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DIPLOMARBEIT
MASTER'S THESIS

Adaptability and Structural Design of Stadia

ausgeführt zum Zwecke der Erlangung des akademischen
Grades eines Diplom-Ingenieurs

unter der Leitung von

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Abstract:

The aim of this master's thesis is to analyse recent developments in the design of stadia and their impact on the structural design. Major events like Olympic Games or championships in any sport have always been the booster for the construction of new stadia and the redevelopment of existing venues. In particular, the aim to make stadia adaptable in terms of use led to new challenges for the structural design. On one side, in order to increase event days per year, there are multi-purpose stadia for various sports, as well as for non-sporting events. Ancillary uses of stadia for hotels, leisure clubs, offices, and suchlike are required to increase the efficiency of a new development. Movable structures for seating tiers, pitches, and roofs developed for stadia that are suitable for various events. The design of these structures and their impact on the permanent structure is discussed in this thesis. On the other side, major events require stadia with pre-determined capacities, which may be unsuitable for a long-term use. For this purpose, demountable structures for spectator accommodation are used to increase the capacity just temporary for the duration of a major event. Such temporary structures can be used for stands and roofs, either as separate structures adjacent to the permanent structure or as structures built in the permanent structure. Furthermore, general concepts for the structural design of stands and roofs are discussed. In addition, case studies of recent developments for major events, multi-purpose stadia, and stadia in the UK are analysed. Due to a study in the UK, there are British guidelines discussed in this thesis.

Kurzzusammenfassung:

Ziel dieser Diplomarbeit ist Entwicklungen in der Planung von Stadien und deren Auswirkung auf Tragwerkskonzepte zu analysieren. Großereignisse, wie zum Beispiel Olympische Spiele oder Meisterschaften in verschiedensten Sportarten waren schon immer der Motor für die Errichtung neuer Stadien, sowie für die Revitalisierung bestehender Sportanlagen. Adaptierbarkeit hinsichtlich der Nutzung im Besonderen hat zu neuen Herausforderungen an die Tragwerksplanung geführt. Um die möglichen Veranstaltungstage eines Stadions zu erhöhen, entstanden Mehrzweckstadien, die nicht nur für Sportveranstaltungen genutzt werden können. Um ein Stadion zu erhalten, das für verschiedene Veranstaltungen genutzt werden kann, wurden bewegliche Tragwerke für Tribünen, Spielfelder und Überdachungen entwickelt. Die Planung derartiger Tragwerke und deren Auswirkung auf die permanenten Tragwerke eines Stadions werden diskutiert. Andererseits erfordern Großereignisse Stadien mit einer vorgegebenen Zuschauerkapazität, die möglicherweise für eine Langzeitnutzung nicht geeignet ist. Aus diesem Grund werden temporäre, demontierbare Tragwerke verwendet um die Kapazität temporär zu erhöhen. Demontierbare, temporäre Bauteile können für Tribünen und Überdachungen, entweder als eigenständige Tragwerke angrenzend an permanente Tribünen oder integriert in bestehende Tribünenkonstruktionen, verwendet werden. Weiters werden grundsätzliche statisch konstruktive Konzepte für Tribünen und Stadiondächer beschrieben. Als Fallbeispiele werden Stadien von Großereignisse, Mehrzweckstadien und Stadien in Großbritannien untersucht. Aufgrund eines Studienaufenthaltes in Großbritannien werden zum Teil britische Vorschriften als Grundlage verwendet und diskutiert.

Preface:

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über praktische Aspekte diskutieren und dabei hilfreiche und wertvolle Anregungen und Informationen sammeln. Für die Unterstützung bei der Besichtigung der österreichischen EM Stadien 2008 möchte ich Herrn Dipl.-Ing. *Peter Haa*s danken.

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1 HISTORY

Since the first Olympic Games around 800 B.C., stadia have always played an important role in the culture of countries. In the first part of this master's thesis, an overview of the historical development of stadia with special emphasis on the development of structures in stadium engineering will be given. In addition, it will discuss how requirements for sports and entertainment venues changed throughout the ages. In order to know how to deal with the problems and requirements of modern stadia, it is important to study the history of stadia. In the past, there have been a lot of interesting solutions and they can be useful to develop solutions for the future.

The most impressive and most quoted historic stadium is the *Colosseum* in Rome, which has a lot in common with modern stadia. As a multi-purpose arena, it was used for different events and could be flooded as well. However, there are a lot of other stadia in the past which are interesting and, hence, affected the development of stadia and stadium engineering.

The history of stadia is also a history of the development of structures. For example, the main constructional element for the *Colosseum* was the arch. As the stands and roofs became larger, there were new structures needed. In the last century, a lot of new developments for longspan and lightweight structures had affected the construction of recent stadia.

1.1 Definition of *stadium* and *arena*

Initially, the *stadium* was purely a running track and the site was used for cultural events. In contrast to the running tracks of gymnasia, they were designed to take spectators. The term *stadia* means an ancient Greek measure of 500, later 600 Greek feet. Nevertheless, there were different lengths of stadia because units were not standardised. So there have been *stadia* with lengths from 149m to 213m. [65]

The term 'arena' is derived 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 page 4 in [38]).

Stadia and *arenas* of today can be described as large buildings with areas for spectator accommodation around an activity area. Modern *stadia* are much more than buildings for sports activities; a modern sports complex can consist of various facilities, including offices, hotels, or even schools. In addition, in contrast to *stadia*, *arenas* are often described as enclosed *stadia*. However, there are also open air sports venues with the term *arena* in their names; for example the football stadium *Allianz Arena* in Munich, Germany.

