Evolution of Stadium Design

by

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ABSTRACT

Stadiums are more than just facilities for organized sport; they offer a gathering site for people with shared interest, provide economic benefits to the surrounding community, and most importantly represent the advancements in architecture and engineering. When stadiums were first developed, their main focus was to provide enclosure for athletes' play and little attention was given to spectators. Most Greek and Roman athletic facilities are guilty of this. While the general geometry of stadiums remains the same today, the structure itself has changed tremendously. As this thesis will point out, there is a multitude of structural systems that have been employed in the design of stadiums. As very big structures attracting a lot of attention, stadiums require good architecture. Designers have not been shy about attacking this problem head on resulting in an abundance of spectacularly designed and built stadiums, many with their own unique features.

After introducing significant design constraints and possible design solutions, this thesis will present a handful of case studies. Stadiums from across America and Europe will be discussed in varying detail in the hopes of opening the reader's eyes to the advancements in stadium design. Upon reading this thesis, readers should gain knowledge on the growth of stadium development and hopefully an understanding of where stadium design will go in the future.

Thesis Supervisor: Jerome J. Connor

Title: Professor of Civil and Environmental Engineering

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Introduction

Since their earliest existence in ancient Greek and Roman civilizations, stadiums have been regarded as architectural masterpieces and focal points in their surrounding cities. "Stadiums are amazing buildings. They can help to shape our towns and cities more than almost any other building type in history and at the same time put a community on the map".[1] Whether it is an Olympic Stadium, a private soccer club stadium, or a city's landmark stadium, the design and development is an exciting challenge for all the architects and engineers involved. 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. As will be discussed in this paper, the Roman Colosseum is the first architecturally and structurally designed building that resembles modern-day stadiums. Following the construction of the Colosseum in AD 70, stadium design took off and similar designs were built across many civilizations.

After a few centuries of minimal improvements in stadium development, the industry made huge advancements starting in the 19th century. Once sports were properly defined and strict guidelines were set in place, architects had specific constraints to drive their designs. With new technology and an increased understanding of engineering capabilities, designers began producing one-of-a-kind stadiums that would be remembered for years to come. Throughout this thesis stadiums will be pointed out for their success and important contributions to the field of stadium design.

As the examples throughout the thesis show, stadium designs have become more complex as well as more imaginative, in terms of architecture, structural systems, and materials used. Scientists are always looking towards inventing newer and stronger materials and engineers are just as eager to implement those materials in awe-inspiring structural designs. The latest trend is the incorporation of moving roofs which are becoming the norm and are being implemented in new construction as well as stadium renovations. Taking it one step further, stadiums are also being equipped with movable pitches, like the Arizona Cardinals Stadium which will be discussed at length later in the thesis. With the option of having a fully roofed facility and a field

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[1] (Geraint, Sheard and Vickery 2007, 21)

with natural grass, "stadiums have been evolving from one-sport stadiums to multi-use venues, and have additionally needed to meet the demands of the new era of media involvement."[2]

The purpose of this thesis is to unravel the development of stadiums as an engineering achievement. In order to accomplish this, the report is broken into nine major chapters. The first three chapters deal with the history of stadiums and their existence from the Greeks and Romans to the 20th century. Following this, a second set of three chapters discusses the design considerations and factors that drive stadium designs. This includes major decisions like the basic use of the stadium, as well as smaller details like the type of steel that is needed. Once these factors are introduced, the thesis focuses on structural systems, specifically those geared towards the roof. The roof of the stadium is often the most complex and awe-inspiring thus requiring the most detail and imagination. Last but not least, the final contextual chapter of this thesis presents multiple case studies. Each case study varies in content and detail but is included in the hopes of sharing some worthy information about the development of stadiums.

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[2] (Culley and Pascoe 2005, xii)

The Origination of Stadiums

1. Introduction

Like many other historical engineering feats, the concept and design for stadiums was first developed in ancient Greece and Rome. Both societies stressed the idea of community gathering and public display of strength and talent. The Greeks had two buildings related to modern day stadiums, the stadium and hippodrome. Likewise, the Romans had the amphitheater and circus. Romans were known for invading surrounding regions and building such structures as a means of integrating people into their society. Stadiums, hippodromes, amphitheaters, and circuses all share many characteristics amongst themselves and with modern day stadiums.

2. Greece

In honor of his father Zeus, Heracles began the Olympic Games in Olympia, Greece in the year 776 BC. Like a majority of ancient history, the origin of the Olympic Games is based on myths and legends. One such legend is that Heracles walked six hundred steps, one after another, to determine the length of the track for the running event at the Olympics. This length, which amounted to about 192 m, was named a 'stadion'.[3] The term 'stadium' was used from here on out as the name for the running event and the site for the foot racecourse.

Figure 1: Ancient Stadium at Olympia
(Olympia Greece n.d.)

Olympia stadium, as it was called, was a rudimentary athletic track 192 m long and 32 m wide. Marble slabs were placed at both ends marking the start and end points. Additionally, a podium

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[3] (World Stadiums 2012)

for judges was fixed on one side, along with a few stone seats. The original site would look like the image in Figure 1. The banks on the sides of the track could accommodate up to 45,000 spectators, although no permanent seats were put in place until Roman times.

Eventually, the Olympic Games became more popular and new events were added. For many years, these new events were limited to longer footraces measured in terms of the 'stadion'. To accommodate these races, the track was turned into an elongated U-shape, forming the template for future stadiums. In order to seat the judges and thousands of spectators, stands were put in place along all three sides of the track.

The construction for Geek stadiums took one of two paths: cut out of a hillside or constructed on flat ground. Building into the hillside provided natural seating along the banks with good sightlines. Examples of this type of stadium include those built at Olympia, Thebes, and Epidauros. These stadiums were essentially elongated ancient Greek theaters and have a direct link to the multi-tiered Roman amphitheaters. Building on flat ground required built up seating and sometimes required excavation for the performance area. Examples of this can be seen at Ephesus, Delphi, and Athens. The stadium at Athens was first constructed in 331 BC and was reconstructed in 1896 for the first modern Olympic Games. The modern stadium, which can still be seen today, had seating similar to that shown in Figure 2, and held 50,000 spectators in 46 rows.

Figure 2: 1896 Athens Olympic Stadium
(World Stadiums 2012)

In addition to the Greek stadiums, there were also hippodromes, which were used for horse and chariot races. Like the stadiums, these hippodromes were U-shaped and were most commonly built on the hillside so that naturally rising tiers of seating resulted. Hippodromes were around 200 m long and 37 m wide (similar in dimension to the stadiums).

3. Rome

Similar to the Greeks, ancient Romans perceived spectacles to be an integral part of their lives. Many spectacles were held in purpose-built buildings. The two that relate most closely to modern-day stadium are the amphitheaters, which were designed specifically for gladiator combat, and the circuses reserved for chariot races. Description and examples of each are detailed below.

3.1. Amphitheaters

Ancient Romans were known as being militaristic and having great interest in public display of strength and combat. The first stadium-like structure that the Romans developed was the amphitheater, which dates back to the 1st century BC. Prior to this time, as early as 218 BC, gladiatorial contests took place in the center of the Roman Forum where spectators watched from temporary wooden stands. When amphitheaters began to emerge, they were characterized by their elliptical shape and rising tiers of seating surrounding the arena. The term "arena" derives its meaning from the Latin word for 'sand' or 'sandy land', referring to the layer of sand that was spread on the activity area to absorb spilled blood from brutal gladiator fights.[4]

The elliptical shape of amphitheaters guaranteed that each spectator's focus was on the central arena. The shape is also the result of combining two Greek theaters together. Because the size of an amphitheater was so large, the Romans could not excavate the entire site to use natural hillsides for seating. Therefore, above ground construction was utilized and seating was built up around the central arena. Originally, this was done in timber, but these did not last long due to fire damage and natural damage from rowdy spectators. Starting in the 1st century AD the Romans began to use stone and concrete. Roman concrete has proven to be a miraculous material with unbelievable strength. A detailed explanation of their mix and use of concrete will follow later in the report.

Once the Romans switched to using concrete, their structures began to last for centuries. The first securely datable stone amphitheater was constructed around 80 BC at Pompeii, while the

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[4] (Geraint, Sheard and Vickery 2007, 4)

first to be built in Rome wasn't until 29 BC. This amphitheater in Rome burned down in the great fire of AD 64 and was replaced by the Colosseum (described later), which is one of Rome's most prominent landmarks. Other significant and well preserved examples of Roman amphitheaters are the Arles Amphitheater and Verona Arena. The amphitheater at Arles is located in the southern French town of Arles and was built around 46 BC. It is said to have held 21,000 spectators in three stories of seating and was covered by a tented roof supported by posts from the third story. Most of the structure has survived until today and is still being used for bullfighting, plays, and concerts.

3.2. Circuses

Parallel to the development of the amphitheater from the Greek theater, the tradition of the Roman circus developed from the hippodrome design. Like the hippodrome, the circus was used for horse races. Once again, the elongated U-shape was utilized, but in this case the open end was closed off with buildings. This entrance housed the stables for the horses and chariots. With a continuous course, races could consist of multiple laps around the circus. A low wall decorated with carvings and statues, known as a 'spina', separated the two long sides of the track. At either end of the 'spina' was a 'metae' which indicated the turning point for the horses. Seats at the circuses rose in tiers along the straight sides and around the curved end. Lower seats were made of stone while the upper tiers were constructed out of wood.

The most notable example of this building typology is the Circus Maximums (Figure 4). In 329 BC the original Circus Maximus was constructed out of wood and seated around 150,000 spectators. Unfortunately, a fire in 31 BC destroyed the wooden structure. Emperor Augustus rebuilt the Circus Maximus, but the great fire in AD 64 destroyed it once again. Finally, in AD 103 Trajan successfully rebuilt the Circus once again and this time it reflected the power of the Roman Empire which was at its height at the time. Possibly the largest stadium ever built, the Circus Maximums was 660 m long and 210 m wide and had seating on all three sides that could accommodate up to 200,000 spectators.

Figure 3: Circus Maximus
(Circus Maximus 2012)

The Circus Maxentius from the 4th century AD is another noteworthy circus. Outside of Rome was the Pessimus Hippodrome, which was unique because it contained a Greek theater and a Roman hippodrome. Linked at the center of the hippodrome, these two structures could host two events separately or one large event by combining the spaces. This hippodrome is a good example of modern day multi-purpose stadium complex that hosts a variety of activities.

3.3. Roman Concrete

More than 2,000 years ago the Romans began developing the building material known today as concrete. Roman concrete, called 'opus caementicium', is like modern concrete in that it mixes together an artificial building material composed of aggregate, a binding agent, and water. Testing has been done on the ancient concrete and it is believed that "Roman concrete is considerably weaker than modern concrete. It's approximately ten times weaker".[5] Although it is considered to be so much weaker, there are several Roman concrete structures that are still standing today, such as the Pantheon and Colosseum. Geologists, archaeologists, and engineers have been studying samples to determine what properties of the cement give it this longevity.

One of the key elements that the Romans incorporated into their concrete mix is volcanic ash, which is believed to provide phenomenal resistance and durability against elements of nature. Early on, the Romans would mine ash from a variety of deposits, but as time went on, builders became more selective and eventually Emperor Augustus began demanding specific ash. Around 27 BC Augustus initiated a citywide program for renovation and erection of new

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[5] (Wayman 2011)

monuments and specifically required the use of ash from the Pozzolane Rosse deposit. This volcanic deposit was the result of an eruption that occurred “456,000 years ago from the Alban Hills volcano, 12 miles southeast of Rome”[6]. When this specific ash couldn’t be found, the Romans used local materials such as lime or gypsum for the binding agent.

The complete formula for Roman concrete includes: limestone (burned into quicklime) added to water, volcanic ash, and fist-size chunks of brick or volcanic rock.[7] Volcanic ash was added in a ratio of 3-to-1 with the lime; the ash reacted with the lime to create a durable mortar that when added to the rocks could be packed to form structures. Romans were using their concrete mixture for large scale projects, such as the Colosseum in AD 70 with such precision that it is believed by many that they began experimenting with the mixture years earlier. Many other civilizations, like the Greeks, probably also used lime-based mortars for construction, but the combination of the mortar with stone is likely a Roman invention.

Listed below are the numerous advantages of Roman concrete:

1. Allowed longer spans for arches, vaults, and domes
2. Flexibility in shape since it was poured and took on the shape of its container
3. Did not require skilled labor
4. Faster construction than laborious stone construction
5. Naturally fireproof and therefore safer than wood construction

One negative aspect of concrete is its unattractive appearance. However, the Romans did a good job of overcoming this downfall by surfacing the concrete with another material that they considered more visually appealing. Around 200 BC the chosen material was tufa, a soft volcanic stone easily found in the area. The pattern of applying the tufa changed with time, starting off as just slabs, then fist size mosaics, and eventually regular sized square blocks diagonally arranged.[8] Around the 2nd century, kiln-baked brick replaced tufa as the chosen covering material.

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[6] (Wayman 2011)
[7] (Wayman 2011)
[8] (Yegul n.d.)

Harbor structures required a different volcanic ash than land structures. While the Pozzoloane Rosse volcanic deposit appeared to withstand chemical decay and damages, the harbor structures needed a component that would protect it from seawater damage. For this reason, the Romans favored Pulvis Puteolanus, which was mined from deposits near the Bay of Naples.[9] Seawater is known to be extremely damaging to modern concrete. Marie Jackson, a geologist and research engineer at the University of California at Berkeley has studied Roman concrete mixes and found that the "Pulvis Puteolanus actually plays a role in mitigating deterioration when water percolates through it".[10] According to Jackson, the reaction between the lime paste, volcanic ash, and seawater created a microscopic structure within the material that trapped the harmful molecules (chlorides and sulfates). While these studies show some insight into the difference between Roman concrete and modern day concrete, it is still unknown why buildings like the Colosseum still manage to be standing today.

3.4. Colosseum

The most famous amphitheater that the Romans produced was the Flavian Amphitheater, better known as the Colosseum. Emperor Vespasian was responsible for planning and starting construction of the Colosseum. It is believed that this was done from a political standpoint as a means of showing the Roman people that the emperor could give as well as take. To this day, the Colosseum is respected as one of Rome's greatest achievements and as one of the world's best fusions of engineering, theater, and art. The four-story amphitheater took 12 years to construct and began in AD 70. Figure 4 and Figure 5 show what the Colosseum looks like today.

Figure 4: Colosseum
(Hopkins 2011)

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[9] (Wayman 2011)
[10] (Wayman 2011)

Figure 5: Aerial View of the Colosseum
(Hopkins 2011)

Although only part of the structure remains, it is estimated that the arena ellipse measured 88 m by 55 m while the exterior ellipse was 189 m by 155 m; its total height is thought to be about 50 m. Seating capacity at the Colosseum surpassed any amphitheater of its time, with a staggering 48,000 seats, a number not reached again until the 20th century.

Unlike many buildings of the time, the Colosseum had most of its details worked out before construction began. The building was designed according a set of architectural principles and conventions developed in the construction of earlier amphitheaters. The Colosseum had a complete foundation design and basement. Drains were built 8m underneath the structure and foundations made of concrete were 12 m deep under the outer walls and seating and raised to only 4 m deep under the inner arena. Soil dug up for the foundation was used to raise the surrounding ground level by around 7 m (in addition to the 4 m that already existed from the debris of an earlier fire) so that the Colosseum could stand higher than the rest of the valley. The elaborate basement of the Colosseum contained animal cages, mechanical elevators, and a complex system of passageways.

The façade contained 80 arch openings on each of the three stories which were connected to columns that varied from Tuscan, Ionic, and Corinthian orders. "So powerful and inventive was this unprecedented façade that it became a primary source of inspiration for the architects of the

Renaissance fourteen centuries later."[11] Figure 6 shows a plan view of the Colosseum and stitches together each story to give a comparison.

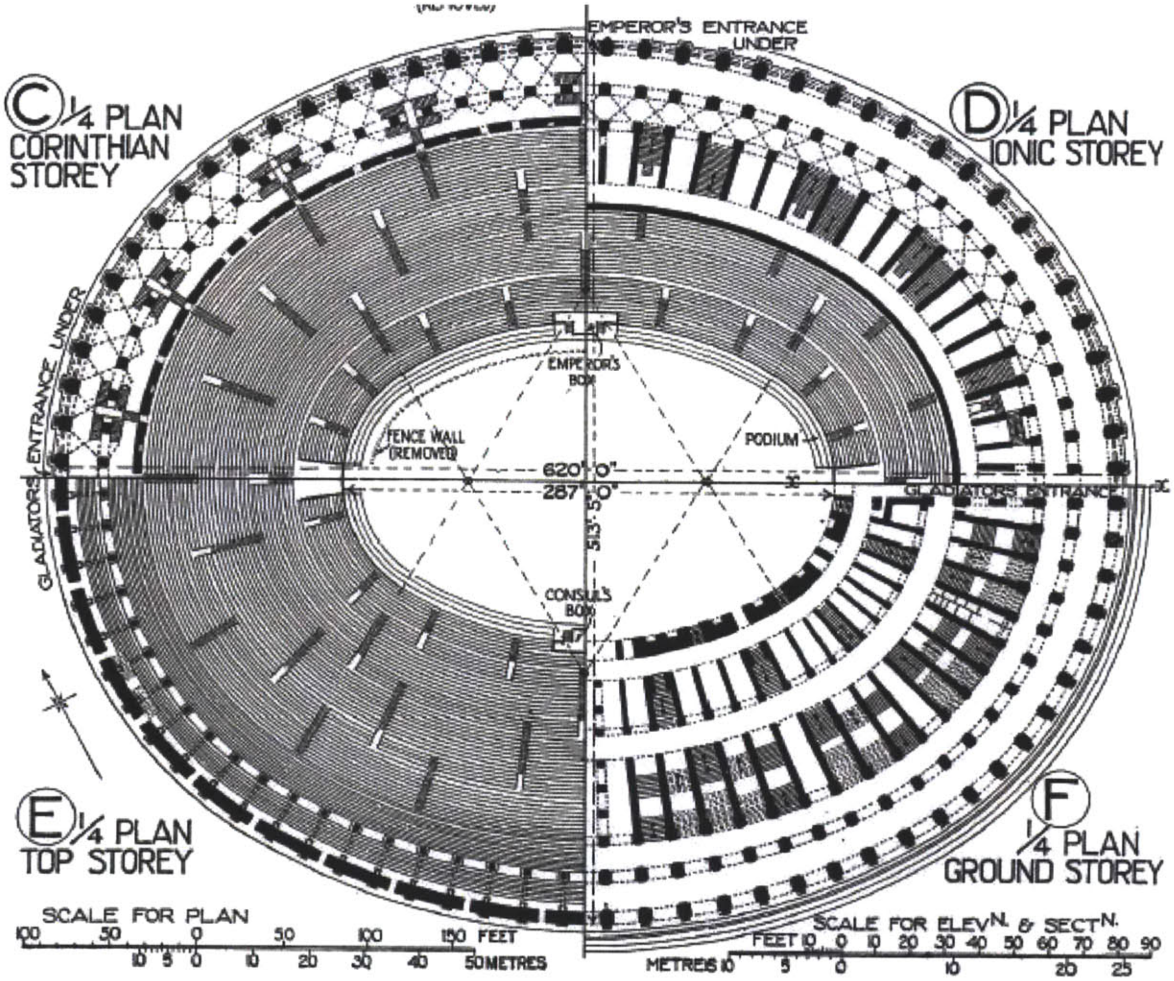

Figure 6: Colosseum Plan View
(Geraint, Sheard and Vickery 2007, 5)

A unique aspect of the structure is the fact that it broadens from top down to the base. This design formed the artificial hillside required for adequate spectator viewing and created a stable structure. Seating tiers were supported on barrel-vaults and arches which distributed the loads to the widening structure, down to the foundation. Additionally, the broadening structure matched the volume of internal space to the number of people at each level (majority of people at base level and few at top).

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[11] (Geraint, Sheard and Vickery 2007, 49)

Several materials were used in the construction of the Colosseum. The original skeletal framework of concrete piers and arches was built of Travertine limestone and then connected with walls. Travertine marble was used to clad the entire building, some of which can still be seen today. Lastly, the seats surrounding the arena were either wood or marble. Women, the poor, and non-Roman citizens sat in the upper sections made of wood. Marble seating was placed at the lower levels for Roman men and those of high social standing.

Like other amphitheaters of the time, the Colosseum could be roofed by spreading a canvas awning across the open top. This canvas, composed of sails, and called the 'velarium', protected the spectators from the weather and heat of the sun. The sails weighed close to 24 tonnes and required the work of two ship's crews to prepare. Posts protruding from the top of the Amphitheater hoisted the sails and fastened them in place. It is also believed that the ropes from the sails extended down to posts at ground level.

