023)

Figure 2.4: Welded Connections.

2.2.2.4 Pinned/ Hinge Connections

Pinned connections or hinge joints is a type of connection that allows rotational movement between two structural members (figure 2.5). These types of connections are designed to transmit axial load while allowing free rotation. Conde et al. (2023) assert that connections are widely employed in civil and mechanical engineering to directly establish a 2D simple support (external restraint) or a perfect hinge (internal constraint).

This type of connection typically involves a central steel rod, referred to as the pin, positioned perpendicular to the applied load. Multiple plates, known as lugs, are integral to the connection, serving either as supports or as components supported by the pin. Circular holes in these plates facilitate the insertion of the pin, forming the connection (Conde et al., 2023).

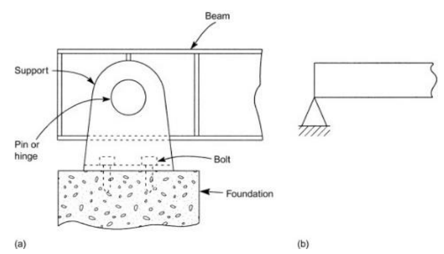
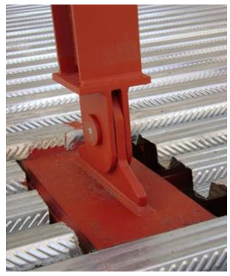
	
Idealization of a pinned support. (Megson, 2019)	Example of a pinned connection in a building (conde et al., 2023)

Figure 2.5: Pinned / Hinged Connection

Pinned or hinge connections are found in almost all trusses. They can be articulated or hidden from view; they can be very expressive or subtle.

2.2.3 Supports

Support and Connection Types (2019) explains that three common types of connections that links a built structure to its foundation; roller, pinned, and fixed supports. Additionally, there is a fourth type, less frequently encountered in building structures, known as a simple support. Supports can be positioned at various point along the structural element. The type of support connection determines what kind of load the support can withstand. Additionally, the kind of support also has a significant impact on the load bearing capability of each unit, and hence the system.

2.2.3.1 Roller Support

According to Support and Connection Types (2019) Roller supports have the freedom to move and rotate on the surface they rest upon, whether it's horizontal, vertical, or sloped at any angle as there is nothing constraining it. The resulting force always acts as a single force, perpendicular to and away from the surface (Figure 2.6).

Carigliano (2023) highlights that roller supports are typically found at the end of lengthy bridges, enabling the bridge structure to adjust to temperature variations. If the structure were fixed in place, the expansion forces could potentially damage the supports at the ends. Roller supports may also be implemented as rubber bearings, rockers, or a set of gears, designed to permit a controlled amount of lateral movement.

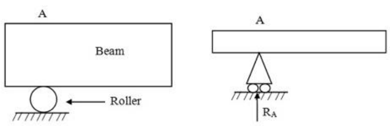
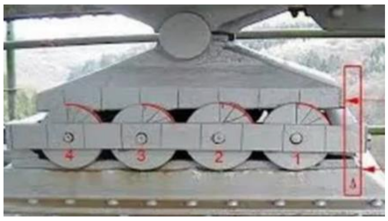
	
Roller support(URL 8,2023)	Example of roller support (URL 8,2023)

Figure 2.6: Roller Support

2.2.3.2 Pinned/ Hinge Support

Williams (2009) states that A pin support allows rotation about any axis but prevents movement in the horizontal and vertical directions. (I.e. it resists horizontal and vertical forces but not a moment) Pinned supports can be used on trusses. By connecting numerous members using hinge connections, the members will press against each other, creating an axial force within the member. The advantage of this is that the members contain no internal moment forces and may be constructed only on their axial force. Its idealized representation and reactions are shown in (Figure 2.7).

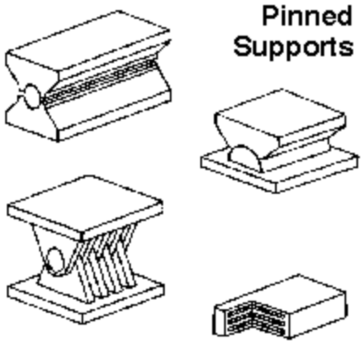
	
Types of pinned supports (URL 9,2023)	Example of a pinned support Sydney Harbor bridge (URL 10,2023)

Figure 2.7: Pinned Or Hinged Support.

2.2.3.3 Fixed Support

Fixed supports are also called rigid supports (Figure 2.8). Is the most inflexible form of support or connection, effectively restraining the structural member in all possible translations and rotations, meaning it cannot move or rotate in any direction. A common example illustrating this concept is a concrete pole or column, which remains completely immobile, resistant to twisting, turning, or shifting in any way at the connection point Carigliano (2023).

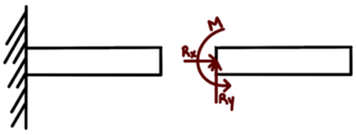
	
Fixed support (URL 10, 2020)	Example of a fixed support (URL 10, 2020)

Figure 2.8: Fixed Support

2.2.3.4 Simple Support

This type of support is used where the structural member has to rest on the external structure (figure 2.9). These types of support are not used widely in daily life. It is very similar to the roller support. They cannot resist lateral movement and moment like roller supports. They only resist vertical movement of support with the help of gravity. Simple supports aren't widely used in real-life structures unless the engineer can be sure that the member will not translate; otherwise, they run the risk of the member simply falling off the support Carigliano (2023).

	
Simple support (URL 11,2023)	Example of a simple support (URL 11,2023)

Figure 2.9: Simple Support

2.3 Structural Response to Dynamic Forces

Structures go through degradation and the primary factor contributing to structural degradation is the way in which they react to motion or force inputted. Most structural systems will be subjected to some form of dynamic loading during their lifetime. The sources of these loads are many and varied (Anderson and Naeim, 2012).

The term "Dynamic Response of Structures" describes how a structure behaves and functions when subjected to dynamic loading circumstances, such earthquakes or other outside forces.

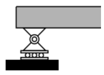
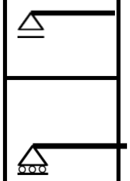
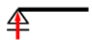
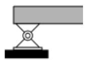
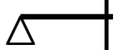
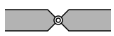
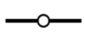
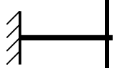
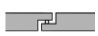
The response of a support might be either a force acting on the support or a restraining end moment arising from the inability to move. The external forces acting on the structure and the support reactions are in balance (Table 2.3).

In especially in earthquake and wind engineering, dynamic response precisely assesses how structures behave under dynamic stresses, improving safety, optimizing design, and lowering the chance of failures.

To aid structural analysis, it is often required to simplify and idealize the behavior of a support and predict the response of structures (Libretexts, 2023). While studying the behavior of connections or supports, factors of friction and mass are typically overlooked. It is critical to understand that all graphical representations of supports are simplified versions of genuine physical connections. It is critical to deliberately seek out and compare idealized models to their real-world equivalents. The table below illustrates the forces and moments that are present or operating at each form of support.

When precisely predicted, these representative forces and moments are anticipated to achieve equilibrium inside each structural part.

Table 2.3: Revised Support Reactions (Sakimoto, 1991, pp 36-40).

Name	**Schematic diagram**	**figure**	**movement**			**Reaction**	
			Vertical	**Horizontal**	**Rotation (Moment)**	**Direction**	**Number**
Roller or simple (movable) support			No	Yes	Yes		1
Pinned or hinged support			No	No	Yes		2
Middle hinge (for axial member)			No	No	Yes		2
Fixed support			No	No	No		3
Middle hinge (for beam member)			No	Yes	No		2

2.4 Characteristics of Structural Systems

According to Sawant (2023b), Structural elements possess the ability to withstand the forces acting on a given form and transmit them to the ground. For simplified analysis, these elements are categorized into One-Dimensional components such as beams, columns, and trusses, as well as Two-Dimensional elements like slabs and plates. When these structural elements are assembled, they form a structural system.

A number of essential qualities describe structural systems, and these characteristics are crucial in the design and construction of solid and safe buildings. Among these features are load distribution and capacity, flexibility, Load resisting.

2.4.1 Load Distribution and Capacity

Structural load refers to the forces and pressures that act on a structure, such as a building, which can affect its stability and integrity (Figure 2.10). Structural loads can be broadly classified into four groups: dead loads, live loads, impact loads, and environmental loads (Libretexts, 2023b).

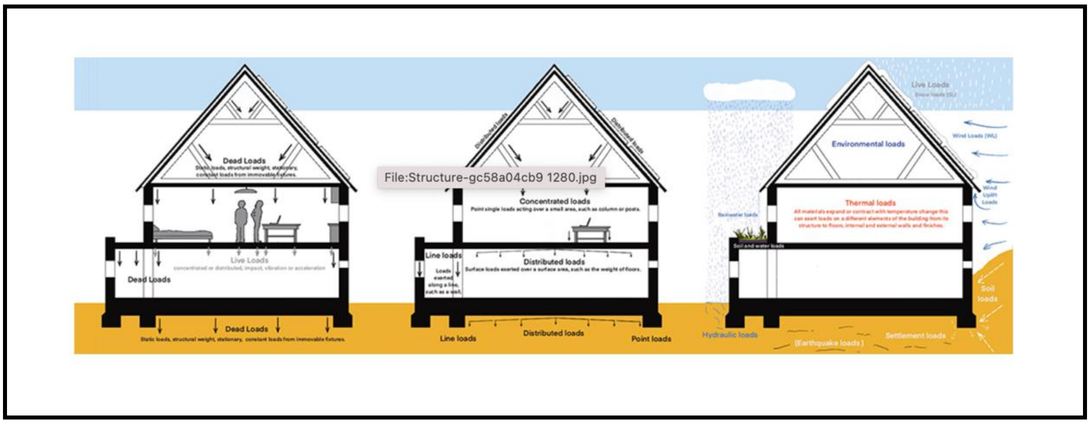


Figure 2.10: Types of Structural Load

Load distribution is the process of distributing the weight or force of the structure evenly across all its components (Figure 2.11). Distributing load is crucial to ensure that each component can bear its designated load without exerting excessive pressure on any specific area. This practice is vital for enabling the structure to withstand various forces and maintain stability.

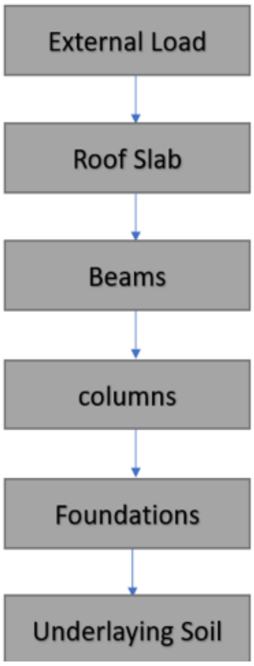
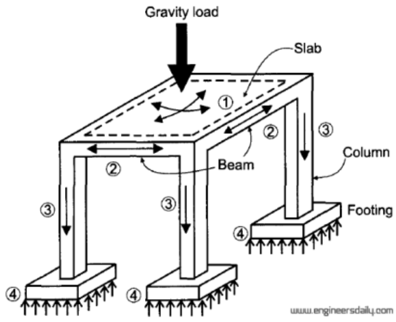
	
Load transfer mechanism in a system	Load transfer in a building (URL 11,2023)

Figure 2.11: Load Distribution in A Building

Load bearing capacity should be considered and on the other hand determines the ability of a structure to support its own weight and any additional loads placed upon it.

2.4.2 Flexibility

According to Lozano et al. (2019), the flexible structural system (FSS) emerges as a solution to the attempt of obtaining a structural system that supports a great adaptation to multiple constraints of volumetric design, as well as the possibility of making easy and affordable changes in the structure of a building, throughout its life (Figure 2.12). In the traditional construction, the structural system has been conceived as something totally static and invariable in time, throughout the life of a building (Lozano et al., 2019).

The most important physical property of earthquake-safe buildings and structures is flexibility whereas on the other hand rigid structures would crumble and collapse during the movement caused by an earthquake meaning flexible structures can significantly reduce the amount of damage cause by quakes.

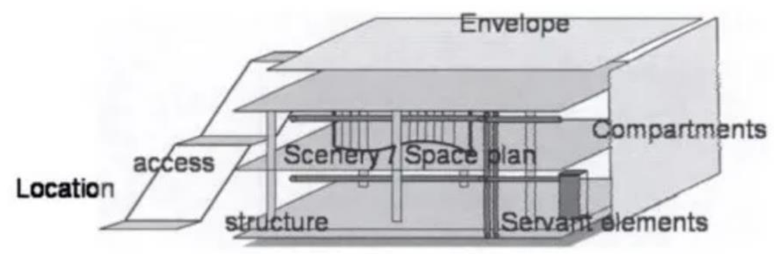


Figure 2.12: Flexible Building Layers (URL 12,2023)

2.4.3 Load Resisting Mechanisms

A typical lateral load-resisting system consists of horizontal and vertical elements connected together so as to transfer lateral forces from the top of a building to the foundations. Forces caused by wind or seismic effects, acting on the east and west walls of the building, are transferred to the horizontally Williams, (2016).

2.5 Functions of Structural System

The prime function structural systems is to transmit safely the loads from the upper portion, or superstructure, of the building to the foundations and the ground (Merritt & Ambrose, 1990).

Furthermore, Singh (2023) states some key reasons why structures are important in construction:

a) Safety: ensures the safety of users. Structural systems endure numerous factors such as gravity, wind, earthquakes, and snow loads. A well-designed building transfers these stresses to the ground, preventing collapses or failures that might jeopardize people's lives.

b) Stability: provides stability to structures and infrastructure. Withstand lateral loads, such as wind or seismic pressures, by transmitting them to the ground using a mix of materials, forms, and connections. Stability guarantees that constructions stay upright and secure under normal and extraordinary situations.

c) Load-bearing capacity: Structural systems are responsible for carrying and distributing loads such as the weight of the structure itself, furniture, people, and environmental loads such as snow or rain. A well designed structural system guarantees that loads are securely transported to the foundation without generating excessive deformation or collapse.

d) Durability: Structural system helps to extend the life and durability of construction projects.

e) Functionality: Allow buildings and infrastructure to function and serve their purpose. They may accommodate a variety of architectural characteristics such as open areas, wide spans, and floor layouts. A well-designed structure maximizes space usage, allowing for efficient and flexible use.

f) Aesthetic appeal: Arches, domes, or other building forms, add to the visual appeal and character of a construction project. They have the ability to improve the overall design and create unforgettable landmarks.

2.6 Structural Materials

A structural material comprises of any substance suitable for construction purposes, ranging from traditional materials like wood, concrete, steel, and cement to aggregates, bricks, clay, and metals, among others. Throughout history, construction relied on basic elements such as bricks, wood, or straw.

Material selection plays a pivotal role in the design process, as highlighted by Wienand (2008).

Ambrose (1993) Highlighted that material selection is influenced by various factors that align with the fundamental design approach. The choice is guided by essential properties such as form, weight, durability, cost, availability, appearance, workability, and strength. These properties, defining the nature of structural materials, are predominantly marked by their rigidity, strength, toughness, and their reactions to environmental elements such as temperature and humidity.

This thesis specifically focuses on stone, timber, concrete, and steel, exploring their properties and evaluating their suitability within the context of critical properties mentioned above.

2.6.1 Stone

Stones are essential used in traditional building construction (Figure 2.13). It is a natural material which can be found in closed environment. It also holds a significant contribution to heritage preservation. Stones are widely used in the world and Greek architecture is an example where around 3500 years they constructed temples and monuments. Stones are natural materials which can be found easily in close environment. There a various types of stone and some of them marbles, sandstones, granite, slatestone and limestone etc. (Raju & Ravindhar, 2021).

The main ‘-advantage of stone is eco-friendly to the environment and provides comfort to the occupants furthermore less pollution (Raju & Ravindhar, 2021).

It is found in most regions of the world exists in various forms alongside materials like mud or timber. It can be shaped into any desired form, particularly when suitable blocks are not readily available. While its hardness and internal composition can vary significantly (Mainstone, 1998).

Additionally natural stones are known for their exceptional durability Stone in the past decades has been the most widely used building material, highly tied to the natural environment. Masonry structures frequently incorporate stone as a primary building material. Stone against the other natural materials (wood, clay, mud, grass, branches, ice, etc.) has excellent mechanical properties such as strength in time (Myriounis et al., 2015).

Figure 2.13: Othello Castle Famagusta (Mangaleu Toukam,2023).

2.6.2 Timber

Timber is one of the oldest known materials used in construction. It has a very high Strength to weight ratio capable of transferring both tension and compression forces and is naturally suitable as a flexural member (Figure 2.14).

Timber is a material that is used for a variety of structural forms such as beams, columns, trusses, girders, and is also used in building systems such as piles, deck members, and railway sleepers and in formwork for concrete (Noh, 2016).

Timber (Indiamart, 2014)

Figure 2.14: Timber

The technological advancements in timber, such as glue lamination and specialized techniques, have overcome previous size and form limitations. These innovations have enabled the creation of larger structures through improved jointing methods (Ambrose, 1993).

When selecting timber as a structural material, considerations such as local availability and cost play crucial roles. Due to its widespread availability, cost-effectiveness, and ease of working, timber is often chosen as the preferred structural material, unless specific limitations need to be addressed (Ambrose, 1993).Timber structures can be highly durable when properly treated, detailed and built (Figure 2.15). Examples of this are seen in many historic buildings all around the world (Noh, 2016) .

Timber building (MacDonald , 2018)

Figure 2.15: Example of Timber Building

2.6.3 Concrete

After the industrial revolution. Materials developed very fast accordingly starting from the 18th century with the use of concrete as building material. Concrete is a cement-based composite generally obtained by mixing a Portland cement binder, water, aggregates, and other additives. The aggregates mayor may not be used; they generally comprise sand and gravel. Examples of additives include pozzolanic materials such as fly ash and silica fume, or simply very fine sand or clay (Naaman, 2001).

There are various forms of structural concrete (Figure 2.16). These various types of concrete could be used for the same purpose depending on the structural goal aimed to achieve hence requiring an adequate selection of the form of concrete.

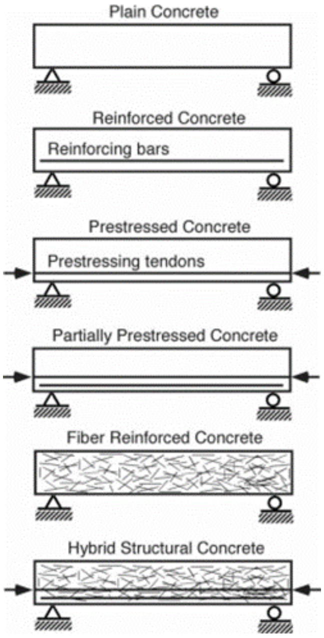


Figure 2.16: Forms of Structural Concrete (Naaman, 2001)

Reinforced concrete is extensively used in the construction industry (Figure 2.17). This concrete type involves embedding steel in a manner that enables the collaboration of the two materials in resisting forces. The reinforcing steel, whether in the form of rods, bars, or mesh, plays a vital role in absorbing tensile, shear, and occasionally compressive stresses in a concrete structure.

Figure 2.17: Reinforced Concrete Building National Theater (Naaman, 2001).

Reinforced concrete is known for possessing both tensile and compressive strength, making it a versatile material suitable for various structural elements.

As Macdonald (1994) points out, it is well-suited for structures carrying bending forces, demonstrating strength while offering flexibility. Its application extends to serving as a skeleton frame for structures requiring robust materials and as a choice for constructing long-span and tall, multistory buildings. Considered a form of composite construction, reinforced concrete incorporates steel bars within the concrete matrix.

This combination renders it highly flexible, allowing it to support its own weight across considerable distances without experiencing significant deformation. However, the use of substantial formwork is essential to mold the concrete into the desired shape until it attains sufficient hardness to bear loads. This requirement for formwork represents a significant limitation on the economical adoption of certain forms (Ambrose, 1993).

2.6.4 Steel

Steel is considered one of the strongest and most enduring construction materials on the planet. Its impressively high strength-to-weight ratio, not found in many other materials, make it a choice solution for simple to complex construction work (Izzie, 2022).

The development of steel can be traced back 4000 years to the beginning of the Iron Age. Proving to be harder and stronger than bronze, which had previously been the most widely used metal, iron began to displace bronze in weaponry and tools (Bell, 2020). Steel is an alloy of iron (metal) and carbon (non-metal) where iron is a primary constituent and carbon is an alloying element. Iron having less than 2 % carbon content by weight is called steel and having more than 2 % of carbon is called cast iron (Figure 2.18).

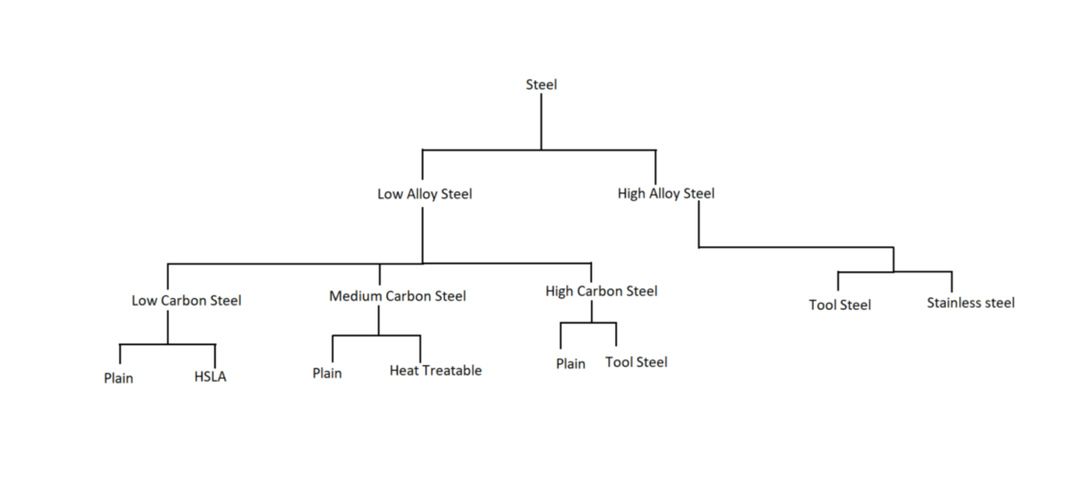


Figure 2.18: Forms of Steel (URL 15, 2023)

Steel is a common construction material mainly due to its durability and high strength and exist in different forms (Figure 2.19)

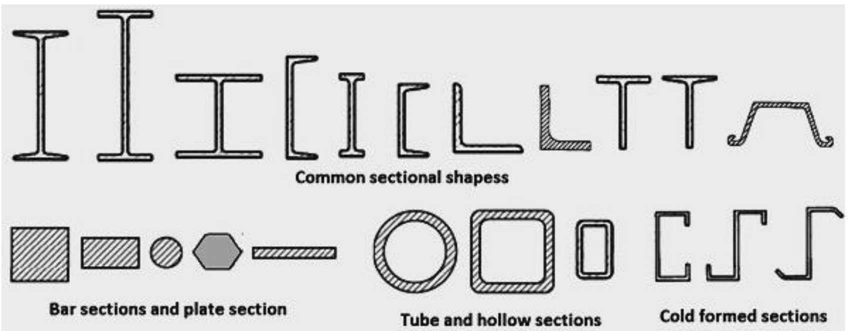


Figure 2.19: Types of Beams and Columns (URL 15, 2023)

Steel is known for being a cost-effective material with high tensile strength. Its versatility in construction is evident through various types, each suitable for different

project requirements. These types include structural steel, rebar, alloy steel, carbon steel, light gauge steel, tool steel, and weathering steel.
The use of iron as a structural material gained momentum in the late nineteenth century due to the emergence of cost-effective manufacturing methods. Subsequently, steel, an advanced development, has found widespread use in various forms across nearly every building type.

Macdonald (1994) highlights the advantage of steel, highlighting its high strength, balanced tension and compression strength, and suitability for diverse structural elements. Steel's versatility extends from substantial columns to the smallest nails, establishing it as the most adaptable structural material (figure 2.20).It possesses exceptional strength and resilience against aging (Ambrose, 1993). Despite its density, the high strength-to-weight ratio ensures that steel components are not unduly heavy in relation to their load-bearing capacity.

Steel is a fully industrialized and fabricated material. Despite its initial bulk cost, the competitive advantage lies in its forming process, making it cost-effective through mass production of standardized items. The vocabulary of steel in building structures has expanded, offering a wide range of applications in different forms (Ambrose, 1993).

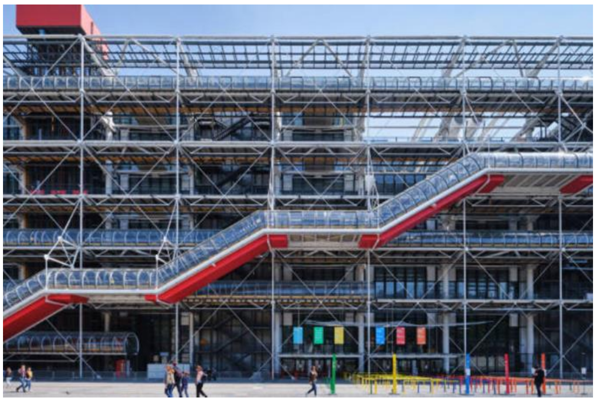


Figure 2.20: Centre Pompidou (Nash Photos/Getty Images)

2.7 Structural System Classification

2.7.1 Structural Systems

Two distinct categories of structural systems exist: traditional and contemporary structures, generating diverse types of spaces, as classified in Table 2.4. Traditional structural systems include; masonry walls, arches, vaults, and domes. In contrast, contemporary structures includes various types of structures using innovative technologies, categorized as form active, vector active, section active, and surface active.

Table 2.4: Classification of Structural Systems (Mangaleu Toukam, 2023).

CONTEMPORARY STRUCTURAL SYSTEMS*			
FORM ACTIVE	**VECTOR ACTIVE**	**SECTION ACTIVE**	**SURFACE ACTIVE**
CABLE	TRUSS 2D + 3D TRUSS	FRAME	SHELL
TENT	SPACEFRAME	SHEARWALL	FOLDEDPLATE
PNEUMATIC	GEODESIC DOME	SLAB	

ARCH			
** Adapted from (ENGEL, 1997)			

Contemporary stadiums represent a category of structural systems that emerged with concrete and steel as novel construction materials. The integration of these materials has significantly influenced the design and construction of modern stadiums.

Costello (2023) explains that; contemporary architecture is popular and will have more sustainable materials, making them more valuable and sought-after in a world where sustainability is essential for the future. Hence classifying structural systems is a crucial step for engineers and architects. This classification enables them to make informed decisions, taking into account various factors such as safety, cost, aesthetics, and environmental impact. By considering these factors, professionals can design and construct buildings and structures that align with the specific requirements and objectives of a project.

This approach ensures that the resulting structures not only meet functional needs but also contribute to broader considerations of sustainability and long-term viability.

2.7.2 Contemporary Structural Systems

Material advancements such as concrete and steel have stimulated the creation of innovative structural systems, allowing for increased design freedom. These systems create uninterrupted free plans. Unlike traditional structural systems, which impose limits on architectural form, these systems have evolved throughout time to align with different design aims, environmental concerns, and safety norms. In this context

Engel's structural system classification would be looked on to and it can be summarized in Table 2.5

Table 2.5: Structural Systems Classification in Buildings (Engel, 1999)

Structure Family		**Definition**	**Structure Type**
1	**FORM-ACTIVE** structure systems	... are structures composed of flexible, non-rigid materials, where the direction of forces is influenced by specific form design and characteristic form stabilization	• Cable Structures • Tent Structures • Pneumatic Structures • Arch Structures
2	**VECTOR-ACTIVE** structure systems	... are structures consisting of short, solid, straight linear members (bars), where the redirection of forces is influenced by vector partition—namely, through the multi-directional splitting of single forces, whether compressive or tensile bars.	• Flat Trusses • Transmitted Flat Trusses • Curved Trusses • Space Trusses
3	**SECTION-ACTIVE** structure systems	... are structures comprised of rigid, solid, linear elements, including their compacted form as a slab, where the redirection of forces is influenced by the mobilization of sectional (inner) forces.	• Beam Structures • Frame Structures • Beam Grid Structures • Slab Structures
4	**SURFACE-ACTIVE** structure system	... are structures consisting of flexible but otherwise rigid planes—resistant to compression, tension, and shear—in which the redirection of forces is influenced by surface resistance and specific surface form.	• Plate Structures • Folded Plate Structures • Shell Structures
5	HEIGHT-ACTIVE structure system	... are systems where the redirection of forces, required for height extension, such as the collection and grounding of storey loads and wind loads, is achieved through typical height-proof structures, commonly known as high-rises.	• Bay-Type High-Rises • Casing High-Rises • Core High-Rises • Bridge High-Rises
6	HYBRID structure system	Two structural systems with different mechanics of redirecting forces can be combined to create a unified and operational structure with	some examples of possible hybrid structural systems: • superposition of section-active and form-active structure systems

		new mechanics, known as a hybrid structure system.	• superposition of form-active and vector-active structure systems

2.7.2.1 Form Active Structures

Form active structures are known by flexibility and absence of rigidity. Their unique features lies in the redirection of forces through specific form design and stabilization methods. These structures excel in their ability to efficiently channel external forces, employing strategies such as compression in arches and tension in suspension cables. Vertical hanger cables, serves as a prototype for these constructions, efficiently transmit weight directly to the point of suspension. Structures like arches and suspension cables, are characterized by simple stresses such as tension or compression, demonstrate a high level of economic efficiency in their weight-to-span ratio.

The arch and suspension cable, as form active structures, are particularly well-suited for achieving extended spans and creating expansive spaces. Their design aligns seamlessly with the natural flow of forces, emphasizing their suitability for spanning large distances with efficiency (Engel, 1997).

2.7.2.1.1 Cable

Form-active structures, especially those involving cables, are characterized by the convergence of multiple cables with diverse geometries to create surfaces exhibiting negative curvature (Figure 2.21). The incorporation of cable structures gained prominence in the 19th century during the industrial revolution, particularly in the design of suspension bridges, and has continued to advance with innovative technologies. These structures find common application in bridge designs and the construction of wide-span roofs, spanning distances ranging from 50 to 200 meters in buildings without the need for vertical support.

In the case of suspension bridges, cable structures can extend across thousands of meters. The main characteristics of cable structures lies in their exclusive reliance on tension forces. Operating solely with tension forces provides advantages such as lightness, strength in tension, and resilience against torsion (Türkçü, 2009).The term "cable" typically refers to linear elements such as steel cables or rods, which serve as the fundamental components of the entire structure. Nevertheless, cables are frequently used in conjunction with other supporting elements like pillars, arches, rings, curtain walls, or truss systems. For instance, a cable roof may be supported by two pillars transferring the load to the ground.

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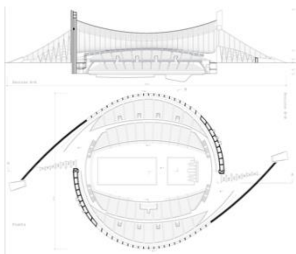
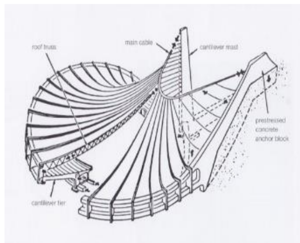
<td></td>
<td>
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<td>Yoyogi national gymnasium Outdoor view (URL 16 ,2023)</td>
<td>Plan and section, (URL 17,2023)</td>
<td>3D Model (URL 18,2023)</td>
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Figure 2.21: Example of Cable Structure

The introduction of high-tensile steel cables has facilitated the transmission of significant axial forces through tension at a low cost. Cables exemplify a cost-effective approach to constructing large buildings with aesthetically pleasing designs.

Cable roof structure concept became notable with the completion of the North Carolina State Fair Arena in the United States in 1953. The primary framework of this building features a cable network supported by two intersecting concrete arches. The cables were pre-tensioned, and the curved form of the roof contributed to its stability (Figure 2.22). Subsequent to the construction of the Arena, other buildings incorporating steel cables in diverse configurations and shapes were envisioned and constructed.

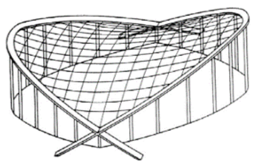
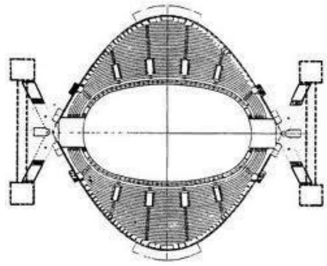
		
North Caroline state Fair Arena (URL 19,2023)	3d North Caroline state Fair Arena (URL 19,2023)	North Caroline state Fair Arena in USAPlan (URL20, 2011)

Figure 2.22: First Cable Roof Structure

Cable roofs have become a popular choice for covering wide spans in structures such as stadiums, sports halls, swimming pools, and concert halls, especially for buildings that necessitate large, column-free areas. Their versatility allows for various architectural forms, making cable roof structures applicable in a wide range of settings. These structures embody architectural, structural, and economic potential, often yielding aesthetically appealing buildings that are both sturdy and efficient.