1.2 Ancient Greek and Roman stadia

At around 15,000 B.C., the first sports activities developed. Before, there were no special sports activities besides hunting. The location used was nature, so there were no man made places for sports and no buildings for spectators. [46]

Today, Football is one of the most popular sports. At around 2,700 B.C., the game developed in China and, originally, was called *cuju* (*cu*=play with the feet, *ju* = ball). It was played with a ball stuffed with feathers. Like today, the aim of the game was to shot the ball into a goal. However, in contrast to today, the goal was about five meter high. The game was brought to Assyria, to Egypt, to Rome, and furthermore to England, where it became popular during the fourteenth century. [46]

In Greece, in 776 B.C., the first Olympic Games were held. This marked an important change in the development of sports, as well as in the development of sports venues. Sports events, especially athletics became popular and the *Olympia* event was the most famous one. Even the time was measured in *Olympiads*. Venues for the Games were built at the religious centres at Olympia, Delphi, Corinth, and Nemea. Due to these developments, sports venues were needed for the competitions, as well as for training purposes. As mentioned previously, the term *stadia* referred to a measure for the length of running tracks. The running track at Olympia was about 192m long, 32m wide, and made of beaten earth. The whole venue was U-shaped and provided space for 45,000 spectators, who were accommodated on stands along the running track. At the beginning, foot races were held as back-and-forth races, so there was a rectangular-shaped activity area. The track was situated at the base of a valley, because the sloping sides provided clear views and, therefore, formed natural stands for spectators.

The next stage in the development of sports venues was to add earth walls, which held the seating tiers for spectator accommodation. Thus, the first material used for construction was earth for the stands. Before, there was no man made venue; hence, natural places were used.

The athletes were famous and a victory in the competitions brought honour on them. Greek sports had an impact on the culture, especially on the art, of the whole country. Greek athletes were portrayed in marble reliefs and on vases. [37], [46]

In Greece, from 600 B.C. on, not only *stadia*, which held the competitions, but also *hippodromes*, *gymnasia*, and *palaestras*, which were used for training purposes, were constructed. *Hippodromes* had also an U-shaped form and were used to stage chariot and horse races, whereas, *gymnasia* and *palaestras* were centres for training purposes, as well as for education. Thus, *gymnasia* were often large buildings for these purposes. The *gymnasium* at Olympia, for example, had even a covered running track. In addition, there was an open courtyard for running, jumping, discus, and javelin throwing. In contrast to *gymnasia*, *palaestras* were places to practice wrestling and boxing. [37], [46], [65]

At around 330 B.C., the *Panathenaic Stadium* in Athens was built. The seating tiers at that stadium were made of stones and formed like steps around the activity area. Due to a curve, which was added at one end of the track, it had also an U-shaped form. [46]

The *Circus Maximus,* Rome:

The Romans were more interested in public displays of mortal combat than in athletic events. From about 400 B.C. on, another famous and large ancient venue was developed, the *Circus Maximus* in Rome. It was used for horse and chariot races and, throughout the ages, redeveloped various time. In its largest form (660m long and 210m wide), it is believed that the circus held 385,000 spectators. The U-shaped form of Roman circuses developed from Greek hippodromes. Seating tiers, parallel to the track, made of stone and wood, were used to accommodate spectators. Between the stands and the activity area, there was a channel and a spiked wall. Another wall, the *spina* divided the activity area into two halves. [37]

In its form today, the *Circus Maximus* is still used as a venue for certain festivals or concerts. The Italian players for example were accepted there enthusiastically after they won the football World Cup 2006 in Germany. There were more than 500,000 people in and around the *Circus Maximus*.

Another type of a Roman venue was the *amphitheatre*. Its elliptical form developed through joining two Greek theatres together. Therefore, more spectators could be accommodated around the activity area. However, there were no natural ground slopes for that form of venue. Thus, they had to build artificial structures for the spectators. These structures were made of timber, stone, and, later on, of concrete. [37]

The *Colosseum,* Rome:

The most famous Roman amphitheatre is the *Colosseum* in Rome, constructed under Vespasian, during 70 A.D. to 82 A.D. The *Colosseum* has a lot in common with modern stadia, especially in the form of spectator accommodation. The Romans used elements of Greek stadia to build a single multi-purpose arena. The typically elliptical form of the amphitheatre can still be seen. The *Colosseum* got its name from the nearby *colossus* statute of Emperor Nero. Due to the events that took place, which were held to entertain the spectators, the seating tiers should provide clear views to the activity area. Therefore, the crowd of people was accommodated in four tiers with a rise at a gradient of 1:2. The venue offered place for 50,000 spectators. Under the elliptical activity area (84m to 54m) with a wooden floor, there was a seven meter high basement. The whole elliptical structure of the stadium had a size of 189m by 155m. [37], [46]

The structure consisted of 80 arched openings, which were formed by an arch and columns and were supported by the lower storeys. The openings at ground level formed the entrances for the spectators.

A cross section of the Colosseum is shown in Fig. 1.1. The broadening structure, from the top to the base, solved three problems [37]:

- The broadening structure formed the artificial hillside that formed the stands. Therefore, it provided optimal views for the spectators
- The structure was stabilised by its form, as well as by a series of barrel vaults and arches
- The broadening structure provided space for internal concourses. For the higher number of spectators at the base, there were larger areas. Therefore, the stadium could have been evacuated in some minutes

The form of the arch, the main structural element of the *Colosseum*, is copied from the nature. The material has to bear bending moments, lateral forces, and normal (compression) forces. Arch structures are characterized by the line of resistance corresponding to the load. The line of resistance symbolises the natural flow of forces. At the areas of bearing, there are horizontal forces that have to be carried by the structure. If the building material is not able to accept tensile forces, then the line of resistance has to be inside the cross section to carry the loads. At the time the *Colosseum* was built, the main construction material was stone which cannot carry tensile forces. The bearing distance was short and the permanent loads were high. Therefore, the arches and the barrel-vaults built a stable structure. The spatial stability was guaranteed through the elliptic form, the arches, and the barrel-vaults. The foundation and the soil had to carry compression forces. [41]