In terms of structural analysis of the Colosseum, the building works on a balance of pressures. Composed of barrel vaults, columns, and walls, forces travel from one component to another, down to the foundation. "Downward vertical thrusts from of external walls match the outwards thrust of the barrel vaults in the circular promenades, which was itself also relieved by the series of radial walls, built like the spokes of a wheel, from the inner ring of the arena".[12] Arches and vaults are two architectural/structural elements that were invented by Roman architects. These brick-faced concrete elements allowed the Romans to span greater distances and provide greater visual variety. Incorporating these elements into the Colosseum permitted thousands of spectators to watch games in a custom made amphitheater. "The Colosseum's imposing exterior was then, and it still is, a marvelous monument to Roman imperial power".[13] To this day, many designers study and contemplate the design of the Colosseum before tackling new stadium designs.

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[12] (Hopkins 2011)

[13] (Hopkins 2011)

Stadiums in the 5th -19th Century

1. Introduction

As history runs its course, different activities are emphasized by society. While the ancient Greeks and Romans put theater, sports, and combat at the center of their everyday lives, this slowly faded out. Eventually, religion began to spread and public activities outside of Church were negligible; this was the case for most of the Middle Ages. However, nations eventually found ways to balance different aspects of life and sports made a comeback during the Renaissance. Since then, stadium construction and rehabilitation has been ongoing across the world.

2. Middle Ages

Throughout the Middle Ages, which encompassed the 5th to the 15th century, religion became the focus of everyone's lives. Christianity swept throughout Europe and all societal emphasis turned to the church. Daily life activities were centered on the church and all engineering and architectural work went towards building new churches. In 314, the Council of Arles banned circus charioteers causing more circuses to transform into non-sports facilities. Years later in 394, emperor Theodosius abolished the Olympic Games, a request made by Milan's Bishop Ambrose, because they were regarded as a pagan rite.[14] All of this affected the development of sports facilities, as no new stadium or amphitheater would be built for fifteen centuries. Existing facilities were neglected, converted for appropriate use, or demolished. The amphitheater at Arles was "transformed into a citadel with about 200 houses and a church inside it, built partly with stone from the amphitheater structure".[15]

3. Renaissance

During the Renaissance, a period spanning the 14th to the 17th century, participation in sports was restored. Running and equestrian events were reintroduced and held in open fields or town squares. Although no permanent structures were constructed, temporary stages and covered areas were occasionally put in place. One example of this is Piazza del Campo in Siena, which is the center square of the city where races were held. To this day the Pallio di Siena hosts horse

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[14] (World Stadiums 2012)

[15] (Geraint, Sheard and Vickery 2007, 6)

races twice a year. Organized sports began to come alive during the Renaissance as well. A modern football-like game, where the only rule was to throw the ball into the goal of the opposite team, was played in the Piazza Santa Croce in Firenze (Figure 7).

Figure 7: Piazza Santa Croce
(World Stadiums 2012)

4. 19th Century

Sports and the stadium as a building experienced huge growth in the 19th century after the industrial revolution. Sport games became properly defined and different clubs and federations were developed. Great Britain was the first to welcome organized sport, with immense enthusiasm for soccer and rugby. Along with the growing fan population, the industrial revolution advanced structural technologies so that appropriate stadiums could be built catered to specific sports.

The Rebirth of the Olympic Games

1. Introduction

Near the end of the 19th century the Olympic Games were revived by the French Baron Pierre de Coubertin. A congress met in 1894 and began organizing the first modern Olympic Games which would be held in Athens in 1894. The ancient stadium from 331 BC was rebuilt for the first modern Games. The traditional U-shape stadium was expanded to hold 50,000 spectators. The revival of the Olympic Games was a critical point in the history of sports and "symbolically marked the start of a new age of stadiums".[16] From here on out, the Olympics would be held every four years (except when war interrupted) and new stadiums would be built to publicize the events and rejuvenate the host's local economy.

2. The First Official Olympic Stadium

Although the concept of stadiums and organized sport was revived first in Great Britain, it quickly spread to all countries, with Greek and Roman facilities being the reference prototypes. New technological innovations helped spread this evolutionary process as Olympic Games, and soon Soccer World Cups as well, began to take place around the globe.

The first generation of stadiums had a similar purpose as ancient Greek and Roman stadiums: gather all spectators in one place to watch an event. Like the early ancient stadiums, these facilities also had little architectural value and were uncomfortable for the spectators. Seating was arranged on the embankments or made of concrete and as the need for additional accommodations arose, non-homogenous additions were made.

In 1908 the Olympic Games were held in London, where the first example of the new stadium concept was unveiled. The White City Stadium (Figure 8), designed by James Fulton specifically for the Olympics, was a steel frame structure with a capacity for 150,000 spectators. The arena, which was considered to be gigantic and could accommodate a multitude of sports, was surrounded by an athletic track and tiers of seating. Of the 150,000 spectators, only 68,000 had seats and 17,000 were covered by the simple roof that ran along the straight sides.[17]

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[16] (Geraint, Sheard and Vickery 2007, 7)
[17] (World Stadiums 2012)

Figure 8: White City Stadium (London)
(World Stadiums 2012)

3. Stadiums Experience Change

Stadium design suffered numerous changes in the late 1950s and early 1960s. The first controlling factor was the increased popularity of television and live broadcast. As televisions became a common household commodity, sport spectators preferred watching events on their home televisions rather than sitting in uncomfortable and overcrowded stadiums. In order to remedy the situation, designers had to better equip the stadiums so that people felt more comfortable and relaxed. As a result, seating sections were made roomier and roof coverings became the norm. They also began incorporating concourses with public restrooms as well as food and beverage outlets.

A second major change came with the 1960 Olympiad in Rome, where a "decentralized plan was decided upon, with the athletic stadium in one part of the city and other facilities some distance away on the urban outskirts".[18] This approach remained the preferred method for the next several years.

4. Noteworthy Olympic Stadiums of the 20th Century

As the Olympic Games made their way across the globe, host cities began to put more emphasis on the design of their Olympic facilities. Architects used this to their advantage and began designing noteworthy structures that would be remembered for years to come.

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[18] (Geraint, Sheard and Vickery 2007, 8)

4.1. 1960 Rome

As the first Olympics to have multiple stadiums, the 1960 Olympiad in Rome had several notable structures, the smaller venues proving to be the most interesting. The main stadium was a simple oval shape, had no roof, and had three tiers of seating. Overall, it was very similar in design to past stadiums. More interesting were the smaller structures: Palazzo dello Sport and Palazzetto dello Sport, both engineered by Pier Luigi Nervi.

The Palazzo dello Sport was designed by architect Marcello Piacentini and has a capacity for 16,000. Circular in shape, the venue is fully enclosed and has no columns in the interior, allowing for unobstructed views of the events taking place.

The second structure, the Palazzetto dello Sport (Figure 9) was designed by the same architect as the main stadium, Annibale Vitellozzi. Similar to the Palazzo, this venue is circular, fully enclosed, and column free, but has a smaller capacity of only 5,000. The interesting aspect of this venue is the concrete domed roof. The concrete shell roof of the structure rests on 36 pre-cast perimeter supports. Because of these supports, the lower half of the dome is non load-bearing and a ribbon of windows could be installed to allow natural light inside.

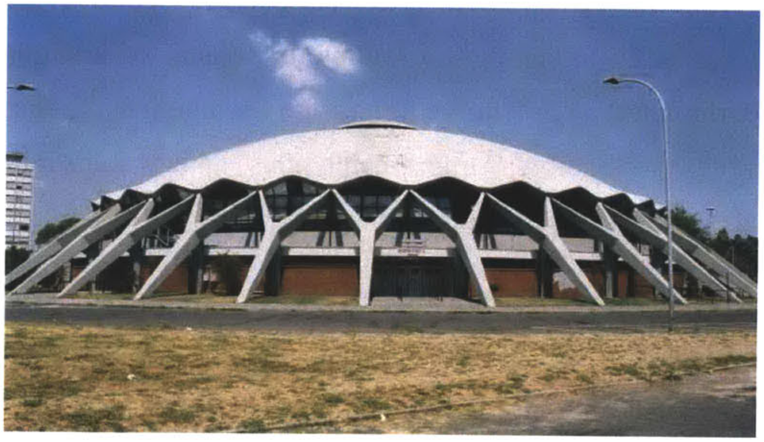

Figure 9: Palazzetto dello Sport
(Structurae 2012)

4.2. 1964 Tokyo

Following Rome's example, Tokyo also took the approach of spreading events out into multiple venues. Kenzo Tange, a Japanese architect designed two of the smaller venues which have gained international fame. The swimming arena, which is large enough for 9,000 standing and 4,000 seating spectators, supports a suspension roof that is composed of steel cables draped from a single tall mast on the perimeter of the circular shape.[19] As seen in Figure 10 below, concrete panels were hung from the cables to form a semi-rigid roof structure that gave the arena a natural look. Advanced for its time, this roof structure was the result of extensive tests, models, and material research.

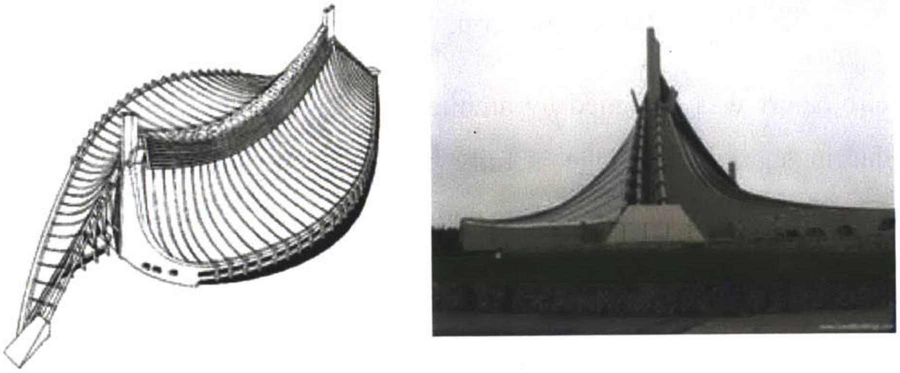

Figure 10: 1964 Tokyo Swimming Arena
(Great Buildings Collection 2012)

4.3. 1972 Munich

Germany had been offered to host the Olympic Games several times. Berlin was chosen to host the 1916 Games but the First World War broke out and the Games were canceled. However, Berlin did prepare for the event and built a stadium of natural form, similar to those of ancient Greece. In 1936 Berlin got the opportunity to host the Olympics again; the original stadium was expanded to hold 110,000 spectators. Unfortunately, this stadium holds more bad memories than good since the Nazis used it for mass political demonstrations.

When Munich, Germany was chosen for the 1972 Olympics, the country made sure to design elegant structures and make efforts to erase the memories tied to the Berlin Olympics. Following this approach, a lightweight roof was thrown on top of the existing stadium in order to create an airy feel. The arena was placed so that the roof, "which consists of transparent acrylic panels on a steel net hung from a series of tapered masts, seems to float above the parkland, its gentle undulations mirroring those of the landscape below".[20] This roof design is an example of a dominant roof, since it provides all visual appeal of the structure, thereby eliminating the visual conflict between roof and façade. The playing surface for the stadium was recessed below

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[19] (Geraint, Sheard and Vickery 2007, 8)
[20] (Geraint, Sheard and Vickery 2007, 9)

ground level thus allowing the stadium to grow into the hillside, virtually eradicating the need for walls altogether.

5. Afterlife of Olympic Stadiums

Numerous Olympic Stadiums are designed, built, and used only for the few days the Olympics actually take place. These stadiums are designed to hold an audience much greater than any single sport, or local organization, can bring in. This creates concerns about the long-term viability of these huge stadiums. In order to remedy the situation, designers began to build both permanent structures as well as temporary additions that could be removed when the Olympics are over.

London, chosen to host the summer 2012 Olympics, is the first country to put a major focus on the legacy of the Olympics. According to the official London 2012 Olympics website, "long after the athletes and spectators have moved on, the Olympics Park will become a fantastic new focal point for the capital".[21] Since their original bid in 2003, London has emphasized their effort in keeping their facilities sustainable and transforming the venues for future use. Some events will take place outside of Olympic Park at existing venues, such as Millennium Stadium and Wembley Arena. Even the new structures were built with the future in mind; some facilities will be completely temporary while others, like the Aquatic Center and Olympic Stadium will have seating sections that will be removed when the Olympics are over.

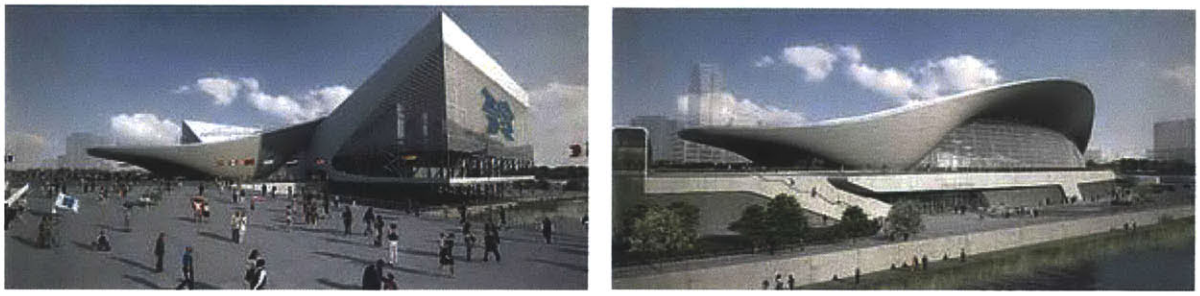

Figure 11: 2012 London Aquatic Center
(Legacy London 2012 2012)

Figure 11 shows renderings of the Aquatic Center during the Olympics (left) and in legacy (right). As seen by both images, the structure will still be an architectural masterpiece both during and after the Olympics.

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[21] (Legacy London 2012 2012)

Stadium Uses

1. Introduction

Along with the multi-use Olympic stadiums that were developed across the world, there was an increase in ambitious facilities for specific sports. As described earlier, in the 19th century sports became properly defined and with that came a set of standards for organized play. This had a huge impact on stadium design because it controlled the dimensions of the playing field and the material of the field. "From the early 20th century and into post World War II America, baseball, basketball, and eventually football became the driving forces in stadium and arena development."[22] Countries throughout Europe were designing for rugby, cricket, and soccer. Each sport has a unique playing field size and shape, thus forcing the stadium design to be driven by its projected use. Eventually, stadiums became multi-use facilities and were designed for a myriad of events, which affected the stadium design in many ways,

2. Playing Surfaces

In the past, informal sport had been played on open fields, city squares, or anywhere large enough to hold a gathering of people. Once rules were specified, organized sporting events required specific playing surfaces. Sports that depend on the interaction between the ball and the playing field (soccer, rugby, and cricket) would require natural grass fields. The issue with natural grass is that it is considered a small ecosystem that responds to changes in the environment; weather, temperature, and other environmental factors. A change in the field condition can then affect the athletes' play.

Natural grass requires the right amount of sunlight and water to stay healthy and practical for use. For this reason, stadiums were originally built without roofs, as seen by stadiums of early history. Once a stadium is equipped with a roof, the grass doesn't receive the nutrients needed and therefore doesn't grow. A perfect example of this would be the 1996 Houston Astrodome, an influential structure in the study of stadiums because it led to the invention of 'Astroturf'- a plastic material used to make artificial playing fields. A detailed case study of the Astrodome will follow in the "Case Study" chapter at the end of the thesis, and will describe why it is one of the most influential structures in stadium history.

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[22] (Lamberth n.d.)

Technological advancements have made artificial grass fields popular, but some sports still require natural grass for play. Structural engineers have used innovative techniques to remedy the situation and provide stadiums with both natural grass surfaces and keep them fully enclosed. One of the best examples of this would be the University of Phoenix Stadium which is equipped with both an operable roof structure and playing field. This stadium will also be discussed in further detail in the "Case Study" chapter at the end of the report.

2.1. Natural Grass Surfaces

Although artificial fields have been gaining popularity, coaches and players still prefer natural grass for its playability. In fact, national federations for major world matches have yet to approve artificial grass as an acceptable option. Natural grass has numerous advantages, most of which are aimed towards the athletes themselves. First, it provides the perfect amount of speed and resistance for most ball sports when wet or dry. Grass also is less injurious when a player falls and has a firmness that is good for running. Other benefits to natural grass are that it is aesthetically appealing and can self repair itself when given the right amount of water and sunlight.

With that being said, the major disadvantage to natural grass is that if not given the proper water and sunlight it could become aesthetically unappealing and unsatisfactory for play. Natural grass fields require daily maintenance and care. This in turn limits natural grass stadiums to being open roofed. Even when transparent material is used for the roof, as will be seen in the discussion of the Astrodome, the grass still does not receive the right nutrients. As a means to facilitate this problem, designers began installing partial roofs on stadiums, but finding the right size aperture for the grass to survive naturally has been a difficult task.

A second disadvantage to natural grass is the useful life of the pitch. Natural grass is known for not being able to survive intense and frequent use. Numerous techniques have been used to deal with this issue of natural grass. A laborious approach is to simply remove the grass when not needed; this could be done when the stadium is used for events that could take place on artificial surfaces (i.e. a concert). Alternatively, the grass could just be removed and reseeded every so often so that it remains useable. It is also important that the correct species of turf is used for the desire playing characteristics. The grass surface at Wimbledon Centre Court "is resown every year with 66 percent Troubadour perennial rye grass, 17 percent Bingo chewings fescue, and 17 percent Regent creeping red fescue".[23] This mixture is what provides the famous Wimbledon court with the perfect playing conditions given the soil and drainage in the area.

2.2. Artificial Surfaces

The obvious advantage to using some type of artificial surface is that it requires much less maintenance and has less of a limitation on the stadium structure. "In completely enclosed stadiums artificial grass will almost certainly be chosen in preference to natural grass".[24] Artificial surfaces are not always the perfect choice though. They have a high initial cost associated with them and are not everlasting. Depending on the material and use of the surface, there is a life expectancy of six to eight years. Artificial surfaces can be made of a variety of materials, and this will have an effect on the required maintenance and repair. The man-made material looks a lot like natural grass, as seen below in Figure 12.

Figure 12: Artificial Turf
(AstroTurf n.d.)

One option for an artificial surface is non-filled turf. Composed of nylon, polypropylene, or polyethylene, this surface consists of a turf-carpet and an underlying shock-absorbing layer. This material comes in various densities and thicknesses and can therefore be suited for nearly any sport. An alternative to this surface is a sand-filled turf: the piles supporting the surface are backfilled with sand 3 mm from the playing surface. The sand requires several months to settle and then requires regular brushing and top-dressing. Both of these surfaces put limitations on the footwear of the players because of both human injury and damage to the surface. Researchers have discovered that using mixed fills helps to avoid player injuries. In this case, the piles are

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[23] (Geraint, Sheard and Vickery 2007, 82)
[24] (Geraint, Sheard and Vickery 2007, 83)

filled with both silica sand and rubber granules. This surface allows players to wear their normal footwear and it provides traction with the ball similar to natural grass.

3. Field Layouts

As mentioned previously, every sport is designed to be played on a pitch that is arranged in a specific shape with specific dimensions. While many sports may be played on a rectangular area, such as soccer, American football, and rugby, each one has custom dimensions. The size, but more importantly the shape, of the field limits the availability for multi-use stadiums. In America two of the most popular sports are baseball and American football, however history has shown that it is difficult to put the two together in the same stadium because the first is played on a diamond-shaped field while the latter on a large rectangle. Appendix A contains diagrams for the field layout of various sports that are played in stadiums.

4. Multi-Use

Multi-use stadiums are more difficult to design for, but they provide the owner with a greater opportunity for profit. Designing a stadium for different sports, especially ones played in different seasons, allows for a minimum number of days per year that the stadium is unused; in other words the goal of multi-use stadiums is to maximize event days. Stadiums can host both sporting and not sporting events, like concerts and conventions. Of course, the type of events all depends on the size and shape of the field, the surface, roof type, and relationship between spectator and athletes/performers.[25]

In Europe, the trend of multi-use stadiums is usually geared towards combining soccer fields with athletic tracks. Also, because stadiums are often owned by a specific soccer club, the fields are usually only used by that team, thereby limiting other events. The athletic track surrounding the field also limits the events that can take place because it acts as a rather large barrier between the spectators and the central area.

The United States takes a different approach towards multi-use stadiums and puts more of a focus on making use of it as often as possible. Stadiums are usually owned by individuals, or companies, and not by the sporting team, although they are usually designed for a city's professional team. The fact that an individual owns the stadiums means that profit is more of a

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[25] (Geraint, Sheard and Vickery 2007, 99)

priority and “rather than leave an expensive asset empty for much of the year these owners prefer to use the building for other events outside the main sport”.[26] Baseball and football are the two most popular sports in America and are therefore joined together in many stadiums, despite the fact that their fields are radically different shapes. Both Yankees Stadium and Wrigley Field are examples of such stadiums.