The utilization of cables is becoming progressively more attractive, economical, and innovative, especially with the integration of steel (Buchholdt, 1999). This trend mirrors the increasing acknowledgment of cable roofs as a pragmatic and aesthetically pleasing solution for large-span architectural designs.

2.7.2.1.2 Tent

A tent is a system that relies on tension forces, serving a dual purpose as both framework and cladding (Figure 2.23). It receives support from pillars, cables, arches, or rings and can be crafted from materials that are flexible, pliable, and lack rigidity. Structurally, membranes share similarities with cables, differing primarily in their structural elements—cables being linear, while membranes are planar. The incorporation of tents in architectural practices dates back to ancient periods, with early examples featuring structures constructed from wooden sticks and animal skin, representing some of the earliest instances of membrane structures (Türkçü, 2009). Tents essentially function as membranes, receiving support from an arch or a column

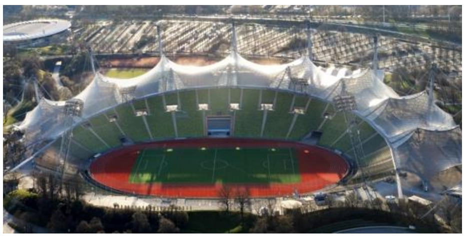
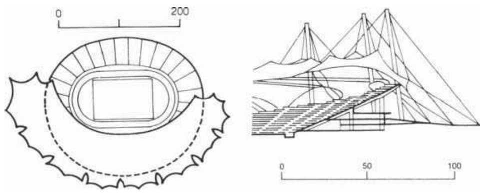
	
The Munich Olympic Stadium, 1972 (URL 21,2023)	3d North Caroline state Fair Arena (URL 22,2023)

Figure 2.23: Example of a Tent Structure

Expansive geometries in tension structures are achieved by employing and combining repeated modules. One of the standout features of tension structures is their remarkable spanning capability, with each unit able to span between 30-80 meters.

The construction technique involves elevating supports to considerable heights, and membranes can be easily stretched to achieve both aesthetic appeal and functional satisfaction (Huntington, 2004).

2.7.2.1.3 Pneumatic

Pneumatic structures are built by inflating a volumetric membrane with air, serving as both the structural framework and the outer cladding. The utilization of such structures in architecture has roots dating back to the early 20th century. Renowned for their lightweight characteristics, cost-effectiveness, and swift, straightforward assembly, pneumatic structures have become notable elements in architectural design (Türkçü, 2009)

Pneumatic structures have the capacity to cover substantial distances without requiring vertical supports, as noted by Eren (2007). Originally utilized for temporary needs like winter sports halls, festival venues, and construction site shelters, these structures have evolved in contemporary architecture. They are now employed in permanent buildings, using innovative methods to achieve spans ranging from 10 to 50 meters.

Despite their advantages, pneumatic structures also come with limitations. They are not universally suitable for all sites and weather conditions, and creating openings in their facades can be challenging. Structurally, they share similarities with tents and can be fabricated from flexible and pliable materials rather than rigid ones. Commonly used materials for pneumatic structures include plastic or metal foils and textiles (Türkçü, 2009).

There are two primary types of pneumatic structures: single-layer and double-layer. In single-layer structures, a compressor is continually employed to pump air into the space, creating a pressure differential between the interior and exterior. The compressor regulates the pressure within the structure. In the second type, air is confined between two layers (Figure 2.24). This design offers distinct advantages over the first type, as there is no constant need to pump air into the space since the air is sealed between the layers, minimizing air loss (Eren, 2007).

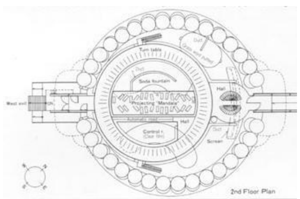
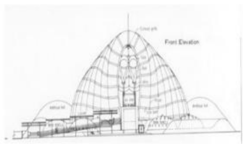
		
Fuji Pavilion Exterior view(URL23, 2023)	Fuji Pavilion plan (URL23, 2023)	Fuji Pavilion Elevation (URL23, 2023)

Figure 2.24: Example of Double Layer Pneumatic Structure.

2.7.2.1.4 Contemporary Arches

Contemporary arch structures have pushed the boundaries of architectural innovation and engineering they combine aesthetics and structural efficiency, redefining the possibilities of modern architecture. Until the 19th century, arches and vaults were the primary structural solutions for wide spans as masonry’s limitations restricted application. However, in the 20th century, significant advancements in materials and construction techniques, particularly in steel and concrete, revolutionized arch-based structures, enabling architects and engineers to explore more creative and cost-effective solutions for large spans (Figure 2.25). This technological shift ushered in an era of architectural innovation, leading to the development of iconic structures that redefined the possibilities of architectural design.

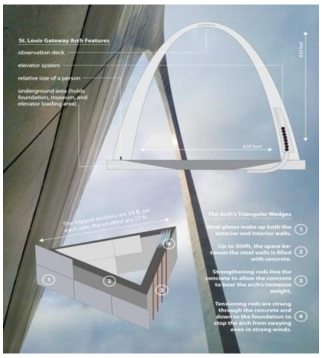
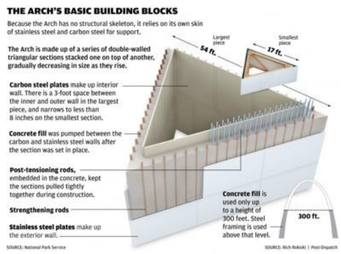
		
Gateway national park Arch (URL 24,2023)	Gateway arch details URL 25, 2023	Gateway Arch blocks URL 26,2023

Figure 2.25: Example of Contemporary Arches.

The concept behind arches revolve around the creation of wide-span structures relying solely on internal compression. The arch's form is shaped by its loading and support conditions. Historically, stone arches carried the weight of the arch itself, with other forces being relatively insignificant.

In modern arch design, the emphasis on structural lightness has transformed the structural system application. Contemporary arches often incorporate continuous ribs constructed from materials such as steel, laminated wood, reinforced concrete, or truss, augmenting the basic compression principle. There are three arch types: fixed arches, two-hinged arches, and three-hinged arches (Figure 2.26)

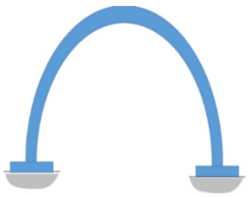
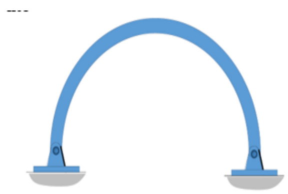
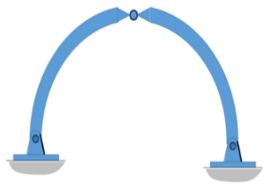
		
Fixed arches	Two hinged arches	Three hinged arches

Figure 2.26: Structure of Contemporary Arches (URL 27, 2023).

a. Fixed arches are commonly found in reinforced concrete bridge and tunnel construction, featuring a series of arches constructed continuously on supporting piers, making them suitable for short to medium spans.
b. Two-hinged arches are typically chosen for longer spans, and their pinned bases effectively accommodate thermal expansion, in contrast to fixed supports.
c. Three-hinged arches are favored for medium-span building roof structures, primarily due to the ease of implementing pinned bases.

While masonry arches traditionally span between 8-20 meters, reinforced concrete, laminated wood, or metal arches can span from 25-70 meters.

2.7.2.1.5 Vaults

Created by repeating adjacent arches side by side, with the key distinction being that a vault forms a surface rather than a planar rib (Figure 2.27). This approach facilitates the creation of intricate three-dimensional structures through the intersection of multiple vaults.

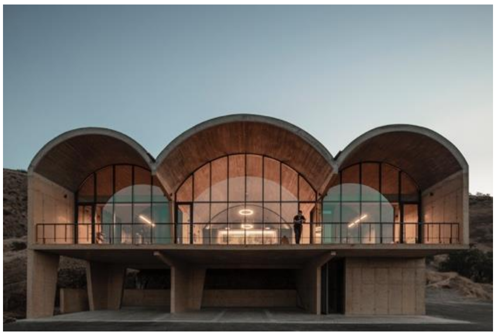
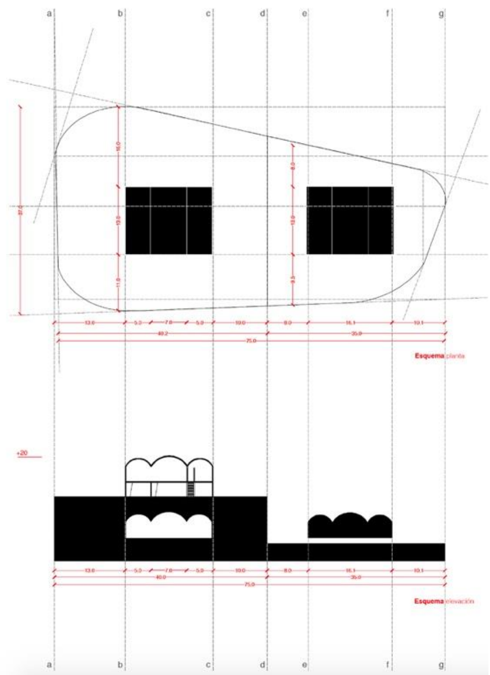
 	
OFMA Offices in a Vineyard (URL 28,2023)	OFMA Offices in a Vineyard (URL 28,2023)

Figure 2.27: Example of Contemporary Vault Structure.

2.7.2.1.6 Domes

Domes involves the rotation of arches around a crown. Unlike vaults, domes have a circular plan, while vaults are often associated with rectangular or cross plans (Figure 2.28). Both vaults and domes can take the form of ribbed structures or direct shell forms (Ambrose, 1993).

Modern domes frequently leverage advanced technologies, including computer-aided design, and employ innovative materials such as glass, steel, and reinforced concrete. This combination results in visually striking and structurally efficient buildings that not only stand as architectural landmarks but also showcase the evolving nature of design in the 21st century.

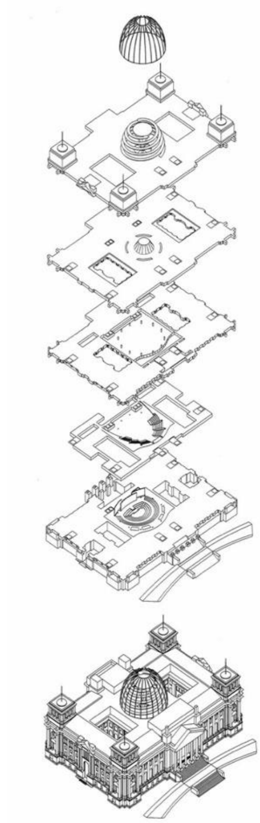
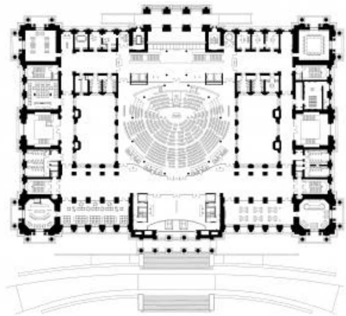
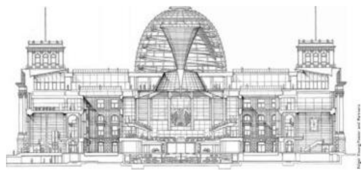
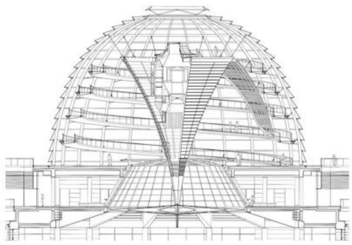
 		  
The Reichstag, Berlin, Germany Outdoor view (URL 29,2023)	The Reichstag, Berlin, Germany Outdoor view (URL 29,2023)	The Reichstag, Berlin, Germany Section (URL 29,2023)

Figure 2.28: Example of Contemporary Dome Structure

2.7.2.2 Vector Active

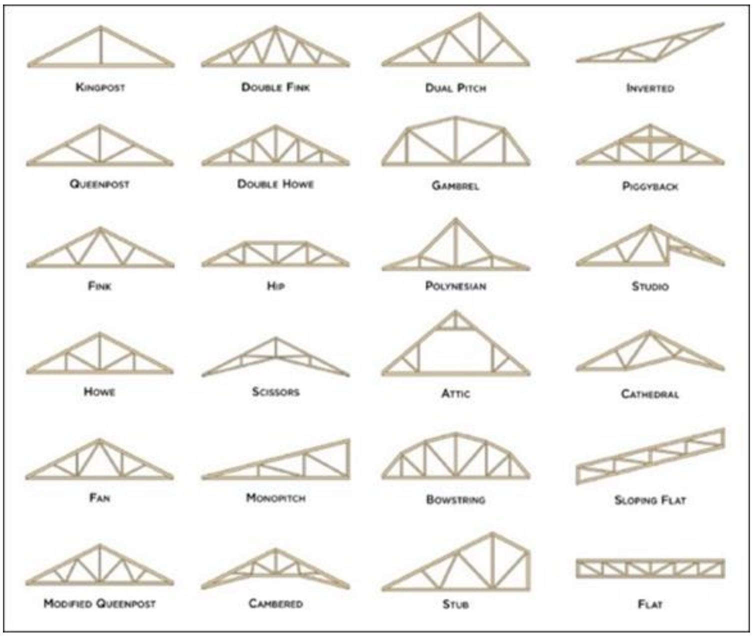
Vector active structures primarily operate with a combination of compression and tension are termed vector active structures. These structures are composed of solid, straight-line elements such as bars and rods, and the redirection of forces is achieved through vector partition (Engel, 1997).

The structural elements of vector active structures are short, solid, straight-line members. Due to their small section relative to their length, they can only transfer forces in the direction of their length—normal stress in the form of compressive and tensile members. Compression and tension elements are arranged in a specific pattern and interconnected at hinged points to create a stable composition. This arrangement forms a mechanism capable of redirecting forces and transferring loads over extended distances without the need for intermediate supports. What sets vector active structures apart is their distinctive triangulated configuration of straight-line members (Engel, 1997).

Moving forward Engel (1997) says that the vector active force redirection mechanism may also be used to other structural systems such as arches, frames, or shells that can be constructed as trussed systems. Because of their endless potential for three-dimensional extension utilizing standardized pieces, vector active structures are well-suited for the dynamic cities of the future.

2.7.2.2.1 2D Truss

Trusses represent a broad category of man-made structures, consisting of a set of rigid bars connected by pin joints. They come in various forms (Figure 2.29).



2D Truss structure (URL30, 2011)

Figure 2.29: Example of Vector Active Structures

Trusses provide the flexibility to design structures in various forms, enabling the spanning of large distances, including bridges, towers, building exoskeletons, and roof supports. The typical spanning capacity of a truss falls within the range of 15-30 meters. The straightforward construction of rod elements, which exert only axial forces, contributes to the effective and distinctive appearance of trusses (Smith, 2002).

The stable geometric units of trusses are achieved through the triangular subdivision of the planar system. This allows for an almost infinite variety of truss configurations. Additionally, truss systems can be adapted to create other structural forms such as rigid frames, arches, or three-dimensional towers (Ambrose, 1993).

2.7.2.2.2 3D Truss

A three-dimensional (3D) truss is a framework employed to provide additional strength and support to structures like bridges and buildings (Figure 2.30)

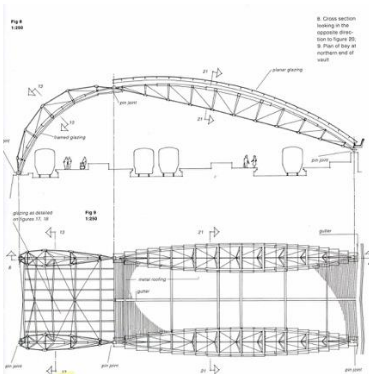
	
Plan section , Waterloo train station (URL31 , 2011)	Waterloo train station (URL32, 2011)

Figure 2.30: Example of Truss Structure

A three-dimensional (3D) truss is composed of triangles organized into three-dimensional triangular shapes, such as tetrahedrons. These trusses exhibit exceptional strength, capable of withstanding significant force without undergoing deformation or breaking.

2.7.2.2.3 Space Frame

In a broad sense, the term "space frame" denotes a three-dimensional structure. However, in a more specific context, a space frame refers to a particular type of structural action occurring in three dimensions. A definition provided by the Working Group on Spatial Steel Structures of the International Association offers further clarity: A space frame is a structural system assembled from linear elements in such a way that forces are transmitted in a three-dimensional manner. In certain instances, the constituent elements may be two-dimensional (Figure 2.31). Macroscopically, a space frame often presents itself as a flat or curved surface (Sulayfani & Saaed, 2008).

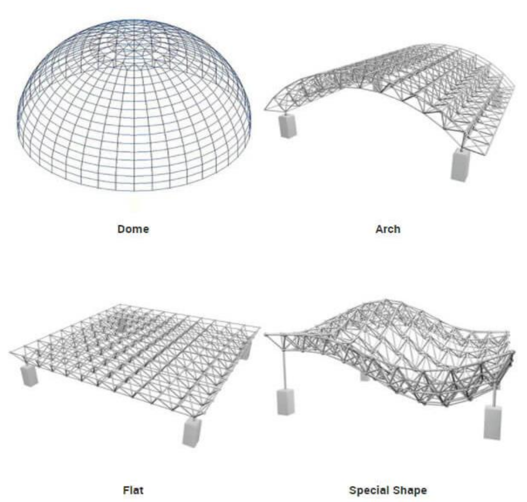
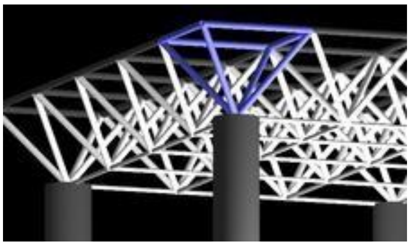
	
Indian Oil Company, Administration (URL33, 2011)	Basic unit of a flat 3d truss (URL34 , 2011)

Figure 2.31: Example of V space Frame

A space frame is typically configured as an array of single, double, or multiple layers of intersecting members. Some authors specifically categorize space frames as double-layer grids. When a single-layer space frame takes on the form of a curved surface, it is often referred to as a braced vault, braced dome, or latticed shell. Occasionally, the term "space truss" is encountered in technical literature. From a structural analysis perspective, a space frame is analyzed with the assumption of rigid joints, leading to internal torsions and moments in the members. In contrast, a space truss is assumed to have hinged joints, resulting in an absence of internal member moments. The choice between space frame and space truss action is primarily influenced by the detailing of joint connections, and the member geometry remains consistent for both (Sulayfani & Saaed, 2008).

2.7.2.2.4 Geodesic Dome

A geodesic dome is a self-supporting structure comprised of interconnecting triangles. These domes are renowned for their durability and efficiency in uniformly dispersing pressure (Figure 2.32). This architectural style gained prominence through the work of Buckminster Fuller and is commonly employed in greenhouses, exhibition halls, and even residential buildings.

The vertices of the triangles are positioned on the surface of a sphere, and in mathematical terms, the shortest path connecting two points on the surface of a sphere is known as a geodesic path (Davis, 2011). Buckminster Fuller developed the geodesic dome and applied it to architecture with the aim of creating an efficient vector system that minimizes energy usage (Türkçü, 2009).

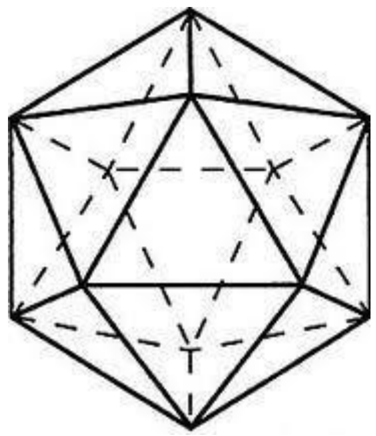
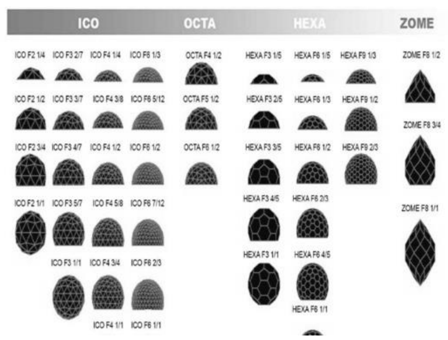
	
Icosahedron (URL35, 2011)	Types of Geodesic dome geometries URL 36 ,2023

Figure 2.32: Geodesic Domes

The form of these domes is derived from the projection of icosahedrons onto the surface of a sphere, as illustrated in Figure 2.33 This method enables the creation of spherical domes (Muttoni, 2006). These domes are characterized by their lightweight construction and have the capability to span considerable distances, reaching up to 200 meters with ease (Eren, 2007).

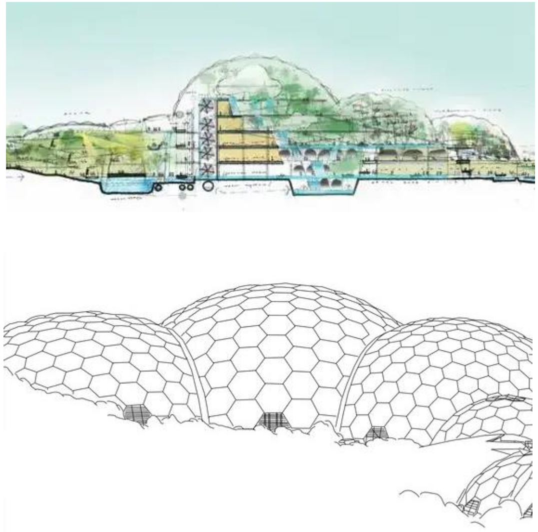
	
Eden Project (Cornwall, UK) URL 37, 2023	Eden Project (Cornwall, UK) section and elevation URL 38 ,2023

Figure 2.33: Example of a Geodesic Dome

2.7.2.3 Section Active Structures

Section active structures primarily rely on the properties of their cross-sectional area and the continuity of materials within. The fundamental principle of this system revolves around containing forces, particularly under bending stress conditions, with a focus on sectional forces. These structures are characterized by solid, rigid linear elements that manage force redirection through sectional forces, predominantly subjecting their members to bending.

Key components of section active structure systems include beams, which are straight, bending-resistant structural elements. Beams are integral to building construction, with their versatility enabling them to withstand forces along their axis and transmit forces perpendicular to their axis to the structure's ends. Architecturally, section active structures often adopt a rectangular form in both plan and elevation. The simplicity of rectangular geometry offers advantages in addressing both structural and aesthetic considerations, making them widely applicable in building design. However, future developments in these structures may face challenges related to low weight-to-span ratios, influenced by pre-stressing techniques and the potential shift from massive beam sections to form active, vector active, or surface active forms.

2.7.2.3.1 Frame System

The utilization of tree trunks and stone post-and-lintel systems in ancient times laid the foundation for the development of the structural system described. As architectural vocabulary evolved, incorporating materials such as concrete, metal, and timber expanded the possibilities of this fundamental building technique. The system is centered around two key elements column and beams.

Frames, which integrate columns and beams to resist both horizontal and vertical forces simultaneously (Eren, 2007), play a pivotal role in this system. In frame systems, structural and covering elements are distinct, allowing walls and ceilings to be clad with various materials based on design considerations. Frames are often more cost-effective and lighter compared to masonry structures (Figure 2.34).

This system can be classified into three primary types based on the materials used: timber, steel, and reinforced concrete frames (Türkçü, 2009). Reinforced concrete frames require the use of formworks, which can prolong the construction process and potentially impact existing structures. On the other hand, steel structures are significantly lighter, more flexible, and transparent, making them a preferred choice for additions to older buildings (Eren, 2007).The span of this system depends on the material used.

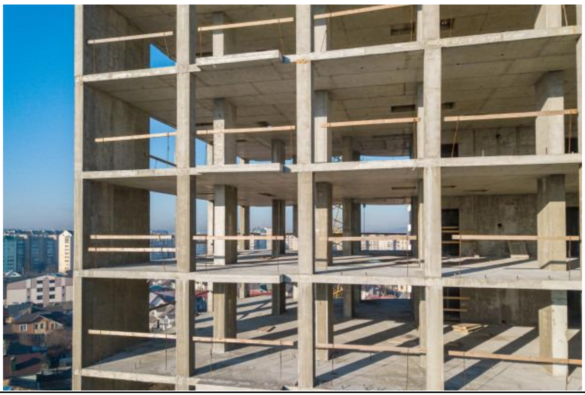
Glued timber frame slabs typically span between 15-40 meters, steel frame slabs reach spans of 15-60 meters, and reinforced concrete slabs cover distances of 10-25 meters.

Commercial steel building (Mangaleu Toukam, 2023)

Figure 2.34: Example of a Concrete Frame Building

The critical aspects of the system involve the relationship between the length and radius or thickness of the post, as well as the depth to span ratio of the beam. To resist horizontal loads, various methods can be employed, such as fixing the base of the post, connecting posts, and utilizing trussing and x-bracing (Ambrose, 1993).

The structural slab is a planar element actively utilizing various bending mechanisms (Figure 2.35). Its effectiveness is most pronounced within a specific span limit (Engel, 1997)



Concrete building showing the slabs (Managleu Toukam, 2023)

Figure 2.35: Example of Slab

Also it can be thought of as a thick, flat plate that serves as a foundation for floors, roofs, or other building components and varies in types (Figure 2.36).

Types of Slabs (URL 39,2023)

Figure 2.36: Types of Slabs

2.7.2.4. Surface Active Structures.

Surface active structures primarily rely on the extension and configuration of surfaces to achieve their architectural and structural goals. These systems operate on the principle of dispersing forces, particularly under surface stress conditions, often referred to as membrane forces. Surface active structures consist of flexible surfaces that can withstand compression, tension, and shear, and they rely on the resistance of the surfaces and specific surface design to redirect forces.

Members within this system primarily endure membrane stresses. Surfaces serve as highly efficient and comprehensible tools for defining spatial boundaries, both within interior spaces and between different elevations, seamlessly connecting one space to another. The reinforcement of surfaces is essential for ensuring the structural integrity of the supporting framework. However, a significant challenge lies in designing the stiffening elements in a manner that avoids abrupt changes in rigidity and deflection tendencies.

Surface structures fulfill the dual role of defining spatial volumes and bearing structural loads. One unique aspect of surface active structures is that they blur the line between structure and building, as the laws of mechanics govern the space and form of the building due to the structural integrity of the surfaces. In essence, the structure and building are inherently interwoven, adhering to the principles of structural mechanics (Engel, 1997).

2.7.2.4.1 Folded Plate

Folded plate structures are formed when structural surface elements, referred to as plates, are oriented at specific angles to create a folded plate system. To qualify as a folded plate structure, a minimum of two distinct surface elements must intersect at an angle (Figure 2.37).

These plates play a vital role in transferring loads from the surface to the vertical structural elements. However, in the case of wide spans, the surface tends to bend downward due to the weight of the structure. Folded plate structures can cover extensive spans without requiring vertical elements in the center of the space, with a spanning capacity ranging from 15 to 50 meters. They are commonly used in the construction of factory buildings and auditoriums where wide spans are necessary. Various materials, including reinforced concrete, metal panels, and plastics (Türkçü, 2009), can be employed for folded plate structures. These materials offer flexibility in design and construction, making folded plate structures suitable for a variety of architectural applications.

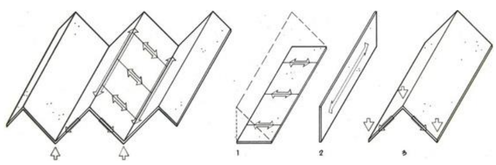
	
Structural behaviour of folded plates (URL40, 2011)	Folded plate stadium (URL 41, 2011)

Figure 2.37: Example of Folded Plate

2.7.2.4.2 Shells

Shells are volumetric structural structures with two basic dimensions that considerably exceeds their thickness (Figure 2.38). These structures serve two functions: they hold the weight while also enclosing and safeguarding the enclosed space, successfully resisting all external pressures. They are distinguished by three important characteristics: curvature, stiffness, and thinness. Shells' outside surfaces can have one-way or two-way curvature, giving them specific structural benefits. When compared to the vast spans they cover, shells are noticeably homogeneous, stiff, and thin.

Valencia. City of Arts and Sciences (URL 42,2023)

Figure 2.38: Shell Structure

According to Engel (1997), Shell structures mostly are used to cover large spans. Spanning between 40-250 m. In addition Türkçü (2009) outlined that Contemporary architecture is replete with numerous instances due to its adaptable nature. The flexibility of this style allows for the design of various curved forms using appropriate materials. Shells, for instance, can be constructed using materials like reinforced concrete, steel, and plastic.

2.8 Selection for Widespan Structural Systems

According to Al Shamrani and Schierle (2007), the selection of structural system and material is often done according to personal experience or perception without being evaluated as it should be for optimum performance. Furthermore he proposed a two stages guideline for the selection of Optimum structural system (Table 2.6).

Table 2.6: Selection of Optimum Structural System According to Al Shamrani and Schierle (2007)

Selection Of Optimum Structural Systems	
Stage one	- Gravity load - Lateral load (wind and seismic) - Climate conditions - Labor and material costs - Code requirements - Building location - Building height limit - Sustainability (durable and recyclable) - Strength - Stiffness - Stability - Synergy
Stage two	Evaluates selected systems and materials for optimum performance of criteria considered critical for a given project

The proposed selection process provides a methodology to determine the selection of the optimum structural system.

2.8.1 Material Type

Designers should take the decision of which material should be used into consideration at an early stage of the project. According to Aghazadeh et al. (2019) Materials selection in construction projects involves a multidisciplinary effort and requires consideration of various factors.

Also, Sahlol et al. (2021) adds that materials selection is a complex task that is determined by a lot of parameters affecting buildings as a whole which include; environmental factors, technical factors and material performance.

Aghazadeh et al. (2019) mentions that there are steps that should be taken before selections as; identifying the criteria and evaluating the materials. Building construction frequently involves the use of several materials, each with its unique advantages and disadvantages. The most commonly employed materials in widespan structures is steel. Reinforced concrete, Timber, Aluminum, Tensile fabric, Fiber-reinforced plastic, Metal, Plastic coated textile material are also widely used

Each of the mentioned materials are well-suited for specific widespan applications. For widespan structure, various factors come into play, encompassing the desired span length, the anticipated loads the structure must bear, site conditions, material availability, and the project budget. It is crucial to carefully assess and choose the most suitable material in accordance with these considerations to guarantee the safety and longevity of the structure.

2.8.2 Span

The span of a wide-span structure is an important factor in its design and construction, as it affects the choice of structural form, the materials used, level of support (span). In general, longer span lengths demand more durable materials and sophisticated support systems to ensure the structure's stability and safety.

Hurol and Baydu (2016) elaborated on the applicability of structural systems, which may be evaluated based on:

- Their span (the distance between two supports)

- Their height, a concept that is also consistent with the information (Table 2.7)

Table 2.7: Relationship Between Structure Type and the Spans Commonly Used (Hurol & Baydu , 2016, P, 44).

Structural system	*Material*	*Span range (m)*
Beam	Timber	4–8
	Laminated timber	10–30
	Reinforced concrete	4–10 (15 for high-strength concrete)
	Steel	7–30
Slab	Reinforced concrete	4–15
Truss	Timber	5–50
	Steel	15–80
3D Truss	Timber	12–25
	Steel	20–80
Space frame	Timber	15–60
	Steel	25–195
Folded plate	Reinforced concrete	10–150
Vault	Timber	20–90
	Reinforced concrete	25–70
	Steel	20–90
Geodesic dome	Timber	40–160
	Steel	50–200
Shell	Reinforced concrete	20–200
Pneumatic	Plastic + metal	10–220
Membrane	Plastic + metal	10–80
Cable	Steel	50–2,000

2.8.3 Structural Form

According to Hurol and Baydu (2016), when dealing with structures defined by their form, it is necessary to identify structural systems from both a structural engineering and an architectural standpoint. Despite the lack of a generally accepted classification system for structural systems, a common vocabulary exists to help specialists understand one another.

2.9 Various Structural Systems Classification.

Although this thesis focuses on classification according to Engel (1997) Structural systems can be classified in various ways based on different criteria, such as the materials used, the load-bearing mechanisms, and the overall structural configuration.

Here are some common classifications of structural systems. In the literature some classification had been done by some scholars (Table 2.8).

Table 2.8: Existing Literature on Structural Systems Hurol and Baydu (2016)

Author	Literature Classification
Lin and Stotesbury (1981)	• Horizontal subsystems •Vertical subsystems • High-rise buildings •Arch, suspension and shell systems •Foundation subsystems.
Engel (1997)	• Vector active structures (such as trusses) •Surface active structures (such as folded plates) •Section active structures (such as beams) • Form active structures (such as cables).
Ambrose and Tripeny (2010)	According to materials. Timber, steel and reinforced concrete structures.
Place (2007)	•Axial members •Beams •Trusses •Compression structures • Tensile spanning structures.