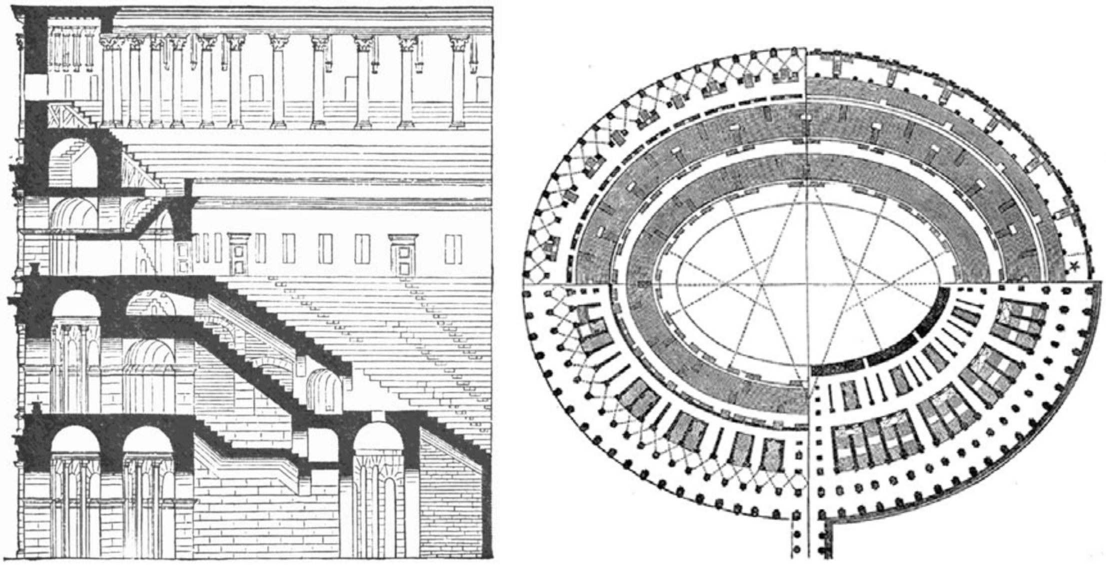


Fig. 1.1: Cross section and horizontal section of the *Colosseum* in Rome [1]

The *Colosseum* was used for some 500 years, which is, compared to modern sports venues, a long lifetime. It provided the scene for gladiator contests and other entertainment events like naval and aquatic displays, for which it even could be flooded with water. In addition, there could be canvas awnings stretched across the open top, to form a roof and provide shelter against the sun. [37]

In its form today, there is still the magnificent structure of the *Colosseum*. However, it has suffered during the ages, from the use of its materials by the popes. Until 1744, they used the valuable travertine for their own purposes. [46].

In 393 A.D., the last Olympic Games until 1896 were held and in 404 A.D. gladiator contests were banned. In contrast to the Greek, the Romans staged their sports events to entertain the crowd of spectators for social and political reasons. These events lost their importance. Furthermore, there were numerous riots in arenas. Due to the Christianization of the Roman Empire and their view on athletic sports, they banned the Olympic Games. The last competitions at the *Circus Maximus* were held in 549 A.D. Thus, no more significant sports venues were constructed until the eighteenth century. However, in the Middle Age, there were buildings for fencing halls, riding, and ball games. The natural living space was used for events; people celebrated in the streets and places of the towns, which were specially decorated, or in the green countryside surrounding the towns. Competitions – like foot races, fencing, or jousts – needed gates and stands for the referee and for the spectators, but these were only built for the duration of the competitions and demolished afterwards. [46], [65]

1.3 Sports for the people

The change came during the 18th century. In particular, in Europe, the Industrial Revolution led to a revival of sports activities. In England, golf, polo, tennis, and rowing, played on natural grass surfaces, were the popular sports, although, they were just played by the upper classes. However, due to the Enlightenment and regulated work times, the middle class and the working class became more and more part of the sports events. The power of passive spectators, gathering together to be entertained by the performers and to enjoy the games, was recognized. *No longer is it the fear of punishment, which keeps the people in check. One must offer them effective temptations which will distract them from evil. What kind of temptations could they be? National games. ... Imagine 300,000 people in the arrangement of an amphitheatre, where no-one can remain hidden from the gaze of the crowd. This arrangement would lead to a remarkable effect* (from page 29 in [46]).

One of these venues built in the eighteenth century was the *Champ de Mars* in Paris. The stands around the U-shaped activity area were formed by earth walls with rows for up to 600,000 spectators. For constructing the venue, there were 12,000 hired worker and 180,000 other people volunteered in their spare time. Therefore, it became a symbol of the French Republic.

At the beginning of the nineteenth century, Emperor Napoleon I built a stadium in Milan as a symbol for the French nation. Originally, the stadium had temporary stands. In 1827, they were redeveloped into permanent stands and the capacity of the stadium was increased to 30,000. As the *Colosseum* in Rome, the stadium had an elliptical form with a size of 326m by 125m.

Throughout the nineteenth century, various venues were built. They were not only used for sports, but also for theatrical events. The models for these venues were the Greek hippodromes and the Roman circuses and amphitheatres. Examples are: the *Royal Albert Hall* in London, UK, the *Cirque d'Hiver* in Paris, France, and the *Madison Square Garden* in New York, USA. As already mentioned, there is a power of a mass of spectators gathering together for sports events. On the other side, exhibitions and trade fairs needed people to display and sell the products. Thus, these events were linked and held at the same time. In 1867 for example, the World's Fair exhibition was held at the *Champ de Mars* in Paris. These developments brought a change in the design and construction of sports stadia.