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[26] (Geraint, Sheard and Vickery 2007, 101)

Controlling Factors in Stadium Design

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1. Introduction

No matter what use the stadium is being designed for, there are three main sets of people it must satisfy: the spectators, the players, and the owners. A successful stadium will meet the needs of all these key players, in addition to boosting the local economy and avoid hindering the public.

2. The Spectators

An athletic stadium cannot be successful unless the spectators are satisfied. Nowadays if a stadium is uncomfortable, overcrowded, and doesn't provide some food/drink outlets fans would stay home and watch the event on their television. Technological advancements have allowed for live broadcast of sporting events so that people can stay in the comfort of their own homes and watch the games from a closer view than if they were at the stadium. However, a home does not provide the same atmosphere as seeing a game live in person. In order to meet the needs, and wants, of the spectators, designers need to ask themselves the following question at the start of the design process: "Who are the spectators, what are they looking for in the facility, and how can their numbers be maximized?".[27]

2.1. Types of Spectators

At this point, it is important to understand that not all spectators are looking for the same thing. As discussed in the book *Stadia* by Geraint John, Rod Sheard, and Ben Vickery, there are the "sports priority" spectators, the "social priority" spectators, and then a mix of the two.[28] The fans that have a sporting interesting are knowledgeable, respond to the action on the playing field, and recognize the players and strategies in the game. These fans come to events dressed casually, have less of an interest in the comfort of the seats, but look for unobstructed views of the action below.

The "social priority" spectators attend events as a way of showing their social standing and entertaining others. These individuals come well dressed and are more often than not found in the clubhouses and private boxes. While they may find the sport to be interesting, their conversations revolve around personal lives and business. This group of spectators interacts

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[27] (Geraint, Sheard and Vickery 2007, 16)

[28] (Geraint, Sheard and Vickery 2007, 17)

minimally with the "sports priority" fans since they often have private bathrooms and waitresses in their isolated seating sections.

Lastly, the third group of spectators has characteristics of both the sports and social priority groups. Spectators that fall into this category are casual supporters of the team and will attend the event if conditions are right. They look for comfort, reasonable prices, and a guaranteed good game, or event. This type of fan is likely to attend important matches or events, such as an NBA Finals game, a World Cup game, or just a matchup of two top tier teams. Some fans have begun to pay just for the sense of being at a game and care very little about the game itself. "Glenn Yaeger, president and general manager of the Triple-A Nashville Sounds, agrees, 'The social aspect is so big that people leave at the end of the game without even knowing the score.'"[29]

It was important to mention the types of spectators that attend stadium events because they are the driving force behind the physical organization of the stands.

2.2. Viewing Distances

Once the use of the stadium is specified, the designers must decide the best way to organize the seating around the playing field. It is the designer's job to make sure the stadium can accommodate the number of spectators required in the project's program and that these seats have a clear view of the event. Determining maximum viewing distances and viewing angles is a purely mathematical problem.

According to *Stadia*, 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".[30] For rugby or American football, this sets the optimal distance at 150 m between the corner of the field and the spectator's eye and the maximum at 190m. Similarly, for tennis the optimal distance is 30 m and maximum 41 m. Using these distances, an optimal seating section can be determined, which usually takes the shape of a circle about the center of the field. Figure 13 shows the optimal and maximum viewing distances for a football field. The right side

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[29] (Lamberth n.d.)

[30] (Geraint, Sheard and Vickery 2007, 128)

of the image shows possible seating orientations and how they overlap with the optimal seating area of the dashed circle.

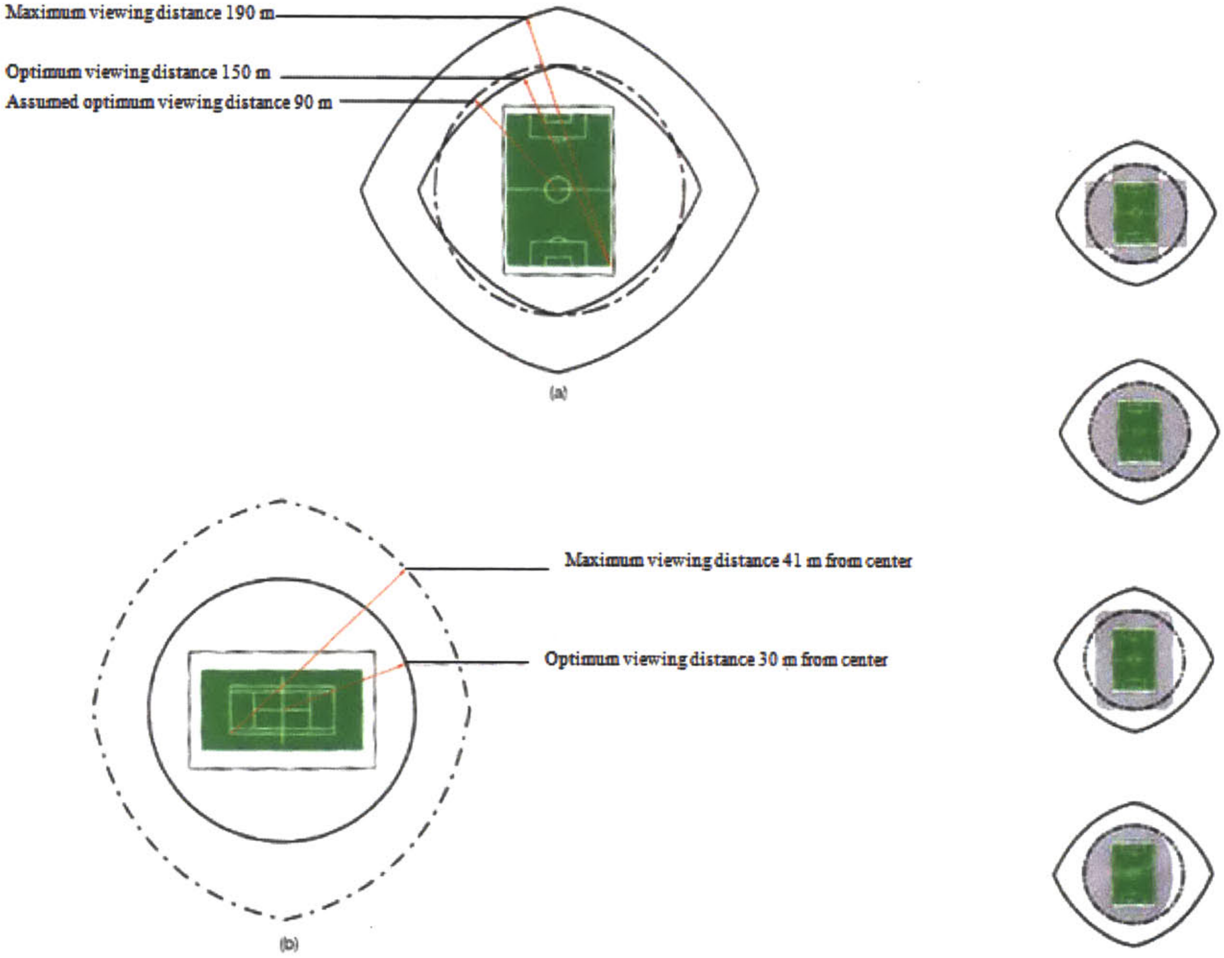

Figure 13: Optimal Viewing
(Geraint, Sheard and Vickery 2007, 129)

Appendix B shows the preferred viewing positions for various other sports.

This simple method is a good starting point for designers. However, it is not always reasonable. Spectators watching a sport like hockey cannot be guaranteed to have visual contact with the puck at all times. The puck is very small and the rink is often crowded with players. For this kind of dilemma, designers could assume that spectators are watching the players and not just the puck.

There are also spectators who could have personal seating preferences that lie outside the calculated distances. While most fans probably prefer watching a football or soccer game from the sidelines, there may be some fans who like to watch the action from behind the goal posts. Because of fans like these designers need to think outside the box and try to imagine all possible seating options.

2.3. Corners

As most sports require rectangular playing fields, designers have to make important decisions regarding the seating at the corners of the field. The two options are to put seating along the four sides and have them meet awkwardly at the corners, or put a 'bowl' type stadium that curves around the field. Using only straight seating segments is the cheaper option in terms of construction but the downfall is that it sacrifices valuable space. Even if the view from the corner is not optimal, there is sure to be some spectator that would pay for those seats. A continuous 'bowl' seating would cost more but it would be more comfortable for the spectators and more aesthetically pleasing. These factors need to be taken into account when designing the shape of the stadium.

2.4. Sightlines

Viewing distances was the first step in determining the shape of the stadium but in order to transform this into a three-dimensional plan the viewing angles need to be determined. Like the distances, optimal angles, or sightlines, can be determined mathematically. The term sightline refers to the "spectator's ability to see the nearest point of interest on the playing field (the 'point of focus') comfortably over the heads of the people in front".[31] Optimal riser height can be calculated using the equation below, which takes into account the sightline and other variables in the stadium design.

$$N = \frac{(R + C)(D + T)}{D} - R$$

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[31] (Geraint, Sheard and Vickery 2007, 132)

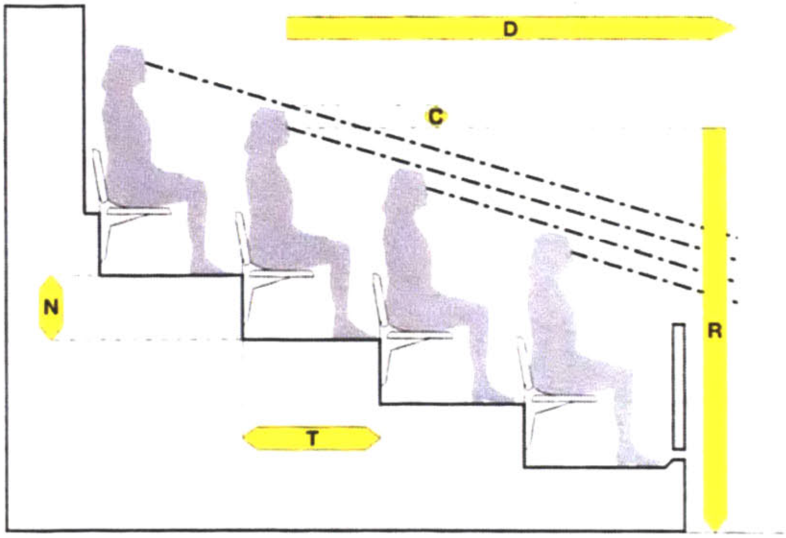

Figure 14: Calculate Optimal Riser Height (Geraint, Sheard and Vickery 2007, 133)

Figure 14 defines all the variables that affect the riser height, N. C is the sightline values; R is the height between the eye and the 'point of focus' on the playing field; D is the distance from the eye to the 'point of focus' on the playing field; and T is the depth of the seating row.

While this method seems simple, in order for it to be accurate and actually influence the design it needs to be calculated many times over for each individual row. For this reason computer programs that test different scenarios to find the optimal solution are often used by top design firms. After determining the riser height, designers need to check the rake, or slope of the seating. A general rule is to limit the rake to 34 degrees, which is the approximate angle of stairs, because anything steeper could make spectators feel a sense of vertigo as they descend. It is crucial to check the sightline and rake of the stands so that spectators are comfortable and content with their seats but also to ensure that the design is feasible and cost effective. Figure 15 shows how the rake changes based on the C-value. Determining the most suitable C-value is a matter of judgment and there is no exact answer, however there is a maximum angle of the rake that should not be surpassed.

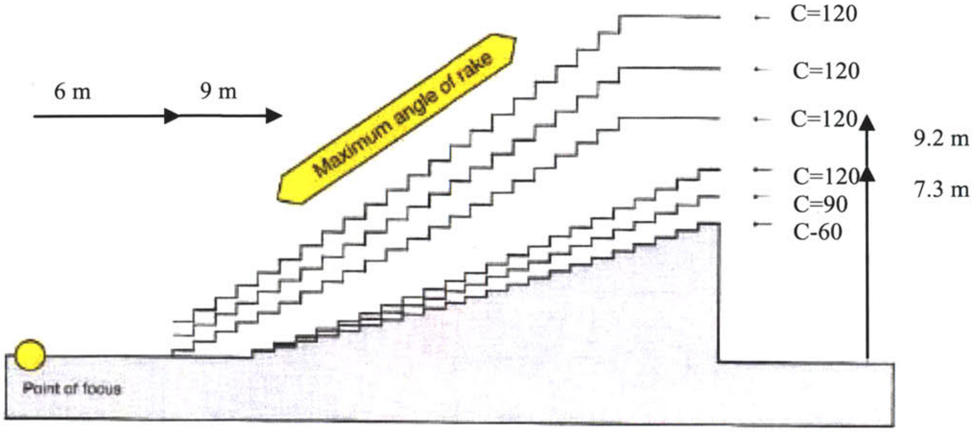

Figure 15: Varying C-Value for Sightlines
(Geraint, Sheard and Vickery 2007, 134)

3. The Athlete

After the fans, the next most influential people in the design of a stadium are the athletes themselves; without them there would be no need for the stadium. Athletes require locker rooms, fitness rooms, and medical trainer rooms. However, these have minimal impact on the design of the stadium. The controlling factor that the athletes bring to the table is the field requirement their sport calls for. "If players require a natural grass pitch, but other design requirements make a grass surface unviable, then very difficult choices must be made about design priorities."[32]

The amount and type of facilities for the athletes depends largely on the sport and whether or not the stadium is designed specifically for one team, a national event, etc. When a stadium is built for a specific team, as is the case for most stadiums in the United States, most of the player accommodations will be geared towards the home team's needs. Since the stadium would likely be used for training and off-season practices, there would need to be adequate room for fitness gyms and locker rooms. If multiple teams share a stadium, like the Boston Celtics and Boston Bruins both calling TD Garden home, then designers need to determine whether teams can share facilities are separate rooms are needed for each team.

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[32] (Geraint, Sheard and Vickery 2007, 18)

Athlete safety is another important aspect of the design. Because athletes are celebrities and fans could become rowdy in their presence, it is important to have direct access from the outside to the athlete facilities. The overall stadium plan should include private entrances for players, coaches, and the medical team.

4. The Owner

Spectators and athletes provide stadium designers with a list of constraints that help define the overall size and shape of the stadium. Before anything can be done though, the owner needs to be satisfied as well, and this usually means that the stadium needs to provide continued financial viability. In order for the owner to benefit from the stadium, there needs to be other means of profit aside from ticket sales to the sporting event. In general, there are three ways the design team can ensure owner profitability: maximize gate income, exploit non-sporting forms of market income, and/or bring in public funding or other forms of subsidy.

4.1. Gate Income

The most important single source of revenue from a stadium comes from ticket sales, also referred to here as gate income. Designers should supply investors with a complete analysis including "guaranteed target market of known size and characteristics, a guaranteed number of event days, and a guaranteed cash flow from these sources".[33] The target market is probably most important because it varies with the use of the stadium and will affect what prices can be charged. Studies have reported that 80% of the revenue from ticket sales comes from only 20% of the attendees.[34] This 20% are the spectators who are paying to sit in the premium seats and eat the higher-end food and beverage choices. In order to determine the target market, the use of the stadium needs to be determined. This goes hand-in-hand with defining the playing field surface, which also controls the roof of the stadium- a major contribution to the structural cost.

4.2. Non-Gate Income

A successful stadium will include secondary forms of income that augment the ticket sales. The items that fall in this category are endless and continue to change with history. Examples of popular non-gate income contributors are catering concessions, merchandise concessions, and parking rentals. There is also advertising and event sponsorship that has grown tremendously as

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[33] (Geraint, Sheard and Vickery 2007, 19)

[34] (Lamberth n.d.)

stadiums provide companies the opportunity to get their name out to not only the people live at the stadium but also spectators who are watching the live broadcast. While these non-gate income opportunities are important, designers should keep them secondary to gate-income factors and make sure that including such features does not lower the attraction to the primary patrons of the stadium.

5. Bringing the Factors Together

While each of the factors discussed above has some level of control on the overall stadium design, "the key to a successful outcome is clarity of understanding between all concerned".[35] The spectators need to understand the athletes' needs, the owners need to understand what the spectators and athletes are looking for, and vice versa. A stadium project will be most profitable if all matters are resolved and especially if done so in the following order: spectator, athlete, and finally owner. The following table provides a comparison of some of the basic points that designers should identify during the design process:

	Spectator	Athlete	Owner
Need	• Safety • Unobstructed views	• Proper lighting • Proper playing field	• Cost effective • Durable
Want	• 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

Lastly, while stadium designers work to satisfy all the above requirements, they must also meet safety regulations and guarantee the most secure structure possible.

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[35] (Geraint, Sheard and Vickery 2007, 19)

Design Considerations

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1. Introduction

Louis Sullivan, a great American architect, coined the phrase "form follows function" in his 1896 article "The Tall Office Building Artistically Considered". Referred to as the "father of skyscrapers", Sullivan used this way of thinking to develop the shape of tall steel skyscrapers in the late 19th century. Skyscrapers are by no means the first type of architecture to abide by "form follows function". Stadiums, which have been around since antiquity, are a prime example of that very principle. Ancient Greek and Roman designers based stadiums on the circle and oval because it was obvious that these shapes solved functional needs, such as clear viewing and efficient circulation. The basic form of stadiums remains very similar to those of antiquity and designers have struggled to make them architecturally interesting. Throughout different stages of the design process, there are a set of constraints and considerations the designer must take into account. This chapter will discuss some of the important decisions that need to be made by both the architect and engineer when developing a design for a stadium.

2. Limits to the Exterior

Sports stadiums are designed so closely geared to specific functional requirements that they often lack aesthetics and visual charm. The number one function of a stadium is to gather spectators to watch a public event that takes place inside. Because of this, the interior of stadiums tends to be more attractive than the outside, which is often seen as unwelcoming. Whether the stadium is located in an urban setting or out in the suburbs, an unwelcoming exterior is never a good thing. In addition to the actual structural exterior design, stadiums are often clad with tough finishes. This is necessary so maintenance is easy and the stadium can withstand the uncaring crowds and deliberate vandalism.

Stadiums located in the outskirts of town have another unattractive feature: parking. In areas where public transportation is not widely accessible, or when stadiums are located beyond the access points, huge amount of parking are required to accommodate spectators. The acres of parking that surround stadiums add to the unwelcoming nature and also cut them off from their surroundings. Luckily, stadiums located in the center of cities (Madison Square Garden in New

York City or Fenway Park in Boston) don't have this problem since the majority of spectators are brought in via public transportation.

3. Choosing a Dominant Element

A complete modern stadium design has three main features: roof, façade, and structure. "Design excellence is achieved in stadiums when structure, enclosure and finishes express at all scales a single concept which functions well, is rich and expressive, and avoids jarring conflicts."[36] Although not all stadiums are equipped with roofs, they are becoming more common. When there is no roof, the designers do not need to decide which feature will be dominant. However, in roofed stadiums, the most important step in achieving a harmonious design is to avoid having equally assertive features competing to be the design's key feature.

One approach designers can take is to make the roof the dominant feature. This can be done several ways, one of which is by building the stadium into the hillside so walls are virtually inexistent. Munich's 1972 Olympic Stadium, discussed earlier in the section "The Rebirth of the Olympic Games" applies this approach. When a hillside is not in the stadium's landscape, this approach can still be followed by reducing the walls to submissive elements that float separately from the prevailing roof.

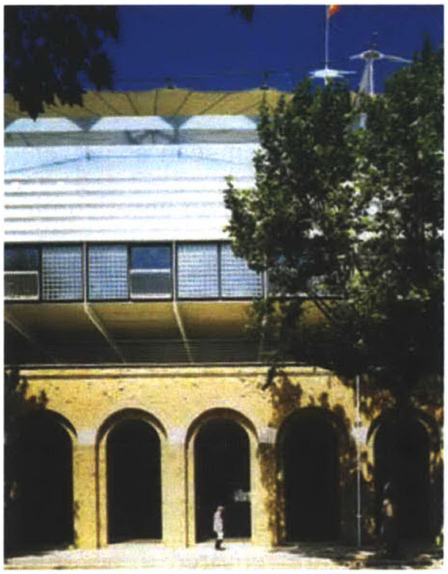

Figure 16: Lord's Cricket Ground
(Geraint, Sheard and Vickery 2007, 52)

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[36] (Geraint, Sheard and Vickery 2007, 49)

Dominant façades are bit more daring and difficult to achieve, but they do exist. These designs are either open stadiums or have simple and/or hidden roofs. Lord's Cricket Ground in London (Figure 16) is a famous example of a dominant façade stadium situated in an urban center. While there is no roof structure (just a tent roof) to compete with, this stadium's designer, Michael Hopkins & Partners, had the challenge of designing a façade that could maintain an urban feel and flow with the surrounding neighborhood.