Subramanian and Clemmie (2017) agrees that Structural systems can be classified into different categories based on their frames and resistance methods of force (Figure 2.39).

- Active structure systems
- Bulk-Active structure systems
- Vector active structure systems
- Surface active systems

Additionally states that Traditional structures are one classification of structural systems, which can be further subdivided into:

- Bulk active structures
- Form active structures
- Vector active systems

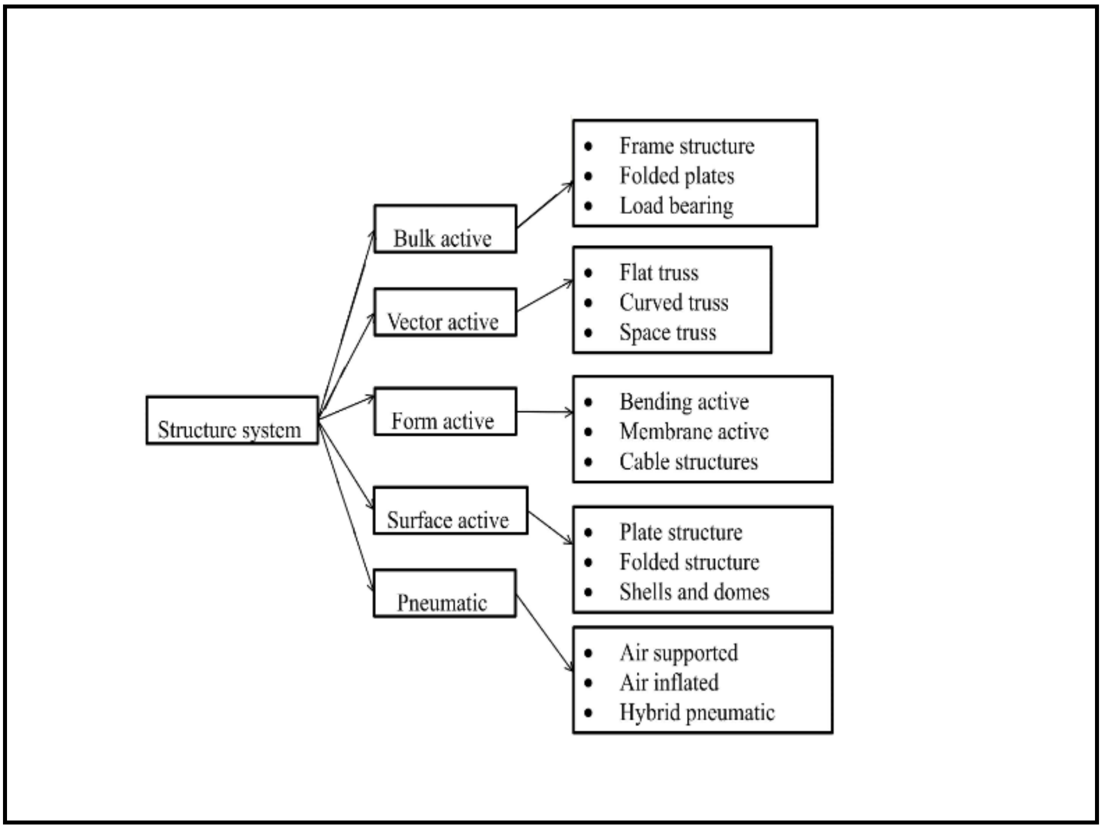


Figure 2.39: Classification of Structural System (Mangaleu Toukam,2023)

2.10 Advancements of Structural Systems

Nowadays long span structures are widely used in various fields such as sports, commercial, industrial, social and other activities. (Subramanian & Clemmie, 2017). The development of structural systems in engineering and construction has been a dynamic process driven by technological advancements, changing needs, and sustainability concerns.

Key advancements include materials innovation, computational analysis, seismic and wind engineering, prefabrication and modular construction, sustainable design, adaptive structures, high-rise building design, cable-stayed and suspension bridges, architecturally exposed structural systems, and innovative foundation systems.

Most importantly Advancements in materials science have led to the development of high-strength and lightweight materials like concrete mixes, steel alloys, and composite materials like fiber-reinforced polymers (FRPs), allowing for more efficient and sustainable structural designs. In the same line Computational analysis has revolutionized structural engineering by allowing engineers to perform complex simulations with the new materials and analyze stress under various loads and conditions.

Adaptive structures, such as responsive facades and smart building systems, are designed to adapt to changing environmental conditions. Building design has seen significant advancements, with innovative structural systems like mega-columns, outrigger systems, and tuned mass dampers for stability and safety.

Innovative foundation systems have improved stability and durability of structures, contributing to more aesthetically pleasing, sustainable, and cost-effective construction. However Engineers and architects continue to explore new technologies and methods to push the boundaries of structural system design.

2.11 Chapter Summary

From the previous experiences it was evident that widespan structures are best capable in solving many problems that cannot be faced with the help of traditional building types. Previous experiences have shown that widespan span structures offer unique advantages and are capable of solving problems that traditional building types cannot address. It should be noted that traditional building types often have limitations in terms of creating large internal spaces and accommodating specific functional requirements. Wide span structures, on the other hand, provide the flexibility and adaptability needed to meet these challenges.

The structural system is a critical component of widespan structures since it determines their stability, use, and aesthetic appeal. The choice of an appropriate structural system, as well as materials and creative techniques, is crucial in achieving the required performance and sustainability goals for widespan structures.

In the selecting the optimum structural system depends on availability, economics, experience, and tradition. Therefore there is a tradition for using a certain type of structural system in some parts of the world. The structural systems mentioned in this chapter provides a classification of structural system and is achieved by distinguishing between traditional and contemporary structural systems. Traditional systems encompass masonry walls, arches, vaults, and domes, while contemporary systems are categorized into Form Active Structures, Vector Active Structures, Section Active Structures, and Surface Active Structures, each illustrated with specific examples.

Technological advancements have played a significant role in the development of structural systems, particularly in the field of widespan structures .These advancements have provided a wide range of material options for constructing long span structures, with steel being the most commonly used material due to its versatility and strength

Modern technology, including the use of computers, has been adopted in the execution and operation of structural systems, allowing for more efficient and precise construction processes.

The use of advanced technology has also enabled the design and construction of active structure systems, bulk-active structure systems, vector active structure systems, and surface active systems, which offer different methods of resistance to forces Additionally, advancements in technology have led to the development of lightweight and expressive structural systems, such as shells of revolution, which can carry enormous spans with short sections

Chapter 3

EVOLUTION OF STADIUM DESIGN AND TECHNOLOGICAL ADVANCEMENTS

Stadiums have undergone significant evolution in design and technological advancements over the past 120 years. According to Yaroni (2012), the conceptualization and design of stadiums can be traced back to ancient Greece and Rome, much like various other historical engineering achievements. In these societies, there was a strong emphasis on the concepts of community gathering and the public display of strength and talent. The Greeks, for instance, had two structures, the stadium and the hippodrome, that share similarities with modern-day stadiums. Similarly, the Romans had the amphitheater and the circus, which served purposes akin to contemporary stadiums.

Designs of these stadiums were very basic in early days, and variations in designs didn’t start appearing until the early 20th century. With the evolution in stadiums designs, now newer stadium buildings can now seat 50,000 to 80,000 or more fans and have slightly different appearances than the traditional stadium. Most importantly, the evolution of stadia design has enabled architects and engineers to push the boundaries of what is possible in terms of structural and aesthetic elements Bullock (2023).

3.1. Definition and Description of Stadiums

Stadiums, which are sometimes viewed just as sporting event locations, have a deeper importance. A stadium is "an enclosure that combines broad space for athletic games and other exhibitions with large seating capacity for spectators" (Encyclopedia Britannica, 2013c).

Jenaway (2013), also gives historical context, indicating that the term "stadium" is derived from the Greek unit of measurement known as a 'Stade,' which was the distance (180-185 meters) in ancient Greek footraces. Originally used to refer to footraces, it evolved into a name for the venue where races were place.

The Olympia Stadium (Figure 3.1) is often regarded as the first stadium. The first spectator-oriented stadium, the Panathenaic Stadium (Figure 3.1), was erected in 338 BC and is credited with inventing the concept (Hellenic Olympic Committee, 2011). Spampinato (2012) digs into the development of stadium designs, beginning with the first Greek amphitheaters constructed into excavated hillsides, such as the original Panathenaic Stadium, however his research is limited.

	
Stadia at Olympia from NW perspective (Olympia Greece 2009).	Panathenaic Stadium (built in 338BC) URL 46

Figure 3.1: Stadia at Olympia

Stadiums are significant not only for teams and fans but also for the cities and urban economies in which they are situated. Stadiums, equipped are with advanced roof systems and diverse material choices, and have been transformed into iconic landmarks, becoming the focal points of the cities they reside in.

3.1.1 Stadium Design Historical Evolution.

Stadia have evolved over time to meet the changing demands and expectations of society (Jenaway, 2013). The evolution of stadium is influenced by technology which have led to a shift in focus towards spectator experience and revenue generation. Also there is a greater emphasis on viewing areas and amenities for spectators. Modern stadiums incorporate advancements in technology and engineering, resulting in bolder and more unique designs. The Stadium evolution can be divided into different time periods however that there can be overlap and regional variations in architectural styles and trends, but this division provides a general overview of the key developments in stadium design over time and could be summarized in table 3.1.

Table 3.1: Evolution of Stadiums (Mangaleu Toukam,2023)

Stages	**Description**	**Architectural details**
Ancient Stadiums approx. 800—200 b.c. Pastoral and spiritual ancient Greek stadiums were often carved out of hillsides to allow a clear view, fostered civic and religious engagement. In 776 B.C. Olympia first drew world to Greece and its games, which were banned as pagan a millennium later.	Greek and Roman civilizations. primarily used for athletic contests and chariot races, and were often simple, open-air structures that could accommodate large crowds of spectators.	- simple structures - Rectangular shape - Natural terrain
APPROX. 200 B.C.—A.D. 500 **Urban Mass Entertainment**	Gladiators battled in arenas, which were named after the Latin word for "sand," which soaked up the blood spilt during their bloody combat. Stadiums throughout the Roman Empire were built to maximum spectacle, entertaining and distracting restless crowds.	- First use of concrete and its discovered - Arch, Columns tunnels - Sitting areas
Medieval and Renaissance Periods	With the rise of Christianity, stadiums fell out of favor—and into disrepair. For almost 14 centuries Europeans did not build any	- No structure open place

	major sports facilities. Instead they erected soaring cathedrals and held sporting events in city squares.	
1890s—1940s **THE OLYMPIC REVIVAL**	The reintroduction of the Olympic Games in 1896 also restored stadiums to their due place as vital civic constructions. The highly urbanized population needed more entertainment, and the iron, steel, and technology of the industrial revolution went into supplying it in vast edifices.	- Use of classical styles and motifs. - Greek and Roman architecture - Use of columns, arches - Decorative elements that evoke classical design. - Design to accommodate large crowds of spectators and athletes - Reinforced concrete was used - Marble - horseshoe-shaped seating - use of ramps and staircases
19th Century Modern Stadiums	Emerged in the 19th century with the rise of organized sports. These stadiums were designed to provide better amenities for spectators and to accommodate larger crowds than their ancient predecessors.	- Steel and concrete construction - Bigger Seating capacity - Covered seating - Multiple levels - wide range of architectural designs, the classic bowl-shaped design of older stadiums - Innovative designs that incorporate elements such as

		retractable roofs, natural grass playing surfaces, and state-of-the-art audio and video systems.
1940s—1970s **POSTWAR INNOVATIONS** Concrete and steel	Modern stadium design that emerged in the mid-20th century.	- use of reinforced concrete and steel in the construction - Structural integrity - Multiple tiers - Roof design: allows for a larger covered area while minimizing the number of support columns that obstruct views of the playing field. - Sustainable features: Solar panels, rainwater harvesting systems, and energy-efficient lighting and HVAC
1980s **RETHINKING ROOFS**	In the face of severe weather during outdoor sporting events, both attendance and revenue tend to fall. To overcome this issue, engineers and designers worked to create stadiums that can effortlessly transform from open-air arenas to enclosed areas with a roof mechanism.	- Focus on the functionality and aesthetic appeal of these structures. - roofs as purely functional elements

		- Experiment with new materials, shapes, and designs to create unique and visually striking structures. - roofs that appeared to float above the building - Curved and asymmetrical roof designs.
2000s—PRESENT MODERN EVOLUTION	Stadiums continue to push the limits of technology and aesthetics and serve as powerful tools for political and artistic statements—and profit	- Focus on technology to new approaches to sustainability and energy efficiency - Bold designs and state-of-the-art features. - multi-purpose functionality
Multipurpose venues	Multipurpose stadiums are sports venues intentionally designed to accommodate various kinds of activities, including sports events, concerts, conventions, and large-scale gatherings. These stadiums are built with a focus on versatility and adaptability, incorporating elements that can be adjusted to meet the requirements of diverse events.	- Flexible seating configurations: can be modified to suit a variety of different occasions. Seating that can be relocated to make extra floor area available for events such as concerts or conventions. - Large floor space: can accommodate a wide range of activities.

		- Variable lighting and sound systems: This allows for optimal acoustics and visibility for both sports and non-sports events. - Accessibility features: accessibility features such as elevators, ramps, and wheelchair-accessible seating areas. - Sustainability features
Specialized venues	Designed to host a specific type of sport or activity. Designed with features that are specific to the needs of that sport, such as playing surfaces, seating arrangements, and lighting.	- Specific playing surface - Unique seating arrangements - lighting: designed to provide optimal visibility for the sport. - Accessibility features - Sustainability features

3.1.2 Buildings Related to Modern Day Stadiums.

Stadium have evolved and its history is divided into 3; Greek, roman and modern periods . The progression from the first stadium has been through an evolution (Figure 3.2). as mentioned above the first stadium focused on the spectators to stadiums. Over time focus further focus on spectator viewing and accessibility (Mezher, 2002).

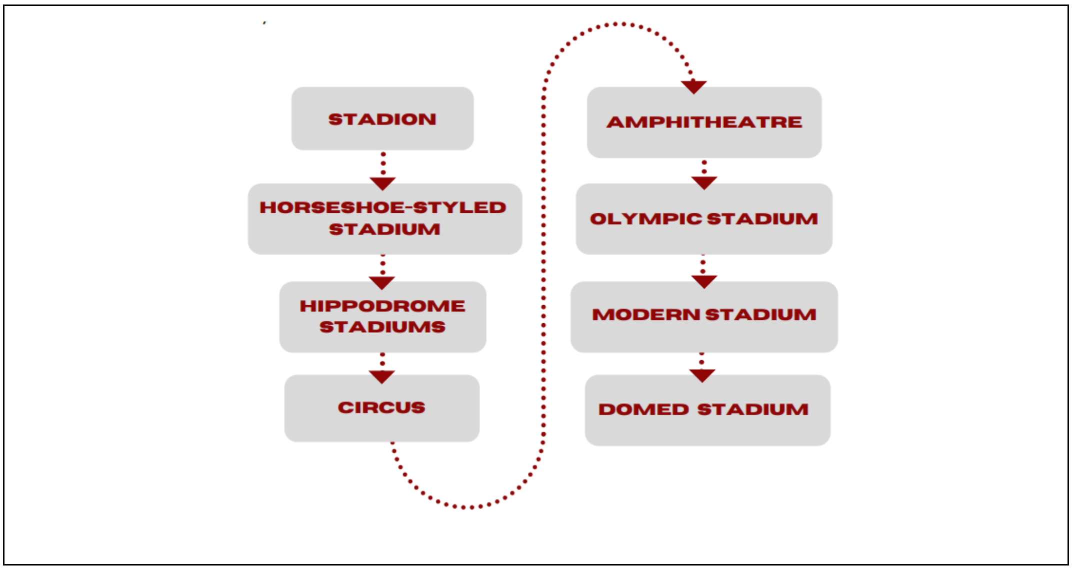


Figure 3.2: Evolution of Stadiums (Mangaleu Toukam, 2023)

Designers in ancient Greece and Rome adopted circular and oval forms for stadiums because these shapes effectively addressed functional requirements, ensuring clear viewing and efficient circulation. As a result, stadiums in ancient Greece and Rome serve as the ancestral prototypes for all current sports facilities. The following buildings, associated with modern-day stadiums, will be elaborated upon:

3.1.2.1. Greece

Ancient Greece was the birthplace of the Olympic Games, which were first recorded around 776 B.C. and held in the city of Olympia.

3.1.2.1.1. Stadiums

One of the known old stadiums is Olympia Stadium. Olympia Stadiumconsisted of a rectangular form of 32m x 192m (Figure3.3). Dated back to the 8th century BC

In Olympia, clay seats were designed. And was applied to a certain part of the stadium, not the entire stadium (Kurumak, 2019).

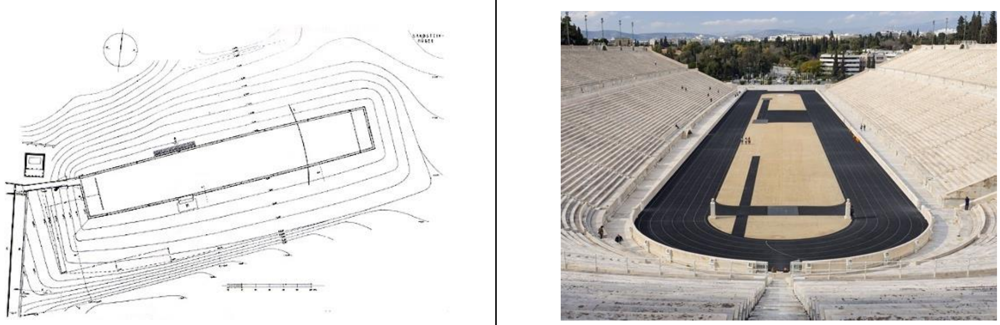


Figure 3.3: Olympia Stadium Plan and View (Arslan, 2016)

The ancient Greek stadium was configured in the shape of an elongated 'U' or a horseshoe. Its design was elongated and narrow, specifically crafted to host the 'stade' event, featuring the starting line at one end and the finish line at the other. Adjacent to the track, a stone stand was erected, serving as a distinct area for judges, commonly known as the 'exedra'.

3.1.2.1.2 Hippodrome

As athletics gained prominence in ancient Greek culture, stadiums were constructed in various locations throughout the empire. In addition to stadiums designed for 'stade' (footrace) events, Hippodromes were built specifically for horse racing, particularly chariot racing.

Similar to the Stadia at Olympia, these ancient Greek Hippodromes were often integrated into the natural topography, carved into hillsides, and utilized excavated materials to construct spectator embankments with seats along the two opposing lengths of the track (Figure 3.4). The Hippodrome typically had an elongated horseshoe or 'U' shape, featuring two long sides with one end squared and the other semi-circular (The Editors of Encyclopaedia Britannica, 1998)

The size of Hippodromes varied based on the requirements and scale of gatherings. For races involving up to ten chariots, the track needed to be as wide as 120 meters and as long as 210 meters (Encyclopaedia Britannica, 2013b).

Notably, the original Hippodrome in the ancient city of Olympia, located in the same vicinity as the first stadium, measured an impressive 780 meters in length and 320 meters in width (Vikatou, 2012).

Figure 3.4: Hippodrome in the Ancient Greek City (Sellies 2006)

3.1.2.2. Romans

As the Roman Empire expanded through the conquest of surrounding regions in the Mediterranean, the Romans assimilated various aspects of the societies they conquered.

3.1.2.2.1 Amphitheater

Amphitheaters were structures built throughout the Roman Empire where ordinary people could witness various spectacles, including gladiator games, mock naval battles, wild animal hunts, and public executions (Figure 3.5). Typically oval in shape, the largest examples could accommodate tens of thousands of people, becoming central to Roman society and a lucrative entertainment business. Amphitheaters stand as enduring examples of ancient Roman architecture, with many still in use today for events ranging from gladiator re-enactments to opera concerts (Cartwright, 2023).

The Roman amphitheater, the earliest precursor to modern stadiums, emerged in the 1st century BC. Gladiatorial contests took place in the center of the Roman amphitheater, with spectators seated on temporary wooden stands. These amphitheaters featured an elliptical shape and rising tiers of seating surrounding the arena. The term "arena" originates from the Latin words ‘sand’ or 'sandy land.' This refers to the layer of sand spread on the activity area, historically intended to absorb spilled blood from gladiator fights (Geraint, Sheard, and Vickery, 2007).The first securely dated amphitheater is the spectacular of Pompeii, built around 75 BCE.

Early structures utilized natural rock and earth hillsides for wooden seating, but by the 1st century BCE, free-standing stone versions were constructed. Amphitheaters, varying in size, proliferated across the empire as Roman culture expanded. Army camps often had dedicated arenas for training and entertainment, typically constructed using timber. The oval or elliptical shape of amphitheaters ensured dynamic action throughout and provided a good view from any seat (Cartwright, 2023).

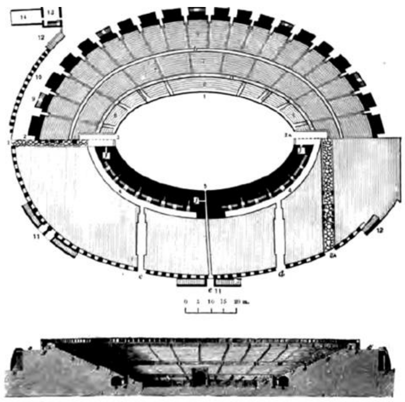
	
Plan of Amphitheatre of Pompeii(Posts, 2013)	Amphitheatre of Pompeii (Mangaleu Toukam, 2023)

Figure 3.5: Amphitheater at Pompei

3.1.2.2.2 Circuses

The Romans adopted the Greek Hippodrome construction into their civilization; however, the Romans improved it further and it became known as a Circus rather than a Hippodrome(Figure 3.6). The Roman Circus, like the Greek Hippodrome, was built in an extended 'U' form for equestrian activities. The Roman Circus, on the other hand, encompassed the whole construction with spectator seats on all sides of the arena, whereas the Hippodrome was open at one end and not totally surrounded by spectator viewing places

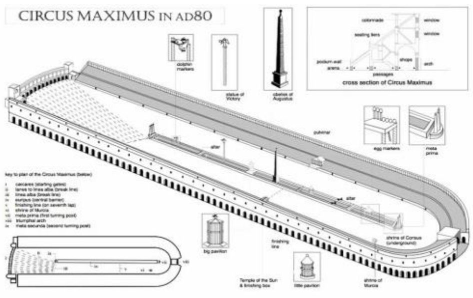
	
Circus Maximus details (URL 43, 2024)	Scale model of the Circus Maximus (McManus 2003)

Figure 3.6: Circus Maximus

3.1.2.2.3 The Colosseum

The Flavian Amphitheatre, commonly known as the Colosseum, was commissioned during the Flavian Dynasty under Emperor Vespasian's rule and reached completion in 80 AD. Situated on the grounds of Nero's former palace, which was ravaged by the Great Fire of Rome in 64 AD, the Colosseum replaced a once-existing artificial lake. This colossal structure stood approximately 50 meters tall, featuring an elliptical exterior measuring 189 meters by 155 meters, and a central elliptical arena spanning 88 meters by 55 meters. With an impressive seating capacity of around 50,000 spectators, the Colosseum boasted a sophisticated system of arches and entrances, designed for efficient crowd ingress and egress.

The construction of the Colosseum involved the meticulous use of Roman Concrete and Travertine Stone for its extensive foundations, reinforced by sturdy brick walls. One of its architectural hallmarks was the strategic incorporation of arches, not only providing structural strength but also reducing the overall use of building materials while enhancing the aesthetic appeal of the exterior façade. The Colosseum's influence extended well beyond its time, leaving an indelible mark on the development of modern stadium design and engineering. This influence is evident in various facets, including seating arrangements and ticketing systems.

The Colosseum, unlike many structures of its era, had the majority of its features and details meticulously planned before construction commenced. Roman engineers demonstrated a keen understanding of the necessity for robust foundations for a structure of such immense scale, and they designed it accordingly (Figure 3.7). While some might argue that it was over-engineered, the fact that the Colosseum still stands today, enduring the test of time, attests to the effectiveness of its construction (Jenaway, 2013, p.24).

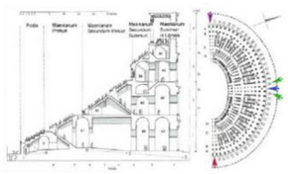
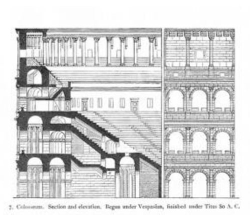
		
The different levels of the Colosseum (Gutiérrez et al., 2007)	Colosseum Section-elevation (Koehler, 2012)	The colosseum(Jarvis, 2012)

Figure 3.7: The Colosseum

3.1.3 Modern Stadiums

Barça Innovation Hub (2023) states that ;The modern stadium concept emerged in the mid-20th century, driven by the desire to provide more comfort and enhance the fan experience, as well as to offer various food and leisure options. This shift in stadium design was influenced by the need to protect spectators from the elements, such as the sun or rain. The Colosseum in ancient Rome set a precedent for this idea, as it provided some level of protection for spectators. However, it wasn't until the mid-20th century that sports club owners began prioritizing spectator comfort and weather protection, leading to the development of modern stadiums.

The advancement in technology and the utilization of Building Information Modeling (BIM) applications have facilitated the design of various structures. Modern stadiums are one-of-a-kind constructions that enhance a city's urban landscape and are frequently used as landmarks. From sustainability to ecologically friendly and zero-emission contributions, modern stadiums offer different ideals. This has resulted in incredible evolutionary breakthroughs in stadium technology, design, building, and use.

According to Sheard (2005), modern stadiums may be divided into five different "generations," each representing the emergence of a brand-new kind during evolution. The concept of "generations" in stadium design refers to the evolution of stadium design over time, with each generation representing a significant shift in design and construction techniques.

3.1.3.1 First Generation Modern Stadiums - Placed a Strong Emphasis on Spectator Capacity.

According to Sheard (2005) the first generation of stadia placed an emphasis of accommodating large numbers of spectators, at a cost of quality and comfort of the facilities of the stadia. First-generation modern stadia emerged in response to the invention of television in the 1930s and 1940s, which reduced the need for spectators to physically attend events .These stadiums aimed to attract audiences by focusing on facilities and comfort for spectators, shifting from the earlier emphasis on ticket sales revenue .

The objective of first-generation stadia was to generate higher spending per spectator at events, offsetting the impact of television broadcasts on ticket sales . An example of a first-generation stadium is Camp Nou 1957 (Figure 3.8), which prioritized high spectator numbers and the sporting arena itself, with little consideration for spectator comfort or wellbeing.

Figure 3.8: Camp Nou (1957) in Barcelona, Spain (URL 44, 2024)

3.1.3.2 Second Generation Modern Stadiums – Enhances Support Facilities and Spectator Comfort.

Sheard (2005) identifies the second generation of stadia as a period marked by a heightened emphasis on hosting events regardless of adverse weather conditions. This shift prompted the installation of floodlights at stadia to facilitate night events for broadcasting on television. Additionally, in the 1950s, under-soil heating was introduced in stadiums located in colder climates, particularly in European cities.

Stadiums in this era prioritized safety and comfort for spectators, with the goal of increasing spending per attendee at events. The second generation also witnessed the introduction of enclosed structures for stadia. The Astrodome in Houston, Texas, constructed in 1965 (Figure 3.9), stands out as the world's first fully air-conditioned enclosed sporting stadium. This innovation was driven by a renewed focus on spectator comfort and facilities, leading to further advancements such as the use of artificial grass on the playing surface (Jenaway, 2013).

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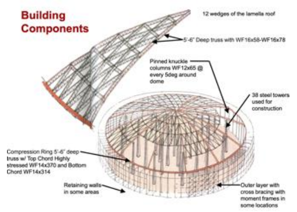
<td>
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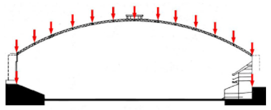
<td></td>
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</tr>
<tr>
<td>Building component Astrodome, Houston, Texas (URL 45,2024)</td>
<td>Section Astrodome, Houston, Texas (URL 45, 2024)</td>
<td>Perspective view Astrodome , Houston, Texas (URL 49,2024)</td>
</tr>
</table>

Figure 3.9: Astrodome , Houston, Texas (1965)

More Examples of second-generation stadia can be found in various countries, including those with lower socioeconomic status that may not be able to upgrade to newer generations due to high costs.

3.1.3.3 The Third-Generation Modern Stadiums - Family Stadium, Which Emphasizes Safety and Lowers Antisocial Behavior.

Stadiums were developed in 1990 to be ready for the arrival of families. Sport was the center point, although it was not always appealing. Furthermore, the primary source of revenue for football clubs shifted, and broadcasting was a pioneer in bringing these critical changes about quickly. In addition, clubs built numerous stores to showcase their wares. Examples of these stadiums.

Third generation stadiums were designed to be family-friendly and compete with family theme parks like Disneyland. Sheard (2005) also mentions that there are still many examples of second and third generation stadia today, though mainly in ‘poorer’ countries with lower social-economic status that may not be able to upgrade or develop modern stadia to a newer level such as fourth or fifth generation stadia due to the high costs involved. However, the literature from Sheard (2005) does not elaborate on these examples.

3.1.3.4 Fourth Generation Modern Stadiums

Advertising and corporate sponsorship are now used to support multipurpose stadiums. The emphasis has turned to utilizing these facilities' versatility in hosting a variety of events throughout the year in order to increase revenue sources. A new focus of fourth-generations stadia was on the multi-functional use aspects of stadia. Traditionally, stadiums are utilized once a week for assorting event for a certain period of the year (Figure 3.10).

At all other times, the stadium is under-utilized and does not bring in any significant revenue for the stadium owners. (Jenaway 2013)These stadiums are characterized by their use of advanced materials, such as carbon fiber and ETFE (ethylene tetrafluoroethylene), which allow for greater flexibility in design and construction. They also incorporate the latest in sustainable design practices, such as the use of renewable energy sources and the implementation of green roofs and walls. Sheard (2005) states that a new focus as part of this generational evolution was on maximizing use between event days through revenue streams such as bars, restaurants and corporate facilities.

	
Tottenham Hotspur Stadium in London, England. (URL 47,2024)	Mercedes-Benz Stadium in Atlanta, Georgia, USA (URL 48,2024)

Figure 3.10: Examples of Fourth Generation Modern Stadiums

3.1.3.5 Fifth Generation Modern Stadiums: An Urban Renewal Catalyst.

Fifth generation of modern stadiums are designed to act as urban redevelopment catalysts . Unlike their predecessors, these stadiums are strategically located in cities and are intended to have a more profound impact on the surrounding community beyond serving as venues for sporting events. The primary goal is to stimulate economic growth and development in the neighboring districts, making them integral to the urban fabric.

The fifth generation of modern stadia represents the latest and current state of stadium design. These stadia leverage the benefits of evolutionary changes from previous generations and incorporate cutting-edge technology to create unique and iconic structures. The emphasis is not only on providing top-notch facilities for sports but also on using stadia as catalysts for overall city improvement (Culf, 2005).

Culley & Pascoe (2005) support this perspective by noting that the evolution of stadiums is ongoing, transitioning from single-sport facilities to multi-use venues. This reflects the continuous progress in what can be termed as "modern stadiums."

3.2 Types of Stadiums

Stadiums are divided into two classes according to their geometric forms and spatial layouts (Figure 3.11). Designing stadiums to increase the number of people in them are separated (Gürel and Akkoç, 2011).

- Stadiums according to their geometric forms; horseshoe stadium , oval stadium, rectangular stadium ,
- Stadiums according to their spatial forms; open stadium and indoor stadium.