In 1896, Baron Pierre de Coubertin (1863 – 1937) introduced the modern Olympic Games. The first Games were held in Athens, Greece, where the site and the foundations of the ancient *Panathenaic Stadium* were used to construct a new stadium for 50,000 spectators. Since 1896, the Olympic Games were held every four years (with some exceptions). As mentioned previously, sports events where linked to trade fairs and, thus, the Olympic Games were linked to World's Fairs. Obviously, this had advantages for both events. As the World's Fairs, the

Olympic Games were held at various countries. Thus, they led to a worldwide construction of new stadia. [37], [46], [65]

In particular, football was already a famous game and played throughout Europe. However, until 1863, there were no standard rules, so the game varied from place to place. In 1863, in the UK, the *Football Association (FA)* was set up to provide rules for British Football and Rugby. Other countries followed and in 1904 the *FIFA* (*Fédération Internationale de Football Association*) was founded in Paris. Due to the rules, a greater number of teams could compare in tournaments. Thus, the number of spectators grew and stadia followed this trend and, became larger.

1.4 Twentieth century stadia

The following is an overview of the developments of stadium engineering through the twentieth century in chronological order. It was not only new technologies, but also social developments, that changed the design and form of stadia, as we know them today.

At the beginning of the twentieth century, the Olympic Games were held in Paris, France (1900) and St. Louis, USA (1904).

1908 A change in the design of sports venues can be seen at the structure of the *White City Stadium*, which was built for the Olympic Games in London, UK, on the grounds of the British Empire Exhibition. It was one of the first stadia that had a steel roof over the stand (see Fig. 1.2). As other venues at that time, it was a multi-purpose arena for various sports activities. The whole complex was used for cycling, running events, tennis, soccer, jumping, throwing events, and had a swimming pool as well. The *White City Stadium* was demolished in the 1980s. [37], [46]

The structural element of this roof is a trussed beam. An ideal framework is characterized by all bars forming triangles. Additionally, loads are acting on the structure at the truss joints, the rod centre line has to be straight, the truss joints have to be jointed, and all rod centre lines at one joint have to cross at one point. Then there are only normal forces as internal forces to be carried by the bars [41]. The structural material steel is applicable because steel can carry tensile as well as compression forces.

With trussed beams, a lighter structure and a longer span than with a normal beam can be realised. However, the columns at the front obstructed the views of spectator on the activity area. A ground section and a cross section of the structure of the *White City Stadium* are shown in Fig. 1.2.

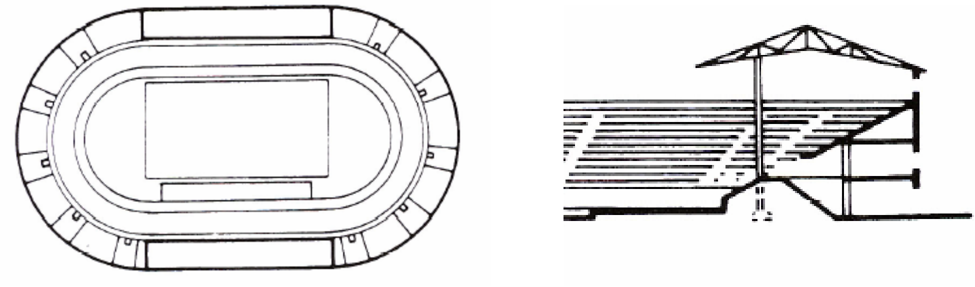


Fig. 1.2: Ground section and cross section of the *White City Stadium*, London, 1908 [38]

1924 Groundbreaking for the architecture of European stadia was the Olympic Stadium in Colombes, Paris, built for the Games in 1924 in France. It was free of decorative elements and was not modelled on any historic stadium. Both longitudinal sides of the stands were roofed by a steel construction. [26]

Like the structure of the *White City Stadium* in London 1908, the structural element of the roof of the Olympic Stadium in Paris is a trussed beam. The difference is that this trussed beam is used to build a cantilever structure. The internal forces for the trussed beam are the same, there are only normal forces and there are two supporting columns. Due to the cantilever, the column at perimeter of the stadium has mostly to carry a tensile load. However, this depends on the forces applied to the roof. The other column has to carry a compression force (see Fig. 1.3). However, like at the *White City Stadium* in 1908, there were columns that obstructed the view within the seating area.

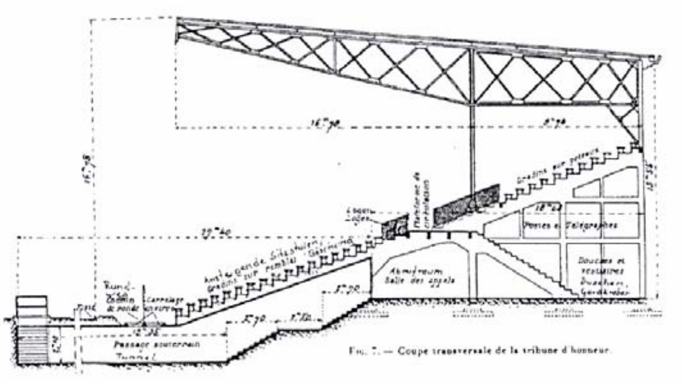


Fig. 1.3: Cross section of the Olympic Stadium in Colombes, Paris, 1924 [26]

1929	First television images were broadcast [46]. This brought additional requirements of a television studio for the stadium. In addition, due to a growing number of spectators, this had an impact on the architectural design of stadia.
1931	The *Prater Stadium* in Vienna, designed by O. E. Schweizer was finished in 1931. The still existing running track is surrounded by the elliptical stand, which is made of board marked concrete. The framed construction had a glass façade – behind this there were rooms, which gave shelter to the spectators when it was raining. To reduce the visual range to the pitch, it was decided to build the stadium without a cycling track. It was planned to build an iron-concrete roof over all stands with a 9m cantilever structure. In its original configuration the stadium offered 60,000 seats for spectators. In the 1950s, the capacity was extended by a third tier. The stadium was renovated and, in 1986, got a roof with a compression/tension ring structure as described in chapter 4. Currently, the stadium provides accommodation for about 50,000 spectators. [26]
1936	The Olympic Games were held in Berlin, Germany. Originally, the stadium was built in 1913. For the Games it was redeveloped by architect Werner March. It was extended to provide accommodation for 110,000 spectators. Fig. 1.4 shows the configuration for the 1936 Olympic Games and the accommodation of spectators in an elliptical form around the activity area, as well as a cross section of the stands. However, after the Games the stadium was not only used for sports events, but also for political events. The stadium was redeveloped and became a historical monument in 1974 (architect: Wilhelm Krahe). In 2006, it was again redeveloped and modernized for the Soccer World Cup 2006. [46]