The last approach designers can take is to make the actual structure the dominant feature by suppressing the façade and roof behind the structural members. Most successful examples of this tactic are seen in stadiums that are situated on large open sites and seen mostly from a distance. A modern example of dominant structure is Arena Zagreb in Croatia. Built in 2009, the prominent element is the pre-stressed concrete curved columns (lamellas) that are positioned around the arena perimeter (Figure 17). These columns are used to carry the loads transferred from the roof bearing structure. The steel roof is supported by 23 suspended girders with 100 m spans, as well as two stabilization spatial girders.

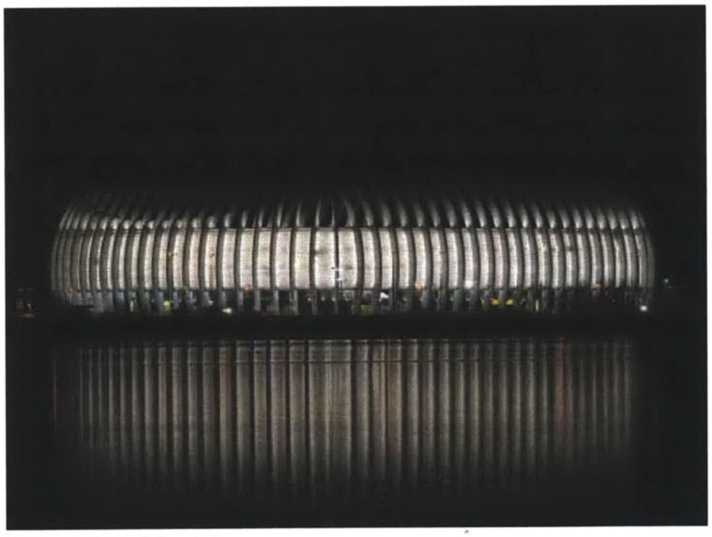


Figure 17: Arena Zagreb
(Arena Zagreb 2010)

Structural dominance can also be linked to a dominant roof. Kenzo Tange's gymnasium (discussed earlier) uses structural concrete to produce its organically-shaped roof which is an obvious dominant feature.

4. Structural Material

Relatively early on in the design process, architects and design engineers need to determine which material will be used for the structure of the stadium: concrete or steel. Each material has its own set of benefits and disadvantages. The stadium construction cost is heavily dependent on the roof, which requires the most structure. Both the structural form and the materials chosen for each individual roof element constitute the cost.

4.1. Concrete

Concrete is a mixture of sand, gravel, and crushed rock held together with a paste of concrete and water. The strength of concrete depends on the exact mixture and can be modified with additional admixtures that change certain characteristics of the concrete. Materials like concrete have been used for construction since antiquity. With a high compressive strength, and low tensile strength, concrete was originally used for structural arches and domes, where compression is the main force.

Although new materials have since been invented, concrete remains the go-to material for the seating profile of most stadiums. Cheaper than steel in many countries, concrete also has the benefit of being naturally fireproof. However, concrete is aesthetically unappealing when left unfinished; cladding can be added on the outside of concrete surfaces but this becomes costly and requires maintenance.

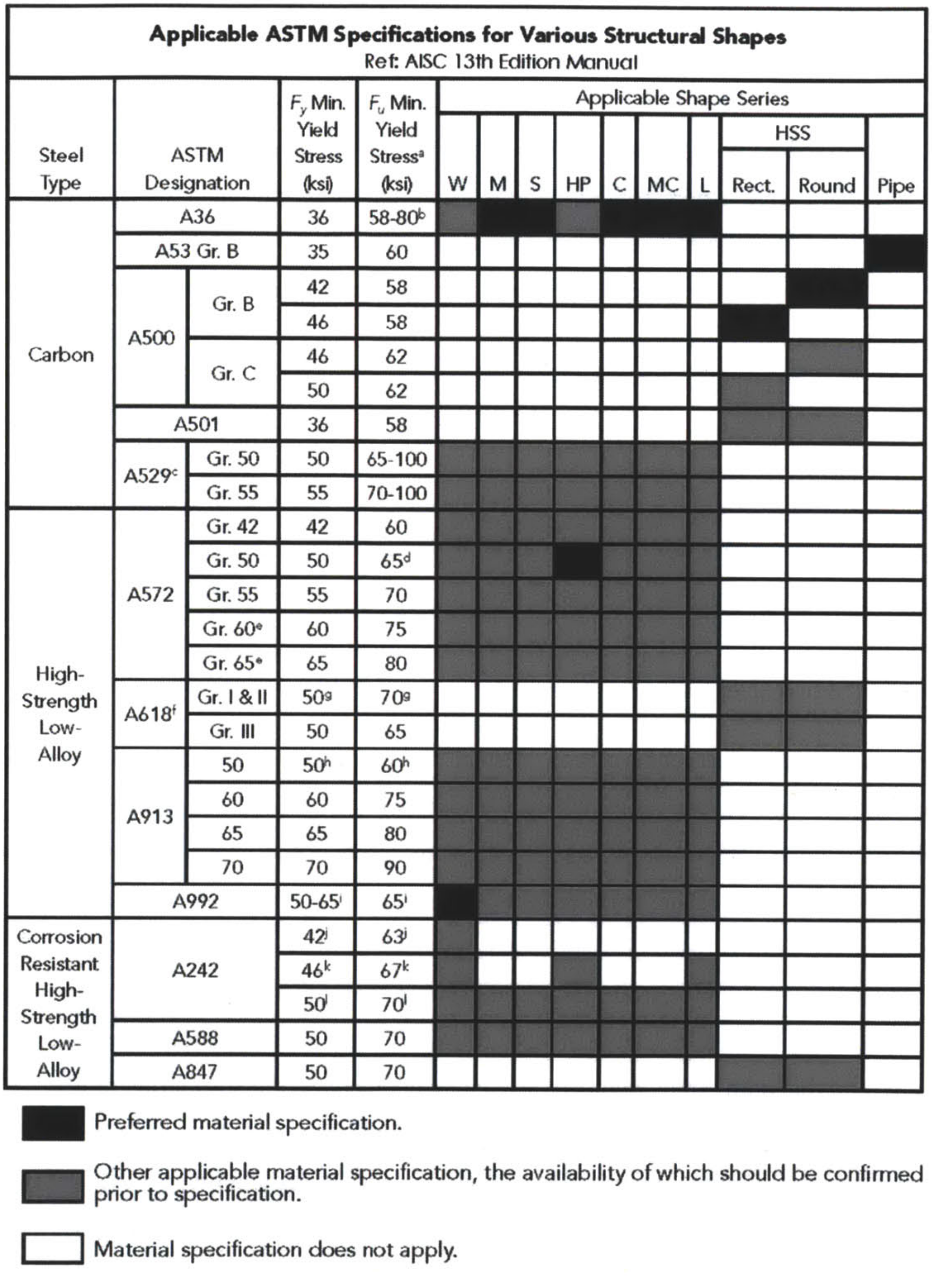
Construction using concrete can be done on site (in situ) or prefabricated (pre-cast). A major benefit to in-situ concrete is that its plastic properties provide for magnificent concrete shapes. Pouring the concrete onsite allows for unique and flexible solutions that meet the demands of the owner and designer. However, in-situ concrete also has many disadvantages, the most prominent being the high labor hours and time requirement for formwork. Lastly, in-situ concrete depends on the weather for proper curing and could face difficulties in carrying out quality control. Pre-cast concrete obviously does not have these issues because the concrete can be poured in an indoor setting where factors can be easily controlled. This material option helps to decrease construction time, which is usually a priority for owners.

With the invention of steel, designers began adding steel reinforcement to concrete as a way to add tensile strength to a material with very little. With both compressive and tensile strength, reinforced concrete began to replace plain concrete for most construction. Providing concrete with an increased tension capacity, designers could add longer spans and cantilevers to their designs. Pushing the capabilities of concrete even further than just reinforced concrete, members can be pre-stressed or post-tensioned. Pre-stressed is used for pre-cast concrete members and applies a compressive stress to the member that balances out the tensile stress it would experience under bending loads. Alternatively, post-tensioned is applied to in-situ concrete. During this process the concrete slab is poured and after some curing the steel members are pulled tightly. Pre-stressing results in lighter and thinner members while post-tensions helps to limit movement in the joints of the structure.

4.2. Steel

As an alternative to reinforced concrete, steel has a better strength-to-weight ratio. Steel was first used in heavy construction in the nineteenth century. However, starting in the late eighteen century iron, a component of steel, was used in various bridge constructions in the form of wrought iron. In 1874 the first structural steel railroad bridge was constructed in St. Louis followed by the first steel frame building in Chicago in 1884.

Depending on the chemical composition of steel, the properties of the material vary. All steels are made of iron and carbon and additional components are added for certain grades of steel. The following three categories of steel exist: plain carbon steels, low-allow steels, and high-allow or specialty steels. Plain carbon steels are mostly iron with an added 1% of carbon; low-allow steels have iron, carbon, plus additional components that make up 5% or less of the mix; lastly, high-allow steels have iron, carbon, and more than 5% of additional components. The added components could be any of the following elements: copper, manganese, nickel, chromium, molybdenum, and silicon. These elements increase the steel strength and reduce the ductility. The American Society for Testing and Materials (ASTM) has designated different structural steels and grouped them based on their yield strengths and other important properties. Certain steel grades have become standard for specific structural shapes, and The American Institute of Steel Construction (AISC) has published their specifications (Figure 18).



Applicable ASTM Specifications for Various Structural Shapes

Ref: AISC 13th Edition Manual

Steel Type	ASTM Designation		F_y Min. Yield Stress (ksi)	F_u Min. Yield Stress[a] (ksi)	Applicable Shape Series									
												HSS		
					W	M	S	HP	C	MC	L	Rect.	Round	Pipe
Carbon	A36		36	58-80[b]	▨	■	■	▨	■	■	■	☐	☐	☐
	A53 Gr. B		35	60	☐	☐	☐	☐	☐	☐	☐	☐	☐	■
	A500	Gr. B	42	58	☐	☐	☐	☐	☐	☐	☐	☐	■	☐
			46	58	☐	☐	☐	☐	☐	☐	☐	■	☐	☐
		Gr. C	46	62	☐	☐	☐	☐	☐	☐	☐	☐	▨	☐
			50	62	☐	☐	☐	☐	☐	☐	☐	▨	☐	☐
	A501		36	58	☐	☐	☐	☐	☐	☐	☐	▨	▨	☐
	A529[c]	Gr. 50	50	65-100	▨	▨	▨	▨	▨	▨	▨	☐	☐	☐
		Gr. 55	55	70-100	▨	▨	▨	▨	▨	▨	▨	☐	☐	☐
High-Strength Low-Alloy	A572	Gr. 42	42	60	▨	▨	▨	▨	▨	▨	▨	☐	☐	☐
		Gr. 50	50	65[d]	▨	▨	▨	■	▨	▨	▨	☐	☐	☐
		Gr. 55	55	70	▨	▨	▨	▨	▨	▨	▨	☐	☐	☐
		Gr. 60[e]	60	75	▨	▨	▨	▨	▨	▨	▨	☐	☐	☐
		Gr. 65[e]	65	80	▨	▨	▨	▨	▨	▨	▨	☐	☐	☐
	A618[f]	Gr. I & II	50[g]	70[g]	☐	☐	☐	☐	☐	☐	☐	▨	▨	☐
		Gr. III	50	65	☐	☐	☐	☐	☐	☐	☐	▨	▨	☐
	A913	50	50[h]	60[h]	▨	▨	▨	▨	▨	▨	▨	☐	☐	☐
		60	60	75	▨	▨	▨	▨	▨	▨	▨	☐	☐	☐
		65	65	80	▨	▨	▨	▨	▨	▨	▨	☐	☐	☐
		70	70	90	▨	▨	▨	▨	▨	▨	▨	☐	☐	☐
	A992		50-65[i]	65[i]	■	▨	▨	▨	▨	▨	▨	☐	☐	☐
Corrosion Resistant High-Strength Low-Alloy	A242		42[j]	63[j]	▨	☐	☐	☐	☐	☐	☐	☐	☐	☐
			46[k]	67[k]	▨	☐	☐	▨	☐	☐	▨	☐	☐	☐
			50[l]	70[l]	▨	▨	▨	▨	▨	▨	▨	☐	☐	☐
	A588		50	70	▨	▨	▨	▨	▨	▨	▨	☐	☐	☐
	A847		50	70	☐	☐	☐	☐	☐	☐	☐	▨	▨	☐

■ Preferred material specification.

▨ Other applicable material specification, the availability of which should be confirmed prior to specification.

☐ Material specification does not apply.

Figure 18: ASTM Specifications for Various Structural Shapes (McCormac and Csernak 2012, 23)

As a versatile structural material, steel provides many advantages as a structural material. Unlike concrete, steel has a high strength to weight ratio, meaning that structures can be light and still provide the necessary strength. Steel also tends to be a very uniform material in terms of material properties; concrete on the other hand is extremely dependent on the mix used and its strength can be compromised by minute details such as where the water for the mix is coming from. Other material advantages of steel are its ductility, toughness, and elastic behavior- all factors that concrete does not possess. All of these attributes make steel the chosen material for most stadium roofs and allows for slender structures that appear graceful and elegant.

Steel, however, is not a miraculous material and it does have its set of shortcomings. A major disadvantage to steel is that it requires adequate fireproofing. This is accomplished by spraying mineral fiber or vermiculite cement on the exposed steel members. Fire-proofing therefore detracts from the slender appearance of steel and also increase the cost tremendously. Steel is also susceptible to corrosion and requires weathering or paint protection. Lastly, steel has a set of failure modes that concrete is not prone to. These include buckling fatigue, and brittle fractures. All of these modes can be prevented with proper design by the structural engineers.

4.3. High Strength Steel

Structures carrying immense loads can be designed with the average steel material, but would greatly benefit with high strength steels. The steel industry continues to experiment and test new steel composites, some of them with yield strengths as high as 300 ksi. High strength refers to anything greater than 36 ksi, and the most common high strength steel currently used in industry is 65ksi, or Grade 65, steel. When working with high strength steel, there are specific considerations that need to be taken into account for both compression and tension members.

Specifically for compression members, the benefits of high strength steel are realized when shorter unbraced lengths are achieved. At longer lengths the member enters Euler buckling and the higher strength will not be beneficial. Figure 19 compares Grade 50 to Grade 65 steel for compression members. The graph shows how as KL/r increases the economical savings of using the Grade 65 steel diminish. The breaking point is around KL/r equals 100.

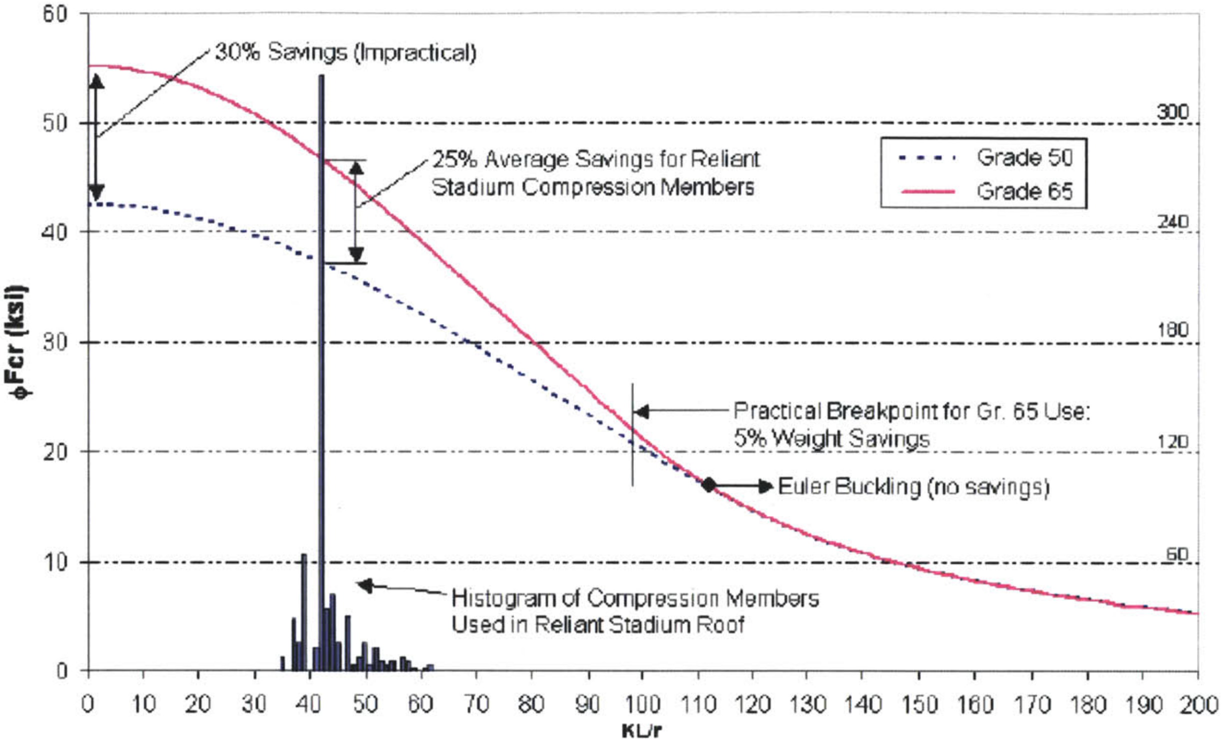


Figure 19: Grade 50 vs. Grade 65 Steel
(Griffls, et al. 2003)

Tension members need to be sized for fracture, and thus depend on the effected net area. In order to avoid fracture, designers take one of two precautions: upsizing the member or providing supplemental plates at the member ends. The supplemental plates increase the net area to make up for the bolt holes. While Grade 65 steel may provide higher strength, it is more inclined to fracture since it has a lower Fu/Fy ratio than Grade 50 or 36 steel. Many long span structures, including Reliant Stadium which will be discussed in detail in the Case Study chapter, make use of high strength steel since it is both economical and beneficial to the design.

5. Significant Loads

Stadiums and arenas are considered long span structures and are thereby characterized by a unique set of challenges. Designing a structure to span long distances requires an emphasis on stability. While the structure will have to support a significant dead load due to the amount of material, the "complexity of long-span design increases exponentially when snow load, wind load, seismic load, deflection, serviceability, and the dead weight of the floor or roof system are all factored in".[37] It is important to analyze these loads for the completed structure but also for each stage of the construction sequence.

In an effort to make long span structures cost effective, designers tend to develop light-weight designs, which are more sensitive to the loadings mentioned above. Dynamic wind loading is often a governing parameter and can be analyzed through a series of wind tunnel tests. Companies like BMT Fluid Mechanics conduct these tests and claim that "boundary layer wind tunnel testing based on high frequency pressure integration (HFPI) techniques allow accurate determination of critical loading scenarios dictating for the structural stiffness of the roof".[38] Similar studies can also be done for snow loads, as snow accumulation and drift can cause significant loadings on large span roofs as well. Depending on the material and chosen structural system, the effect of these loads with vary.

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[37] (Ruby 2007)

[38] (Stadia & Large Span Roof Structures n.d.)

Structural Systems for the Roof

1. Introduction

A stadium's roof is a critical part of the design since it affects the cost and construction time, and controls most of the spectators' requests. As an architectural element, the roof also provides the designer with an opportunity to create something intriguing that will make a name for the stadium, and the designer. "The roof plays the major role when it comes to the question of unique design and easy recognition. It is the most important element to create the stadium look."[39] Throughout history a multitude of structural forms and systems have been applied to stadiums, and new ones continue to be invented as designers think outside the box. Below are descriptions of some of the most prevalent structural forms.

2. Post and Beam Structure

Post and Beam is the simplest structural system and is comprised of two elements: columns and beams. Columns are set up in a grid pattern and large beams, called girders, connect the columns. Smaller beams are then placed between girders and support the roof structure above. Compared to more complex structural system, the Post and Beam system is cheaper and simpler to construct. A major downfall of using a Post and Beam structure is that it limits the geometry of the stadium to a shape with linear edges. Lastly, depending where columns are placed, they could cause obstruction to spectator views.

3. Goal Post Structure

A Goal Post structure is very similar to a Post and Beam structure, except it only has columns at the perimeter. This means that the each section of the roof is supported by a single girder. Because the girders are much longer, they are also much deeper; typically, the girder depth is about one twelfth of the length.[40] Like Post and Beam, stadiums built with Goal Post structure are limited to a rectangular shape. Another disadvantage to this system is that regular inspection and maintenance in necessary since the entire roof is dependent on a single girder. An example of the Goal Post structure is Ibrox Stadium, seen below in Figure 20.

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[39] (Goeppert and Stein 2009)

[40] (Geraint, Sheard and Vickery 2007, 64)

Figure 20: Ibrox Stadium
(Geraint, Sheard and Vickery 2007, 54)

Engineers have modified the traditional Goal Post system by replacing the girder with an arched truss. This modified system can be seen on Galpharm Stadium which has curved prismatic trusses supporting the roofs (Figure 21).