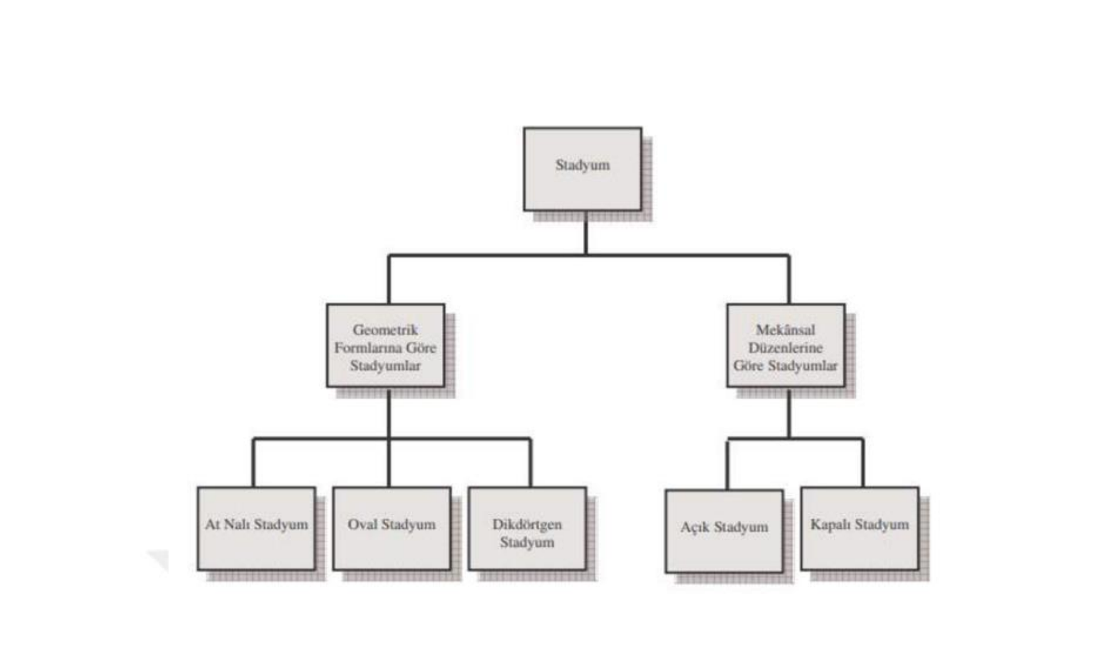


Figure 3.11: Types of Stadiums (Gürel & Akkoç, 2011).

3.2.1 Stadiums According to Their Geometric Forms

These are a category of stadiums based on the shape and layout of their seating areas and playing fields. And they include:

3.2.1.1 Horseshoe Stadium

It is a stadium type with a U-shaped plan an opened at the end. In Ancient stadium structures it is a frequently seen typology (Figure 3.12). A running area planned in a U shape consists of seating areas placed around the form. Horseshoe In stadiums, natural slope is used for seating areas and the audience. They are provided with a suitable viewing angle to see the sand track. The form is designed to provide a more intimate and engaging experience for fans, with crowd noise and energy directed toward the field of play

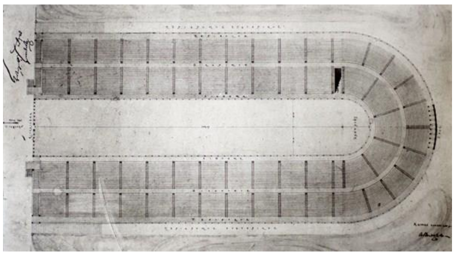
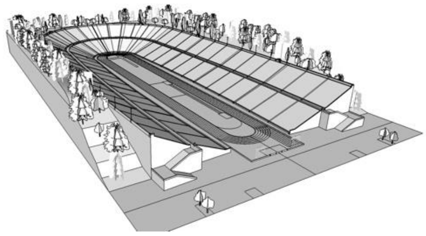
	
Panathenaic Stadium Plan (URL 49,2023)	Panathenaic Stadium 3d (Author)

Figure 3.12: Panathenaic Stadium

3.2.1.2 Oval Stadium

An oval stadium is a stadium that consists symmetrical, oval-shaped seating bowl surrounding the playing field in an oval stadium (Figure 3.13). It is predominantly used for track and field events, although it may also be utilized for other sports such as soccer, football, or rugby. The seating capacity of an oval stadium might vary based on the stadium's unique design and the needs of the stadium design. Viewing angles at an oval stadium may be less than optimal for particular sports due to the form, which can provide obscured views or poor sight lines for supporters sitting in the seats in certain areas of the stadium.

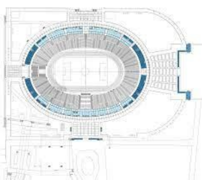
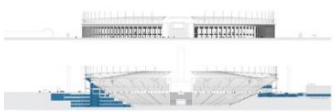
		
Plan Berlin Olympic stadium (URL 50,2023)	Section Elevation Berlin Olympic Stadium (URL 51,2023)	Berlin Olympic Stadium (URL 52,extracted 2023)

Figure 3.13: Oval Stadium, Berlin Olympic Stadium, Germany

3.2.1.3 Rectangular Stadium

A rectangular stadium is a stadium that is either square or rectangular in shape (Figure 3.14). This structure, which was created specifically for football stadiums, enables for more supporters to have an ideal viewing range. It enables the seating units to be enlarged, allowing individuals to view more. The rectangular shape of the stadium allows for the inclusion of extra facilities. Rectangular stadiums can be open or closed, depending on the climate and the team or the needs of the stadium design.

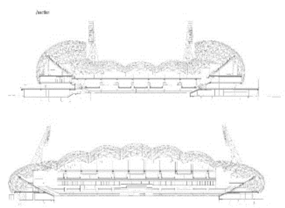
		
The Melbourne Rectangular Stadium (URL 53, 2024)	Section Elevation The Melbourne Rectangular Stadium (URL 53,2024)	The Melbourne Rectangular Stadium(URL 54,2024)

Figure 3.14: Rectangular Stadium

3.2.2 Stadiums According to Their Spatial layout

The categorization of stadiums based on how they are structured and whether they are open to the outdoor environment or enclosed within a roof. The two primary categories within this classification are as follows:

3.2.2.4 Open Stadiums

Open stadiums are a category of sports venues that lack roofs or any form of coverage for both the seating area and the playing field, leaving both the field and stands exposed to the elements. Because there is a lack of coverage or roof weather conditions, whether good or bad, directly impact the audience's experience. Also this has adverse effects on both players and ticket sales, making it less favorable for football clubs.

Open stadiums are susceptible to various climatic events, including heat, sunlight, and humidity. They are often chosen for sports and events that aim to provide an outdoor atmosphere and where climatic conditions permit, creating a unique ambiance (Figure 3.15).

İzmir Atatürk Stadium (URL 55, extracted 2024)

Figure 3.15: Open Stadium

3.2.2.5 Closed/ Semi-Closed Stadiums

Closed or semi-closed stadiums are types of stadiums where part of the stadium's is partially, retractable roof or is completely covered (Figure 3.16).The design of these are generally less expensive due to the lack of a roof which reduces the construction and maintenance costs.

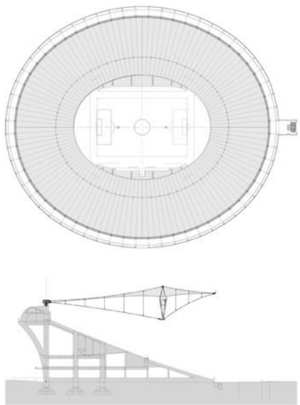
	
Maracanã Stadium Plan section (URL 56, 2024)	Maracanã Stadium (URL 57,2024)

Figure 3.16: Closed Stadium

3.2.3 Olympic Stadiums

Olympic stadiums are large sport facilities that have been specifically designed and built to host the Olympic Games (Kiuri & Teller, 2015).They are directly associated with the Olympic Games, which have been influential in shaping their design and purpose (Figure 3.17).

These stadiums hold cultural significance and are considered as heritage sites due to their historical and architectural value. They serve as testimonies of the evolution of sport and its importance in past and present societies. Olympic stadiums are characterized by their uniqueness and singularity, both in terms of their architectural design and their connection to the landscape. They are considered as part of the cultural heritage of the Olympic movement. (Kiuri & Teller, 2015).

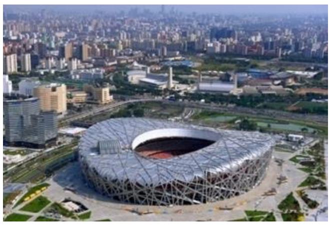
		
Beijing Stadium (URL 58,2023)	London Olympic stadium (URL 59,2023)	Wembley stadium, (URL 60,2023)

Figure 3.17: Olympic Stadiums

3.2.4 Football Stadiums

Usydus, (2020) defines football stadiums "as highly recognizable buildings within cities and serve as central points of new commercial districts. They have historical significance and purpose, but contemporary urban planning concepts have transformed them into service and entertainment complexes.''

Football stadiums set a new trend both as to their appearance, location and the function they perform within urban space. The vast majority of these structures is characterized by a unique appearance and interesting architectural design solutions (Figure 3.18) . In general, they become not only formal buildings but can sometimes even be considered to be architectural wonders Usydus, (2020).

Football stadium can depend on factors such as location, climate, budget, and the intended use of the stadium.

		
Azadi Stadium, (URL 61,2024)	Ibronx Stadium, Glasgow (URL 62,2024)	Allianz Juventus Stadium (URL 63,2023)

Figure 3.18: Football Stadiums.

3.2.5 Multipurpose Stadiums

Trends in the development of the morphology of modern stadiums, and innovativeness of architectural and design solutions for sports facilities has pushed stadiums towards multipurpose stadiums. Increasing the use of stadiums can also make them more sustainable (FIFA , 2022a).

These stadiums are designed to host various sports and events, accommodating different types of activities and functions Usydus, (2020).

3.2.6 Stadiums for Specific Purpose

Stadiums are often used for purposes other than football to improve their financial feasibility and generate regular operational income (FIFA, 2022a).

Here are various types of stadiums, each designed to accommodate specific sports or events. (Figure 3.19) Stadiums come in a variety of types, each designed to accommodate specific sports or events. For example, baseball stadiums are designed for baseball, while football stadiums are designed for American football.

Soccer stadiums have a rectangular playing field, seating that wraps around the field, and may have an elevated grandstand or canopy. Basketball arenas feature a rectangular court surrounded by seating, while hockey arenas are designed for ice hockey games.

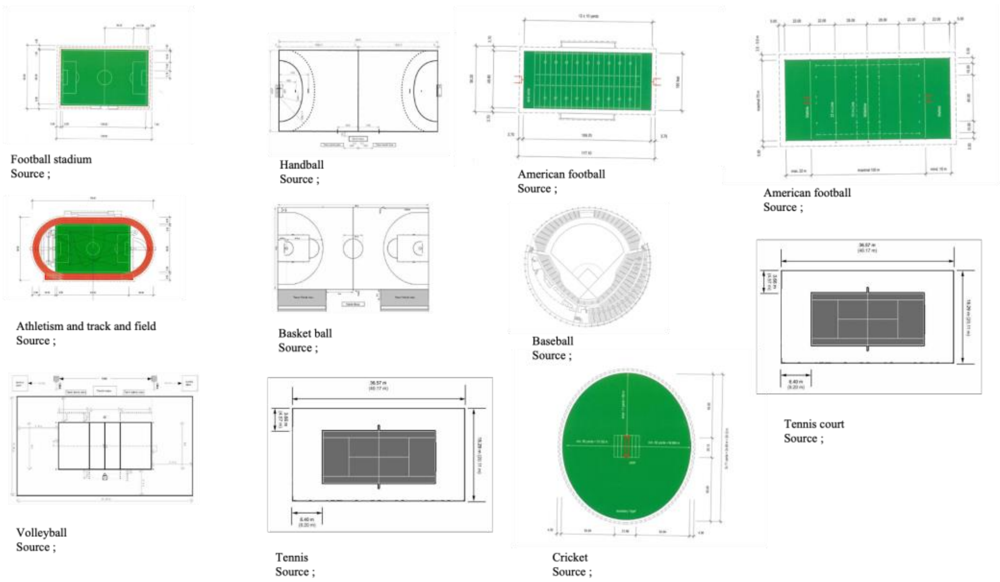


Figure 3.19: Types of Stadiums for Specific Sports (Mangaleu Toukam,2023)

3.3 Stadium Design Requirements

Standards and regulations in stadium design are important to ensure the safety and comfort of spectators (Sartori & Nienhoff , 2013).

Stadiums necessitate a thorough understanding of the design constraints that determine their form and function. The plan of a stadium for instance includes a careful balancing of several issues, from hosting large crowds to assuring safety, accessibility, and an exceptional spectator experience.

Stadium design criterial vary depending on the sport, function, and location of the stadium. When designing stadiums, some general design needs are usually considered. According to Sports (2023), Stadium design criteria should consider the following;

- Identify the purpose and requirements of the stadium, such as seating capacity, facilities, and amenities.
- Conduct feasibility studies, site analysis, and environmental impact assessments.
- Develop detailed architectural plans, including seating arrangement, entrances, exits, and amenities.
- Conduct structural engineering analysis to ensure the stadium can withstand the required loads.

It should be noted that modern stadiums are occasionally designed with a multi-use philosophy, although stadiums were historically primarily designed for one purpose (i.e., one type of sport, such as football or basketball). However, this is dependent on the type of the principal use. Baseball stadiums in North America, for example, have a specific layout and are frequently created exclusively for that sport.

However, so many different sports are supported and played in other nations, like Australia, the USA, England, and India. For example, a multipurpose stadium can be built with an oval field for activities like cricket and Australian Rules football, or it can be altered to accommodate rearranging the seating for activities like football, rugby league, or rugby union. Stadiums with several uses are more challenging to design and build than those with only one purpose, but they provide more flexibility and, in the end, generate higher revenues. To accommodate the space requirements of each sport, stadiums have been designed with a variety of features following certain regulations.

3.3.1 Stadium Design Regulations.

Stadium regulations and recommendations are design and construction guidelines that assist in protecting the health and safety of individuals who utilize them. Stadiums are subject to various regulations and guidelines imposed by local authorities, sports governing bodies, and safety organizations. Standards and regulations in stadium design are important to ensure the safety and comfort of spectators (Sartori & Nienhoff , 2013).

These regulations may cover aspects such as seating capacity, accessibility, safety measures, structural integrity, and environmental considerations. Stadium design regulations may also include requirements for field dimensions, playing surface materials, and spectator amenities. It is important for stadium designers to consider these regulations to ensure compliance and create a safe and enjoyable experience for athletes and spectators. These regulations cover a variety of conditions that have been described in established standards, technical manuals, and suggestions developed by specialists working on relevant committees.

Furthermore, these criteria are intended to guarantee that these recommendations may be applied to a variety of projects and budgets. Some of these rules will not apply to all stadiums as they differ in function and are adapted to contexts. Nonetheless, architects and stadium designers should select the ones that are appropriate for their setting.

While these principles are largely applicable to football stadiums, it should be emphasized that in many circumstances, a stadium must be used in other ways to ensure the long-term success of the project. As a result, the multi-use characteristics of stadium design and operation are also considered. While some of these needs require core, permanent stadium infrastructure, others can be met by modifying existing infrastructure and/or installing temporary overlay amenities. The most used and common requirements are that of The UEFA and FIFA which are mainly for football stadiums.

FIFA is the governing body for world football, overseeing international competitions such as the FIFA World Cup while UEFA, on the other hand, is responsible for the organization of European football, including the UEFA European Championship (commonly known as the Euro).

These governing bodies govern the football over the world. According to (Saumya, 2022) Both FIFA and UEFA play crucial roles in governing and regulating football. They establish rules and regulations, ensure fair play, promote development programs, and organize international and regional competitions. Their efforts contribute to the growth and global popularity of the sport.

3.3.2 Design Requirements that Affect Structure of Stadiums

The design requirements for football stadiums vary based on their category, with different guidelines recommended for each category of new-build stadiums. These principles can be used as a source of best-practice recommendations for any football stadium project, regardless of its location or level.

For the purpose of this thesis the requirements we will focus on the FIFA requirements (Table 3.2) as the research context explore football stadiums and factors that affect the overall structural system of stadiums design factors affecting the widespan of the said stadiums will be looked into.

Table 3.2: Summary of Technical Guidelines/Recommendations on Stadium Design. (According to Football Stadiums Guidelines – FIFA 2022)

General process guidelines	Initiation and feasibility	• Stadium vision • Climatic issues • Site selection • Project plan • Multiuse • Project team
	Design	• Design • Using technology • Stadium orientation • Stadium Bowl • Turf and pitch • Roof • Facade • Sustainability • Accessibility • Future plans
	Construction	• Construction stages • Construction provisions
		• Precinct and perimeter • Seating and standing

Technical guidelines	Stadium guidelines	• Pitch dimensions • Safety and security • Technical details
	Main users Group	• Main users Groups • Complementary functions
	Stadium Categories	• Categories 1-4

3.3.2.1 Primary Requirements

Primary requirements in stadium design refer to the fundamental criteria that directly influence the widespan structure of the facility, forming the essential backbone of its construction. These requirements are crucial for ensuring the structural integrity, safety, and functionality of the stadium. The widespan structure, which encompasses the roof and supporting elements, is pivotal in providing unobstructed views for spectators, accommodating large crowds, and offering protection from the elements. Engineers and architects must carefully analyze and integrate these primary requirements to create a stable and secure widespan structure that meets the performance demands of a stadium while adhering to safety standards and regulations.

3.3.2.1.1 Use of CAD

CAD tools play a crucial role in optimizing stadium designs by ensuring clear views from each seat and avoiding potential obstructions that could lead to financial losses for operators during construction. Joseph et al., (2014) states that ; applying computational optimization tools for sport stadium designs has become common practice. Contemporary stadium designs often incorporate parametric design tools to optimize two key aspects of stadium architecture: maximizing the number of seats and enhancing sightlines to the sports ground.

Controversially, nowadays stadiums focus on these Key design considerations including the orientation of the pitch, location of the main stand and broadcast camera positions, roof and facade design for visual appearance and protection, and capacity and design of the stadium bowl for spectator viewing. Instead of focusing on the structures first. Stadiums are now constructed and developed using CAD and advanced technology and consider all the elements of stadiums simultaneously.

According to Bellerby (2008), overcome the challenges encountered in previous stadium designs, it is becoming more and more crucial to employ 3D building information modelling (BIM) to expedite the workflow on stadium construction projects. The design phase is when 3D modelling is most advantageous, but it may also be helpful to all parties engaged in a building project. After modifications are made to the design lifecycle, the model may be updated automatically to enable effective progress tracking and sharing between all parties.

BIM technology is easier to design and work on even the most complicated building projects, including the modern stadiums. 3D BIM technology provides huge potential cost benefit and productivity (Bellerby, 2008).

3.3.2.1.2 Site and Location

In the last two decades, various scholars of planning and managing sports facilities have emphasized the importance of location and have described criteria related to site selection for sports facilities (Erturan-Ogut & Kula, 2022) .

In one of the early works by Miller (1997), a comprehensive list of factors essential for the selection of a sports facility site is presented. The criteria encompass considerations such as Plot size, expansion potential, adherence to zoning regulations, visibility, accessibility via public transportation, impact of surrounding traffic generators, security measures, weather conditions, climate, competitive landscape, demographic and psychographic aspects, environmental conditions, parking availability, growth trends, population shifts, incentives, workforce availability, established enterprise zones, and labor costs.

More recently, Arthur (2010) has underscored the significance of location selection for sports facilities, focusing on considerations such as cost-effectiveness, adherence to budget constraints, design quality aligned with market preferences, safety measures, and efficient energy control for maintenance, heating, lighting, and related factors.

Currently, the existing literature falls short in providing a thorough examination of the criteria that should take precedence over others when selecting sports facility sites. As Fried (2015, p. 114) states, "often site selection comes down to a 'gut' decision." Despite the rich descriptive work on sports facility location, the literature

Except the work of Kwon et al. (2020) – lacks a systematic categorization of factors, frameworks or methods to selectoptimal locations for sports facilities analytically. According to FIFA and UEFA regulations The potential locations for the new stadium can be divided into three categories: central urban, semi-urban, and out-of-town greenfield sites (Figure 3.20).

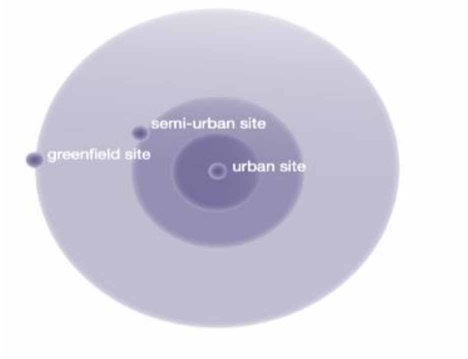


Figure 3.20: Categories for Stadium Locations (Mangaleu Toukam, 2023)

The specific location and other details of the site are crucial factors to consider in the planning and development of the new stadium. This factor can affect the type of widespan structure. Because for each category there is a different stadium need reflecting on its structure. For example In a more urban context the structure structural system might have to need to be covered to avoid noise pollution to the neighbors or in an greenfield area due to the need for urban regeneration the roofing might be opened affecting the structural system . Therefore the Site and location should be choose properly.

3.3.2.1.3 Stadium Orientation

The stadium's orientation is important to the overall design since it affects various elements such as the pitch, roof style, spectator viewing experience, and TV transmission. Stadium orientation is a significant criterion in many competitions and tournaments, guided by regulations and standards such as DIN (2003), Nixdorf (2007), FIFA Football Stadiums (2022), UEFA (2011), and Geraint et al. (2013). These guidelines define or recommend ideal orientations for stadiums, considering factors like sun exposure.

Specifically, they suggest slopes within certain ranges that deviate from the axis of operation in stadiums, which lies between the play zone and the North/South axis. To prevent athletes from being blinded by the sun, stadium site layouts should be arranged according to these preferred slopes. It is critical to consider the stadium's orientation in terms of direct sunlight and prevailing winds. This factor is critical for optimizing both sunshine exposure and natural ventilation on the playing field.

The design of the stadium roof and possibly parts of the facade should also be taken into account, taking into account the potential for unwanted heat gain to internal areas. The extent of shading and/or wind protection from existing developments and topographical features should also be evaluated.

The massing of the stadium is also likely to be influenced by the potential to cause a reduction in light levels to neighboring buildings, which can affect the massing and orientation of the stadium (Figure 3.21).

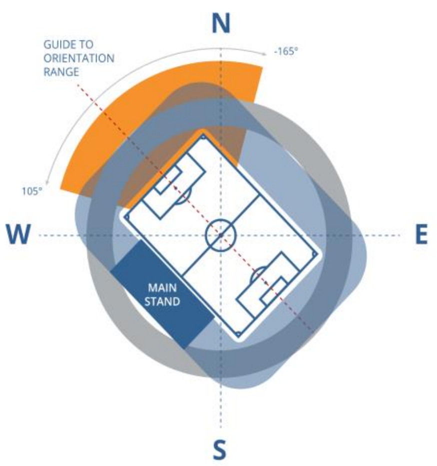


Figure 3.21: North-South Axis Orientation for Acceptable Range of Orientation Nixdorf (2007).

3.3.2.1.4 Capacity of Stadiums

Stadium capacity is a fundamental consideration in designing the stadium bowl, with both gross and net capacities being reviewed The most characteristic and noticeable feature of football stadiums is their size.

UEFA's and FIFIA regulations categorize these stadiums into four categories (1, 2, 3, 4) or label them as uncategorized, based on specific qualitative and quantitative requirements related to infrastructure and equipment (Table 3.3). These requirements encompass aspects like the playing field, access and exits, lighting, safety and security, parking spaces, and spectator areas, detailed in UEFA's regulations (UEFA, 2018).

Also UEFA (2018) adds that , These regulations do not specify the capacity of stadiums directly, but rather focus on the minimum structural criteria that need to be fulfilled for a stadium to be classified into a particular category . However, the regulations do mention that the relevant UEFA competition regulations may define further and/or stricter structural criteria for the required category, which could potentially include capacity requirements.

Table 3.3: Classification of Stadiums According to UEFA Standards.

Category	Minimum capacity	Intention
1	40,000	Very large professional football venue capable of hosting the largest clubs and major international competitions (e.g. FIFA World Cup finals matches)
2	20,000	Large professional football venue capable of hosting large club matches and international competitions
3	10,000	Medium professional football venue capable of hosting club competitions and smaller international competition finals (e.g. youth tournaments)
4	3,000	Small professional football venue capable of hosting smaller club matches and smaller international competition group stages (e.g. youth tournaments)
5	250	Minimum FIFA standard for any football stadium, including development group and community use

3.3.2.1.5 Stadium Structure

The forces generated by the weight of the seating structure, roof and other loads. The structural systems of stadiums show significant variations especially in mass, stiffness, and damping. These variations are the product of several factors: the uneven distribution of the crowd occupying the structure, the inherent capability of the human body to absorb energy, the interactions between people, and also the motion differences within their own body (posture and reaction to different events) (Çatbaş et al., 2017).

The stadium structures built earlier and the structures built in the recent times reduces the ratio of dead load/live load more than 100 times. This is due to the effective exploitation of the properties of high strength materials and new materials (Kumavat, 2021).The stadium overall structure relies on a network of beams, columns and supports that provide stability and distribute load. These elements are typically made of steel R. C and are designed to withstand

Also (Çatbaş et al., 2017) states that technologically advanced stadiums have been designed and constructed using structurally innovative methods. Hence we can deduct from this that the structure of a stadium can vary greatly depending on factors like size, purpose, location, and architectural style. However, there are common components and features that are typically found in stadium structures. Here are some key elements:

3.3.2.1.5.1 Span Length

Widespan structures are characterized by their large clear spans. In sports complex most of the structures have wide spans due to the provided fields, tracks or courts provided, which results in widespan buildings Kumavat (2021).

Baldwin(2022) states that “stadiums reveal widespan solutions that amount to innovative roof design.” The design must ensure that the span length is sufficient to accommodate the seating area, as well as any other features like hospitality suites, concourses, and amenities. Stadium design must find a balance between offering an entertaining experience for fans, assuring structural integrity, housing an adequate number of seats, and remaining within price limits. Stadium designers take these aspects into account carefully in order to develop facilities that fulfill the demands of both teams and spectators. The way span affects stadium design can be understood in several ways:

3.3.2.1.5.2 Roof Design

Nixdorf(2007) states that *" Modern stadia are incorporated with roofing systems in order to provide comfort for spectators and fulfil the requirements and regulations established by different sport federations "*

According to Geraint et al., (2013), *'nine principle structural forms are defined for stadiums roof structures: Goal Post structures, Cantilever structures ,Concrete shell structures, Compression/Tension Ring, Tension Structures, Membrane structures, Air-supported roof, Space Frames, Opening/retractable Roofs'.*

According to Tran et al.(2021) The climatic zone and the economic growth of the place or country determine the roof type for stadiums. Open or partly covered stands are more typically selected in developing countries such as Central and South America and Africa. Countries such as Canada and Russia, on the other hand, often demand fully covered stadiums, particularly in colder climates as enclosure tendency is especially noticeable in colder where winter athletic events are prevalent.

3.3.2.1.5.2.1 Evolution of Stadium Roofs

The Origins can be traced back to ancient times when roman covered their theatres, amphitheater and circus with foldable awnings. They used simple systems for unfolding the roofs. The roof provides natural conditions for grass growth in the pitch inside the building, and to provoke different perception and experience of people. (Kumavat, 2021)

Stadium requires an unobstructed view and lightweight roofing (structurally) .Over time, the roof systems in stadiums have evolved, and there have been significant changes in their designs. In the early days, stadium structures were designed with a 'U' shape, but as time passed, the forms evolved, and this transformation has contributed to the advancement of roof systems (Figure 3.22).

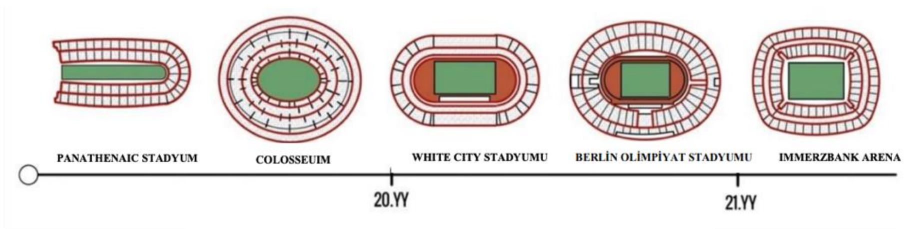


Figure 3.22: Stadium Roof Forms (Gürer & Arslan, 2020)

The primary goal of roof design and construction is to lower the structure's dead load and the ratio of dead to live loads. Structures built earlier and structures built recently have reduced the dead load/live load ratio by more than 100 times. The development of BIM-based programs has also enabled precise detailing of how the designs and materials of each roof ought to be, resulting in more unique and stadium roofs. This different development has formed to various cover systems.

There are many structural systems for stadium roofing. According to Geraint et al., (2013), nine principle structural forms are defined for stadiums roof structures:

- Goal Post structures
- Cantilever structures
- Concrete shell structures
- Compression/Tension Ring
- Tension Structures
- Membrane structures

- Air-supported roof
- Space Frames
- Opening/retractable Roofs

Every structural system has its own set of characteristics and constraints. There are several design criteria for stadium roofing, as well as numerous considerations to take while developing and implementing an acceptable structural system for a specific stadium. Also Covering materials depend on the roof type, roof design. Varies depending on its occurrence.

3.3.2.1.5.2.2 Roof Span

The span of a stadium's roof is a critical factor in stadium design. A larger roof span allows for a larger, more open interior space, which can provide better sightlines for spectators and accommodate more seating. It also affects the aesthetics and the ability to cover the playing field and spectators, providing shelter from the weather. However, a larger span requires more substantial structural support, which can increase construction costs.

3.3.2.1.5.3 Façade

Gehl (2010) defines the façade as "the transition zone between the subjective and the public spaces", that is, an interface. From this point of view, the façades are important as the element of architecture where the people living in the city interact with the structure.

In a similar way, Şenyiğit (2010) expressed that "Façades are the peripheries of urban spaces and in this sense, they are the elements that limit urban spaces".Despite many studies conducted on how people perceive the façades of buildings, there is no specific research on stadiums. The competitions for the most popular or best stadiums held every year are based on visual surveys, and especially people who have not studied architecture evaluate these stadiums looking at their façades. (Arslan & Yıldırım, 2023) .

3.3.2.1.5.4 Seating Arrangement

The choice of seating and its configuration within the stadium bowl should be evaluated at an early stage of the design process, considering factors such as comfort, safety, and the local climate. Also, The local climate can influence seat choice and color, with certain materials and construction methods being more effective in different conditions. UV stability of the materials should be reviewed in high UV level conditions (FIFA 2022). Other factors are as follows;

3.3.2.1.5.4.1 Viewing Distances

According Nigar et al. (2017) The recommended viewing distances for different sports in Olympic stadiums are defined or recommended in regulations and standards such as BSI, FIFA, Nixdorf, and Geraint et al.

A good view clearly depends on how far the seat is from the action. A tight bowl configuration will aim to bring even the most distant seats as close as possible to the pitch, increasing viewing quality and helping to create a “cauldron” effect. The aim should always be to keep theseats within the maximum distances set out by UEFA and FIFA regulations. Determining maximum viewing distances and viewing angles is a purely mathematical problem.

The "calculation of maximum viewing distance is based on the fact that the human eye finds it difficult to perceive anything clearly that subtends a angle of less than about 0.4 degrees" (John et al., 2007).

The optimum viewing distance for seats in the stadium bowl is within an arc of 150m from the far corner of the pitch, and the maximum distance is within an arc of 190m from the far corner of the pitch (Figure 3.23) . Where possible, the footprint of the stadium bowl should not exceed the optimum or maximum viewing distances.

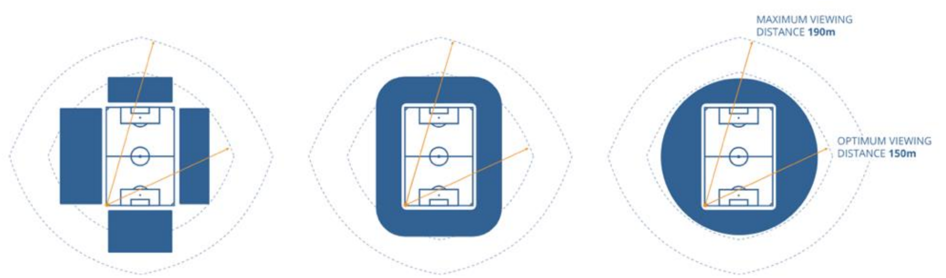


Figure 3.23: Optimum and Maximum Viewing Distances for Seating Within Various Stadium Bowl Layouts (FIFA , 2022).

3.3.2.1.5.4.2 Sightlines

In the stadium bowl's design process, it's important to consider various factors, including potential requirements for wheelchair users and ambulant disabled spectators. Additionally, the impact of potential obstructions, such as advertising boards, on spectators' sightlines should be taken into account.

The C-value is a measure used to judge the quality of spectators' views of the field of play. This rating assesses the clarity of the vision to the neighboring side or goal line, as well as the level of obstruction produced by the spectator in the row directly front.

The ideal C-value is 120mm, while C=60 is the minimum recommended value. The stadium bowl design team must determine the C-value in order to determine the profile of the tiers. The calculation shown in (Figure 3.24) should be used to calculate the riser height for each row required to attain the specified C-value (FIFA, 2022).