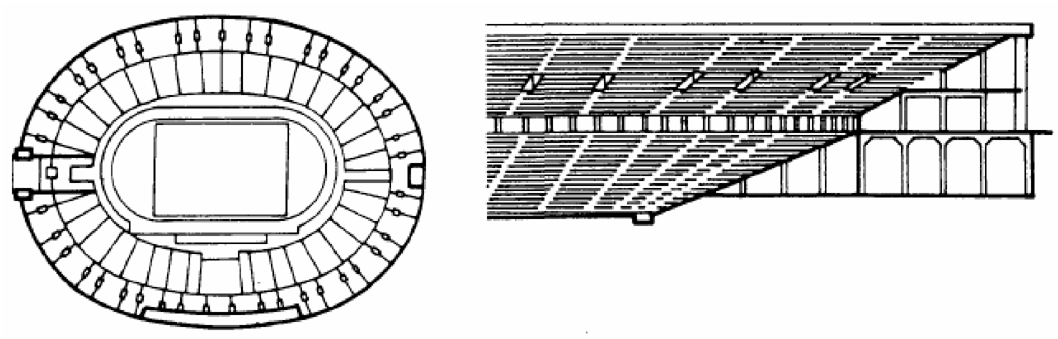


Fig. 1.4: Ground section and cross section of the Olympic Stadium in Berlin, 1936 [38]

1947-1950	The world's largest stadium, the *Estádio Mário Filho* in Rio de Janeiro (also known as the *Maracaña Stadium*) was inaugurated for the Soccer World Cup in 1950. It accommodated up to 140,000 spectators. In 1963, it is believed to have held 180,000 spectators. [46]
1956-1958	The *Yale Whale*, a stadium at the Yale University, was built by the Finnish architect Eero Saarinen. Due to its form, it got the name after a stranded whale. [46]
1960	The Olympic Games were held in Rome. Before, the games were staged at one single venue. However, there were various sites throughout Rome used for the events. The main stadium, used for athletic events, was similar to the previous Olympic stadia. The stands were formed by a three-storey building around the elliptical activity area and were not covered by a roof. The architect was Annibale Vitellozzi. The Olympic Stadium was redeveloped for the Soccer World Cup in 1990 and became a roof over the existing bowl structure. The *Stadio Flaminio* and the *Palazzetto dello Sport*, are other venues constructed for the Olympic Games 1960 in Rome. They were designed by the Italian engineer Pier Luigi Nervi (as structural engineer in collaboration with the architects Antonio Nervi and Annibale Vitellozzi). The structure, used for the enclosed venues, was a shell that rested on 36 Y-shaped supports (see Fig. 1.5). [37]

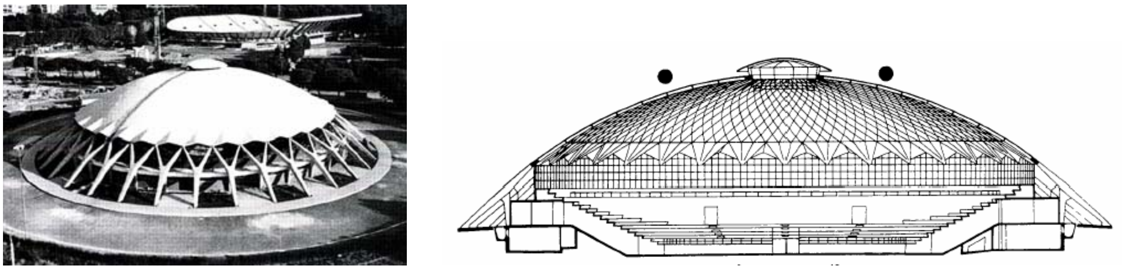


Fig. 1.5: *Palzzetto dello Sport* in Rome for the Olympic Games 1960 [38], [46]

Shell structures are not a new development of the twentieth century; they were already used in the antiquity as cupolas. In the late Bronze Age, a lot of graves were formed by cupolas with a diameter up to 13.20m. In 118 A.D., the *Pantheon* in Rome was built. The cupola, which forms the roof of the *Pantheon*, has a diameter of 43.3m. The construction material was Roman concrete and there was an outer and an inner shell. In the sixteenth century, another great cupola was built at the *Petersdome* in Rome. In the nineteenth century, lighter structures made of steel – lattice shells – were developed.

From 1900 on, lighter and thinner structures were possible because of developments in mathematics and engineering science, as well as new materials like reinforced concrete and pre-stressed concrete.

The form of shell structures is copied from nature. Shells create an optimal structure for steady subjection to pressure. Internal forces are mostly membrane forces, which means there are mostly normal forces as compression forces. [41]

1964 The Olympic Games were held in Tokyo, Japan. As in Rome, there were several venues designed for the Games. The main stadium (the *Jingu National Stadium*) was redeveloped to increase the capacity. In addition, there were two fully-enclosed venues: the *Swimming Arena* (for 4,000 spectators) and the *Sports Arena* (for 15,000 spectators); both designed by Kenzo Tange. The president of the International Olympic Committee (IOC), Avery Brundage, called the Swimming arena *a cathedral for swimming*. It was the dramatic roof structure that was impressive. Supported by a single tall mast on the perimeter of a circular plan, the semi-rigid roof was formed by concrete panels that hung from the cables, which were draped from the mast. [37]