Figure 21: Galpharm Stadium
(Hunt n.d.)

These prismatic trusses form an inverted triangle with two compression booms on the top. The metal deck roof is then made to hang from the lower tension boom. Each of the four seating sections is equipped with one of these "banana" trusses. Adjacent segments have large concrete columns at the corners where the trusses join at pinned connections.

Goal Post system tend me be relatively inexpensive, although cost is largely dependent on the span that needs to be covered and the size of the main girders. Because the columns are only placed at the ends, there is the added benefit of zero obstruction of view but this is coupled with complete elimination of corner seats. As in Galpharm Stadium, the system works best when separate seating sections are built around the playing field and no seating is needed at the connecting areas.

4. Cantilever Structure

Cantilevered roof structures are supported at the exterior end and hang freely over the stands. Like a simple cantilevered beam, the load is carried to the supported edge where it is resisted by moment and shear stress. A major benefit of a cantilevered roof is the unobstructed views it guarantees spectators. Unlike the Goal Post system, cantilevered roofs are not restricted to rectangular shapes; in fact, they are often incorporated into circular and elliptical stadiums. Cantilevered roofs can cover any length and is generally kept to depths around 45m. Because of the dramatic look cantilevered roofs have, architects often incorporate them as a highlight in the design. The structure supporting the hanging roof is also often exposed as a way of broadcasting the design. One example of a cantilevered roof can be seen at the University of Washington's Husky Stadium in Seattle (Figure 22). These roofs have unique acoustics that tend to trap the noise of the fans below making for some of the loudest and most intimidating college football games in the country.

Figure 22: Husky Stadium
(Husky Stadium 2011)

Like any other structural system, cantilevered roofs do have their disadvantages. One issue many designers have is the cost factor; when the depth of the cantilever becomes too large the cost of the structural members becomes very expensive. More often than not the cost of the roof is the controlling factor in the design decision. Wind forces are another major consideration for cantilevered roof, especially when the roofs are put on separate seating sections not connected at the corners. If the wind uplift forces are expected to be high, the supports at the exterior edges need to be relatively large to withstand the compressive force generated. This in turn works against the slim profile designers aim for with cantilevered roofs. Depending on the site of the stadium, designers need to be careful to not make the support too obstructive or intimidating. A support system like the one applied to Stamford Bridge in London (Figure 23) would not work in a setting where the stadium needs to fit into its surroundings. Lucky for the designers of The Bridge, most people view the roof as an engineering marvel and one of the most striking stands in the country.

Figure 23: Stamford Bridge
(World Stadiums 2012)

5. Concrete Shell Structure

Concrete, as pointed out earlier, is a plastic material that can be shaped into various curves and geometric forms. Since engineering advancements have increased the strength of concrete, it has been used to create concrete shells, which are thin surface structures that curve in one or two directions. The strength of these shells comes from the geometric shape and not the thickness of the material. This concept can easily be tested with a sheet of paper: if a sheet of paper is held at its end it immediately bends down, but if it is held with a slight upward curvature it can support additional weight. This test can be seen in Figure 24.

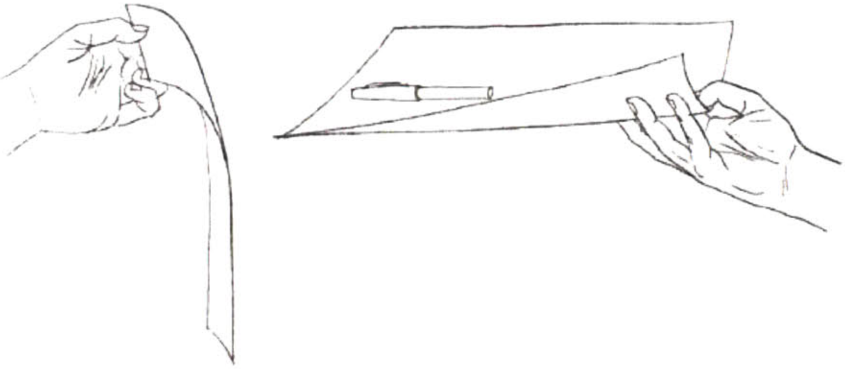

Figure 24: Paper Strength
(Salvadori 1980, 187)

"This principle of strength through curvature can be applied to thin sheets of reinforced concrete and has been efficiently used to build stadium roofs."[41] Both the Palazzo dello Sport and Palazzetto dello Sport (seen before in Figure 9) from the 1960 Olympics in Rome make use of concrete shell forms. Another example is the covering of Zarzuela Hippodrome (Figure 25), a racecourse in Madrid, Spain.

Figure 25: Zarzuela Hippodrome
(World Stadiums 2012)

Eduardo Torroja designed this roof in the form of a hyperboloid of revolution. It supports a 43 ft cantilevered span and the concrete is only 5.5 in thick at the edges.

Concrete shell roofs are most notable for their aesthetics and ability to push the envelope of structural engineering. To help enhance their visual elegance, shell structures often have self-finished surfaces on the top and bottom. The negative aspects of using concrete-shells are the

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[41] (Salvadori 1980, 186)

cost and requirement for specialized designers. Construction costs for shell structures are naturally high, but even more so if in situ-concrete is used. The time and expertise needed to create the birdcage formwork drives the construction cost up substantially. Therefore, pre-cast concrete is recommended for shell structures.

6. Compression/Tension Ring

A roof structure suitable only for circular/elliptical stadiums is the compression/tension ring system. Such a roof consists of a compression ring around the exterior and a tension ring on the inside, creating a doughnut shape. These two rings are connected with radial members that carry the roof covering. Roofs using this structural system can span large depths with ease, such as Vienna Prater Stadium at 48 m and the roof added to the Olympic Stadium in Rome (Figure 26) which is 52 m. This roof type also achieves a weightless appearance from both the inside and outside and doesn't interfere with the designers' attempts at making beautiful architecture. An additional benefit of the compression/tension ring system is that it can be used to add a roof to an existing stadium without taking away from the original design, as seen with the Olympic Stadium in Rome which had the roof added in 1990. As with all properly designed roofs, this system provides a completely column-free interior with no obstructions whatsoever to the spectators.

Figure 26: Olympic Stadium in Rome
(Rome Olympic Stadium n.d.)

Modern stadiums have modified the simple compression/tension ring system to achieve more unique designs. This has been done by adding fabric as the roof structure, creating various geometries with the radial members, and by placing the rings out of plane with one another so three-dimensional roofs are created. An example of one of these modern stadiums is the 2006 Century Lotus Stadium in China seen below in Figure 27. This roof consists of a lower compression ring, an upper compression ring, and an inner tension ring. The upper compression ring is a 1 m diameter steel tube and makes a circle with a 155 m radius.

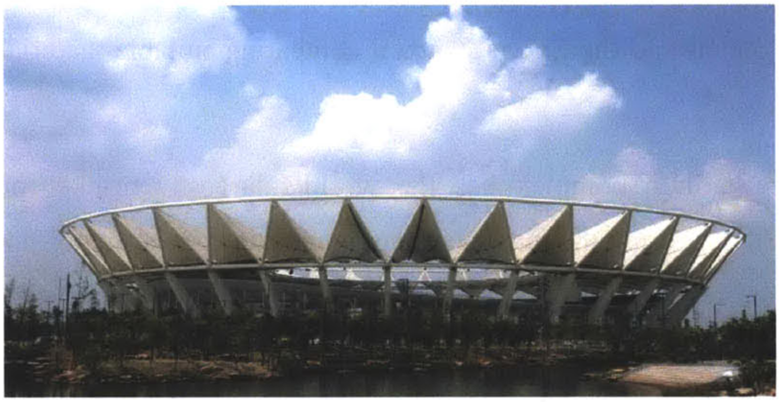

Figure 27: Century Lotus Stadium
(Tong, et al. 2009)

Connecting the upper and lower compression rings to the inner tension ring is a system of folded membrane units. Steel struts connect the two compression rings to one another and then a set of upper and lower radial cables connect those to the inner tension ring. The following image, Figure 28, shows these different members.

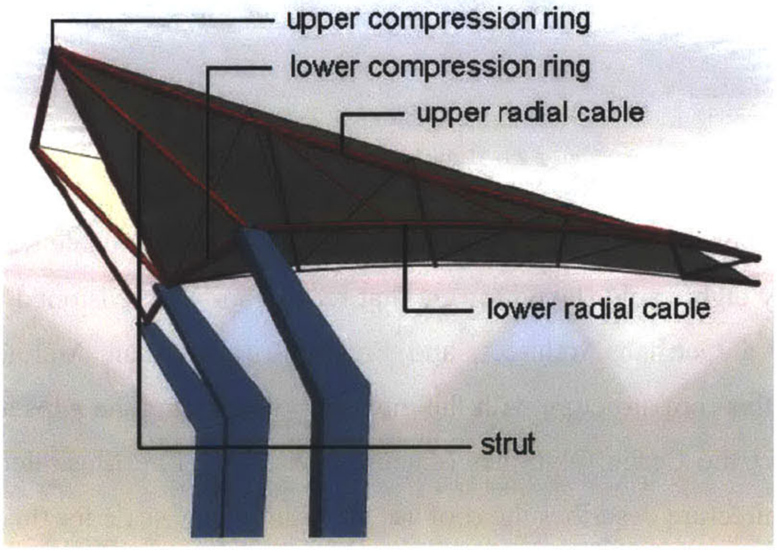

Figure 28: Century Lotus Stadium's Folded Membrane
(Tong, et al. 2009)

7. Cable Net Structure

Cable net structures consist of two parts: the structural three-dimensional steel net made of steel cables and the fabric covering. The covering tends to be some form of plastic: acrylic, PVC, or polycarbonate. Glass and other fabrics have also been used since material scientists invented new materials that can better withstand the forces. A table published by the Football Stadia Advisory Design Council and the Sports Council comparing suitable materials can be found in Appendix C.

Munich's Olympic Stadium complex has the world's largest tent-like roof with cable net structure (Figure 29). Covering the main stadium, gymnastic arena, indoor pool, and connecting paths, the translucent Plexiglas roof system covers a total of 74,800 square meters.

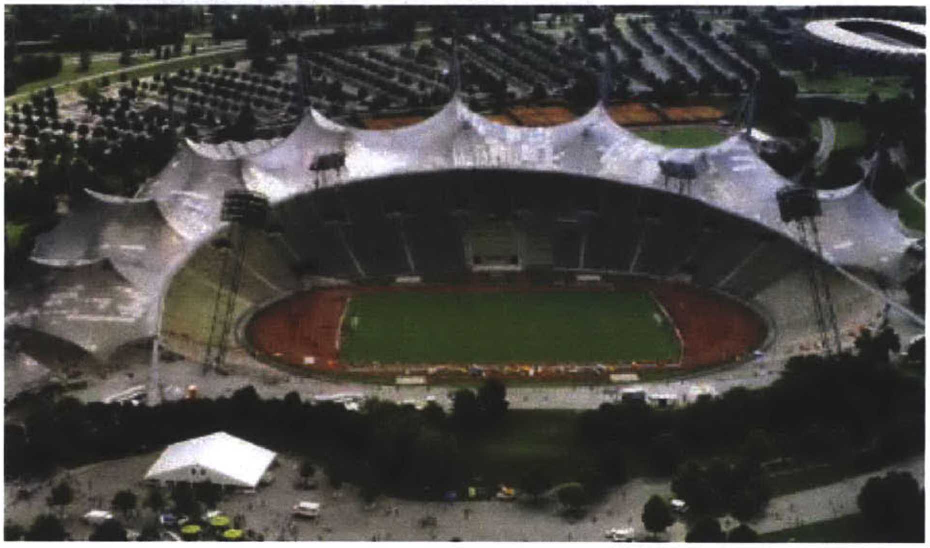

Figure 29: Munich Olympic Games Tent (Geraint, Sheard and Vickery 2007, 51)

Each section of the roof is supported by either cable-stayed towers or cable trusses. The stadium roof is supported by eight cable-stayed towers that reach 76 m and tensioned by a curved cable. Gunther Behnisch, a German Architect, and Frei Otto, a German Architect and structural engineer, designed this roof structure with the intension of imitating the Alps and create a lighter feeling to counteract the Berlin Olympics (discussed earlier). The Illustrated Encyclopedia of Architects and Architecture describes the roof as "an entirely new scale for this type of structure" and something that "led to the pioneering of purely mathematical computer-based procedures for determining their shape and behavior".[42] Advanced mathematical analysis and form finding techniques are often used to determine the optimal positioning of the steel cables so that the structure is in complete tension. Because of this, cable net systems require designers who specialize in finite element analysis and form finding methods.

8. Membrane Structure

Unlike the cable net structure, the roof covering of a membrane structure provides both the structure and the enclosure. This system "provides the opportunity to design a beautiful form, with large uncluttered spans thus creating exceptional lighting characteristics often not achievable with conventional materials and systems".[43] Two of the most popular material choices for the membrane are PVC-coated polyester fabric and Teflon-coated glass fiber fabric (PTFE-coated glass fiber fabric). The later is the more expensive option but has a much longer lifespan. The PVC coating tends to get sticky with time and requires frequent cleaning while Teflon provides a somewhat self-cleaning surface for the second material. Some countries have banned the use of PTFE-coated glass fiber because it produces toxic fumes if a fire occurs; for this reason expert designers and fire engineering is required for such roof systems.

A major benefit to membrane structures is that they can be applied to any geometry and do not dictate the shape of the stadium. They also provide a more airy and open appearance because there is no need for a dense skeleton of steel below the fabric. Depending on the material choice, there are also natural and artificial light benefits that come with membrane structure. Given a translucent material, typical daylight transmission is between 9% and 18%, thereby eliminating the need for artificial lighting. Membrane materials are also highly reflective, "returning 75-85% of heat and light externally".[44] This reflective quality also applies to interior lighting, therefore reducing the amount of light required at night by more than 40%.[45] Designers need to be very careful in the design and material choice of the covering too make that the grass field gets the lighting requires and spectators can adequate light and/or shade. Like cable net structures, membrane structures require specialized structural engineers who have worked with form finding algorithms.

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[42] (Great Buildings Collection 2012)

[43] (Structurflex 2010)

[44] (Structurflex 2010)

[45] (Structurflex 2010)

A stadium equipped with a membrane structure is Olympiyskiy Stadium in Kiev, Ukraine (Figure 30). Originally built for the 1989 Summer Olympics, the stadium was renovated in 2011 for the final soccer match of Euro 2012. As part of the renovation a 48,000 square meter membrane roof was added to cover all the stadium seats. The membrane is a glass cloth coated with Teflon on both sides and has a 12% transparency. Weighing only 1 kg per square meter, the membrane offers strength of up to 13 tons per square meter.[46]

Figure 30: Olympiyskiy Stadium
(Membrane Roofing of Olimpiysky Stadium in Kiev 2012)

9. Air-supported Roofs

One last roof structure worth discussing is an air-supported roof: a plastic membrane forming an enclosure and held up with internal pressure created by fans. The structural integrity of the roof structure comes from the internal pressurized air permitting these roofs to span great distances, as long as a constant air supply is provided. While air-supported roofs have low capital costs they also have short design lives and are susceptible to damage.

Throughout history there have been numerous stadiums with air-supported roofs in the United States: Hoosier Dome in Indianapolis, Indiana; Metrodome in Minneapolis, Minnesota; and the Silverdome in Pontiac, Michigan. Each of these roofs is made with a Teflon coated fiberglass material and is very similar in design, as seen below in Figure 31.

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[46] (Membrane Roofing of Olimpiysky Stadium in Kiev 2012)

Figure 31: Air-Supported Roofs (Hoosier Dome, Metrodome, and Silverdome) (World Stadiums 2012)

When the Silverdome was constructed in 1975, it was the first successful example use of fiberglass fabric for roofs and the largest air-supported roof.

10. Combining Systems

As designers become more inventive and try to create new structural forms, they tend to combine different structural systems. Most of the systems discussed can be modified and joined together to create roof structures. For example, a compression/tension ring system can be designed along with a membrane fabric or concrete shell to create a complete structure. As engineers continue to experiment and research new methods and materials the limits on structural systems expands. A perfect example of this can be seen by the advancement in operable roofs that allow for larger openings with faster mechanical systems.

Retractable and Operable Roofs

1. Introduction

An increasing numbers of stadiums are being designed, and others are retrofitted, with retractable roofs thereby making them viable for a wider range of uses. Retractable roofs offer the best of both fully enclosed and open stadiums. 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. Retractable roofs can be applied to many geometric forms and can be equipped with a myriad of mechanical devices. Although joining motion systems with structural design is by no means a new idea, technology has finally reached the level to allow for many possible variations of operable roofs.

2. Rigid Body Movement

The earliest designs of retractable roofs involved crane technology and worked with a system of rails. Frei Otto, the German architect and structural engineer, developed a series of rigid retractable construction methods seen below in Figure 32.

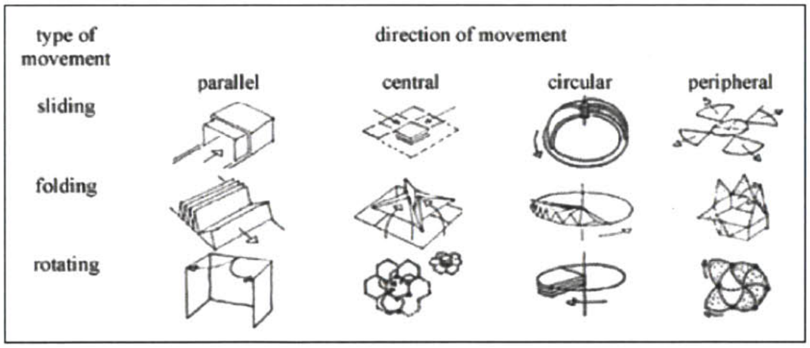

Figure 32: Rigid Body Movement
(Friedman and Farkas 2011)

According to this diagram, retractable motion can be achieved by three main movements: sliding, folding, or rotating. Pittsburgh Civic Arena, also known as the Mellon Arena (Figure 33), was the first retractable dome structure and opened in 1961. The domed roof was split into eight sections, six of which would slide under the stationary ones. According to the matrix in Figure 32, this stadium was equipped with a circular sliding mechanism that could open in just two minutes. All eight sections of the dome are connected to a huge cantilever arm that arches 260 feet leaving the interior free of supports.

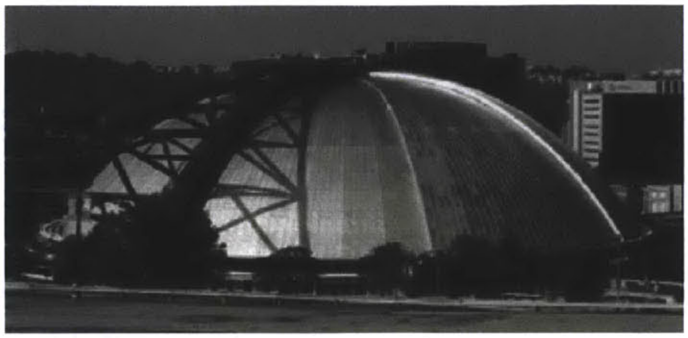

Figure 33: Mellon Arena
(Friedman and Farkas 2011)

In 1976 the Montreal Olympic Stadium was designed with an early and novice version of an operable roof. The stadium featured a 175 m tall inclined tower that had cables connected it to a fabric roof. Similar to an umbrella, the fabric roof would fold back into the tower. The fabric roof was made of Kevlar and was stretched over 5,500 square meters. Unfortunately, this roof had many problems: construction delays lasting 11 years, difficulty retracting, and inoperability in winds greater than 40 km/h (25mph). Since then, technology of retractable roofs has greatly improved and there have been many successful examples.

In Japan, the 1993 Fukuoka stadium (Figure 34) works with two rotatable sections and one stationary. This stadium does not incorporate an exterior support, like the truss in Mellon Arena, and instead, each roof section is an independent framework. Sliding is enabled by 24 bogie wheel assemblies that open the roof in 20 minutes.