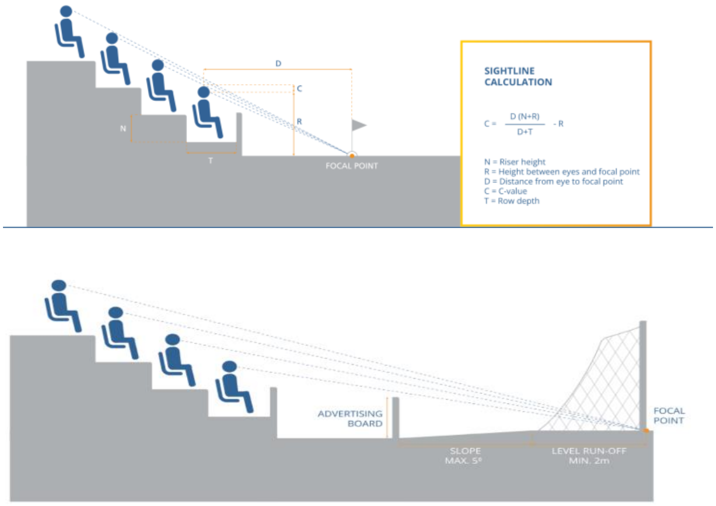


Figure 3.24: Sideline Calculation. (FIFA, 2022.)

3.3.2.1.5.4.3 Seating Area

According (Tran et al., 2021) an essential requirement is to have a diversity of seating and maintain a clear seat-way to allow the movement of spectators along the seat row. There are a wide range of seat selections in terms of materials, types of seats, retractable or fixed, and dimensions (Figure 3.25).

- ADA: special seating or space for wheelchairs is required; area also has to be easily accessible.
- Regular: treat fixed, riser fixed, nose fixed with arms or bench seat.
- VIP: provide private viewing or high standard seats.

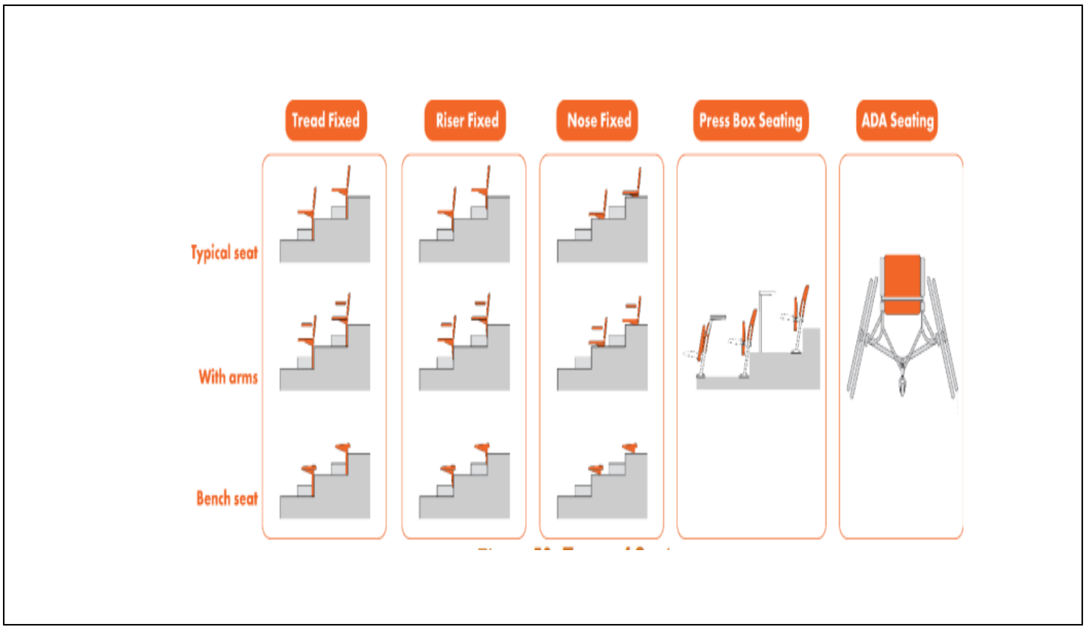


Figure 3.25 Types of Seats (Tran et al., 2021)

In accordance with FIFA regulations, seats must possess fire-resistant properties and endure the challenges of the prevailing weather conditions without significant deterioration or color loss (FIFA, 2007). Specific dimensions for seats have been outlined to ensure the comfort of spectators.

The regulations pertaining to places of assembly specify a minimum seat depth of 40 cm and a tread of 40 cm, resulting in a total seating/standing width of 80 cm (MVStattV, 2005). Similarly, FIFA mandates a minimum seat depth and tread of 40 cm each. Additionally, FIFA sets the minimum width at 45 cm and recommends a minimum width of 47 cm for each seat (Figure 2.26). Conversely, Nixdorf (2008) proposes the following dimensions for seating arrangements: Regular seat: 50 x 80 cm, Executive seat: 60 x 90 cm, Wheelchair: 90 x 150 cm, Media/press: 50 x 150 cm, Commentators: 160 x 180 cm.

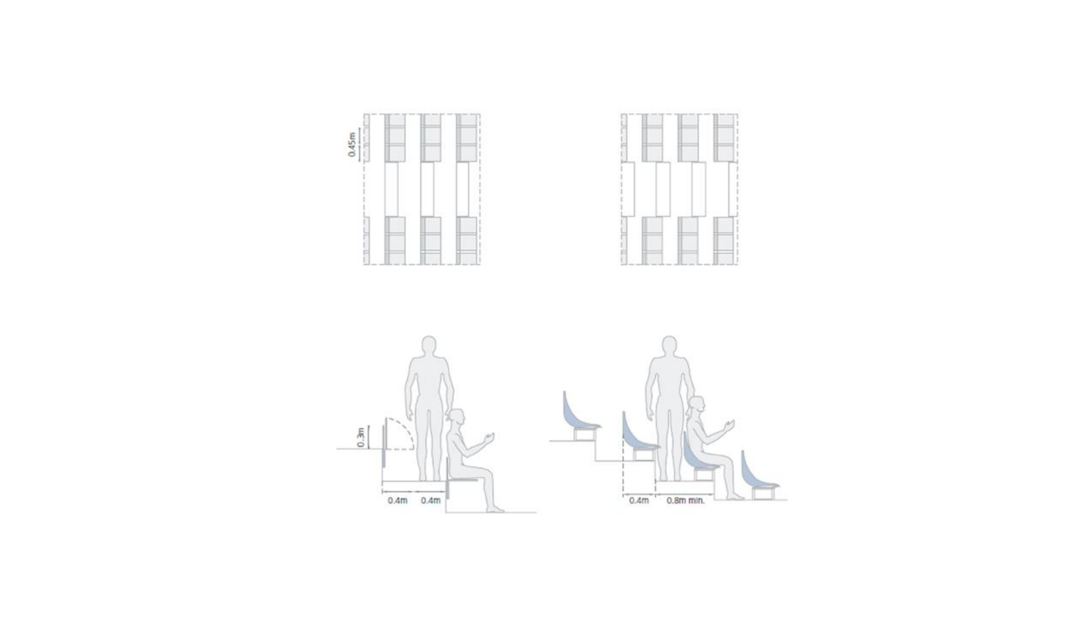


Figure 3.26: Diagram Illustrating the Required Width and Depth for Seats by FIFA (FIFA, 2007, p. 106).

3.3.2.1.5.4.4 Stand Design

The seating area, commonly referred to as the auditorium, is an inclined construction created to host observers who have the option to either stand or sit while viewing an event. This arrangement comprises different levels with diverse capacities and design principles. Nixdorf (2008) categorizes nine basic grandstand configurations employed in the design of stadiums. These configurations essentially depict geometric alterations of either rectangular or circular forms (Figure 3.27).

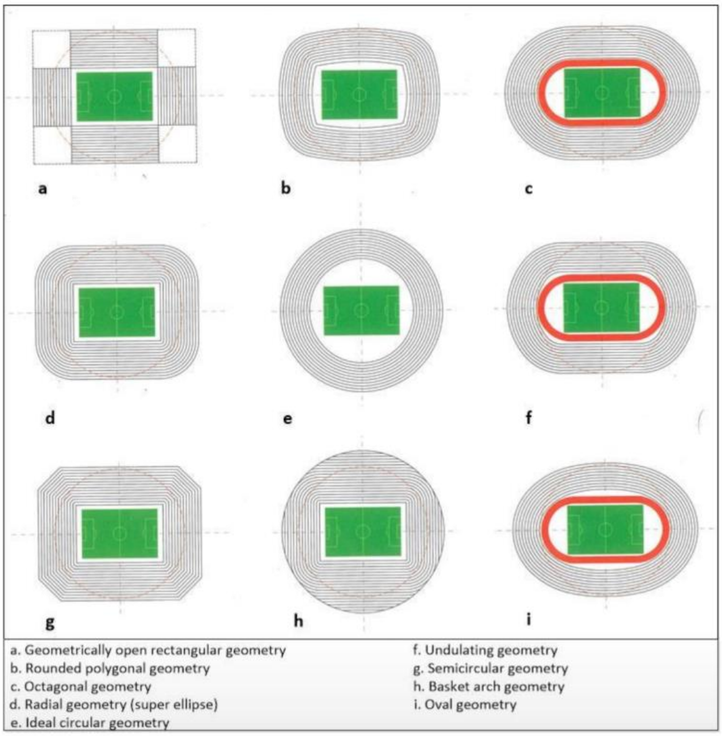


Figure 3.27: Types of Stands Layouts for Stadiums (Nixdorf, 2008, p.143).

The layout arrangement must be optimized for sightlines, accessibility, and comfort for spectators. It should provide unobstructed views of the playing field or event.

3.3.2.1.6 Designing the Stadium Bowl

According to (FIFA, 2022c), Stadium capacity is a fundamental consideration in designing the stadium bowl, with both gross and net capacities being reviewed.

The starting point of any stadium bowl design is to define the stadium's capacity. After the pitch, the stadium bowl is the most important element of any football venue. The characteristics of the bowl will go a long way to determining the quality of the spectator experience in terms of comfort, view atmosphere and "connection" to the action on the pitch. A good bowl design should satisfy three requirements , safety, visibility and comfort.

3.3.2.1.7 Pitch Design

Pitch design is an important aspect of stadium construction, as the quality of the pitch affects the overall performance, appearance, and reputation of the stadium (FIFA, 2022a).

The pitch is the bottom of the bowl and its dimensions determine which activities can be accommodated according to the spatial requirements The soccer field, or the "field of play," is a rectangular space enclosed by goal lines and touchlines. The recommended dimensions for the field are 105 meters in length and 68 meters in width (FIFA, 2022a).

It's essential for this area to be delineated with continuous lines that denote the areas they bound. Only lines specified in Law 1 of the Laws of the Game should be present on the field of play.The field of play must maintain a level surface without any undulations. The grassed area should be ample to ensure player safety by allowing enough room in front of advertising boards and preventing an abrupt surface change immediately beyond the touchlines or goal lines, which could potentially affect a player's footing.

The pitch holds significant importance within a stadium, serving as the primary focal point. In many ways, the pitch can be likened to the central stage where the main events unfold (Figure 3.28).

Figure 3.28: Turf and Pitch Organization (FIFA, 2007)

A stadium can be designed and arranged to accommodate a wide range of events besides football. Here are some general principles that can be applied to create a versatile stadium that can host a variety of events:

- Flexible Seating
- Multipurpose Spaces
- Lighting and Sound
- Accessibility
- Backstage Areas

- Parking and Transportation

By incorporating these principles into the design and layout of the stadium, it can become a versatile venue that can host a wide range of events and activities and the purpose of the activities makes the structural system specific for each case (Figure 3.29).

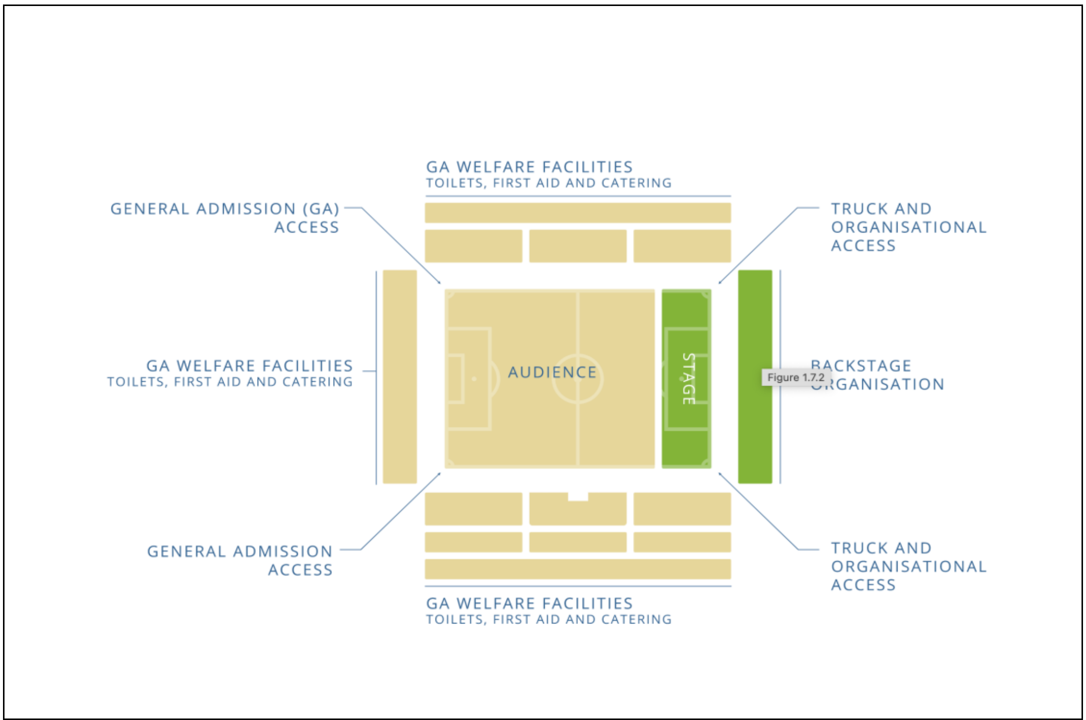


Figure 3.29: Pitch Arrangement in a Multipurpose Stadium in a Case of Concert (FIFA, 2007)

Complementing the primary design specifications. While primary requirements address the fundamental features and core functionalities, secondary design requirements are aspects that enhance usability, aesthetics, and user satisfaction. These considerations go beyond the basic functionalities, focusing on elements such as user interface design, accessibility, scalability, and adaptability.

3.3.2.1.8 Security and Safety

A well designed stadium should have robust security measures, including surveillance, crowd control, and emergency evacuation plans to ensure the safety of attendees. According to the literature, there have been instances of fan accidents during and after sporting events due to various reasons such as flying objects, falls, or poor management by facility managers.

During the early design phase, it is critical to design the stadium's location on its site and comprehend the links between its key components. It is recommended that a plan layout consisting of five safety zones dividing the stadium into five main portions be employed in this regard (Geraint et al., 2013; Nixdorf, 2008) (Figure 3.30).

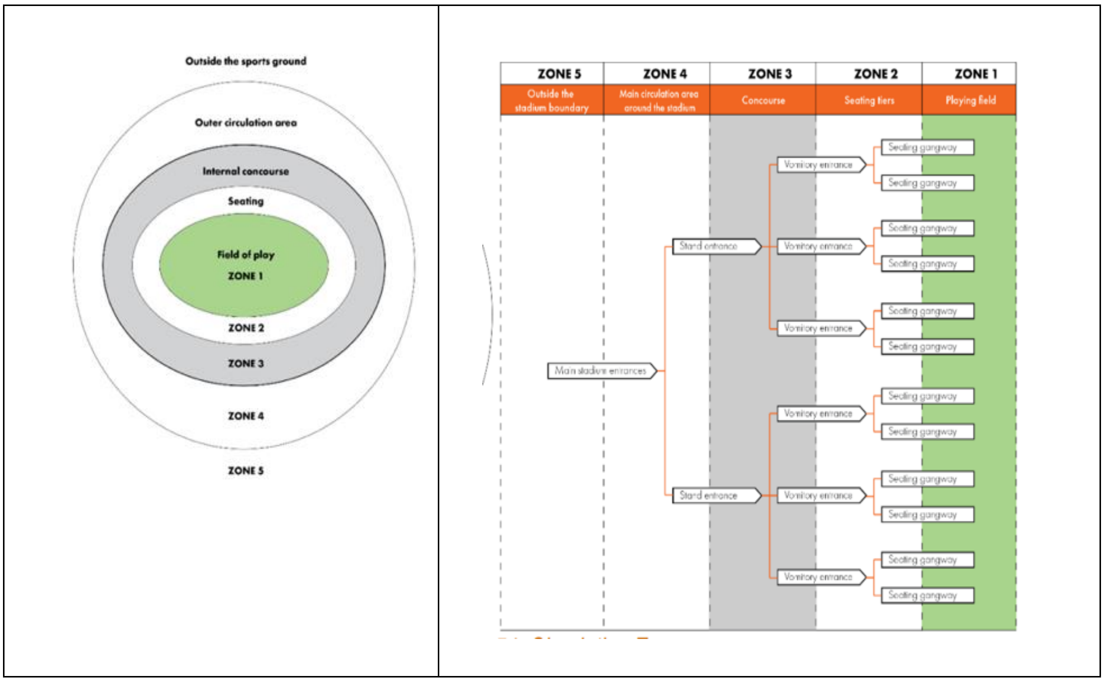


Figure 3.30: Safety Zones/Circulation Zones (Geraint et al, 2008 p,31)

The term "zone" in this context, according to Geraint et al. (2013), refers to a schematic representation of a ring-shaped security belt architecture depicted in.

The regulations focus on five main areas that form the basis for creating a safe stadium, with a particular emphasis on five safety zones. Figure 9.0 shows these zones, which are precisely constructed to assist the safe evacuation of spectators, including those with impairments, in the event of an emergency. They can move from their areas to designated safety zones thanks to this arrangement. The underlying approach entails first reaching intermediate safety zones and then moving to places of long-term safety located outside the stadium grounds.

- For Zones 4 and 5 A belt of space is provided for the spectators easy access from their cars in Zone 5 to the proper entrance in Zone 4, which connects to Zone 3 and then to Zone 2 where their seats are placed. Zones 4 and 5 must allow for simple circling of the stadium to ensure that spectators can easily reach the right gate.
- Zone 5 is a permanent safety zone with no vehicles and direct and easy access. Its effective area should be large enough to handle the majority of the stadium's populace, and the zone's recommended density, including the surrounding roadways, is 4 to 6 persons per square meter.
- Zone 4 operates as both a perimeter zone and a security checkpoint, where access is restricted to those with valid tickets. This zone additionally functions as a transitional safety area positioned between Zone 3 and Zone 5. Spectators have the option to evacuate from the stadium to Zone 4 and subsequently proceed towards the enduring safety haven in Zone 5.
- Zone 3 is an internal concourse and social space equipped with rigorous fire safety measures, allowing a large number of spectators to safely migrate towards the ultimate places of refuge in Zones 4 and 5.

- Zone 2 is a relatively secure sector composed of viewing terraces separated from the performance zone by fences. Crowd control and smooth mobility must be considered in the design of these barriers to guarantee that spectators can quickly exit during fires or other crises, reaching Zone 1.
- Finally, Zone 1 acts as the primary core, acting as both a performance space and a temporary safe zone. The escape paths and barricades are precisely planned to provide fans access to the playing field area in the event of an emergency.

Safety and security are critical aspects in stadiums, and it is essential to ensure the well-being of everyone who enters the venue. Ensuring the safety and security of all individuals within a football stadium is of utmost importance in both the design and management of the facility, regardless of available funding. Adherence to Safety Regulations is crucial to guaranteeing the safety of all individuals during events. The stadium must meet the safety standards of local authorities and international best practices, which are widely recognized as the norm. This includes all areas, such as entrances, exits, stairways, roofs, and public/private areas. There are different codes and practices available for stadium design, and if any are used, they should be appropriately referenced in the stadium records.

3.3.2.1.9 Aesthetics

Interaction Design Foundation (2016) defines Aesthetics as core design principle that defines a design’s pleasing qualities. In visual terms, aesthetics includes factors such as balance, color, movement, pattern, scale, shape and visual weight. Designers use aesthetics to complement their designs’ usability, and so enhance functionality with attractive layouts. The design should consider aesthetics to create an iconic and visually appealing stadium. This may involve the use of architectural features and materials that contribute to the stadium's unique character.

3.4 Future Stadium Use and Adaptability

Considering future growth and development is crucial in the detailed design of a stadium, including increasing seating capacity, modifying hospitality concepts, enhancing player areas and spectator facilities, and upgrading building systems, to extend the stadium's economic lifetime (FIFA, 2022b).

For many years, the trend with sports arenas has been moving away from single-use (The Future of Sports Venues Is About Creating Vibrant, Multiuse Districts, 2023). Stadium design should allow for future expansions and adaptability to accommodate changing needs and technologies. it is essential to give full consideration to possible future use.

When reviewing how a stadium might grow and develop over time, there are two forms of change that can be considered (FIFA, 2022b). The considerations are;

- Temporary expansion, which is designed to be a reversible change using the concept of overlay. This is often associated with the temporary expansion of facilities for a major tournament or event, where a temporary increase in capacity of the seating bowl and other facilities can only be justified for a one-off event. These "overlay facilities" are then removed after the event to leave the existing stadium infrastructure operating as before.
- Permanent expansion, which is designed to be a permanent change. This involves increasing the capacity of the seating bowl and making modifications

to various areas of the stadium, such as hospitality concepts, players' areas, spectator facilities, and MEP systems in the building.

Any plans to use the venue for non-football purposes also need to be given careful consideration, as these may have major effect on planning requirements, although this is generally less relevant for small stadiums. If there are plans to install an athletics track around the perimeter of the pitch, this may have a considerable bearing on the overall design parameters. Careful thought needs to be given to how this will impact on factors such as net capacity, sightlines, viewing distances, etc. Leading to the aspect of Future stadium we could discuss Technological advancements trends in Stadium construction.

3.4.1 Technological Advancements Trends in Stadium Construction

Technology constitutes a key social and cultural component in the creation and maintenance of the built environment. In the past years, the construction materials and approaches applied led to a detrimental environmental impact, while an ongoing population growth takes place.

The evolution of stadium structures in design has undergone significant transformation over time. In the early periods, stadiums lacked seating units and featured open tops. However, contemporary stadium structures prioritize user comfort and are equipped with advanced features to address adverse weather conditions.

Technological advancements have played a crucial role in this transformation, allowing for the development of stadium upper roofs that can be partially or fully closed or opened, incorporating efficient closing systems. The historical significance of Ancient Greek and Roman stadiums laid the foundation for iconic structures, while the growing interest in sports, particularly football, has driven continuous innovation in stadium design.User needs and the changing landscape of technology have propelled stadium structures to evolve both functionally and aesthetically. The financing of stadiums by clubs, coupled with larger budgets, has further fueled this evolution. The popularity of stadiums has surged due to the integration of developing technologies, increased material diversity, and the application of Building Information Modeling (BIM).The incorporation of these elements in design has not only made stadium structures more functional but has also elevated them to iconic status, capturing the attention of fans and enthusiasts alike. The contemporary approach to stadium design reflects a harmonious blend of form and function, making them integral and celebrated elements in the realm of sports architecture (Mangaleu toukam, 2023).

Stadium design is evolving – these buildings are moving away from the once a week usage of times gone by. Now stadiums are focal points within the community for regeneration and development. Once a powerhouse of structural engineering that were largely environmentally uncontrolled, these buildings are now advancing to create high performance spaces to suit a variety of needs. Be it a state of the art media center, a VIP viewing room, restaurant or at the heart of it, creating an unforgettable experience for the fans with an exciting atmosphere that lingers long after the game has finished.

Today, designers and engineers involved with stadium design and construction are looking more and more towards new technologies in order to improve stadium functionality, design, overall look, environmental footprint and long term sustainability. This has led to incorporation of many new and unique elements in modern stadia as engineers look to create the most memorable, sustainable and environmentally sensitive stadiums.

Technological innovations have led stadia to focus on more sustainable designs and incorporate renewable resources and energy whenever they can. Three examples would be looked on to and it will show us how technology has advanced and serve as an introduction to see possibilities on how technology can be used in our case studies. The three examples cover , modular design advancement, Design and structural modifications and material (Mangaleu Toukam, 2023).

3.4.1.1 Modular Design Advancement Project Details

Name: Stadium 974

Location : Ras Abu Aboud, Doha, Qatar

Capacity: 40,000

Year of Completion: 2021

Client: Supreme Committee for Delivery & Legacy

Architect: Fenwick Iribarren Architects

Architect of Record: Meinhart Group

Structural Engineer: Schlaich Bergerman & Partners

MEP Engineer: Hilson Moran Engineers

Project Management: TIME Qatar

Design and Build Contractors: HBK Contracting WLL (Qatar)

Construction Supervision: WSPe

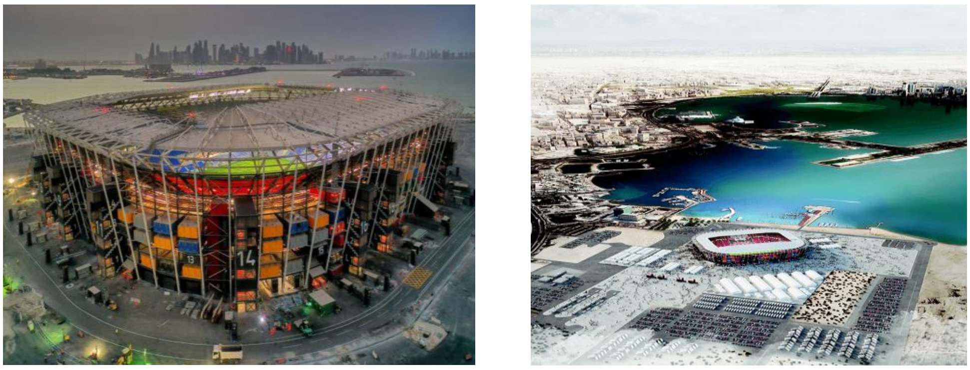


Figure 3.31: Stadium 974,Qatar (World & Elengica, 2022)

The Stadium 974 in Qatar (Figure 3.31), is designated for the FIFA World Cup Qatar 2022TM, is an innovative 40,000-seat facility entirely constructed using modular components, involving approximately 1,000 shipping containers. Modular structures are widely adopted in the sports events industry due to their heightened flexibility compared to conventional construction methods. Situated by the sea, this stadium leverages its location to facilitate the loading and unloading of stadium containers.

Modular design entails creating initial or permanent stadium structures that can be later adjusted. The primary objectives include cost reduction (both in capital and operational expenditure), enhancing short-term flexibility, efficient stadium utilization, and minimizing waste tied to constructing structures and systems that aren't extensively required throughout a stadium's lifecycle. This approach aligns with the evolving trends in sustainable and adaptable stadium construction (FIFA, 2022b).

The architects have envisione' two scenarios on this topic, where in the first case, the stadium's components would be restructured to build smaller venues, in countries in need of sporting infrastructure, whereas the second course of action would see the structure effectively reconstructed at a different location Elengical (2022).

The stadium was built from 974 shipping containers coupled to a steel structural frame, making it extremely lightweight and versatile, with modules that can be relocated in and out as needed. This concept embraces the trend of shipping container architecture on a never-before-seen scale.This stadium necessitated the use of two distinct modular design concepts(Figure 2.32). The first was to create a grid column-and-beam structure (Meccano concept), while the second was to have modular volumes for the stadium’s many functions (Lego concept).” Following the competition, the stadium will be dismantled and repurposed for both football-related and non-sporting purpose Elengical (2022)

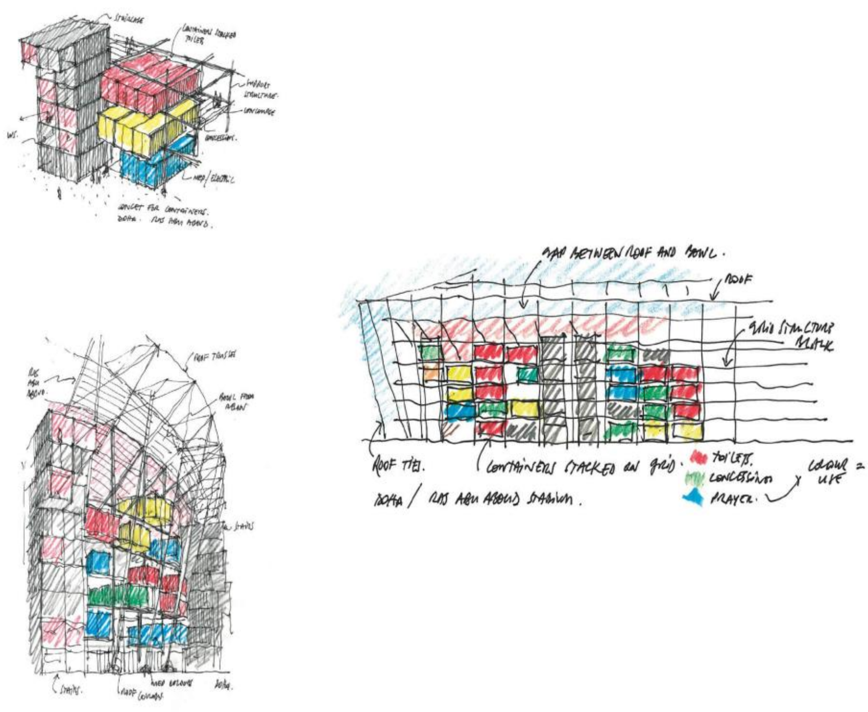


Figure 3.32: Concept of Stadium 974 (World & Elengica, 2022).

The structural members were created with specialized bolted node connections that were created just for this purpose, and they were intended to be bolted together (Figure 3.33). With the exception of the corners, where the grid is radial, the grid enclosing the structural design is 9 meters by 8.5 meters in plan. Where appropriate, the façade's angled steel columns and steel bracing provide extra strength. The stadium can be put up using only 10 different components, which shows how dedicated the architects were to their original concept.

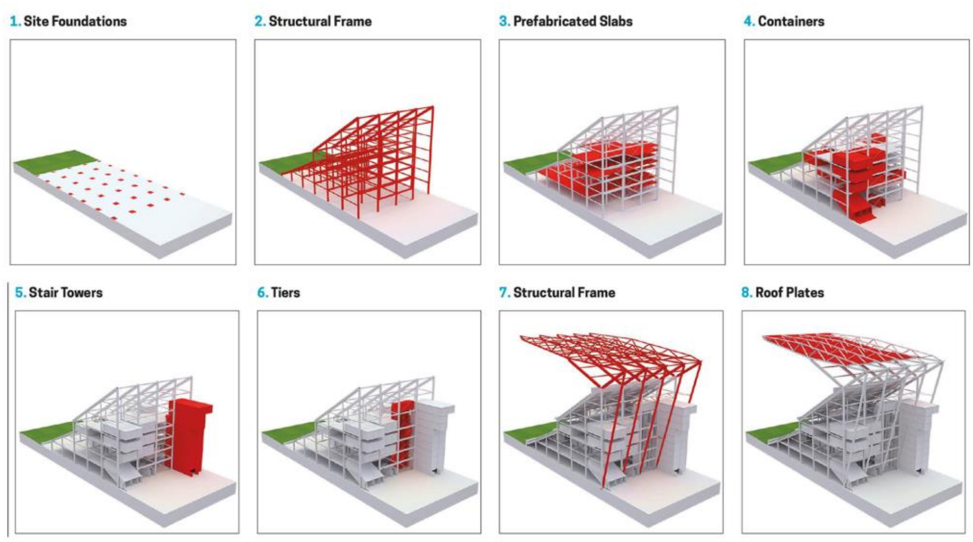


Figure 3.33: Diagram of Construction Stadium 974 Process Elengical (2022)

3.4.1.2 Structural Design Advancement Project Details

Project Details

Name: Al Janoub Stadium

Location: Qatar

Capacity: 40,000 could be reduced to 20,00

Year of Completion: May 2019

Client: Supreme Committee for Delivery and Legacy of the 2022 FIFA World Cup Qatar

Architect: — Zaha Hadid Architects (ZHA), Aecom

Structural Engineer: Schlaich Bergerman & Partners

Architect and lead designer: Zaha Hadid Architects

Design: Zaha Hadid, Patrik Schumacher

Project director: Jim Heverin

Project Associate / Project Architect: Johannes Hoffmann

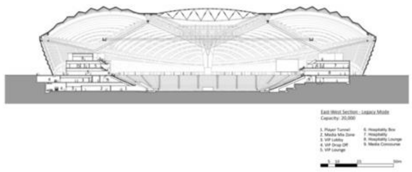


Figure 3.34: Al Janoub Stadium Roof (Zhen, 2022).

Al Janoub Stadium was the first new venue commissioned in 2013 for the 2022 FIFA World Cup in Qatar. The stadium has an operable fabric roof and cooling technologies. When deployed, the roof operates like a sail to shade the field of play. The client asked the design reflect Al Wakrah's maritime heritage, in particular, the dhow — a traditional boat of the region. The stadium's roof design is an abstraction of the hulls of dhows turned upside-down and huddled together to provide shade and shelter (Baldwin, 2022).