1968 The Olympic Games were held in Mexico, where stadia were redeveloped or new designed. The Stands for the Olympic Stadium (87,000) were mainly supported by an earth wall. Another venue, used to stage the Games, was the *Aztec Stadium*. It was the larger one and accommodated 107,000 spectators, all covered by a roof. [37]

1972 The Olympic Stadium in Munich, with its impressive roof structure, was the main attraction. In addition, there was a swimming hall and a sports hall included in the stadium complex. The roof over the stands of the Olympic Stadium is formed by a cable net structure in the form of a tent, a construction of some 78,000 m² (see Fig. 1.6). It is just over one part of the stadium, the other part is uncovered. The cable net is supported at the rear of the stands. Therefore, the roof structure provides an unobstructed view for the spectators. PVC-coated polyester fabric is stretched over the cable net structure and used as roof covering material. The architects were Günter Behnisch and Partners, the structural engineers Frei Otto and Fritz Leonardt. [37], [46]

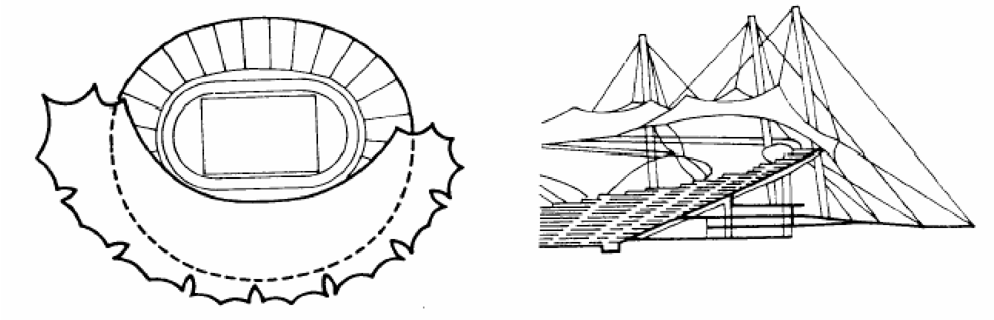


Fig. 1.6: Ground section and cross section of the Olympic Stadium in Berlin, 1972 [38]

Throughout the twentieth century, longspan and lightweight structures were developed out of historical forms of the sail, the tent, and the vault. New structures and materials led to a wider span and lighter form. These new structures were air supported structures, tents, cable structures and nets, grid shells and compression vaults. The new materials used included high strength PVC-coated polyester fabrics. Historically, the Olympic Stadium in Munich with its cable-net structure is one of the most important developments.

It becomes more and more important to build enclosures to be independent of the weather conditions. Such structures need to be wide span and they need to be able to support a wide range of external loads [8]. Large moving roofs, retractable membranes, and sliding roofs developed and were also designed for stadia. Examples for venues with a retractable roof are: the *Ajax Stadium* in Amsterdam, the Netherlands and the *Millenium Stadium* in Cardiff, UK.

Another development for longspan structures are air supported structures. The *Sports Centre* at Riyadh University, the *Pontiac Silver Dome*, USA, and the *Tokyo Dome,* Japan, are examples of these.

1976 The main stadium for the Olympic Games in Montreal was designed by the French architect Roger Tallibert. It even had a retractable roof that was supported by cables from a high reinforced concrete tower. However, the intended retractable system proved too ambitious and the retractable roof was replaced by a fixed permanent roof later on (see chapter 3).

The same architect worked together with the Swiss engineer Heinz Isler. Heinz Isler designed some sports venues with a concrete shell roof structure. Examples are the indoor swimming pool in Brugg (1981) and the tennis centre *Marin La Théne* in Neuchâtel (1983). [46]

1987 In Australia, the first indoor ski centre (*Snowdome*) opened. This brought the change to enjoy winter sports activities, in an enclosed sports venue, throughout the year. In addition, it introduced the challenge to control the climate within a venue. [46]

1989 The disaster at the *Hillsborough Stadium* in Sheffield, UK, where 95 people died, changed the design of stadia in the UK. It was not the first disaster at a sports ground. However, there was a lack of guides for the design of stadia. A public inquiry, led by Lord Justice Taylor followed the catastrophe. The government in the UK acted and set up the *Football Stadia Advisory Design Council* to provide design guidelines. The first step was to introduce all-seater stadia for more safety.

1996 The Olympic Games were held in Atlanta. First concepts for the use of stadia after major events were made. The stadium built for the 1996 Olympic Games in Atlanta was designed to be converted after the games into a baseball stadium. [38]

1998 The Soccer World Cup was held in France. The main stadium was the *Stade de France* in Paris with a capacity of 80,000. The cantilever roof structure is described as an *enormous discis*. [46]

In particular for Olympic Games, stadia were designed as multi-purpose venues. However, during the twentieth century, a lot of stadia, which were designed for one specific sports activity, were developed. Due to different requirements of each sport, there are specific forms for these stadia. The big stadia were designed for the most popular sports: football (also called soccer in the UK and USA), rugby, American football, baseball, tennis, and cricket. At the end of the century, there was the inverse development and stadia had to be more functional, useable for different sports or events.

1.5 Recent developments

In the last century, stadia changed from multi-purpose venues to buildings for one specific sport and back again to multi-purpose stadia. At the end of the last century and the beginning of the twenty first century, how to use the stadia, after major events like the Olympic Games, became more and more of a problem. The *European Football Championship* in Portugal is an ideal *negative* example. This Football Championship was held in ten stadia around the country. In five of these stadia only two games were played, and now the municipality or the local clubs (which do no attract a large crowd of fans) have to handle the running costs of these big stadia. These problems led to the development of making stadia multi-functional and useable for a greater variety of events. Due to the problems above, a modern stadium has to be more flexible. In addition, a modern stadium is divided into categories for various users. Hospitality areas and private boxes for the spectators provide an attraction for a new category of spectators.