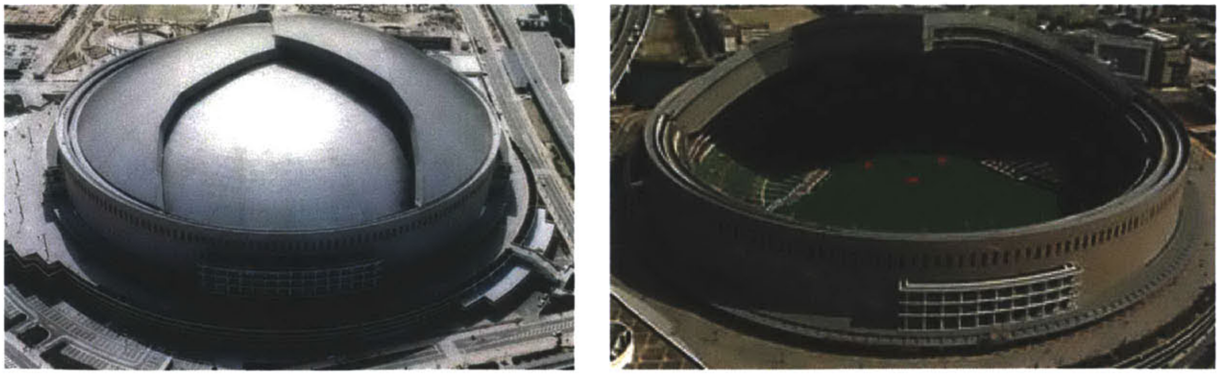

Figure 34: Fukuoka Stadium
(World Stadiums 2012)

Japan became home to another retractable structure in 2001 when Oita Stadium, also known as the "Big Eye", was constructed. Its roof has a two-layer spherical surface consisting of a fixed lower layer made of titanium and a retractable upper layer made of lightweight Teflon. Like an eyelid closing, the outer layer slides over the inner layer to a closed position in just 20 minutes (Figure 35). In order to allow natural lighting into the stadium the Teflon coating is transparent, thereby reducing energy costs for the stadium.

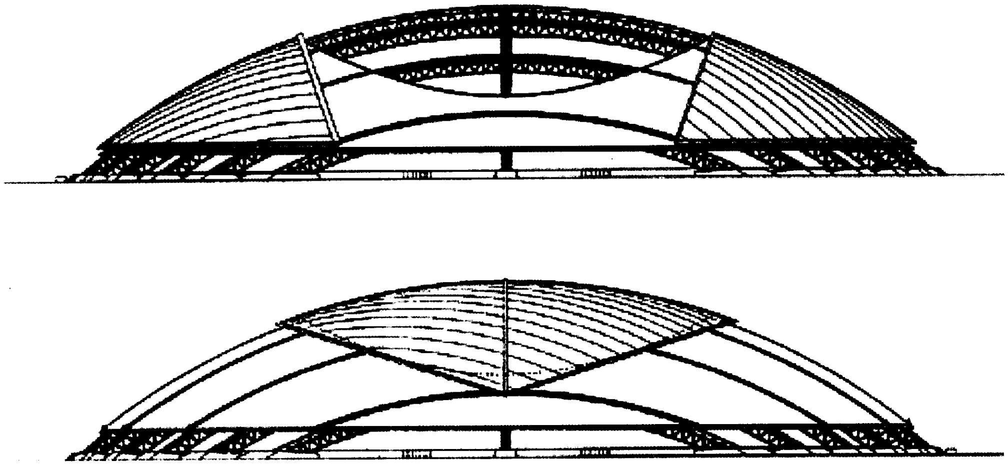

Figure 35: Oita Stadium
(Big Eye Stadium, Oita Prefectural Sports Park n.d.)

3. Foldable Structures

One alternative to rigid body motion based operable roofs are those that use scissor-like deployable structures to fold into a bundle. These roofs use scissor like elements, SLEs, which consist of two bars connected to each other with a revolute joint. Figure 36 shows various SLE configurations that are used for deployable structures.

Figure 36: Scissor-Like Elements for Deployable Structures
(Friedman and Farkas 2011)

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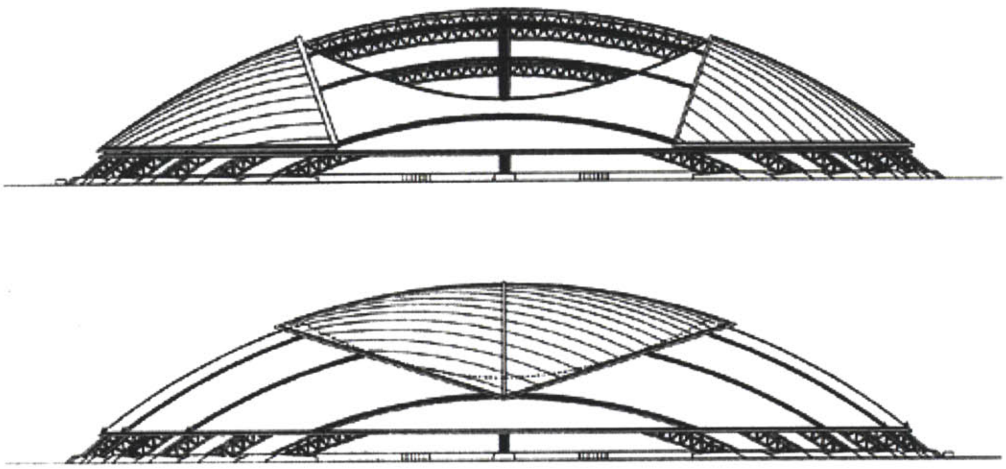

Figure 35: Oita Stadium
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Figure 36: Scissor-Like Elements for Deployable Structures
(Friedman and Farkas 2011)

"The scissor hinge allows one relative rotation, about its own axis, between connected members while other relative rotations and translations are inhibited".[47] While the joints of such elements are relatively simple, the major disadvantage is the complexity in connecting the structure to a permanent foundation. The first structures to incorporate this method had heavy and large joints as well as additional intermediate bars and tension elements. With time, designers realized that similar deployable structures could be self-stable if inner SLEs are added and the structure is built to a special geometric configuration.

Around 1990, American engineer Hoberman made considerable advancements in the design of deployable structure with the invention of the angulated element. "By the refraction of the two straight rods of a single SLE the angulated element is formed. This element is able to open and close while maintaining the end nodes on radial lines that subtend a constant angle."[48] According to Figure 37 below, the two angulated elements, AED and BEC are connected at the scissor-like joint. When the element is activated, points A and D travel along the line PO while B and C do the same along line QO.

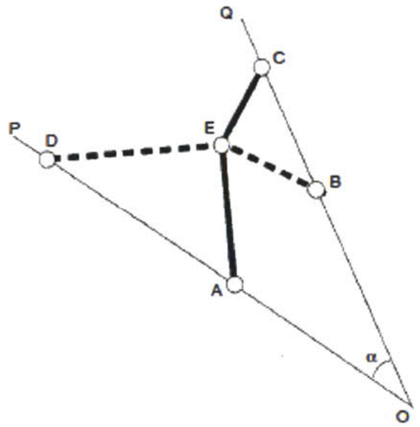

Figure 37: Hoberman's Angulated Element
(Jensen and Pellegrino 2008)

Hoberman used the undulated element to create the retractable roof of the Iris Dome in 2000. A complete enclosure was possible by covering the elements with rigid plates that overlap in the retracted position.

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[47] (Jensen and Pellegrino 2008)
[48] (Friedman and Farkas 2011)

Case Studies

1. Introduction

This final chapter will present detailed case studies of various stadiums from around the world and focus on important structural aspects. The bulk of this thesis focused on historical achievements in stadium design as well as important design factors and considerations. Here, a select few stadiums will be discussed to show how far stadiums have come since antiquity and how designers and engineers implement the design factors in various ways.

2. Houston Astrodome (Houston, Texas)

Known as "The Eighth Wonder of the World"[49], the Astrodome was significant to the development in stadium design. When the stadium opened in 1965 it was the first multi-purpose, domed sports stadium. Originally conceived as a way to bring major league baseball to Houston, the Astrodome was eventually designed to facilitate both football and baseball. Covering over 9 acres of land, the dome has a diameter of 710 ft and rests 18 stories, or 208 ft, above the playing surface.

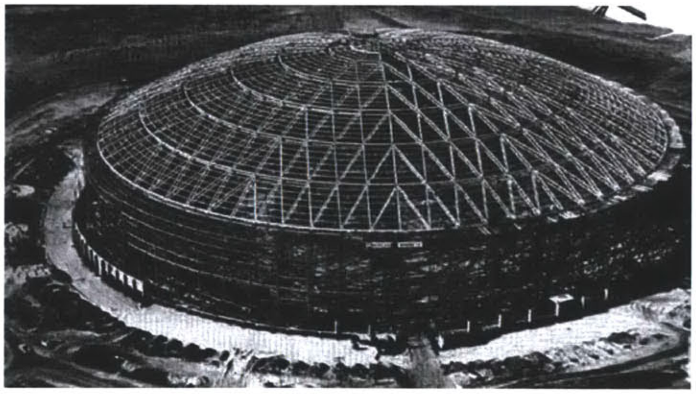

Figure 38: Astrodome Lamella Trusses
(Bass 1965)

The dome itself is made of concrete and sits atop a steel framed building. A 1/8th in scale model was used for wind tunnel testing. In addition to the numerous wind tests, preliminary analysis of the roof structure was analyzed with a shell analogy. The loads used for analysis included: 15 psf live load, 30psf dead load, and a one-sided loading of 7.5 psf. Results from the analysis

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[49] (Astrodome History & Historical Analysis 2012)

required "2,150 tons of steel in the 350,000 sq ft of roof frame, plus a 376 ton tension ring".[50] The domed roof is supported by 5 ft deep Lamella trusses, which form interlocking diamond shapes (Figure 38). With a clear span of 624 ft, the Astrodome roof proved to be a challenge for stadium engineers. Although this may be considered a short span for bridge engineers, this structural system had only previously been used for domes spanning up to 285 ft.

Home to both a football and baseball team, the Astrodome had to be designed to fit both a rectangular field and a diamond. In order to satisfy both, the Astrodome was equipped with movable lower seating areas, totaling about 10,000 seats. The seats at field level rotate 35 degrees from their baseball position to a parallel position for football games.[51] Figure 39 shows how the layout for baseball (left) compares with football (right) inside the Astrodome.

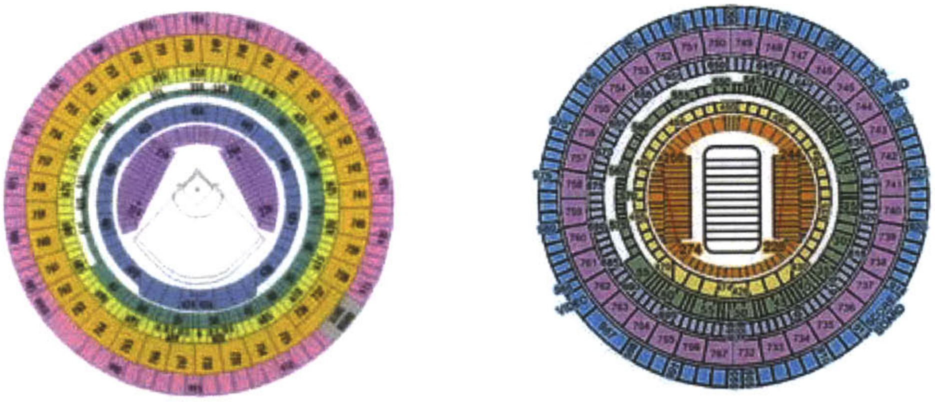

Figure 39: Astrodome Layouts
(Astrodome History & Historical Analysis 2012)

Construction of the Astrodome began in 1962, two years before the invention of synthetic field materials so the only option was natural grass. In order to determine the best type of grass to use, a special greenhouse was set up to do testing. After testing multiple strains, it was determined that Tifway 419 Bermuda grass yielded the best results. In order for the natural grass to survive indoors sufficient light would have to be let through the domed roof. The dome was equipped with 4,600 Lucite skylights made with two layers of plastic to control condensation. Players quickly complained about the sun blinding them and making it difficult to catch the ball.

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[50] (Bass 1965)
[51] (Bass 1965)

As a solution thirty percent of the panels were coated with paint, but this significantly reduced the amount of sunlight and killed the natural grass.

In 1966 the natural grass playing field was replaced with an artificial turf, which was later called AstroTurf, named after the stadium. The original AstroTurf was a green surface made of nylon grass. Since this first installation of AstroTurf, the company has invented a wide array of synthetic turf systems. As mentioned in the earlier section, *Artificial Surfaces*, the artificial turf changes the game slightly because of its effect on the ball. The ball bounces higher and travels faster on the turf than on the natural grass. When used for baseball, it forces the infielders to play further back than they would normally. This discussion shows how the Houston Astrodome made advancement in both the structure of stadiums and the actual playing field of sports.

3. Reliant Stadium (Houston, Texas)

Reliant Stadium (Figure 40), home to the Houston Texans and Houston Livestock Show and Rodeo, opened in 2002 and became the first NFL stadium with an operable roof. At the time, it was the largest such roof in the United States at 3.75 acres but this was quickly surpassed by other stadiums. The stadium itself covers more than 12 acres of land and is comprised of 1.9 million square feet.

Figure 40: Reliant Stadium
(Griffls, et al. 2003)

A retractable roof was included in the design so that football could be played in either an open-air environment or in a cool air-conditioned atmosphere when temperatures are too high. It also provided a setting for the Houston Livestock Show and Rodeo to take place in February. "An impressive structure accommodating a myriad of complex requirements. The scale of the opening roof and the supporting super-trusses are recognizable feats of structural design."[52] The moving section of the roof consists of two panels that bi-part at the 50-yard line. "Each 385 ft by 500 ft panel is framed with five arched trichord trusses, which are clad with PTFE fabric and tensioned between trusses by a major valley cable to form a distinctive anticlastic roof shape."[53] These panels move towards the end zones with the help of forty 5HP, 460 volt three phase electric motors and standard steel wheels that drive the roof on a single 175 lb crane rail; this roof closes in just 10 minutes.

The structural steel system supporting the operable roof is as impressive as the mechanical roof itself. Above either sideline sits a massive trapezoidal supertruss that clears 650 ft between the concrete supercolumns. In an effort to accommodate sightlines for all spectators, the bottom chord of the supertrusses is arched so that the depth is 50 ft at midspan and 75 ft at the ends. These supertrusses remain visible outside the stadium, as they stick out 164 ft beyond the supercolumns to support the operable panels in the open position. Connecting the two supertrusses are twelve trichord trusses: one fixed at either end and 10 moveable ones connected to the operable roof panels. A simplified image of Reliant Stadium's structural system can be seen in Figure 41.

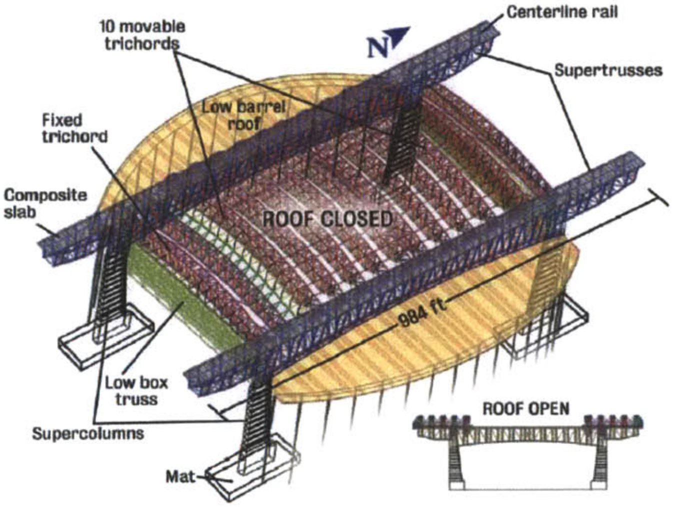

Figure 41: Reliant Stadium's Structural System
(Reliant Stadium 2004)

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[52] (Reliant Stadium 2004)
[53] (Reliant Stadium 2004)

In order for the design to be a success, the steel supertrusses are made integral with the concrete supercolumns, thus creating a large portal frame. The trusses are made composite with the concrete slab that serves as a service platform on top. "One of the keys to achieving efficiency in the long-span roof of Reliant Stadium was the use of high-strength steel in the form of ASTM A913 Grade 65."[54] Designers chose to use this high-strength steel throughout the structure to reduce steel tonnage.

Figure 42 below shows the various trusses used in Reliant Stadium. The supertrusses, which experience high loads, use double W14 sections laced together with single angles for the compression members and single W14 sections for the tension members. Lacing is applied to the compression members to help decrease the unbraced lengths and reap the full benefits of the Grade 65 steel. The smaller trichord trusses uses single W14 sections for both compression and tension members.

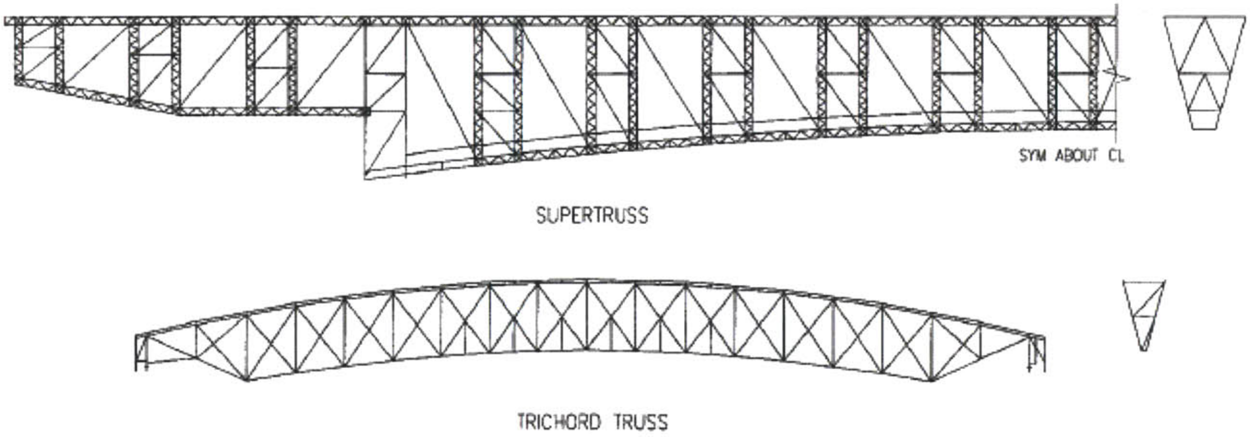

Figure 42: Reliant Stadium Trusses
(Griffls, et al. 2003)

"The operable roof of Reliant Stadium is the product of countless hours of exceptional effort by engineers, fabricators, and erectors cumulatively responding to an architectural vision for the City of Houston that could only be realized in structural steel."[55] In fact, the design would most probably not be as successful as it is, if possible at all, without the use of A913 Grade 65 steel. The total structure used about 300 tons of this steel, which amounts to 26% of the overall steel tonnage. While that may sound like a low percentage, the use of the high strength steel "led to

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[54] (Griffls, et al. 2003)
[55] (Reliant Stadium 2004)

an estimated overall tonnage savings of 825 tons, about 7% of the total roof tonnage."[56] Reliant Stadium has thus become an excellent example of the benefits of high strength steel for long span structures.

4. Arizona Cardinals Stadium (Glendale, Arizona)

In 2006 the University of Phoenix opened a new football stadium for the Arizona Cardinals designed by architect Peter Eisenman and engineer HOK Sport & Venue & Event (Figure 43). Situated in the middle of the desert in Glendale, Arizona the stadium's design was heavily influenced by the climate and surrounding landscape. Gaining recognition for its architectural and engineering innovations, the stadium is just the second NFL stadium to be equipped with a retractable roof, but more impressive, it is the first in North America to have an operable playing field.

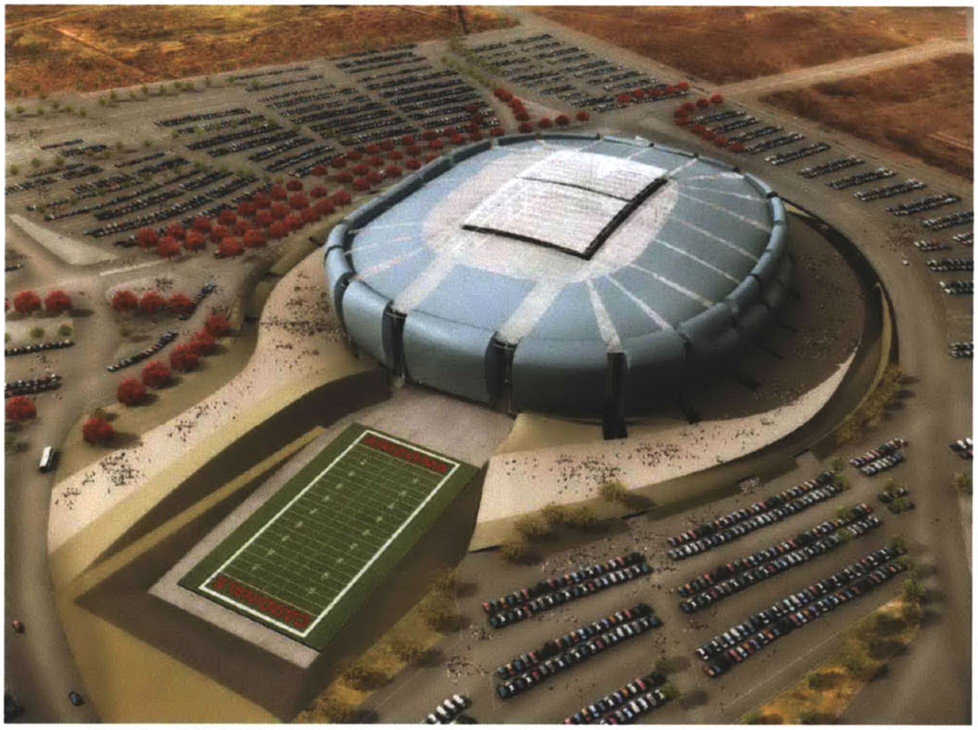

Figure 43: Arizona Cardinals Stadium
(World Stadiums 2012)

The designers of the project used the surrounding landscape to develop the exterior of the structure. In an attempt to represent the barrel cactus, a popular plant in the deserts of Arizona,

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[56] (Griffls, et al. 2003)

the stadium is clad in alternating metal panels and glass slits. Both the project architect and engineer agreed that a retractable roof was a necessity for the stadium. Temperatures in Arizona reach above 100 degrees Fahrenheit in the summer and drop to only 70-80 degrees throughout the year. Spectators would therefore benefit from an open roof for the sunny warm days and air conditioning in the scorching summers. The retractable roof meets both of these needs.