Schlaich Bergermann Partner developed the stadium's revolutionary roof, as well as the seating bowl's cooling system. These advances allow the stadium to be used even during Qatar’s scorching summers, representing a huge technological breakthrough in stadium construction. While the technology employed in the stadiums is based on known HVAC and air conditioning methods, Qatar’s cooling team has taken a unique approach that may not be immediately evident to many specialists in the industry(Figure 3.35 , 3.36and 3.37). This strategy represents a forward-thinking approach to solving the issues of maintaining comfort in such settings.

Preventing Hot Air Infiltration

A

Figure 3.35: Janoub Stadium Roof Deflecting the Outside Warm Air (Zhen, 2022)

Spot Cooling

B

Figure 3.36: Supply Vents Underneath the Stadium Seats (Zhen, 2022)

Figure 3.37: Football Stands Airflow Pattern (Zhen, 2022)

The cover works together with air diffusers and under-seat cooling nozzles to circulate cool air around the stadium, which is collected in the bowl. The stadium's cool air will be re-cooled and returned back into the stadium.

Qatar has a hot climate in general. The stadium's cooling is accomplished by a combination of shade, aerodynamic, and mechanical cooling, all of which are meant to keep the field of play at an optimal 26oC and the stands between 24oC and 28oC. Mechanical cooling from below the chairs will consume a lot of energy, especially if the event is held in the summer.

In order to minimize the amount of energy required, the structure is designed to do as much of the work through shading and aerodynamics as possible. "The starting point was to use as much of the roof and geometry to shade as we could,"(Zhen, 2022).

3.4.1.3 Material Advancements

National Aquatics Stadium – Beijing, China

Project Details

Name: National Aquatics Stadium – Beijing, China

Location: Beijing China

Capacity: 40,000 could be reduced to 20,00

Completed: 2008 in 6 months

Architect: PTW

Architect of Record: China Construction Design Institute (CCDI)

Structural Engineering: ARUP

Construction Engineering: China State Construction Engineering Co (CSCEC)

Client: Beijing State-Owned Assets Management Co

Figure 3.38: Beijing National Aquatic Center (Zhen, 2022)

The National Aquatic Center, also known as the “Water Cube,” was conceived and built for the 2008 Summer Olympics in Beijing, China. This architectural marvel embodies a fusion of innovative design, sustainability, and practical engineering.. The stadium was designed and built by PTW architects, an Australian architectural team who won a competition to design the new Olympic Games stadiums in Beijing. The Water Cube is distinguished by its distinct features and is intended to harness diffuse natural light due to its building materials. The novel ETFE (ethylene tetrafluoroethylene) façade, which resembles blue bubbles, functions as a natural greenhouse (Figure 3.39). This translucent material allows daylight to penetrate the inside while also acting as an insulator to passively warm the building and pool water. This environmentally friendly method resulted in a 30% reduction in energy use, which is equivalent to covering the entire roof with photovoltaic panels.

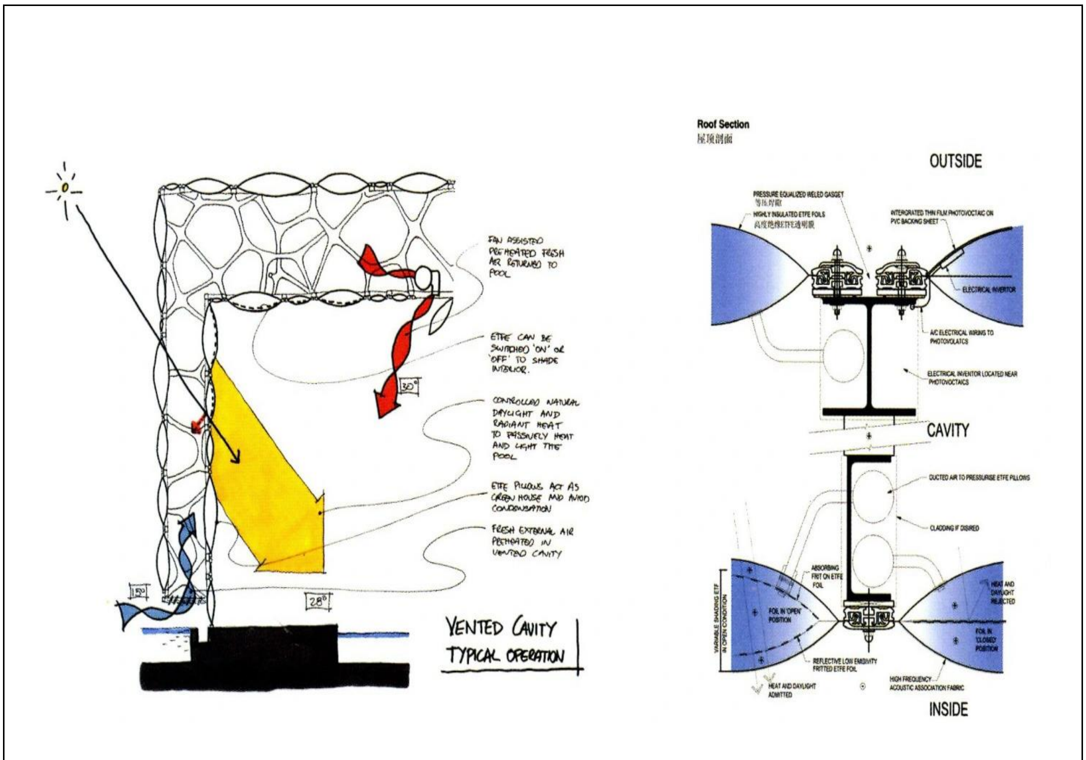


Figure 3.39: Façade Detail Beijing National Aquatic Center(Zhen, 2022)

The bubble cladding lets in more light than glass and thoroughly cleans itself with every rain shower. The primary structural support system features a “soap bubble” pattern predominantly made of steel, complemented by ETFE cladding panels wedged between the steel components. This arrangement safeguards the steel from external atmospheric elements and the internal corrosive atmosphere generated by the swimming pool's chemicals, such as chlorine.

3.5 Chapter Summary

Stadiums have seen a significant metamorphosis in terms of design and technical elements during the last 120 years. Since the turn of the twentieth century, stadium evolution has been highlighted different phases marked by innovative materials, building processes, and a renewed emphasis on increasing the spectator experience. Stadiums now are not just for international games, but also for teams competing in national and regional leagues.

Stadiums have come a long way from their origins . it is seen that there are formal differences, differences in design and function between ancient stadiums and modern there are similarities. Evolution of stadiums are a catalyst for the way that stadiums are both designed and function today, and many of these old and early practices or concepts are still in use in some form or another. The ancient Roman Empire had a significant impact on modern day stadiums, especially the way in which they operate, and this legacy will continue into the future through their evolution and reinterpretation of many of the concepts initially applied by these stadium pioneers. Advancing technology and a greater consideration for human comfort have led to changes in the design of stadium buildings. With the development of technology, materials, design possibilities, and increased interest in sports as spectators, stadiums are now being designed not only for a specific sports discipline but also for multiple sports events. Stadium design regulations are constantly changing and being reevaluated, making it a complex process to adapt an existing stadium to meet current standards.Different stadium forms have been designed for various sports, taking into account user and climatic conditions, leading to both open and closed-roof stadiums.

Advancements in structural types have made it possible to span longer distances without the need for columns. The use of steel structures has allowed for the iconic design and implementation of roof systems. Composite structures are also being used in structural choices, and seating console levels are being prefabricated and poured outside the field before being assembled on-site. Thanks to advancing technology, structures, materials, and BIM programs, stadium buildings, which have become iconic symbols of cities, have started to be constructed. Also BIM makes roofing systems of roofs going beyond limits and factors Weather is no longer a limiting factor and there is also less of a limit on the playing field surface since sunlight can be let in when the roof is in the open position. The five generations of modern stadia highlight that stadiums have undergone several different changes and the shift and focus has changed significantly over the last century, which is driven primarily by spectators or numbers of viewers tuning in via television on an international scale.

Chapter 4

CASE STUDY: AHMADOU AHIDJO STADIUM AND OLEMBE PAUL BIYA STADIUM.

4.1 Introduction

Stadiums (plural of stadium, also used as stadia) are designed with the intent to hold large number of people. Over the years, stadiums have become an integral part of the building and entertainment sectors, functioning as the main location for large social events and as a significant resource for revenue. With the recent population growth and expansion of the entertainment industry, demand for such structures has increased dramatically, resulting in the need for new designs capable of accommodating even larger crowds. However, these new designs must also satisfy the architectural and esthetic considerations (Çatbaş et al., 2017).

Sports stadiums are monumental structures in Cameroon . These architectural marvels serve as venues for unforgettable moments, uniting people in the pursuit of excellence and excitement.

In this chapter, we embark on an exploration of two main iconic stadiums in Cameroon , the Ahmadou Ahidjo Stadium and the Olembe Paul Biya Stadium. These venues, located in different eras and regions, represent not only the rich tapestry of sporting history but also the evolution of stadium design and functionality. These stadiums have been used for various games, football matches etc. the examination of these stadiums were done in terms of some an analytic method.

Ahmadou Ahidjo Stadium, constructed in the 1970s, embodies the legacy of a bygone era. Its architectural style, materials, and design principles reflect the prevailing norms of that period. Meanwhile, Olembe Paul Biya Stadium, a state-of-the-art facility inaugurated in 2021, is a testament to modern technology, sustainability, and the changing expectations of fans and athletes. These two stadiums, though both devoted to the beautiful game of football, stand as symbols of the transformation in stadium construction and the adaptation to evolving user preferences.

As we look into this case study, our aim is to dissect the two stadiums from various angles. According to Yaroni 2021 A complete modem stadium design has three main features: roof, façade, and structure(Yaroni, 2021).

Hence we will focus on these three features as well as the user experience, cultural relevance,. By closely scrutinizing these two remarkable structures, we seek to draw meaningful insights into the world of sports architecture, and how stadiums continue to shape our collective experiences.

4.1.1 History and Background of Football in Cameroon

According to FriDoliN (2022)' s research , Football made its entry into Cameroon in 1920, a period when the country was still under French administration. The catalysts for this introduction were two individuals: Charles Lalanne, a primary school teacher, and George Goethe, a photographer and trade agent from Sierra Leone. In 1924, Goethe established one of Cameroon's earliest football teams, known as the "Club

Athlétique du Cameroun" (Cameroon's Athletic Club), setting a precedent that led to the formation of numerous other te'ms.

The Cameroonian Football Federatio's Association (FECAFOOT) was established"in 1959 and gained affiliation with FIFA in 1962 and the African Football Confederation (CAF) in 1963. The Cameroon national football team came into existence in 1959, marking its official international debut on April 13, 1960, against Somalia, where they emerged victorious with a score of 9-2. This event marked the commencement of the international legacy of the national team, officially named the "Indomitable Lions of Cameroon" by presidential decree in 1972.

The selection of the team's name was a politically significant decision, reflecting a strong governmental interest in football as a symbol of national unity and development. Presidents Ahidjo and Paul Biya emphasized football as a model for the nation's development, highlighting its role in fostering a "fighting spirit" and promoting national integration. Football, with its capacity to transcend religious, political, and cultural boundaries among the country's over 200 diverse communities, serves as a unifying force and instrument of social cohesion. The significance of football in Cameroon is underscored by its central position in daily discussions, where debates about the national team, players, and their performances are commonplace. The government recognizes the importance of football, frequently intervening in the sport's affairs to align with broader political objectives.

4.2 Limitation for Case Study

Selected case study areas create different data as well as interpretations. So for this section limitation have been elaborated accordingly. These limitations and differences provide a well-rounded and contextually relevant analysis. These limitations define the scope and objectives of the research as follows:

- **Age and Era of Construction**

The Ahmadou Ahidjo Stadium was built in the 1970s, while the Olembe Paul Biya Stadium was constructed in 2021. This significant time gap means they were designed and built according to different standards, technologies, and architectural trends. Therefore, the differences in their design, construction methods, and materials may limit direct comparisons.

- **Roof and the roof structure**

The roofing of the two stadiums differ significantly. The Ahmadou Ahidjo Stadium, being older, may has a roof covered to 30% , which is be less advanced in terms of materials and design compared to the Olembe Paul Biya Stadium. The roofing material, style, and technology used in the newer stadium offers improved coverage and protection from the elements. It should be noted that roof structure in this context refers to the framework that supports the roof covering in the case of the ahmadou Ahidjo stadium. It is the internal framework that provides stability and shape to the roof.

Common roof structures include trusses, rafters, and joists. The choice of structure depends on factors such as the design of the building, the span of the roof, and the load-bearing requirements.

- **Structural Differences:**

As stated, a modern stadium design encompasses three main features: roof, façade, and structure. The structural elements of the stadiums, including the materials used, load-bearing capacities, and architectural designs, are likely to vary. This structural difference could impact the overall user experience, safety, and the longevity of the stadiums.

- **International Stadium Design Approach**

Both stadiums might have been influenced by FIFA and UEFA international stadium design approaches and recommendations; but there is an extent to which they adhere to these standards may vary.

- **Evolving Design Trends**

Stadium design trends evolve over time. The older stadium, Ahmadou Ahidjo, may not incorporate the latest innovations and features seen in the newer Olembe Paul Biya Stadium. This could impact the comparative analysis, as one stadium might not represent the most up-to-date design practices.

4.3 Methodology

A set of tables was created to facilitate the analysis of the case studies. The "Stadium overview" table includes details about the case studies, along with selected photos and drawings of the buildings for visual reference. The chosen images and drawings aim to offer a holistic view of the stadiums.

The analysis encompasses a range of parameters to ensure a comprehensive understanding of these stadiums. Key parameters for consideration include:

4.3.1 Analysis of Design Elements

a. Structural Analysis

- Widespan structures
- Materials used in construction for their strength, durability, and ability to withstand environmental conditions.
- Façade analysis will be done through a visual methodology

b. **Engineering Design and Innovation:**

- Evaluate the architectural design choices, such as the shape, form, and layout of the widespan structures.
- Innovations in Construction: Explore any innovative engineering or construction techniques employed in the creation of these stadiums.

c. **FIFA Standards and Guidelines.**

- Analyze the size, arrangement, and comfort of audience seating, considering FIFA standards and guidelines.
- Evaluate the visibility of the playing field from various seating positions to ensure an optimal viewing experience for spectators.

d. **Cultural and Architectural Significance**

- How the stadiums integrate local cultural elements and traditions into their design.
- Symbolic significance of these stadiums in representing national identity and pride.

4.4 Case Studies

4.4.1 Introduction

According to Tuekam (2021), The African Cup of Nations (AFCON) is considered to be the biggest sporting event in Africa. The project was proposed by Cameroon to the Confederation of African Football (CAF) and was announced on September 20, 2014. The aim of the project was to organize the 32^{nd} AFCON in Cameroon, with 32 matches scheduled to take place over 3 weeks. The matches were supposed to be held in at least 4 football stadiums that meet CAF standards.

In addition to the construction of new stadiums(Olembe stadium , Japoma and training fields) there was a redevelopment of old ones, as it required the improvement of the quality and quantity of the facilities (Tuekam, 2021).

This section examines two notable stadiums in Cameroon: Ahmadou Ahidjo Stadium and Olembe Stadium, with a particular emphasis on three essential aspects: roof structural systems, façade, and architectural concerns. A complete examination emerges via these case studies, investigating the historical history of these stadiums as well as the related to context .

Particular emphasis is placed on the pivotal role of Ahmadou Ahidjo Stadium in hosting significant football matches and international events, shedding light on its achievements and its influence on the country's sports landscape. Transitioning to a contemporary perspective, Olembe Stadium offers insights into new considerations in modern stadium design.

The analysis of the stadiums' morphology shifts towards how wide-span structures influence seating arrangements, spatial organization, and the overall architectural composition. Thoughtful integration of aesthetics and architectural designs of stadium facades within the broader urban context is also examined.

Through the meticulous examination of wide-span structures in Ahmadou Ahidjo Stadium and Olembe Stadium, this chapter aims to provide valuable insights into the design and construction considerations for stadiums with substantial capacities. The analysis contributes to a deeper understanding of the architectural and engineering principles applied in crafting iconic sports venues and how these principles shape the holistic stadium experience.

4.4.2 Location.

Stadium complexes, are across extensive areas within urban plans, and plays a significant role in shaping a city's in general and as well ; transportation , infrastructure. Consequently, their design prioritizes seamless accessibility for users from various city sectors, ensuring convenient transportation options from every corner.

In this context Yaoundé,, the capital city of Cameroon (Figure 4.1) has a population exceeding 2.8 million according to the latest census, , boasts a distinctive topography that contributes to its unique urban layout which one of the stadiums utilizes.

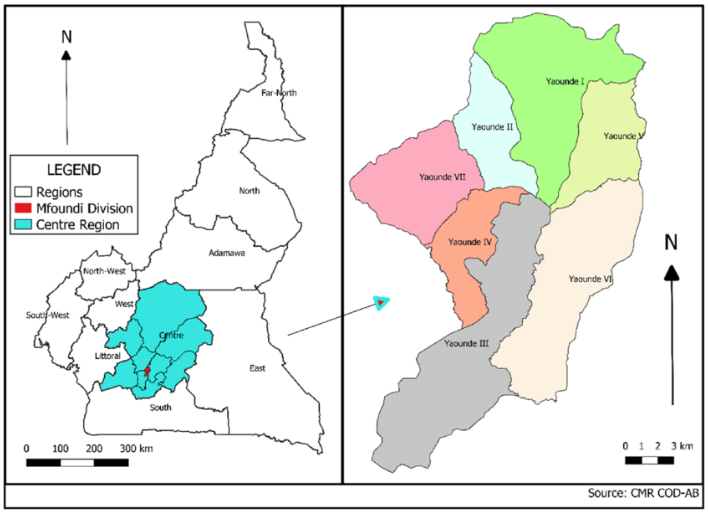


Figure 4.1: Map of Cameroon Showing the Various Regions (Left) and Partition of Subdivisions in Yaounde (Right) of the Centre Region (Veeyee et al., 2020)

Currently, Yaoundé is the home of two iconic stadiums-located in two peripheries of Cameroon The stadiums are located 25 minutes from each other and are complementary to each other. The most significance importance of the stadiums are that they are built in two different periods and also their characteristics are different. Finally comprises of different structural configuration

The importance of location plays a crucial role in the success and impact of Olembe Stadium and Ahmadou Ahidjo Stadium. Olembe Stadium and Ahmadou Ahidjo Stadium as they are strategically situated in areas that provide easy access for fans, players, and staff. Urban integration is vital for its integration into the city's infrastructure and overall development, and cultural and symbolic significance can hold cultural and symbolic significance for a nation or city.

Olembe Stadium and Ahmadou Ahidjo Stadium are situated in areas where they can have a positive impact on the surrounding community and urban environment, and they serve as catalysts for urban regeneration. Olembe Stadium being constructed in a prominent area of Yaoundé will serve as a new landmark and enhance the city's reputation as a sports destination. We will focus on Ahmadou Ahidjo Stadium and Olembe Paul Biya Stadium, two prime examples of widespan structures utilized as stadiums in Cameroon.

These stadiums not only underscore the country's substantial investment in sporting infrastructure but also highlight their paramount importance as venues for major sports events. They play a pivotal role in the advancement of sports and entertainment within Cameroon while providing an exceptional platform for national and international competitions. Furthermore, the incorporation of widespan structures in these stadiums showcases the remarkable architectural and engineering prowess involved in crafting functional and visually stunning sports facilitie

Both Ahmadou Ahidjo Stadium and Olembe Paul Biya Stadium exemplify widespan structures used as stadiums in Cameroon. They showcase the country's investment in sporting infrastructure and their significance as venues for major sports events. These stadiums contribute to the development of sports and entertainment in Cameroon and provide a platform for national and international competitions. The presence of widespan structures in these stadiums demonstrates the architectural and engineering expertise involved in creating functional and visually impressive sports facilities.

4.5 Case Study: Ahmadu Ahidjo Stadium – Second Generation Stadium

4.5.1 Stadium Overview

Table 4.1: Ahmadou Ahidjo Stadium Overview (Mangaleu Toukam,2023)

BUILDING. DESIGN	**Built**	1972	 Figure 4.2: Aerial View of Ahmadou Ahidjo Stadium (Mangaleu Toukam , 2022)
	Renovated	1981, 2005, 2007 , 2016 , 2019	
	Construction cost	163 billion CFA	
	Architect	Arab contractors(2016 Renovation)	
	Structural engineer	n/a	
	Services engineer	n/a	
	General contractor	n/a	
	Roof spam	Open roof covered at 10%	
	Structural system	Hybrid structure – Vector	

<table>
<tr><td></td><td colspan="2">Active and
section active</td><td></td></tr>
<tr><td rowspan="2">DRAWINGS</td><td colspan="2">DESCRIPTION</td><td rowspan="2">The Ahmadou Ahidjo Stadium is a multi-purpose stadium in Yaoundé, Cameroon. It is used mostly for football matches and it also has athletics facilities. It was built in 1972.

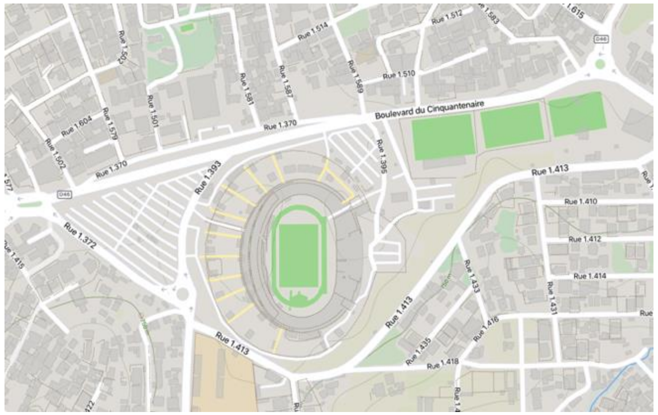
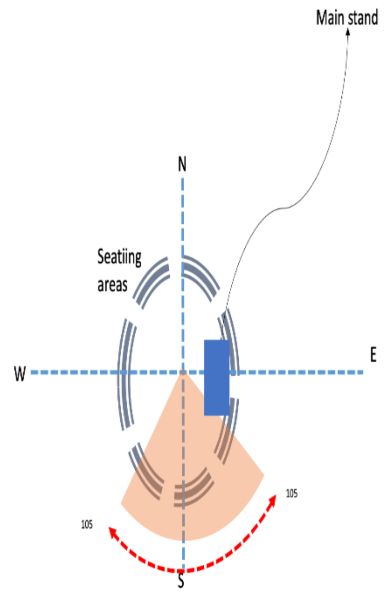


Figure 4.3: Site Plan of Ahmadou Ahidjo Stadium (Google maps)</td></tr>
<tr><td>PLAN</td><td>Elliptical plan
Minimalistic architecture
Easy accessibility</td></tr>
</table>

		• Material Composition of concrete • Formwork and Moulding is typically done for this type of façade • Colouring initial concrete colour	 Figure 4.4: Ahmadou Ahidjo Stadiums Façade (Mangaleu Toukam, 2023)

CONSTRUCTION STAGES	• Original Construction (1972): • Renovations and Upgrades: • Maintenance and Repairs: • Security and Safety Improvements:	**STRUCTURE**  Figure 4.5: Ahmadou Ahidjo Stadium Original Structure (Mangaleu Toukam, 2023)	**CONSTRUCTION**  Figure 4.6: Ahmadou 169 Tiliz Stadiums Current State (Mangaleu Toukam, 2023)

FAÇADE	• initial Concrete façade as it was a common construction material for stadiums in the 1970s. • the tensile façade of the • Façade panels, with colors of the Cameroon flag: green, red, and yellow	 Figure 4.7: Façade of Ahmadou Ahidjo Stadium (Mangaleu Toukam, 2023)

Morphology	• open seating arrangements, with fewer enclosed structures. • simplicity and functionalism • good view of the action from various vantage points	 Figure 4.8: Morphology of Ahmadou Ahidjo Stadium

4.5.2 Historical Context and Design Philosophy

The stadium was named after Ahmadou Ahidjo, the first President of Cameroon, and was opened in 1972. It has a rich history of hosting various sporting events and cultural activities .It was the biggest stadium before the construction of the Olembe stadium The Ahmadou Ahidjo Stadium is a an example of the first stadium a widespan structure in Cameroon. It features a distinctive circular design with an open roof that provides partial coverage to the seating areas. The stadium underwent renovations in the past to improve its facilities.

4.5.3Analysis of Design Elements

4.5.3.1Amenities and Facilities

The stadium capacity of 40,122, encompasses a natural grass playing field measuring 105x68m, enclosed by an 8-lane athletics track, a Media Center, and a Media Tribune. Additionally, there are two training grounds designed in accordance with international standards for team training, a gymnasium with a seating capacity of 2,000, a parking lot with 1,580 spaces (including 145 for individuals with reduced mobility), and a restaurant. The infrastructure also includes a pair of training grounds conforming to global team training standards, a 2,000-seat gymnasium, a parking facility with 1,580 spaces (including 145 designated for individuals with reduced mobility), and a restaurant.

4.5.3.2 Accessibility

The stadium provides extensive automobile, pedestrian, and disability access.(Figure 4.9) On days when the stadium is not in use, these open spaces (parking) could be utilized as meeting places, exhibition grounds, trade fairs, outdoor sports venues, and so on.

Figure 4.9: Ahmadou Ahidjo Stadiums and Environs (Mangaleu Toukam, 2023)

The stadium entrance is located at the ground level and spectators can easily take their seats below via a circulation ring(figure 4.10)

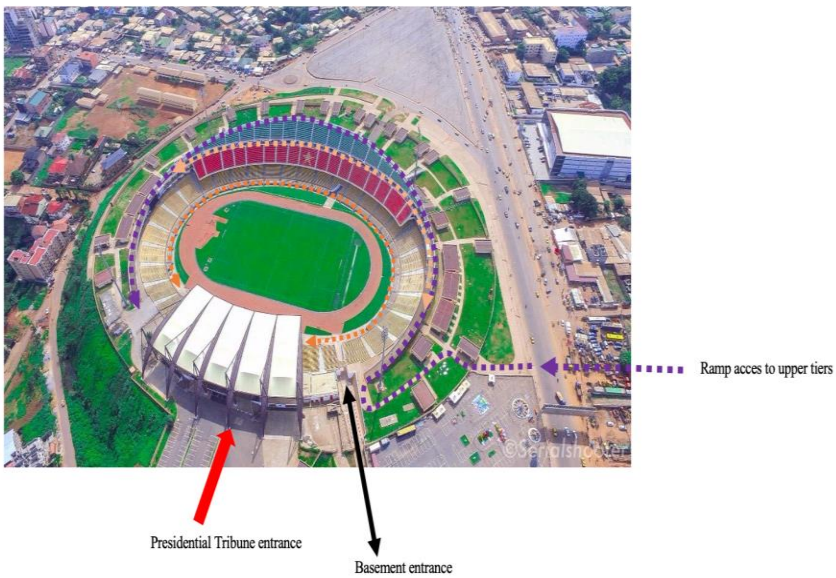


Figure 4.10: Accessibility into the Stadium (Mangaleu Toukam, 2023)

The type of access pattern is known as access via one top ring hence making the top ring later serving circulation to all tiers (figure 4.11). In the case of the Ahmadou Ahidjo the principle of accessibility to the stadium is set into the ground figure therefore .

Figure 4.11: Ahmadou Ahidjo Sit Access (Mangaleu Toukam, 2023)

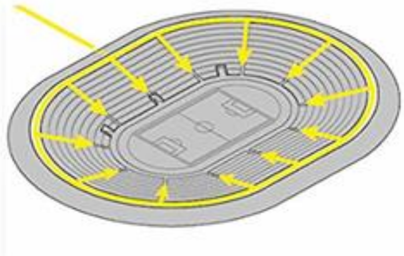


Figure 4.12: Access Via Top Ring (Mangaleu Toukam, 2023)

Improved accessibility for people with disabilities, including adding ramps, wheelchair seating areas, and accessible restrooms (Figure 4.13).

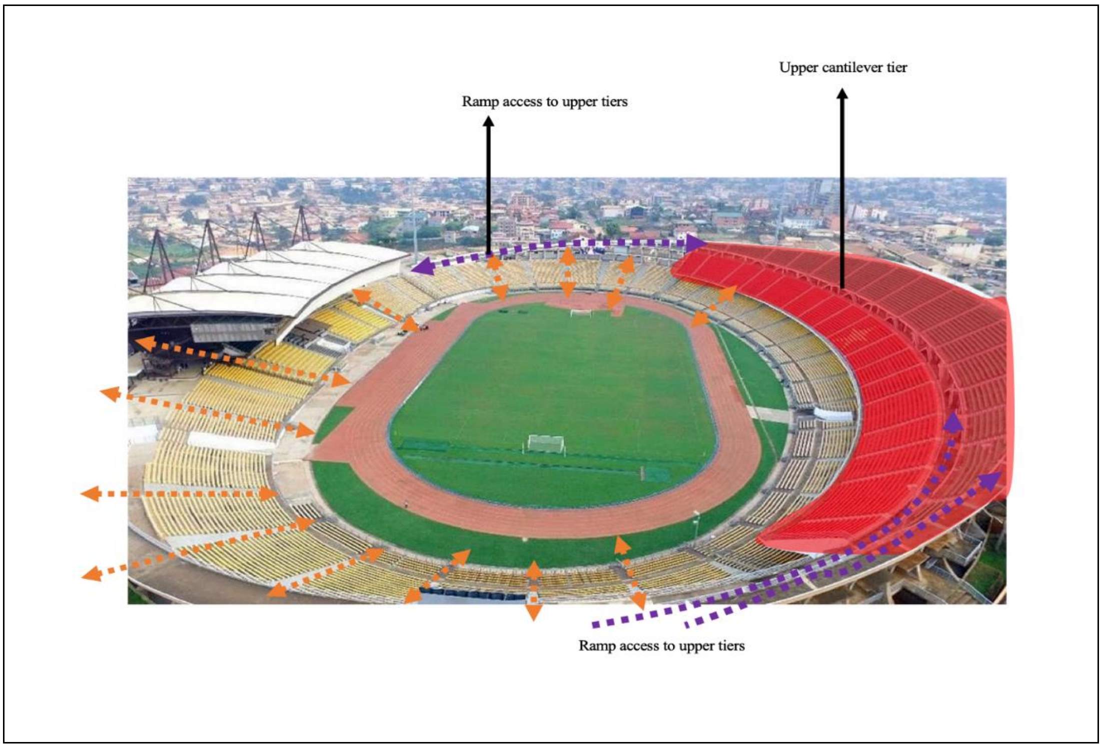


Figure 4.13: Accessibility Path (Mangaleu Toukam, 2023).

4.5.3.3 Stadium Orientation and Form

The ellipse form of a stadium, characterized by its oval form , with several advantages contribute to both functional and aesthetic aspects of the stadium in terms of sightlines, acoustics, structural efficiency, space utilization, architectural aesthetics, seating flexibility, natural ventilation, and versatility .These factors collectively contribute to creating a more enjoyable and functional venue for both spectators and organizers.

The stadium orientation is optimum for the stadium. On the north west a cantilever tier is introduced to give shading user on the lower level even though it obstructs the view (figure 4.13).

4.5.3.4 Seating

The stadium includes 40,000 seats for the general public, 3,000 seats for officials and VIP's, 150 media tables, the extension of the total capacity as well as the realization of the stadium sectorization. The stadium has four levels of seating, including a lower bowl, upper bowl, VIP section, and media section. The seating is made of plastic and is color-coded in green, red, yellow, and white, which are the colors of the Cameroonian flag.

4.5.3.5 Color and Material Concept

Colors and materials have been used to represent the country's colors green red and yellow (Figure 4.14) .They create an atmosphere unique to each venue, giving an identity that reflects on the fans, city or culture where the stadium is located. In this case Stadium, the architect chose these aspects of the design with a strong regard to local values and culture.