Ancillary uses are integrated in the whole stadium complex to create a site that can be used 365 days a year. Hotels, shopping centres, swimming pools, museums, and other leisure facilities are used to attract people and to increase the financial viability of the development.

The most important events for stadium engineering are still the Olympic Games and World Championships in different sports.

2000 Australia was the site for the Olympic Games in 2000. The Olympic Stadium in Sydney was designed to hold 110,000 spectators during the Games. However, after the Games, the stadium was reconfigured and the capacity reduced to 80,000. Life cycle costs and sustainability become factors considered in the design of stadia. Fig. 1.7 shows the two configurations: for the Games and for long term use.

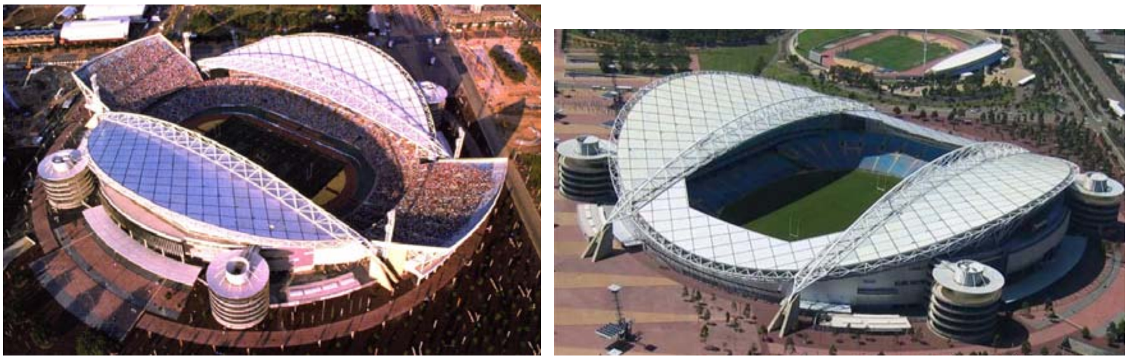


Fig. 1.7: Olympic Stadium in Sydney during and after the Olympic Games, 2000 [67], [76]

2002 The *City of Manchester Stadium* was built for the Commonwealth Games in Manchester, UK. As the *Stadium Australia*, it was designed to provide a configuration for the Games. The roof of the stadium is supported by a cable net structure. The venue was reconfigured after the Games and became the home of the *City of Manchester Football Club* in 2003. In order to increase the capacity, the activity area was lowered by excavating the ground and adding a new lower tier. This had also the advantage of bringing the spectators closer to the activity. In addition, the temporary stand at the open end of the U-shaped stand structure was removed and the gap was closed.

2004 The *UEFA* (*Union of European Football Associations*) European Football Championship is held in Portugal. As mentioned previously, there were ten stadia used for the Championship. The most remarkable is the stadium in Braga, designed by architect Eduardo Souto Moura. The difference to other stadia was the configuration of the stands: they are just on the long sides of the pitch. The roof is formed by a catenary tension structure, supported by the structure of the two stands. [46]

2004 The Olympic Games were held in Athens. The most impressive building was the main stadium, which was originally built in 1980 and could accommodate 80,000 spectators. The existing stands were covered by a new roof, designed by Santiago Calatrava (see Fig. 1.8). Each of the roof segments is held by a steel arch, spanning a distance of 304m and rising to a height of 60m above the stadium. There is a second arch, a compression arch, from which the steel roof beams cantilever out at 5m centres. The ends of the beams are supported by secondary cables from the upper arch. The roof is covered by translucent, blue polycarbonate slabs. [45]

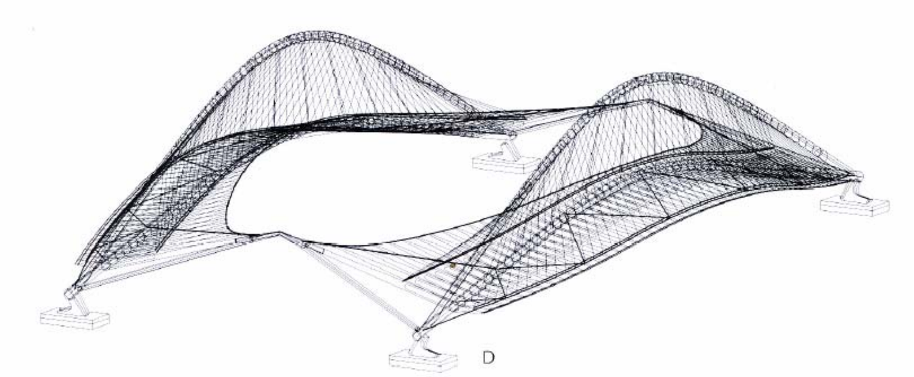


Fig. 1.8: Isometric of roof structure, Olympic Stadium in Athens, 2004 [45]

2005 London was chosen to stage the Olympic Games in 2012. The design of stadia for future Games is influenced by experiences from the last Games. As mentioned previously, the changes include concepts for increasing and reducing the capacity of stadia. As for the Olympic Stadium in Sydney, mobile stands to increase and reduce the capacity are becoming more important. [46]

2006 The Soccer World Cup was held in Germany, where twelve stadia were built or redeveloped. All stadia have roofs over the stands to provide the shelter against the elements. Some of them even have retractable roofs. The *Allianz Arena* in Munich is described as the most modern stadium [46]. The main stadium, the Olympic Stadium in Berlin, designed in 1936 and renovated in 1974, was again renovated for the Soccer World Cup 2006 in Germany. A new roof was added and the stadium was modernized, as a historical monument, according to landmark standards.

Most of the stadia are built only for the use of football. In Germany, especially football is very popular, so there is no problem with usage after the World Cup (contrary to Portugal). Nevertheless, due to financial reasons, it is necessary to integrate more functions in the stadium.