Retractable roofs are a hug expense and their cost increases drastically with the span. Peter Eisenman opted to equip the stadium with a retractable natural grass playing field to help keep the costs down. Since the grass field can now be pulled out of the stadium to receive the necessary sun exposure, the opening in the roof does not need to be as large. The retractable field saved the owner $50 million in construction cost. Moving at a speed of 11.5 ft/min the field tray rests on 13 rail tracks and moves on 542 wheel assemblies. Measuring 234 ft by 400 ft the tray itself weight 12 million lbs.[57]

Uni-Systems, the leading company in retractable roof systems, designed the Cardinals Stadium's roof. The signature aspect of the 500,000 sq ft roof is the pair of Brunel trusses that span 700 ft along the east and west sidelines between the concrete supercolumns. The Brunel trusses support the secondary trusses, which span to the perimeter of the structure, and the fixed trusses that span between the Brunel trusses. Each panel of the retractable roof measures 180 ft by 270 ft and when they are in the open position, the roof opening is 360 ft by 240 ft. The panels are constructed with "8 lenticular, vierendeel-style trusses composed of square and rectangular hollow structural sections".[58] The ends of the panels are supported with eight sets of wheeled carriers that ride on a rail clamped to a built-up box rail girder located at the center of the Brunel truss.

A final detail of this stadium worth discussing is the final roof lift (Figure 44) that has been regarded as a landmark in construction. The 5,400 ton lift is the heaviest of its kind in North America and is the most daring aspect of the project. Starting at 7:00 am, the construction crew worked until 3:00 pm lifting the Brunel trusses and the structure in between into their final resting position above four 171 ft tall concrete supercolumns.

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[57] (University of Phoenix Stadium Statistics n.d.)

[58] (Ales 2008)

Figure 44: Cardinal Stadium's Landmark Lift
(Ales 2008)

5. Wembley Stadium (London, UK)

Joann Gonchar, AIA, states in an *Architectural Record* article, that roofs do much more than satisfy practical requirements; in many cases they also serve as the building's signature element.[59] A stadium with such a roof structure is Wembley Stadium (Figure 45), a new soccer stadium in London that opened in 2007. Architects Foster and Partners, along with HOK Sport, designed this iconic stadium to replace the 1920s Wembley Stadium.

Figure 45: Wembley Stadium
(Gonchar and Reina n.d.)

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[59] (Gonchar and Reina n.d.)

The new Wembley Stadium has 90,000 seats situated under a retractable roof and a 133 m tall arch that is visible from around the city. Spanning 315 m, the stadium has one of the longest single span roof structures in the world. The actual body of the stadium is a bowl with relatively steep banks so that no seat has a restricted view. A retractable roof was incorporated into the design because according to the Union of European Football Associations (UEFA), a high quality grass pitch is required for official games.

Norman Foster designed the actual arch for the stadium which supports the entire north roof and most of the south roof too. The arch was designed to be both functional and cosmetic. Shaped in a lattice form (Figure 46), the arch consists of "41 circular stiffening diaphragms linked by more than 500, 1 -ft-6-in diameter spiraling steel tubes".[60] The arch is held in place with a northward learn (68 degrees from the horizontal) by cables attached to the stadium's perimeter. In an attempt to spread the loads, the cables from the arch are arranged in a diagonal pattern. This arrangement helps to control in-plane bending and provides out-of-plane restraint to resist bucking.

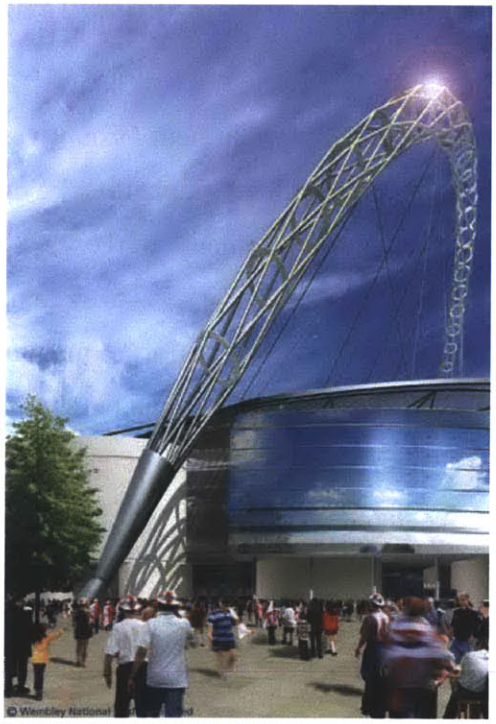

Figure 46: Wembley Stadium Arch
(Wembley Stadium, London, United Kingdom n.d.)

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[60] (Gonchar and Reina n.d.)

The total roof comprises 50,000 sq m and weighs 7,000 tonnes. A number of retractable edge sections can be maneuvered so that every inch of the grass field is exposed to sunlight. Every segment of the roof can be put into the closed position to cover all seats in the stadium in just 15 minutes.

Construction of the new Wembley Stadium required "90,000 cubic meters of concrete, 23,000 tons of steel and 35 miles of heavy-duty power cables".[61] The arch itself was constructed on site and lifted into place in four stages. The project was completed on a fixed-cost contract and the final stadium costs amounted to £800 million. The original Wembley Stadium, also known as the Twin Towers, was a hard structure to replace because it held such meaning to the people of London. The new stadium surpassed all expectations, and six years after it was built, people around the world still view Wembley Stadium as a magical form of modern architecture.

6. Cowboys Stadium (Arlington, Texas)

In June 2009, the Dallas Cowboys moved into their new stadium (Figure 47) that took the title as the largest NFL venue ever built with a column-free span stretching a quarter mile in length. Their original stadium, dating back to 1971, no longer portrayed the team's success and so the new stadium was being developed in an effort to exemplify the team's winning tradition and commitment to success. HKS Sports & Entertainment Group was the architect for the project and designed the stadium so that it enhanced the "international Cowboys brand with its modern, progressive architecture while incorporating elements of Texas Stadium's heritage such as the shape of the roof's opening and the Ring of Honor".[62] A trademark element of the Cowboys' original stadium was the hole in the roof, and in an effort to maintain this characteristic, the new stadium was equipped with a retractable roof. While the entire site encompasses 140 acres, the stadium itself sits on 73 acres. With construction costs around $1.1 billion, the stadium has become one of the world's premier stadiums.

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[61] (Wembley Stadium, London, United Kingdom n.d.)

[62] (Cowboys Stadium n.d.)

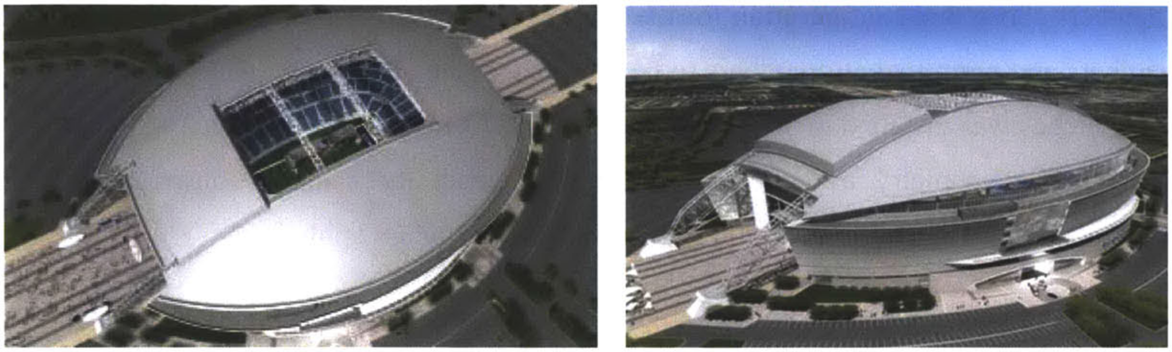

Figure 47: Cowboys Stadium
(Aniol, Dowd and Platten 2008)

With a roof area of 660,800 sq ft, the Cowboys Stadium has the record of the world's longest single span roof structure. Two monumental arches, designed as arch box trusses, support this roof 292 ft above the field surface. Each truss has a radius of 1,025 ft, measures 17 ft wide by 35 ft deep, and weighs 6.5 million lbs.[63]

Walter P Moore, the lead structural engineer on the project, designed the truss chords with ASTM A913 Grade 65 steel with sizes ranging from W14x311 to W14x730. In an attempt to save on steel and utilize a 25% increase in yield strength, the engineers minimized the arch truss chord slenderness ratios. The trusses were designed with a Quadrangular Warren web configuration; Figure 48 below is a sample Quadrangular Warren truss and shows the diamond pattern that is created by the web members.

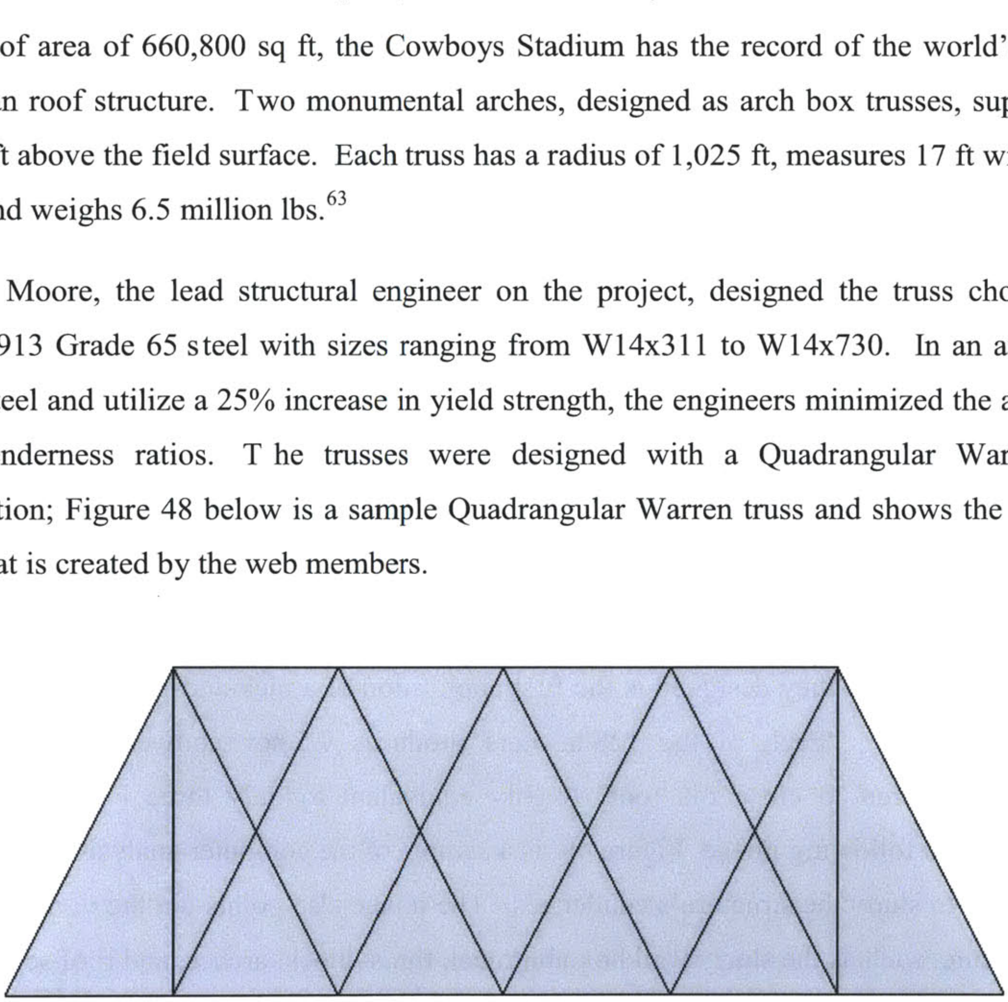

Figure 48: Quadrangular Warren

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[63] (Cowboys Stadium n.d.)

Engineers chose this configuration for the truss because it reduced the stress on the heavy chord members and permitted all members to be less than or equal to the W14x730 shape limit. Each of the arches was installed in 56 ft segments as a means to simplify the construction process, and so the basic geometry of each segment could remain the same. Constructed with many segments, each arch required 46,500 ASTM A490 bolts for assembly.[64]

The arch pin bearing assembly was designed by Uni-Systems. This pin sits on a concrete thrust block measuring 25 ft by 11 ft and jutting out of the ground at 32 degrees. Below ground is a slurry wall box abutment that transfers the large load from the thrust block to the surrounding soil.

The Cowboys Stadium was equipped with an operable roof for two main reasons: keep the hole in the roof design that was part of the original stadium and so that the new stadium could be used for different sports throughout the year. The owners hoped that the stadium could be configured to host national events like the NCAA Basketball Final Four Tournament, the Cotton Bowl, and even the Super Bowl. In order to satisfy the requirements for all these events the stadium needs to have a fully enclosed roof (basketball) and an open roof (football). Like many operable roofs, the moveable segments of the Cowboys Stadium are made with a fiberglass fabric and coated with Teflon. Each panel measures 290 ft by 220 ft and can close in a matter of 12 minutes. Alternatively, the stationary roof sections are steel with a PVC membrane.

Uni-Systems also designed the mechanization system, which consist of 128 motors, 32 per roof quadrant. The system they designed is the first application of a rack-and-pinion retractable roof in North America. "Each of the 128 motors produces 7.5 horsepower, making the 960 horsepower required to close the roof roughly equivalent to only three Ford Mustang GT engines."[65] The following image, Figure 49, is a sample of the computer analysis model used by the engineers to study the structure's challenges. The image also points out the various elements of the structure, such as the slurry wall box abutment, thrust block, arches, and roof segments.

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[64] (Aniol, Dowd and Platten 2008)

[65] (Aniol, Dowd and Platten 2008)

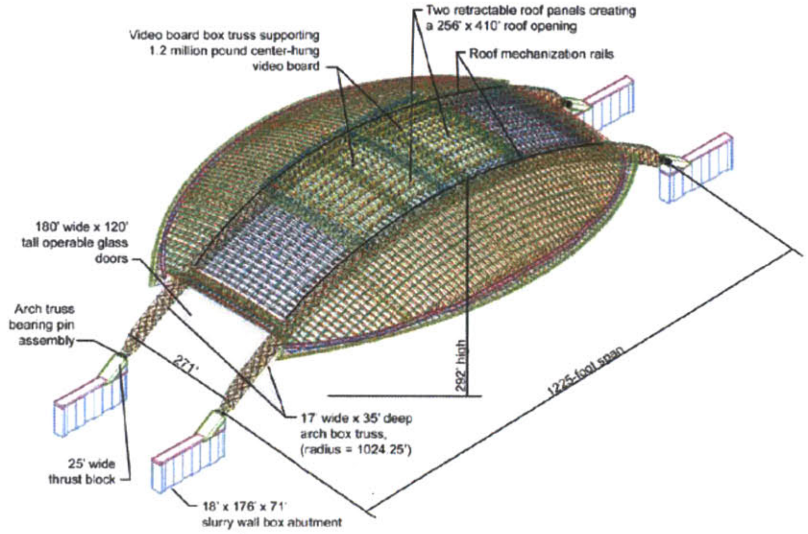

Figure 49: Cowboys Stadium Analysis Model
(Aniol, Dowd and Platten 2008)

In addition to the retractable roof, the stadium features retractable end zone doors. These glass doors, each measuring 120 ft high by 180 ft wide, are the largest retractable doors in the world. The use of glass provides spectators with a panoramic view from within the seating bowl. More importantly, the ability to open the doors provides excellent air circulation throughout the stadium. One last compelling feature of the stadium design is the slanted glass exterior wall. The curtain wall surface measures 86 ft high and slopes outward at a 14 degree angle. Mark Williams, principal and project direction for HKS Sports & Entertainment Group explains the project best: "The Dallas Cowboy's new venue represents an innovative culmination of sports, entertainment and high design. The architecture provides fans with an unprecedented immersion into the world of sports."[66]

7. Nelson Mandela Bay Stadium (Port Elizabeth, South Africa)

Port Elizabeth, one of South Africa's largest cities, was selected as a venue for the 2010 FIFA World Cup. The Eastern Cape province did not have any existing world-class soccer stadiums and took this opportunity to develop an iconic landmark for the "Windy City". Situated on a site with many challenges, the 46,000 capacity Nelson Mandela Bay Stadium was built with a roof that many consider an engineering masterpiece (Figure 50).

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[66] (Cowboys Stadium n.d.)

Figure 50: Nelson Mandela Bay Stadium
(K. 2010)

Nelson Mandela Bay Stadium is located just 50 m from Port Elizabeth's North End Lake and 1 km from the sea. This proximity meant that the site rested on expansive soils, a high water table, and a pitch level 1 m below the overflow weir level of the lake. These soil and water conditions drove the foundation design: 2,300 piles with lengths as long as 12.5 m. The stadium is then situated on a raised podium.

The focus of the stadium is the distinctive roof design that "results from the alternating arrangement of clad girders and areas of membrane stretched between them".[67] The primary structure is made of concrete while the roof skeleton is in steel. The concrete was constructed in eight segments, each done by a different construction team so that it could be done quickly and on schedule. Each concrete segment had a highly reinforced ring slab on top containing the securing bolts for the structural steel roof. It was imperative that these connections were in their exact positions because the steel roof trusses were predetermined and could not be altered.

Designed by specialist roof design engineers in Germany, the steel roof structure was manufactured and assembled off site to verify the exact dimensions and connections. The designers wanted to minimize the weight of the space frame tubular truss and keep each of the 36 trusses at 55 tonnes. Each truss segment was pre-assembled in a jig at the ground and then installed from the outside of the stadium as seen below in Figure 51.

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[67] (K. 2010)

Figure 51: Roof Girder Installation
(Nelson Mandela Multi-Purpose Stadium 2010)

The geometry of the roof takes the shape of leaves unfolding and was designed to protect the crowd from the sun and strong winds, which are frequent in Port Elizabeth. The design was made more dramatic with the inclusion of an external top cord with an elevated ridge. The membrane zones of the roof covering are made of PTFE and the parabolic girders are clad in aluminum. From inside the stadium, the roof trusses are exposed and the alternation between opaque and translucent coverings is obvious. As a complete structure, Nelson Mandela Bay Stadium represents a significant contribution to modern stadium architecture.

Conclusion

Coming a long way since the days of the Greeks and Romans, a variety of contributing factors has brought Stadium design to the forefront of structural engineering and architectural design. With the advancements in television broadcasting more and more people are directly exposed to sports and with that the culture has greatly evolved. While in the 20th century there were concerns that the public would prefer watching sport competitions from the comfort of their living room or sports bar, the true fans realized that there are no substitutions for attending events in person at the stadium. Coupled with the global competition to build the tallest structure, the longest bridge or the most advanced and innovative stadium, stadium design has attracted the most innovative minds to produce the next generation of stadium. The desire to widen the consumer base and improve the overall experience for the spectators while addressing the players' needs as well as the arena owners' has forced the designers to think outside the box and introduce design elements which were never before considered in the scope of stadium design.

The recent idea of pulling the natural turf playing surface out of the arena allows designers to reduce the size of the operable roof and thus gain substantial savings. With a new way of supplying natural grass with sunlight, designers can put more focus on elaborate stationary roofs without having to think about roof mechanical systems. This kind of innovative approach opens the design to a whole new era in stadium design one that is not confined by prior designs.

While countries and cities are still vying to build the tallest building, the challenge of being home to the largest and most advanced stadium is rapidly gaining momentum. Stadiums built around the world provide a source of tremendous pride to the hosting country and an innovative platform for the engineers who are eager to challenge themselves.