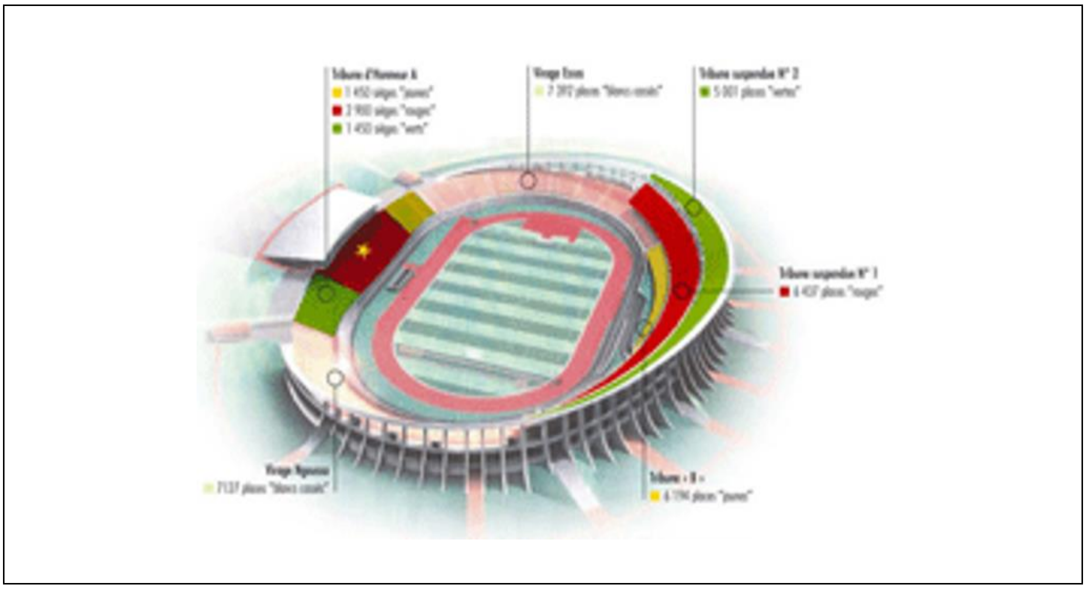


Figure 4.14: Color and Material Concept (Mangaleu Toukam 2023)

The Ahmadou Ahidjo Stadium initially seat up to 12,000 people, before it was renovated and expanded in 2016 for the 2016 women's AFCON to reach a total of 42,500 seats. Using Technology for the design process.

4.5.3.6 Seating Field/Court Configuration

Oval-shaped stadiums has the advantage of continuous seating that surrounds the field or playing area, creating an intimate feel and bringing fans closer to the action regardless of seat placement. This design also maximizes sightlines, ensuring clear views of the field from all sitting positions.

Furthermore, an ellipse stadium stands are smartly designed with a progressive increase in elevation as you travel away from the playing field (Figure 4.15). This strategic placement ensures that even viewers in the upper rows get a good view of the action. Additionally, the tiered seating structure in oval stadiums not only boosts overall capacity but also enables a variety of seating options at varying price ranges, fitting a wide range of preferences and budgets.

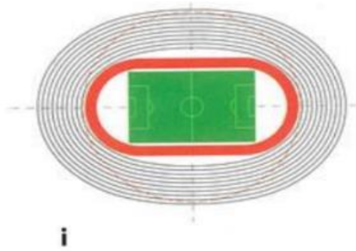


Figure 4.15: Ahmadou Ahidjo Stadium Stand Design

4.6 Structural Analysis

The structural system is characterized by the prevalent use of concrete as a primary building material. Currently, there is notable shift towards modern, functional, and large-scale stadium designs, and concrete emerged as a popular choice due to its durability, strength, and versatility in construction. The Stadium structure has been rehabilitated hence improving the structural performance positively.

4.6.1 Roof

Ahmadou Ahidjo stadiums is Covered at 20%. And has two different structure which are cantilevered structure located on the west and the presidential tribune on the east. The roof details showcase an extraordinary and distinct feature that captivates attention.

The Ahmadou Ahidjo Stadium, incorporates a combination of structural systems to support its various elements. While detailed technical information might not be readily available, we can generally discuss the types of structural systems through visual methodology these may include:

4.6.1.1 Cantilevered Roof Structure

This system involves a single horizontal beam projecting outward from a main support, providing partial coverage for spectators (Figure 4.16). Located on the west part of the stadium The Roof serves as sitting area for the upper tier which could be accessed through ramps. The main disadvantage of this roof is that it obstruct view for the fans who are sited at the back of the ground tier.

Figure 4.16: Partial Cantilever Ahmadou Ahidjo Stadium (Mangaleu Toukam, 2023)

4.6.1.2 Concrete Frame Structure

Concrete frame structures support the seating areas, entryways, and other components. The reinforced concrete provides the necessary strength to withstand loads and forces.

4.6.1.3 Steel Truss System

Steel trusses are frequently employed to span large distances without the need for additional support columns. These trusses can support the roof and help create unobstructed views for spectators.

Located On the east side It comprises a series of 6 curved horizontal 3d trusses, securely supported by the ground, with each truss connected by segment arcs. Triangular design sustains vertical, horizontal, and inclined loads (Figure 4.17)

Figure 4.17: Curved Trusses Analysis A (Mangaleu Toukam).

Within each curved truss, a primary vertical triangular lacing is present, which finds support from the ground. This primary lacing intersects with two secondary triangular lacing configurations on each side. One of the secondary lacing configurations is attached to the same support as the curved spaceframe, while the other has support at the intersection and carries the weight of the remaining segment.

Both secondary triangular lacing configurations are equipped with two ladder bars on each side, enhancing the support and stability of the curved trusses. This well-designed configuration effectively distributes the weight and ensures the overall stability of the cantilever structure (4.18)

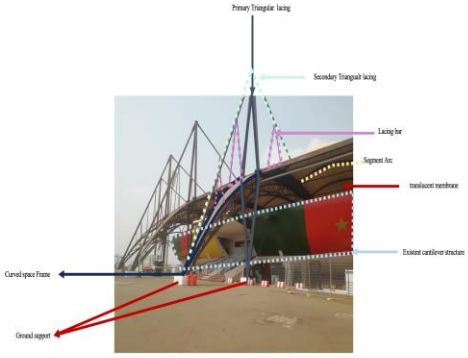
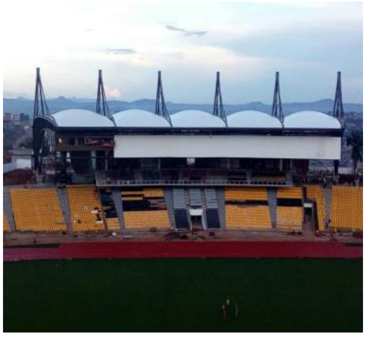
	
Structure Analysis	Tribune Facade (Roure, 2016)

Figure 4.18: Curved Trusses Analysis B.(Mangaleu Toukam).

Precontraint 1502 S2 was used to the Roof, this is a perfect exemple on how Lightweight Composite membranes can bring life back to an old fashion building.(Roure, 2016). The composite membrane Achieves desired properties such as strength, flexibility, and waterproofing for the roof.

4.6.1.4 Structural Evaluation

Table 4.2: Structural Evaluation Ahmadou Ahidjo Stadium

STRUCTURAL APPROACH				
STRUCTURAL SYSTEM	**FORM ACTIVE**	**VECTOR ACTIVE**	**SECTION ACTIVE**	**SURFACE**
		• **Curved trusses** support the roof and help create unobstructed views for spectators.	• **Concrete frame structure** reinforced concrete frame structures support the seating areas, entryways, and other components.	
MATERIAL	**STEEL**	**TIMBER**	**R.C.**	**STEEL**
	✓		✓	✓

CONNECTION	**RIVITED CONNECTIONS**		**BOLTED CONNECTIONS**	**WELDED CONNECTIONS**	**PINNED / HINGED CONNECTION**
	✓		✓	✓	✓
SUPPORT	**ROLLER SUPPORT**		**PINNED / HINGED SUPPORT**	**FIXED SUPPORT**	**SIMPLE SUPPORT**
			✓	✓	✓
ROOF STRUCTURE	**EXTENT OF COVERAGE**	**CLIMATE CONTROL MEASURES**	**ROOFING MATERIALS**	**TECHNOLOGICAL INTEGRATION**	**OVERALL INTEGRATION WITH STADIUM**

<table>
<tr><td rowspan="3"></td><td rowspan="3">Roof covered at 20%</td><td rowspan="3">-coverage of the presidential tribune

-</td><td rowspan="3">• Steel
• Concrete
• PTFE</td><td>INTEGRATION OF LIGHTING SYSTEMS</td><td>✓</td><td rowspan="3">The roof structure is partially integrated to the rest of the stadium structure having a different structure</td></tr>
<tr><td>SOUND SYSTEMS</td><td>✓</td></tr>
<tr><td>ELECTRONIC DISPLAYS</td><td>✓</td></tr>
<tr><td rowspan="2">FAÇADE</td><td colspan="2">MATERIALS AND FINISHES</td><td>VISUAL IMPACT</td><td colspan="2">QUALITY OF FAÇADE MATERIALS</td><td>COHERENCE WITH OVERALL STADIUM AESTHETICS</td></tr>
<tr><td colspan="2">Concrete Façade tensile panel.</td><td>Integrates to the national colors</td><td colspan="2">• The façade serves cover rehabilitated structure
• Covered with Concrete panels</td><td>Gives the old structure a new face and give a new visual perception</td></tr>
</table>

4.6.2 Façade

The façade of the Ahmadou Ahidjo stadium over the years have been rehabilitated. In the 70's the stadium was designed with Concrete panels and architectural detailing reflecting design trends of the period.

In the latest renovations the façade was constructed using a tensile structure. This type of architectural design incorporates cables and structural steel support elements to tension fabric and other materials, resulting in the creation of a structure, canopy, or covering.

Figure 4.19: Façade made with Magic Springs Systems from PRAT SA (Roure, 2016)

In 2016, the tensile façade of the Ahmadou Ahidjo Stadium was adorned with Serge Ferrari Soltis FT381 (Figure 4.19). The Façade panels, crafted to resemble the colors of the Cameroon flag: green, red, and yellow (Roure 2016)

Prat Structures Avancées, a specialized company in lightweight structures and tensile architecture, meticulously designed and installed 39 panels of various shapes. These panels were strategically placed to maintain outward visibility while also mitigating heat accumulation within the building.

4.6.2.1 Façade Evaluation

Table 4.3: Façade Evaluation (Mangaleu Toukam, 2023)

Case study	System	Principles	Solution
Ahmadou ahidjo stadium	Panel system	Wall holder Load bearing Thermal bridge Flexible design	● Covering of the existing concrete structure ● Thermal insulation, in which stored heat from solar radiation is eliminated directly.

4.7 Engineering Design and Innovation

The integration of new functions into an existing stadium presents a different challenge compared to the conceptualization of a new stadium, as it requires compliance with current standards and regulations (Sartori, & Nienhoff 2013).

Ahmadou Ahidjo stadium from it first construction was an open stadium. As part of the stadium’s rehabilitation, a 4,700 square meter roof covered with Flexlight Advanced 1502 S2, a translucent membrane particularly suited to roof constructions subjected to significant mechanical stress, was added in 2016(Figure 4.20)

Figure 4.20: Innovation of Façade Ahmadou Ahidjo Stadium (Mangaleu Toukam)

4.7.1 FIFA Standards and Guidelines

Over the years, the Ahmadou Ahidjo Stadium has been upgraded to become a multifunctional facility that meets multiple criteria and can hold a large number of games, as it was the only structure capable of hosting athletic events for a long time. Its conversion into a multifunctional facility is a bold step forward in urban infrastructure planning and sports venue design. Architectural enhancements play a critical part in this transformation, catering to a wide range of activities other than typical athletic events.

One important element is the use of adaptable seating configurations that can be quickly altered to suit a variety of activities, ranging from sporting events to cultural performances and concerts. This versatility not only improves the stadium's general operation. But also ensures a dynamic and inclusive space for the community.

Another critical aspect of the architectural upgrades lies in the integration of state-of-the-art technology and amenities to meet the evolving expectations of modern audiences. This includes the installation of advanced lighting and sound systems, high-definition video displays, and cutting-edge communication infrastructure. Such enhancements not only elevate the spectator experience during sporting events but also make the stadium an attractive venue for conferences, exhibitions, and entertainment shows. The goal is to create a seamless blend of sporting prowess and cultural vibrancy, turning Ahmadou Ahidjo Stadium into a dynamic hub that fosters community engagement and contributes to the overall urban development of the region.

4.8 Cultural and Architectural Significance

The Ahmadou Ahidjo Stadium stands as a powerful symbol of Cameroon's national identity and pride, embodying a profound connection between the community and its rich cultural heritage.

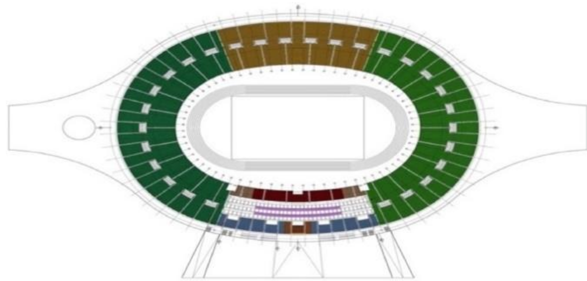
Beyond being a mere sports arena, the stadium serves as a testament to the unity and pride that defines the nation. For an extended period, it held the distinction of being the sole venue capable of hosting a diverse array of games, further solidifying its status as a symbol of national unity. This iconic structure not only fosters a sense of collective identity but also stands as a tangible representation of the enduring spirit that unites the people of Cameroon.

4.9 Case study: Olembe Stadium

4.9.1 Stadium Overview

Table 4.4: Olembe Stadium Overview

BUILDING DESIGN	**Built**	2018–2021	 Figure 4.21: Olembe Stadium Complex (Mangaleu Toukam 2023)
	Opened	4 September 2021; 2 years ago	
	Construction cost	163 billion CFA	
	Architect	Studio SHESA Architects – arch. Suarez	
	Structural engineer	MJW structures	
	Services engineer	Beta Progetti	
	General contractor	Gruppo Piccini S.A.	
	Roof spam	Semi- enclosed 300m x 245m highest Highest point 46m (Steel roof)	
	Height	40m	

	Structural system	Form active structure	
Drawings			
	PLAN	The oval shape of a stadium enables for the hosting of a greater variety of sport Strategically designed to minimize glare or maximize natural lighting for optimal playing conditions, while others may have shading structures or architectural features to provide shade for spectators.	 Figure 4.22: Plan of Olembe Stadium (Shesha, 2021)

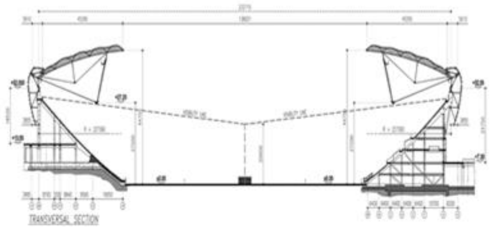
	SECTION/ELEVATIONS	Mixed steel/concrete system comprising structural elements made from steel and reinforced or prestressed concrete.	 Figure 4.23: Section Olembe Stadium (Shesha, 2021)
CONSTRUCTION STAGES	• The Olembé sports complex project consists ofPhase one main stadium main stadium, two annexes, a shopping center, a hotel, a cinema center, and a supermarket. • The second-*phase* of *construction*, covering the swimming pool and other sports courts, is intended to be completed after the end of AFCON.	**STRUCTURE** 	**CONSTRUCTION** 

		 Figure 4.24: Construction Stages of Olembe Stadium (Mangaleu Toukam)

FAÇADE	• entirely covered by pangolin scales • Principle of nature ensures that the building skin is flexible. • visually appealing components	 Figure 4.25: Façade of Olembe Stadium (Mangaleu Toukam 2023)

4.9.2 Historical Context and Design Philosophy.

4.9.3 Analysis of Design Elements

The Olembe Sports Complex is an extensive project that encompasses various facilities constructed in various phases.

4.9.3.1 Amenities and Facilities

It includes a main stadium with a seating capacity of up to 60,000 spectators.

Figure 4.26: Olembe Stadium Complex (Mangaleu Toukam, 2023)

Along with two training stadiums that can accommodate 1,000 seats each. Additionally, the complex features an Omnisport gymnasium, an Olympic swimming pool, an outdoor sports center, a 70-room hotel, and a shopping center comprising a commercial center, cinema, and conference rooms.

The main stadium, serving as the centerpiece of the complex, has been successfully completed. Similarly, the two training stadiums have also reached completion and are now ready to host competitions and other events. This marks the completion of phase one of the complex’s development.

4.9.3.2 Accessibility

The Olembé sports complex brings renewed life to the Olembé district. Like most stadiums, it features a significant parking area that can be utilized for various events. Accessible from the main road, the circulation flow within the complex is divided into two parts (Figure 4.27).

Part A of the circulation revolves around the stadium, leading to two drop-off zones that provide direct access to the entrance points. This arrangement ensures smooth and convenient entry for visitors.

Part B of the circulation leads directly to the parking areas and the remaining service facilities, allowing for efficient movement and access to the various amenities within the complex.

Figure 4.27: Circulation Map (Generated on Google Earth Map)

The movement within the stadium occurs through the upper tiers. Spectators enter the two-tiered stand through the middle and proceed to their seats using an encircling pathway situated above or below (Figure 4.28)

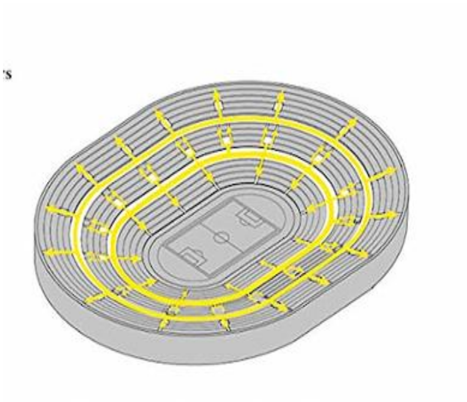
	
Access illustration	Panoramic access view

Figure 4.28: Circulation Analysis Olembe Stadium (Mangaleu Toukam, 2023).

Overall, the stadium's accessibility plan is comprehensive, encompassing private and public transportation options, as well as specific accessibility for individuals with varying mobility needs, thereby fostering an inclusive and convenient experience for all visitors.

4.9.3.3 Stadium Orientation and Form

Olembe stadium strategically designed to minimize glare or maximize natural lighting for optimal playing conditions, while others may have shading structures or architectural features to provide shade for spectators.(Figure 4.29) .

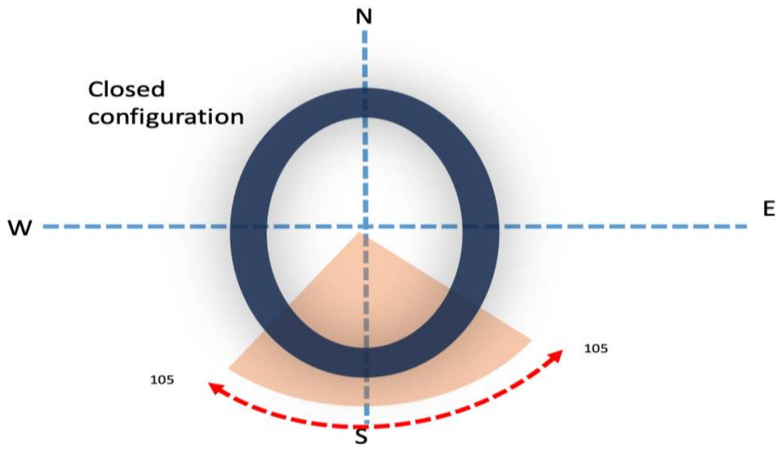


Figure 4.29: Olembe Stadium Morphology (Mangaleu Toukam, 2023)

4.9.3.4 Seating

The seating arrangement in the auditorium consists of single-tier stands, with seats forming a mosaic in green and red, resembling the colors of the behind the goal, a captivating yellow star pattern adorns a selection of seats, while on the opposite side, the seats are ingeniously arranged to form an awe-inspiring lion's head (Figure 4.30)


Figure 4.30: Seating Panoramic View (Managleu Toukam, 2023)

4.9.3.5 Field/Court Configuration

The oval shape of a stadium enables for the hosting of a greater variety of sports, including cricket and athletics, in addition to football (Figure 4.31). The Stadium hold (or intend to host). Examples of oval-shaped stadiums are the Olympic Stadium in Berlin and the stadium in Durban. Also the is configuration is to reduce the number of seats in the corner, farthest away from the pitch.

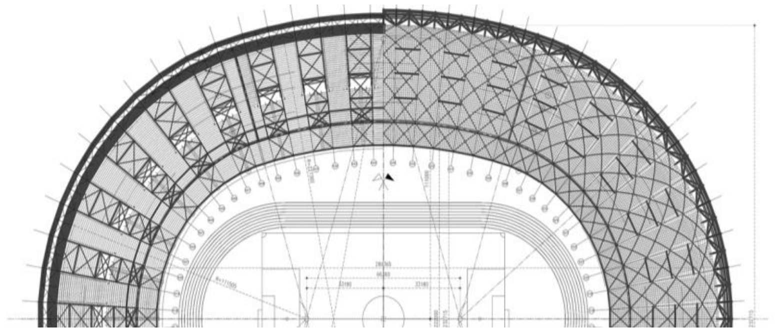


Figure 4.31: Partial Plan (Ingenta Connect, 2021)

4.10 Structural Analysis

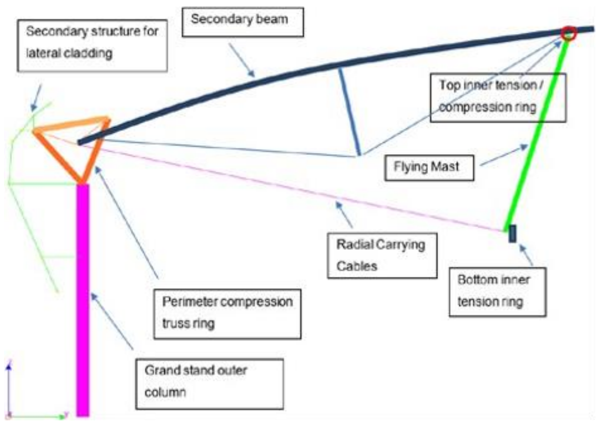
Structural concept is based on equilibrium between external compression ring forces and tensile forces in the inner ring. Structural static and dynamic stiffeners are related to the stadium transversal section geometry.

The structure is a mixed steel/concrete system comprising structural elements made from steel and reinforced or prestressed concrete. The technical challenge in this system was to get these materials to work to their optimum capacity, particularly in compression strength for concrete and in tensile strength for steel.

4.10.1 Roof

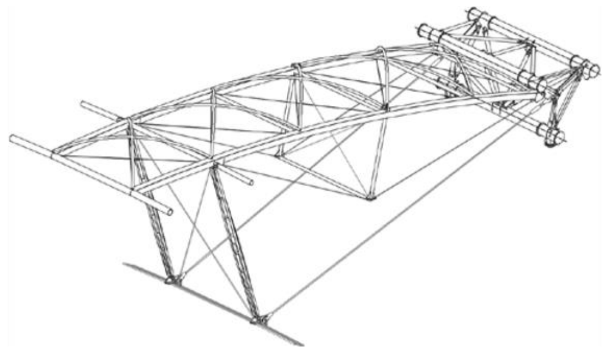
This stadium typology permits a light and flexible structure. The roof is composed of A tensile structure a solution based on pre-tensioned cables; composed of two internal tension rings (TR= Tension ring, an upper and a lower one) and an external compression truss ring. Known as a spoke wheel roof. In spoke wheel roofs, pre-stressing cables, the structure is stable under structural loads and compression forces will be created in the struts and the outer ring (Moore, 2011, p146).

The roof measures 300 m x 245 m and its highest point is 46 m above the ground. The rest of the venue. These rings are connected with radial bottom carrying cables and radial top secondary beams (Figure 4.32) , (Figure 4.32).



(A)

Figure 4.32: Typical Roof Structural Module: Schematic Description Source: (Upgrading the Spoke Wheel Stadium Roof Concept: Ingenta Connect, 2020).



(B)

Figure 4.33: Typical Roof Structural Module: Isometric View Source : (Upgrading the Spoke Wheel Stadium Roof Concept: Ingenta Connect, 2020).

The rest of the structure is composed by prefabricated concrete and steel elements that, built in the factory with a more controlled environment in respect to an on-site construction, allow for a time and cost reduction.

4.10.2. Façade

The Olembe Stadium is entirely covered by pangolin scales like panels giving it a more exotic view, just like the bird nest stadium in China and the calabash stadium in South Africa (Figure 4.33). In west Africa and specifically in Cameroon pangolins are killed for their meat and their scales,which have been used medicinally (UNODC,2020).

With their skin and scale being valuable it’s The flexible skin of the pangolin is imitated in the parts that fix the glass panels of the building so that the changes in the air pressure caused by the trains entering and leaving the terminal do not damage the building. So that the glass skin of the building can move in response to applied air pressure forcesAdaptation principle of nature ensures that the building skin is flexible, transformable and responsive. This makes the building skin multifunctional and necessitates each system (function-form-structure-material) of the building skin to integrate.

The facade of Olembe Stadium mixes practicality with visually appealing components. The stadium achieves a distinct and contemporary appearance by using novel materials and design features, all while maintaining longevity, sustainability, and practicality.

Terracotta cladding has been used as an architectural covering material to handle the local climatic conditions. This option has various advantages, including thermal insulation and weather protection. The cladding is made from natural and aged raw clay and fired at high temperatures without the use of any additional chemicals. Green, red, and yellow, which represent the national colors, as well as blue, were used for the cladding, resulting in an aesthetically beautiful facade.

Figure 4.34: Façade Panels Installation at Olembe Stadium (Mangaleu Toukam,2023)

Based on the principles of the natural models, particularly the pangolin, thus making it a unique resource and an innovative idea for architects and for solving problems the building could experience (Figure 4.34).

The facade approach as follows;

Table 4.5: Approach of Facade Concept of Olembe Stadium Figure Principles of Natural Skins and Solutions for Building Skin (Mangaleu Toukam, 2023)

CASE STUDY	ORGANISM	NATURAL PRINCIPLES	SOLUTION FOR BUILDING SKIN
Olembe stadium	Pangolin	● Overlapping, ● flexible, ● sharp scale Extra defense Regulating the temperature ● Allow to air circulation	Flexible structure Movable panels Responsive skin Flexible skin materials

The flexible skin of pangolin is imitated in the parts panels of the building so that the changes in the air pressure caused by the air pressure entering and leaving do not damage the building. Furthermore, the porous façade allows air movement through the envelope to ventilate the bowl and keep everyone at a comfortable temperature (Figure 4.35).

The pangolin's scaly body fig, pangolin scaly body can curl up into a ball when threatened, with its overlapping scales acting as armor. The scales are sharp, providing extra defense against unwary paws.

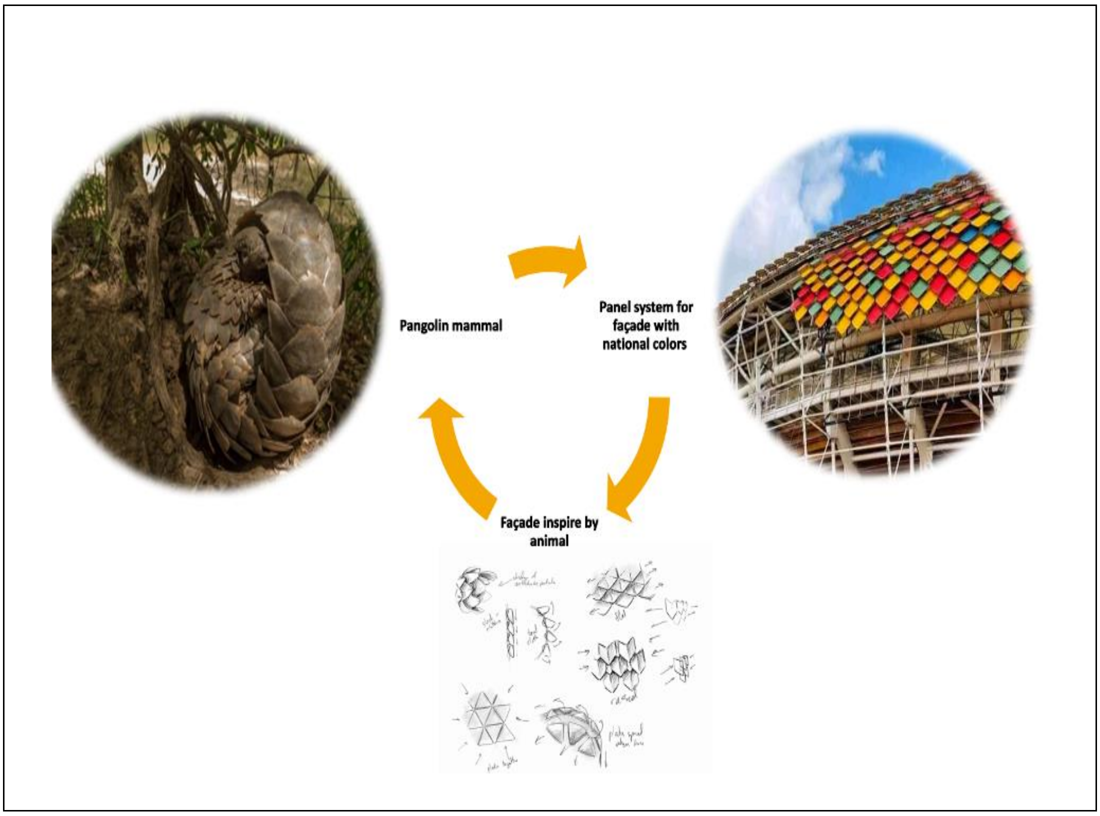


Figure 4.35: Olembe Facade Concept (Mangaleu Toukam, 2023)

Enhancing the visual spectacle, the stadium facade boasts an array of metal panels designed in the shape of scales, showcasing a captivating combination of yellow, orange, red, and blue hues.

4.10.3 Structural Evaluation

Table 4.6: Structural Evaluation Olembe Stadium.

STRUCTURAL APPROACH				
STRUCTURAL SYSTEM	**FORM ACTIVE**	**VECTOR ACTIVE**	**SECTION ACTIVE**	**SURFACE ACTIVE**
	Cable structure The stadium's roof structure includes an inner tension ring, inner tension-compression ring, and perimeter compression truss ring. Compressed sub-vertical flying masts connect the top compression inner ring with lower cable groups. Radial hybrid string beams, stiffened by lower cables and posts, support the radial beams, with supports about 40m apart.			
MATERIAL	**STEEL**	**TIMBER**	**R.C.**	**Other**
	steel grandstands (West sector).	N/a	reinforced precast concrete (North, South and East sectors) prefabricated concrete	roof covering is made of fiberglass membrane coated with PTFE **PVC membrane divided into 68 panels**
CONNECTION	RIVITED CONNECTIONS	BOLTED CONNECTIONS	WELDED CONNECTIONS	PINNED / HINGED CONNECTION

<table>
<tr><td></td><td colspan="2"></td><td>✓</td><td colspan="2">✓</td><td></td></tr>
<tr><td rowspan="2">SUPPORT</td><td colspan="2">ROLLER SUPPORT</td><td>PINNED / HINGED SUPPORT</td><td colspan="2">FIXED SUPPORT</td><td>SIMPLE SUPPORT</td></tr>
<tr><td colspan="2">✓</td><td>✓</td><td colspan="2">✓</td><td>✓</td></tr>
<tr><td rowspan="4">ROOF STRUCTURE –

Upgraded spoke wheel</td><td>EXTENT OF COVERAGE</td><td>CLIMATE CONTROL MEASURES</td><td>ROOFING MATERIALS</td><td colspan="2">TECHNOLOGICAL INTEGRATION</td><td>OVERALL INTEGRATION WITH STADIUM</td></tr>
<tr><td rowspan="3">Semi- enclosed

Not fully covered</td><td rowspan="3">✓</td><td rowspan="3">Fiberglass membrane coated with PTFE

Steel roof</td><td>INTEGRATION OF LIGHTING SYSTEMS</td><td>✓</td><td rowspan="3">Fits into the urban context as a Urban regenerative stadium.</td></tr>
<tr><td>SOUND SYSTEMS</td><td>✓</td></tr>
<tr><td>ELECTRONIC DISPLAYS</td><td>✓</td></tr>
</table>

FACADE	MATERIALS AND FINISHES	VISUAL IMPACT	QUALITY OF FACADE MATERIALS	COHERENCE WITH OVERALL STADIUM AESTHETICS
	Terracotta	Matches with the colors of the country flag according to the concept	Renewable material	colorful scalelike panels that make up its unique façade due to blended colors

4.11 Engineering Design and Innovation

The main structural system of the roof is an upgrade of the “spoke wheel” structural scheme .The first spoke wheel roof was built in 1958 for the U.S. Pavilion during the World Expo in Brussels (Boom 2012). Later this type of roof was used in the Utica Arena in New York, 1964 (Figure 4.36).

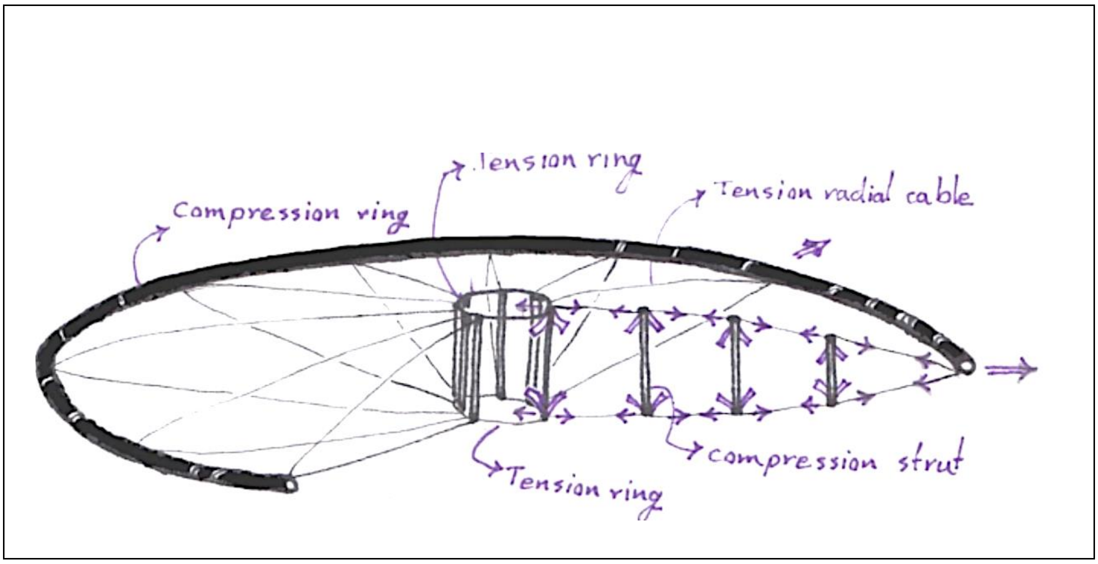


Figure 4.36: Structure of the Compression Ring Roof, Utica Arena, New York, 1964. (Edward et al. 2010).

4.12 Cultural and Architectural Significance

The evolution of stadium development in Cameroon has given rise to structures that are increasingly distinctive and can only be found in this context , ushering in a new typology of stadium. The recently constructed Olembe stadium stands as a testament to the constant innovation in stadium design, incorporating a myriad of features that have evolved to meet the ever-evolving demands of stadiums globally.

Advancing into its second phase, the project has already achieved significant milestones since its inception, with the main stadium now fully operational. From an architectural standpoint, it highlights the strides made in structural innovation and underscores the capacity of Cameroon's architectural industry to undertake such ambitious constructions.Designed as one of the stadiums for the AFCON 2021, Olembe Stadium signifies a transition into a new era and serves as a tangible reminder of this momentous occasion.

4.13 Chapter Summary

Football holds a special place in the national identity of Cameroon, with stadiums serving as exclusive venues for this popular sport. Given that football is regarded as a national pastime, fans eagerly attend matches to passionately support their teams. For many, football is not merely a sport; it's a revered aspect of their lives, akin to a religious devotion, and stadiums stand as their sacred temples.

Stadiums, primarily designed for hosting football matches, have evolved into versatile structures that accommodate various activities. Beyond sports competitions, these structures have become adaptable spaces for hosting events like concerts and theaters.

The incorporation of innovative structures , iconic cover systems has elevated stadium structures, turning them into focal points that attract domestic and international tourists. Recent football stadiums such as the Olembe stadium constructed in the last few years, showcase the integration of Building Information Modeling (BIM) technology. The use of innovative materials and advanced covering systems has garnered attention, especially in the context of the thesis's focus on iconic stadium structures.

Chapter 5

COMPARATIVE ANALYSIS

5.1 Introduction

By successfully organizing and hosting international competitions in these FIFA-standard stadiums, Cameroon has elevated its global standing in the sports community, showcasing prowess in infrastructure, organization, and talent. The effective design of these stadiums not only promotes sports excellence but also fosters national pride, contributing to shaping the country's image in the international sports arena.

This success solidifies Cameroon's position as a respected participant in global sporting events. As of September 2021, Cameroon boasts five stadiums meeting international standards (figure 5.1). While the exact number may change due to stadium constructions, renovations, or adjustments in international standards, several noteworthy international stadiums stand out in Cameroon.

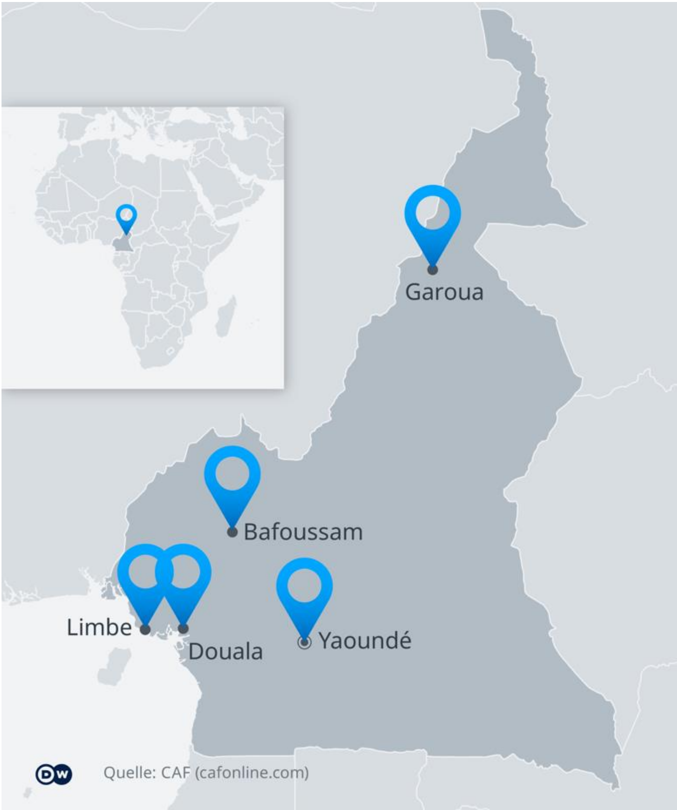


Figure 5.1: Location of Standard Stadiums in Cameroon

The primary objective of this study is to conduct a comprehensive analysis of widespan structures within the context of stadiums in Cameroon, with a specific focus on the case studies of Ahmadou Ahidjo Stadium and Olembe Paul Biya Stadium. The aim is to gain insights into the architectural and structural aspects of these stadiums. Furthermore, the study endeavors to provide recommendations based on its findings to guide future widespan stadium projects in Cameroon or similar contexts

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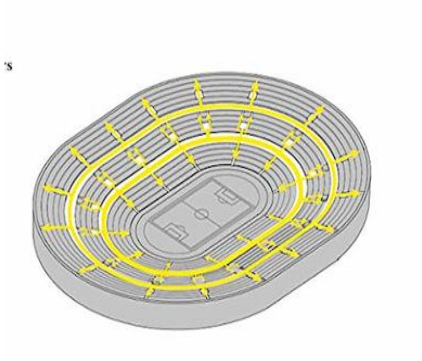
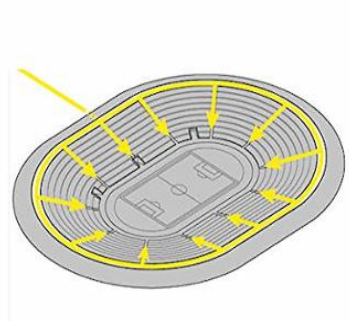
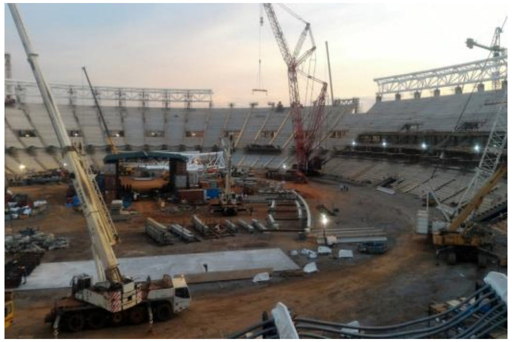
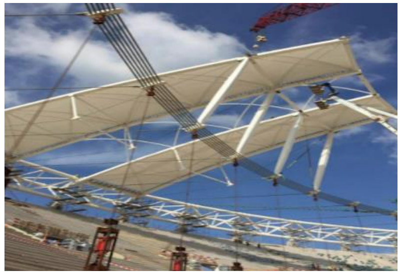
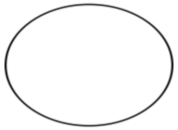
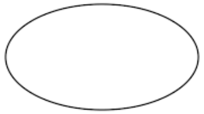
Table 5.1: Summary-Comparison Olembe and Ahmadou Ahidjo Stadium

		OLEMBE	**AHMADOU AHIDJO STADIUM**
ACCESIBILITY	movement of spectators, including entrances, exits, corridors, and seating arrangements. smooth and safe circulation within the stadiums.	 Figure 5.2 Olembe Circulation Ring	 Figure 5.3: Ahmadou Ahidjo Circulation Ring
ARCHITECTURE	**DESIGN ELEMENTS**		

	Risers Precast	prefabricated off site thereby minimizing the construction time  Figure 5.4: Olembe Stadium Foundation	concrete structures _ Already existing structure so data foundations couldn’t be found . Due to computerization some drawings and data after the year 2010 were lost
	Grandstands Structure	Cast in situ and steel	Cast in situ

		 Figure 5.5: Olembe Stadium Compression Ring Installation	 Figure 5.6: Current View of Ahmadou Ahidjo Stadium
	Roof structures	Roof Spoke Wheel structure  Figure 5.7: Roof Structure Olembe Stadium	curved 3d trusses spaceframe cantilever roof with 3d Trusses  Figure 5.8: Ahmadou Ahidjo Stadium

			Open Cantilever roof  Figure 5.9: Panoramic Access View Ahmadou Ahidjo Stadium 3d Trusses
	Roof Cover	Membrane	Membrane , Open roof , Cantilever cover roof

		 Figure 5.10: Olembe Roof	 Figure 5.11: Ahmadou Ahidjo Stadium Aerial View
	Foundation	Slab on ground and piles	Slabs on ground and piles
FORMAT STRUCTURE	GEOMETRY	Oval Shape  Figure 5.12: Oval Shape	Ellipse Shape  Figure 5.13: Ellipse Shape

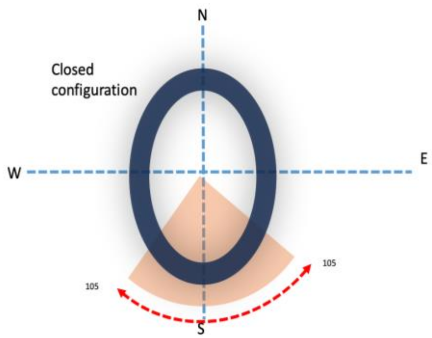
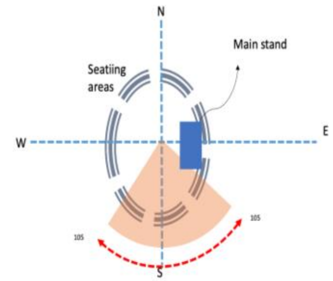
MORPHOLOGY	Roof Morphology Plan Orientation Degree Of Enclosure	Closed Configuration  Figure 5.14: Olembe Stadium Morphology	Open Configuration  Figure 5.15: Morphology of Ahmadou Ahidjo Stadium
STADIUM CATEGORY		Category 1	Second generation Stadium

Table 5.2: Comparative Analysis of Ahmadou Ahidjo Stadium and Olembe Stadium.

ASPECT	DETAILS	OLEMBE STADIUM	AHMADOU AHIDJO STADIUM
Cost of Construction	- construction costs, including	250 billion FCFA	Renovation costs FCFA 300 million
	land acquisition, infrastructure development,	Government	Government
	materials	R.c, Steel , glass , terroccota , concrete, PTFE, plastic	R.c, Steel , glass , concrete, PTFE
	labor	Foreign labor and Local Labor	Local labor

	Analyze for cost overruns or unforeseen expenses during construction.	1.5 million euros per year	N/a
Construction Complexity	architectural and engineering complexity,	Complex	Concrete structure
	design, technology integration, and innovative features.	By spoke wheel upgrade	Structural upgrade
	- Evaluate construction timeline and potential delays.	Delay in commissioning	Respected timeline for first deliever Delay in renovation commissioning
Long-Term Durability	- Examine materials used in construction and assess their durability over time.	Durable material Easy to maintain Easy to replace missing parts of materials or danged part	Durable material Easy to maintain Easy to replace missing parts of materials or danged part

Operational Efficiency	- Evaluate operational efficiency for hosting events, crowd management, and facilities for players and spectators.	Hosting Efficient	Has a little deficiency in managing crowd because of all point accessibility Congestion due to urban growth
	Technological advancements and sustainable features for overall efficiency.	The technological advancement helps to support the HVAC system and reduce the Carbon print of the stadium	No sustainable feature available
Environmental Impact	- Environmental impact during construction and operation, including energy efficiency, waste management, and adherence to environmental regulations.	N/a	N/a

Community Impact	- Examine impact on the surrounding community, including economic benefits, job creation, and social or cultural contributions.	Urban regenerator Touristic Attraction Local job opportunities and businesses Identity and pride	Landmark Community programs and involvement Increased economic activities around the stadium Direct employment

5.2 Summary of Key Findings

The findings were rigorously examined in light of the technical advice and guidelines recognized or proclaimed by international sports committees, federations, organizations, and standards(Table 5.3) This thorough method guarantees that stadium efficiency is not only evaluated based on actual outcomes, but also against globally recognized and approved criteria in the domain of sports infrastructure and amenities.

The integration of findings and criteria offers a solid platform for generating meaningful conclusions about the performance and appropriateness of the stadia under consideration.

Concrete and steel were the primary materials found in the most of the stadium structures in Cameroon . concrete is an easily available mater and Simultaneously, the strength, lightweight, and flexibility of steel make it a desirable material for structures. The chart below analyzes the strength and weaknesses of each material (Table 5.3).

Table 5.3: Material Analysis

	CONCRETE	STEEL	HIGH DENSITY POLYETHYLENE
STRENGTHS	• Limit corrosion of the reinforcement • Suitable in corrosive salt water • Less • expensive in general	• Promisingmaterials • Strong, durable, light, and UV resistant • Suitable for • long termuse	• Strong, lightweight, and flexible • Provide more spaces and thinner structural elements than concrete • Requires less

			buoyancy force • Can be extended in the future
WEAKNESSES	• Heavy weight • Requires large buoyancy force • Future extensions difficult • Limits in compression structural • design	• Built-in as modules	• Limited types can be used because of the corrosion Cost • Limited on tensile structural design

5.2.1 Architectural Innovations

Advancements in technology and materials have transformed the design approach for stadium structures, prompting the need for innovation in stadium roof systems. Cable-Supported Systems, Space Frame Systems, have taken the forefront and become eye-catching additions to cities. New design criteria have been applied to stadium roof systems. The newly compiled design features, drawn from a review of the literature, have been used as design criteria when evaluating sample stadiums in the field study. These design criteria are listed below:

5.2.1.1 New Technologies Used in Roof Systems

The incorporation of cutting-edge technologies into roof systems is a key design criterion. Advancements in structural engineering, automation, and materials should be harnessed to create more efficient and dynamic roof systems as follows

- New Materials for Roof Systems and Surfaces. The choice of innovative materials for both the roof structure and its surface is critical. Modern materials should offer improved performance, durability, and aesthetic qualities.
- Urban Visibility, Image, and Contribution to the City. Stadium roof systems have enhanced the urban landscape and contribute positively to the city's image. They should be designed to be visually prominent and add to the city's overall character.
- Shaping Sports Architectural Icons with Roof System Form. The form of the roof system should play a vital role in creating architectural icons within the realm of sports architecture. Unique and iconic roof designs can define the stadium and make it instantly recognizable.

Urban focal points. Stadiums, given their substantial size and multifaceted functions, emerge as urban focal points influencing social, cultural, and physical dimensions. They shape the architectural imagery of the city by providing diverse public services and asserting their spatial dominance on the cityscape.

These structures possess the potential to centralize daily life, becoming integral components of the urban fabric. However, their substantial demands on city infrastructure and resources, such as water, necessitate strategic positioning to avert potential damage. When not appropriately situated, stadiums can become catalysts for urban transformation, as emphasized by Yensoy and Tutal (2015). Therefore, the selection of lands for stadium construction should align with various urban needs, capable of accommodating the strain on resources.

Considering the urban context, the optimal location for stadium buildings involves placement within development zones, ensuring accessibility to fundamental services, and proximity to transportation networks. Attention should be given to incorporating alternative transportation options and establishing a symbiotic relationship with the built environment.

- Proximity to Basic Services. Stadium buildings, given their purpose, attract substantial human traffic, necessitating access to essential services. This includes provisions for food, beverages, accommodations, and other fundamental needs. Meeting these requirements individually is impractical; hence, when selecting locations for stadium construction, it is essential to identify areas where these basic necessities are readily available within walking distance. In the criterion of proximity to basic services, the objective is to position stadiums in development zones without disconnecting them from the broader urban context.
- Urban Visibility of the Cover System / Iconic Architecture and Contributions to the City Stadiums from different eras in different size have altered the cityscape, earning iconic status through the transformative changes they bring about. Notably, structures like the Coliseum Stadium in Rome, a testament to this evolution, remain iconic representations of the city, preserving their status from their inception.

Today, in contemporary architecture, stadiums are dynamic and evolving structures. Their significance lies not only in their sheer size on the urban landscape but also in the innovative materials used and distinctive designs that make them focal points of cities.

Broda (2006) outlines specific criteria for iconic buildings, including innovative designs, association with renowned architects, recognition by city residents, and their scale and representation of an idea.

Jencks (2005) further specifies criteria such as a desire for greatness, utilization of innovations, introduction of unusual shapes or forms, and pioneering new concepts.

In recent years, the prominence of iconic roof designs has become evident in stadium structures. The roof systems of these iconic stadiums contribute to the dynamic silhouette of the city, turning them into veritable brand names for their respective locales. The increasing values associated with these iconic structures underscore their growing influence in contemporary architectural landscapes.

- Proximity to Public Transport Network. Stadium buildings, are characterized by their high capacity and the resulting transportation demands, become hubs of intense commuting activities. Stadiums meeting this criterion contribute to energy conservation and a reduction in oil consumption related to transportation. This strategic placement aims to minimize the environmental impact of vehicles utilizing derivative fuels.
- Improvement of Existing Stadiums. Rather than undergoing complete reconstruction, there is a preference for revitalizing and enhancing existing structures in their current locations. This approach seeks to extend the usability period of stadiums through renovation and improvement operations within the context of specific events.

- Improved audience comfort Stadiums inherently comprise two distinct areas, a concept dating back to ancient times, which remains consistent to this day. The first of these areas is the active space—the playing field where the event unfolds. The second is the area designated for spectators, known as the tribune. Consequently, ensuring audience comfort becomes a pivotal element in the design of stadiums.

5.2.1.2 New Approach to Stadium Design

The new approach of stadiums are designed to prioritize the fan experience and accommodate various events and activities, boosting the venue's bottom line.

The upcoming era of stadiums needs to integrate features and facilities that elevate the overall fan experience while being versatile enough to host a variety of events, contributing positively to the venue's financial performance. factors must be sassed during the planning stage that can have a significant impact on both construction expenses and the ongoing operational budget.

The stadium's design should facilitate easy conversion between different configurations to accommodate various sports and events seamlessly. Prioritizing fan satisfaction is paramount, necessitating amenities and features that improve comfort, convenience, and entertainment. Additionally, sustainability and energy efficiency should be key considerations in the design, aiming to reduce the venue's long-term operating costs. The new approach in stadium Design solves the design of the stadium as shown in (Figure 5.16)

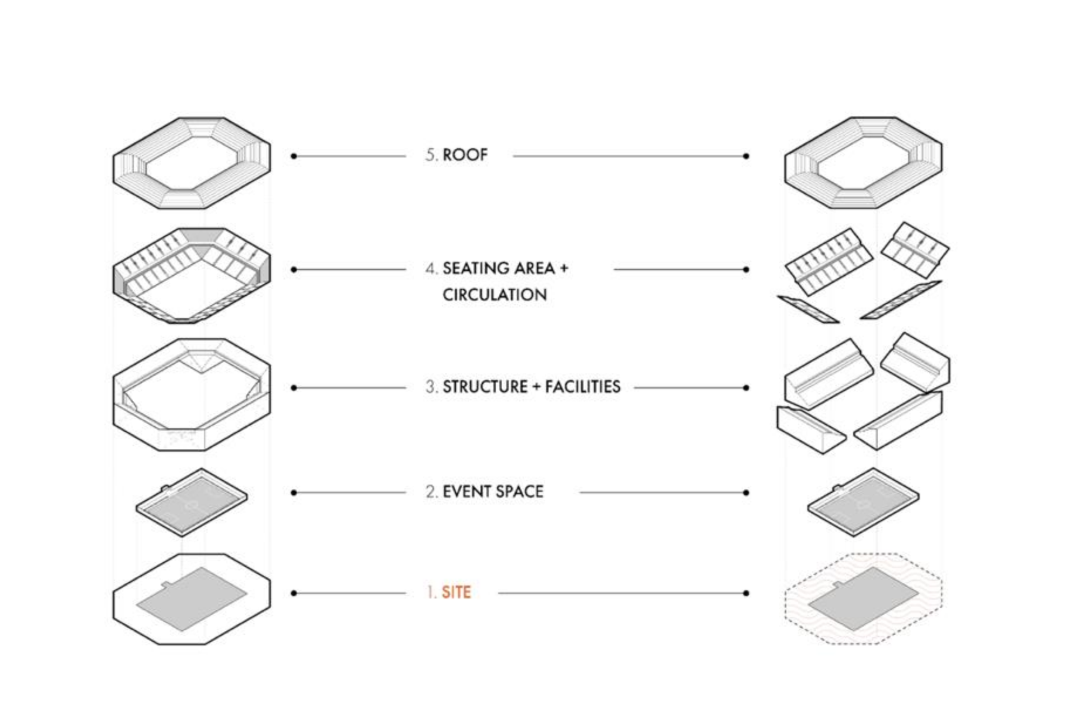


Figure 5.16: New Approach of Stadium Design (Tran et al., 2021)

According to Initially, Cameroon was supposed to host the 2019 edition of the championships (Ekonde, 2021). However, there were delays in infrastructural development of the desired levels for the competition, particularly stadium infrastructure which meant that the 2019 edition was organized in Egypt. Due to the new typologies the construction process takes a longer time than.

5.2.2 Overall Design

Regardless of its intended role, the Stadium must please three types of users: spectators, players, and owners. A successful stadium will meet the needs of these necessary parties while also benefiting the neighborhood's economy and without upsetting the broader public. (Table 5.4)

Table 5.4: Stadium Users. (Mangaleu Toukam, 2023)

	SPECTATOR	**ATHLETE**	**OWNER**
NEEDS	-Safety -Unobstructed views	Proper lighting Proper playing field	Cost-effective Durable
WANTS	-Protection from sun -Shelter from wind and rain -Aesthetically pleasing -Air condition/heating -Overall comfort	Good atmosphere Ventilation	Flexible East to maintain Ability for broadcasting Energy efficient

5.2.2.1 Structural System

In the formation structure of stadiums in Cameroon, there is a morphology in the plan . While all of them are constructed geometrically depending on the system thanks to changing and developing structural systems, more stadiums have been covered and / rehabilitated to partially covered structures for widespan.

5.2.2.2 Significance of the Stadiums in Cameroon's Sports and Cultural Landscape.

Stadiums being part of the cultural heritage of their country is determined by the usage for other activities out of sport for many sports types and cultural activities. However data on post-event use of Cameroonian stadiums have not been elaborated.

The involvement of football tournaments in Cameroonian stadiums in general and then the great interest of people to football and sports allowed the organization of football games in the form of leagues by the FECAFOOT . Through their architectural and engineering aspects, these stadiums represent the advancement and progress of stadium design in Cameroon and a positive response to architectural innovation.

5.2.2.3 Implications for Future Stadium Projects

While there is existing literature discussing the future trajectory of stadiums, it remains somewhat limited and constrained. This underscores the necessity for future studies and additional research in the domain of stadium design and construction, especially as a new evolutionary phase for stadiums appears imminent.

According to Knight (2010), the future of stadia is likely moving towards the development of portable and/or modular structures.

This perspective is echoed by Panganiban (2012), who asserts that experts commonly foresee modular structures as the emerging trend in stadium design. Panganiban specifically points to the 2012 London Olympic Stadium as an early example of this trend.

While the prevailing theory suggests the continuity of this trend into the future, the concept of a fully realized portable and modular stadium is still in its infancy, offering a mere glimpse into what the future may hold for stadium design and construction. An example of this modular structures is seen as an example in this thesis with the case of the 974 stadium in Qatar. Moreover, the increasing emphasis on sustainability within these stadium structures is expected to play a pivotal role in shaping their future development

Chapter 6

CONCLUSION

Stadium buildings have evolved beyond functional spaces to become iconic structures shaping the prestige of a city. A formal and structural analysis has been conducted, examining the historical development of stadiums and the impact of technological advancements on their design.

Over time, stadiums have undergone significant changes and developments, influenced by the evolution of carrier systems, building materials, and structural designs. The transition from ancient standing spectacles to seated stadiums in the 3rd century BC marked a pivotal moment in the establishment of the modern stadium concept. Unlike their historical counterparts, contemporary stadiums serve not only as venues for athletic events but also as hosts for diverse large-scale organizations.

The design of stadiums has diversified, encompassing natural and synthetic fields, district fields, miniature fields, and AstroTurf fields, accommodating various sports and events. Technological progress has enabled the construction of stadiums with retractable roofs and diverse forms, demonstrating the versatility of these structures. During the process of design to make it easy we could suggest a checklist (Table 6.1)

In addition requirements form the different bodies, the structural evaluation to be done and a checklist is elaborated (Table 6.1) stadium may need to meet additional criteria depending on the specific competition or event being held there. For example, a stadium hosting a major international tournament may be required to have a certain number of luxury boxes or VIP seating areas. So a check list was proposed taking into consideration the structure, façade and aesthetic elements.

Table 6.1: Stadium Design Checklist

ASPECT	CONSIDERATIONS/ACTIONS	OBSERVATION	OBSERVATION
ANALYSIS	- Assess site suitability - accessibility, and environmental impact. - Consider climate, topography, and soil characteristics.		✓
PROGRAM REQUIREMENTS	- Functional requirements - Seating capacity, amenities, and supporting facilities. - Incorporate technological advancements for enhanced fan experience.		✓
WIDESPAN CONSTRUCTIONS	- widespan construction options based on requirements or use - structural implications on sightlines and accessibility. - How factors affecting widespan structures are solved		✓

STRUCTURAL SYSTEM	- structural system considering load capacity. - compliance with building codes and standards.		✓
ROOF STRUCTURE	- Design of roof structure - Type of roof; retractable or movable roofs for climate control		✓
ARCHITECTURAL FLEXIBILITY	- Flexibility - type Of design elements.		✓
COST-EFFECTIVENESS	- estimate and budget for the entire construction project. - cost-effective construction methods.		✓
CONSTRUCTION METHODS	- type of construction -Selection of construction type		✓
TECHNOLOGY INTEGRATION	- Innovative technology integration - Energy efficiency		✓

TECHNICAL GUIDELINES	- Adherence to technical guidelines		✓
ACCESSIBILITY AND SAFETY	- Design for accessibility, including ramps and seating for disabilities. - Safety measures and emergency exits.		✓
LANDSCAPING AND AESTHETICS	- Integrate landscaping for aesthetic appeal and environmental considerations. - Visual impact - Aesthetic impact		✓
COMMUNITY IMPACT	- Social and economic impact on the local community.		✓

The 19th century witnessed the specialization of sports structures, with stadiums tailored to specific sports branches. The construction of the Victoria Ground Stadium in England in 1878 marked the inception of stadiums designed specifically for football purposes. As football gained popularity, there was a growing emphasis on enhancing stadium visuality to reflect the prestige of teams and cities.

Modern stadiums, primarily designed for football, feature smaller capacities, averaging 40-50 thousand seats. Emphasis has shifted from seat quantity to individual seat comfort, reflecting the evolving nature of sports as entertainment. Shell and interior designs have incorporated unique and interesting elements to enhance the overall experience.

Technological advancements, including the use of reinforced concrete, steel, and membranes, have facilitated the creation of large openings and intricate designs. Structural systems such as surface carriers, cable networks, space cages, spring geometric, and fractal geometric systems have been employed. Organic forms have emerged alongside geometric structures, emphasizing not only functionality but also aesthetics and comfort.

The symbolic representation of a city and its team, along with the choice of structural systems by designers, plays a role in shaping the form of stadiums. The integration of city symbols, team colors, and structural choices contribute to the distinctive appearance of stadiums.Stadium design often adopts an analogical approach, combining geometric and organic elements in both plan and section planes. Recent trends highlight the integration of visual impact through organic shaping, emphasizing the city's prestige and creating structures that attract attention.

In summary, stadium design depends on many parameters like structure, roof façade etc. The continuous development of technology, structural systems, and building materials has granted designers the freedom to create stadiums in diverse forms. The analogical approach, emphasizing visual appeal, has led to the production of stadiums that serve as iconic symbols of cities.

It is seen that concept of widespan structures in the context of Cameroonian stadiums, has a special emphasis on the structural systems and structural system on the stadium roofs. The structural and architectural aspects of two prominent stadiums, Ahmadou Ahidjo Stadium and Olembe Paul Biya Stadium, are closely related to each other in terms of their evolution. Also the most important aspect is the evolution of stadium design and construction from different eras.

One of the key contributions of this study is the identification of a substantial gap in the existing literature on this topic, making it a valuable resource for architects, builders, and researchers. By evaluating five significant stadiums in Cameroon and providing technical advice and guidelines for roof structures, this thesis offers practical insights that can enhance the cost-effectiveness, durability, and visual appeal of future stadium projects, not only within Cameroon but also as a reference for global stadium design.

Furthermore, the study underscores the role of widespan constructions in shaping the architectural landscape of Cameroon and their enduring cultural significance.

Finally the thesis research contributes to the body of knowledge in stadium design and construction, providing a comprehensive understanding of widespan structures in

Cameroonian stadiums. During the comparison of results, significant findings were observed and the following conclusions can be drawn from those observations:

- The evolution of stadium design server as a precedent to many stadium design all over the world hence we can see a movement from basic , open-air structures to advanced technology.
- The research findings have demonstrated a notable diversity in the structural systems employed in the construction of widespan elements in these two stadiums. This variation can be justified by the differences in the time periods during which these stadiums were built. The Ahmadou Ahidjo Stadium, constructed in the 1970s, primarily involved civil engineers who focused on the structural integrity, resulting in a visibly robust and sturdy structure. In contrast, the Olembe Stadium reflects a more versatile and aesthetic approach to construction. This difference is evident in its design and construction process, which involved a collaborative team effort. Furthermore, in this approach, detailed models were created to assess and address potential hazards or obstacles that might arise during the construction of widespan elements.

The stadiums in Cameroon go beyond their functional purpose and hold cultural importance as they become landmarks ; as they are symbol of national pride. Also each stadium is unique as the have innovative designs harmoniously integrating themselves into the architectural landscape of the country as they transform the landscape and standout due to innovative designs and distinctive ones in some cases

- Out of the stadiums that fit into FIFA standards it should be highlighte that ther has been and incorporation of advanced technologies such as : innovative materials, engineering solution and adaptability of stadium widespan construction pushing the evolution of stadium construction further thus having a great significance.

- Ahmadou Ahidjo Stadium and Olembe Paul Biya Stadium can serve as global references for widespan stadium design. Their innovative design and structural systems can inspire future infrastructure projects worldwide.
- All the stadiums were designed with consideration for the local climate, environmental conditions, and the needs of the local population, showcasing the importance of context in architectural decisions. Hence we see different types or morphological configuration.

In summary, contemporary widespan structures in Cameroon have a profound impact on the country's architecture. They promote innovation, celebrate culture, enhance the urban landscape, drive economic growth, gain global recognition, and serve as sources of inspiration for future architectural endeavors.

6.1 Recommendation

In the light of these findings, it is expected that this study will be a point of reference for stadiums as widespan structures focusing on the structural systems in the context of Cameroon hence Suggestion some points for Further Research The following recommendations are suggested for future research:

- A Contrast with the structural systems and architectural aspects of Cameroonian stadiums with those of comparable size and importance. To show the stadium aligns with global trends ‘
- In the future an investigation to the incorporation of sustainable and environmentally-friendly design principles in Cameroonian stadiums. An

Analysis on how these stadiums can be made more energy-efficient, eco-friendly, and sustainable in the long term.

- Considering taking case studies from different climatic regions
- Research the utilization of locally sourced materials and construction techniques in stadium design. Investigate their feasibility, cost-effectiveness, and sustainability.
- Analyze the incorporation of cultural symbols and traditional elements in contemporary stadium architecture.
- Exploring the cultural and architectural significance of these stadiums within the context of Cameroon's history and identity.
- Conduct an in-depth structural analysis of stadiums Stadium, exploring the design choices and innovations that contribute to their widespan structures.
- Exploring the technological advancements and construction methods used in the development of widespan structures for stadiums in Cameroon.
- Explore and future possibilities in widespan stadium design, considering advancements in technology, sustainability practices, and evolving fan expectations

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