The benefits to the design field will be felt well beyond stadium design and it will affect structural engineering and overall design approach throughout the construction industry. "Sporting design has not merely come of age; it may well be ready to take center stage. If the nineteenth century may be defined as the age of railways, why not sport and leisure in the twenty-first".[68]

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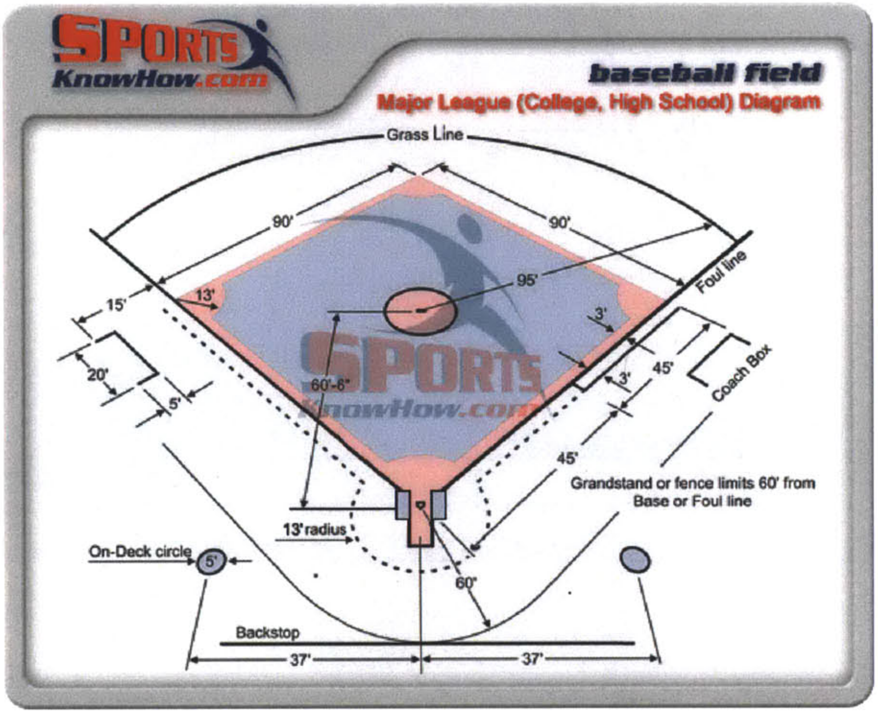
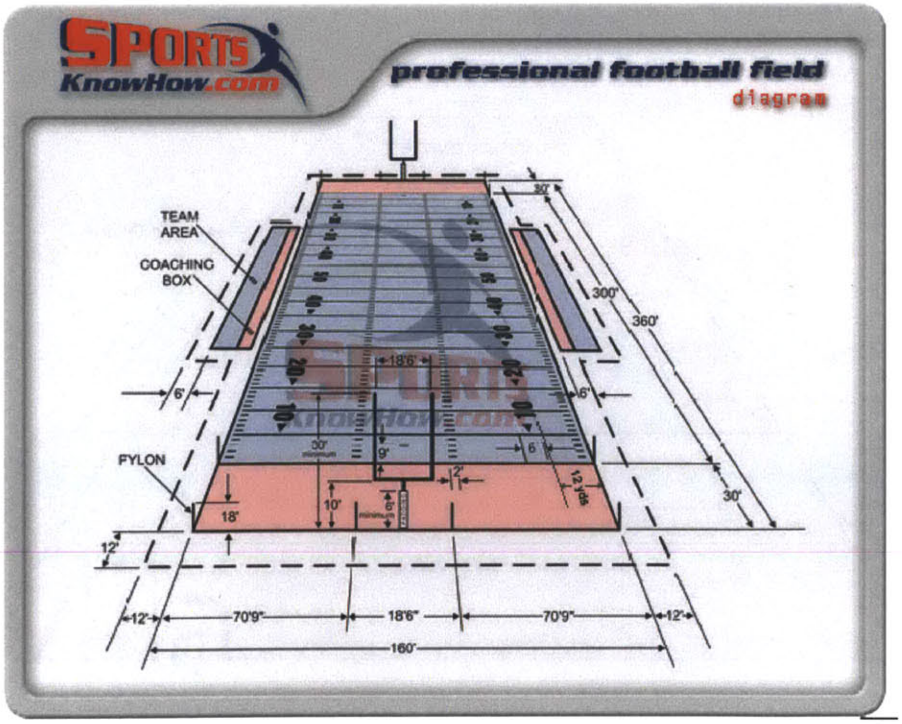
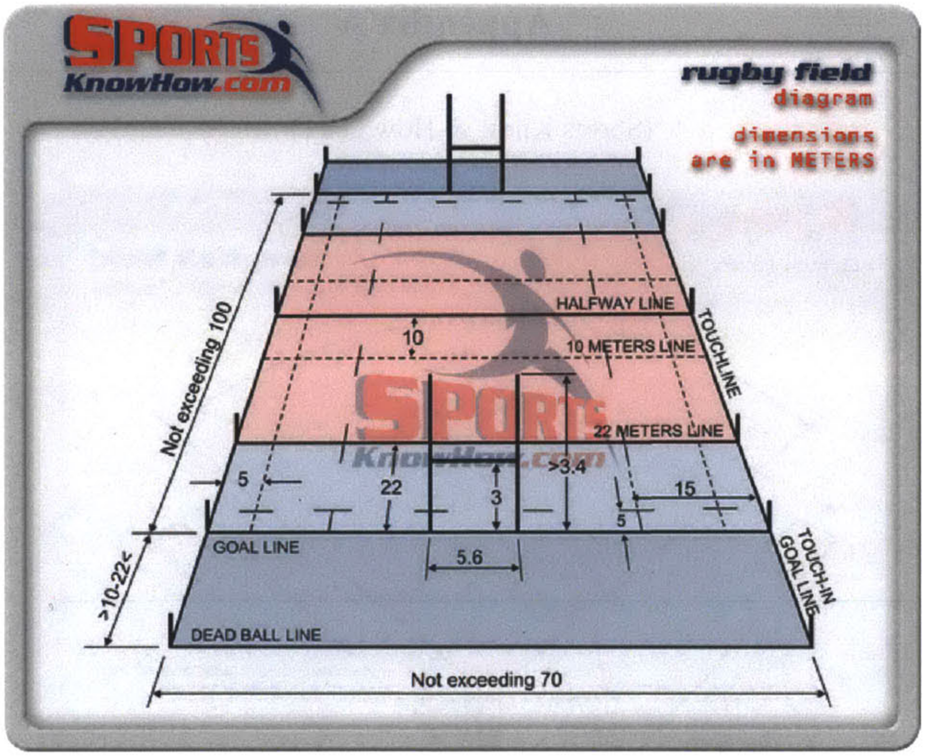
[68] (Culley and Pascoe 2005, xii)

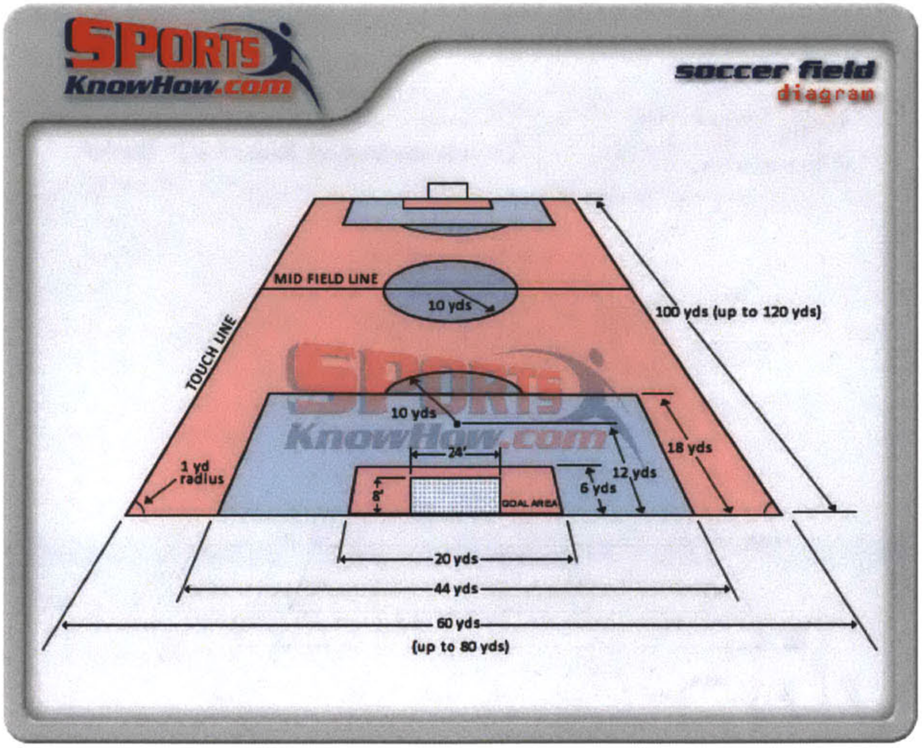
Appendix A

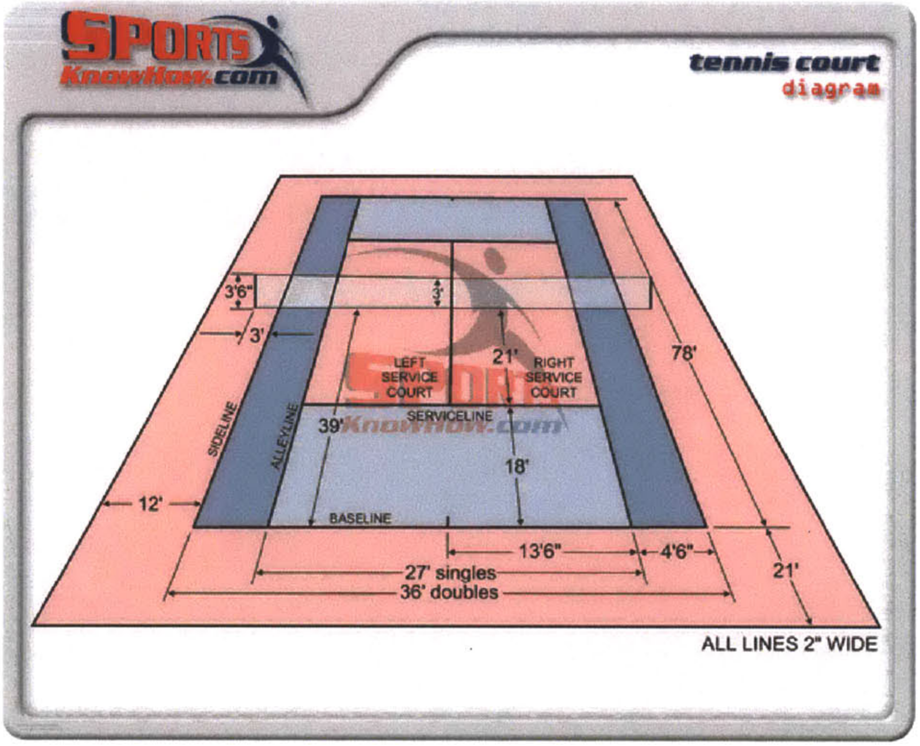
(Sports Know & How 2011)

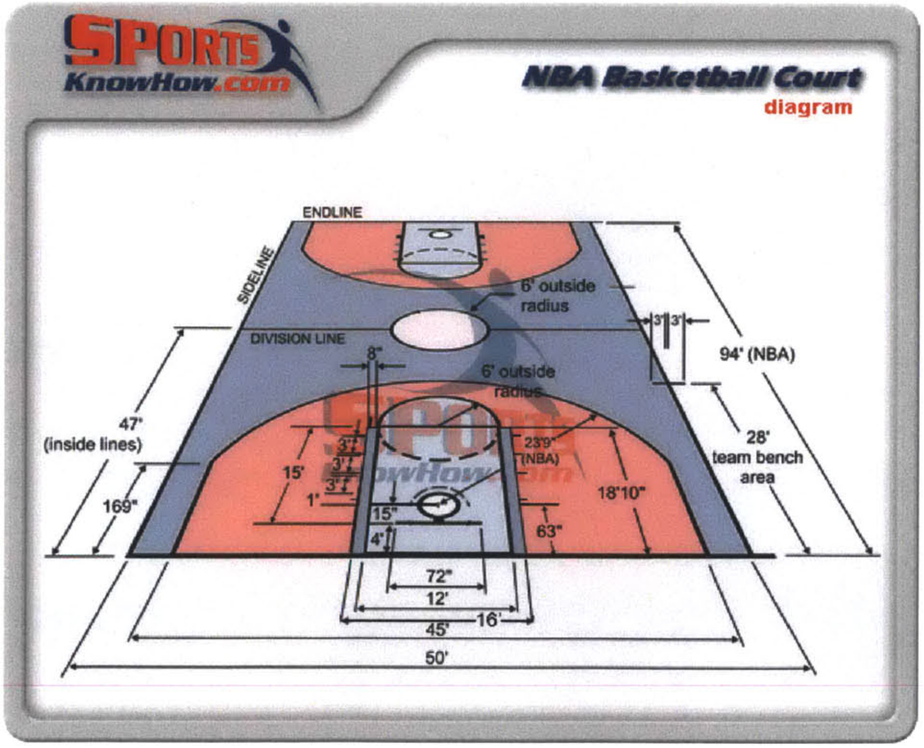





SPORTS KnowHow.com
rugby field diagram
dimensions are in METERS
HALFWAY LINE
TOUCHLINE
10
10 METERS LINE
Not exceeding 100
22 METERS LINE
>3.4
5
22
3
15
5
GOAL LINE
5.6
TOUCH-IN GOAL LINE
>10-22<
DEAD BALL LINE
Not exceeding 70

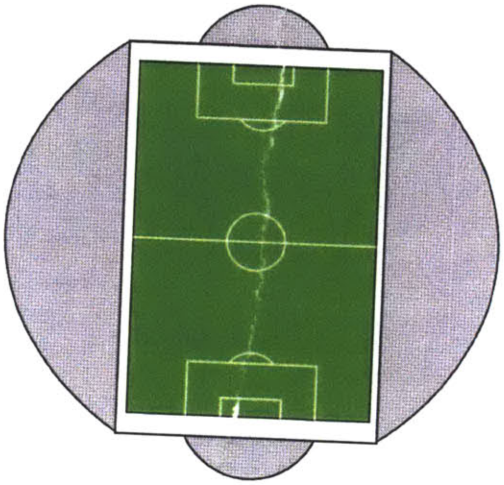

SPORTS KnowHow.com
soccer field diagram
MID FIELD LINE
10 yds
100 yds (up to 120 yds)
TOUCH LINE
10 yds
24'
18 yds
12 yds
6 yds
1 yd radius
8'
GOAL AREA
20 yds
44 yds
60 yds
(up to 80 yds)


SPORTS KnowHow.com
tennis court
diagram
3'6"
3'
3'
LEFT SERVICE COURT
21'
RIGHT SERVICE COURT
78'
SERVICELINE
39'
SIDELINE
ALLEYLINE
18'
12'
BASELINE
13'6"
4'6"
27' singles
36' doubles
21'
ALL LINES 2" WIDE

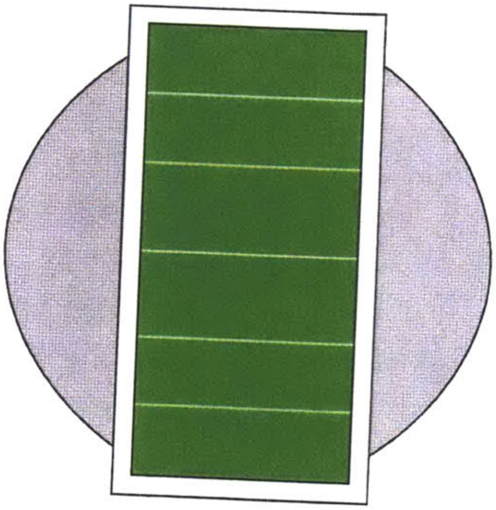

SPORTS KnowHow.com
NBA Basketball Court
diagram
ENDLINE
SIDELINE
6' outside radius
DIVISION LINE
3' 3'
94' (NBA)
8"
6' outside radius
47' (inside lines)
3'
3'
3'
23'9" (NBA)
28' team bench area
15'
18'10"
169"
1'
15"
4'
63"
72"
12'
16'
45'
50'

Appendix B

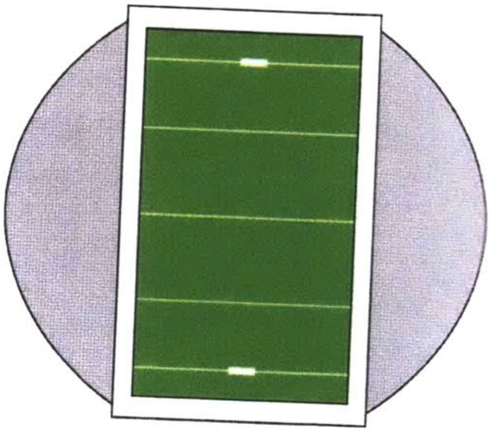
Preferred Viewing Positions for Various Sports (Geraint, Sheard and Vickery 2007, 130)



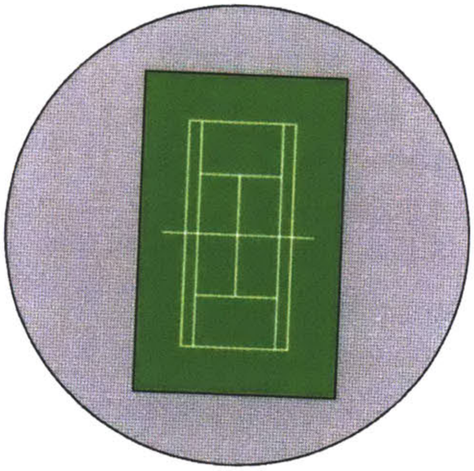
Soccer



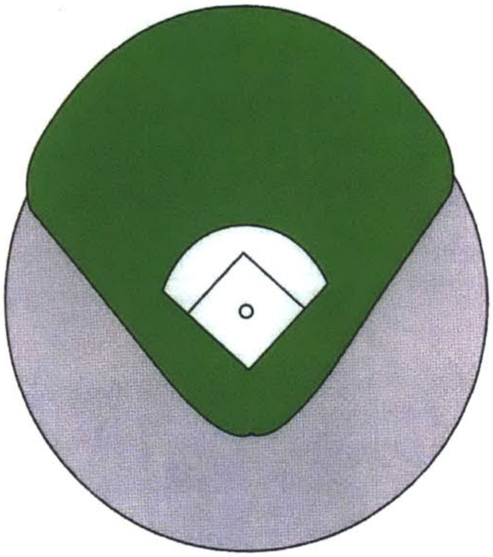
American Football



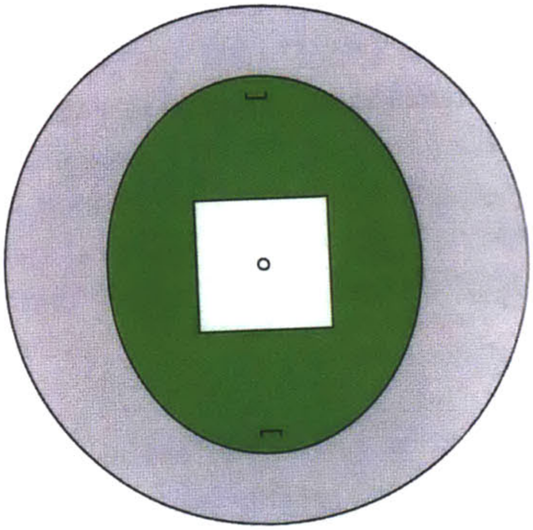
Rugby



Lawn Tennis



Baseball



Australian Football

Appendix C

Roof Covering Materials (Geraint, Sheard and Vickery 2007, 68)

	Profiled metal sheeting		Concrete	PVC		Acrylic	GRP	Polycarbonate		Fabric	
	Steel	Aluminium		Single glaze	Double glaze			Single glaze	Double glaze	PVC-coated	PTFE-coated
Relative cost factor (supply and fix) as at 1992 in the UK	1.2		2.5 to 8.0	2.4 to 4.0	3.0 to 5.0	2.4 to 4.0	1.5 to 3.5	4.5 to 7.0	6.0 to 8.0	3.0 to 5.0	5.0 to 8.0
Durability	Good	Good	Good	Medium	Medium	Medium	Medium	Good	Good	Medium	Good
Flame retardancy	Incombustible		Incombustible	Self-extinguishing		Class 1 (when edges are protected)	Class 1	Self-extinguishing		Approx Class 1 equiv.	Class 0
Transparency	Opaque		Opaque	Transparent: 70% to 85% light transmission, which lessens markedly with time.		Translucent or transparent: 50% to 70% possible light transmission, which lessens moderately with time.	Opaque	Transparent: 80% to 90% visible light transmission, which lessens slightly with time.		Translucent	

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