1.6 Summary and outlook

Stadia developed from natural arenas to modern multi-purpose buildings with high comfort levels for the spectators. To meet the requirements of spectators, roof-structures had to be developed to protect or even make them independent of weather conditions. Just as architects and engineers of ancient stadia solved the problems of their times, so architects and engineers of modern arenas have to solve the problems of today. In particular, these problems are caused by financial requirements. Modern stadia have to be economic and interesting for spectators as well as for investors.

For each major event, latest knowledge is used to design new stadia. The next coming major events are:

- European Football Championship in Austria and Switzerland, 2008
- Summer Olympic Games in Beijing, 2008
- Winter Olympic Games in Vancouver, 2010
- Soccer World Cup in South Africa, 2010
- Summer Olympic Games in London, 2012

A model of the Olympic Stadium for the Summer Olympic Games 2008 in Beijing is shown in Fig. 1.9.

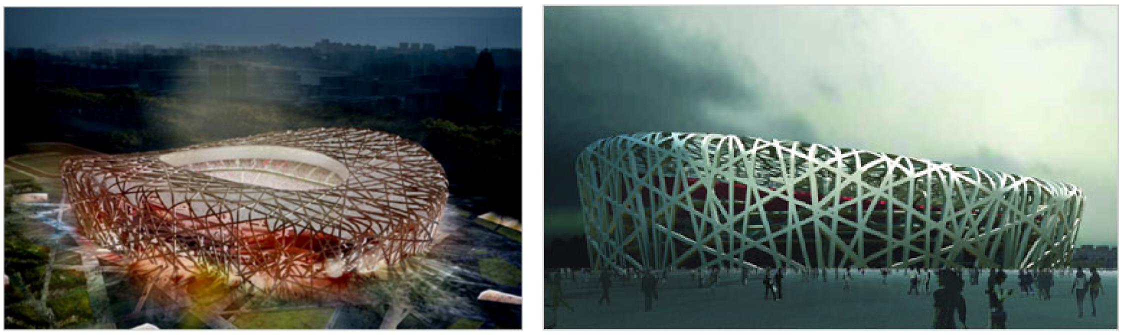


Fig. 1.9: Model of the Olympic Stadium in Beijing, 2008 [51]

2 REQUIREMENTS FOR STADIUM DESIGN

The aim of the second part of this thesis is to provide an overview of parameter and disciplines, which influence the design of stadia, especially over those requirements that in turn influence the structural design of stadia. Many specialists are involved in the design process and a lot of decisions have to be made.

2.1 Basics

Firstly, it must be decided what the building should be used for. Different sports activities need different requirements, not only from the activity area, but also from the viewing requirements for spectators. On the other hand, to increase economic viability of a venue, it is often necessary to incorporate different sports into one venue. The design of stadia has to ensure that the venue provides suitable conditions for all these different uses.

First of all, the designers have to know for whom they design a building. In the case of sports stadia, there are three fundamental parties of people who use a sports venue [38]:

Spectator – player – owner

Each of these groups has different requirements and, hence, influences the stadium design in that way.

In order to attract spectators, a stadium has to provide a comfortable and safe atmosphere. Spectators are part of the event and, thus, they are definitely the most important group. Therefore, they mainly influence the technical design of stadia. New technologies have led to the question of why spectators still go to see live events. They could sit at home in front of their televisions and watch the game there. To ensure that spectators will still attend matches in the future, higher levels of comfort and quality at stadia, as well as a great atmosphere, are necessary.

Players are the second important party. They influence the design of a stadium as much as the spectators. The activity area is determined by the activity itself and the needs of the athletes. If it is necessary to stage different events at the same venue, a decision has to be made about the surface of the activity area [38]. However, players do not only need a pitch to play, they also need rooms to stay before and after a match. Changing rooms, showers, relaxing facilities, club facilities, offices, and such rooms have to be included in the building.

The two parties discussed above, influence the building in its form and design. The third party, the owner, influences the design, because he has to ensure that the building will be financially viable. It may be necessary to increase the number of possible events, for financial reasons. This in turn will affect the design of the building. For stadia, which are only used for one specific sport, economic viability is hardly possible. [38]

A stadium is a complex building that needs not only to be designed for the spectators, players, and owners, but also for media purposes. Nearly all of the major events are broadcast live. Hence the stadium has also to fulfil the function of a television studio.

Safety at sports venues is of special consideration. There are still problems with safety at some existing venues. After two people died in Italy in January and February 2007, games of the Italian football league were suspended. Safety at stadia is a complex issue, which requires not only designing for safety but also managing the crowd of spectators.

Besides these groups of users, the design has to consider the effects on the surrounding area. Stadia are usually huge buildings which can affect, for example, levels of shade or changes in wind flow. These effects have to be determined and should be minimized, wherever possible. In addition, due to their size, stadia have an impact on the townscape or landscape.

Hence, the planning team has to consider all these points, by devising an attractive stadium that will become a long-term success.

2.2 Masterplaning

A masterplan is necessary to ensure the quality of the development. In the case of sports complexes, a development may not only consist of a stadium, but also of adjacent buildings for additional uses. In addition, sports complexes are often designed over a number of years, or even decades [38]. For *Croke Park*, in Dublin, Ireland, for example, a masterplan was made for the redevelopment of the stadium in 1990. The stadium was constructed in phases and finished in 2004 [49]. If a stadium is constructed in phases, the masterplan is also required to ensure that each phase is consistent with the whole development [38]. Another example for a phased development is the *Galpharm Stadium* in Huddersfield, UK. Fig. 2.1 shows the Masterplan for this stadium. It was completed with the last phase, the North Stand (see Number 4 in the image) in 1998 [67].

Masterplanning must start with the determining factors of the stadia. These are the pitch (or activity area), seating capacity, orientation of the pitch and building, and safety zoning. The pitch is the centre of the building and the starting point of the design. The orientation of the pitch is determined by the events to be staged and the masterplan must be structured around this [38]. For safety reasons, zoning is necessary. This is discussed in section 2.7.

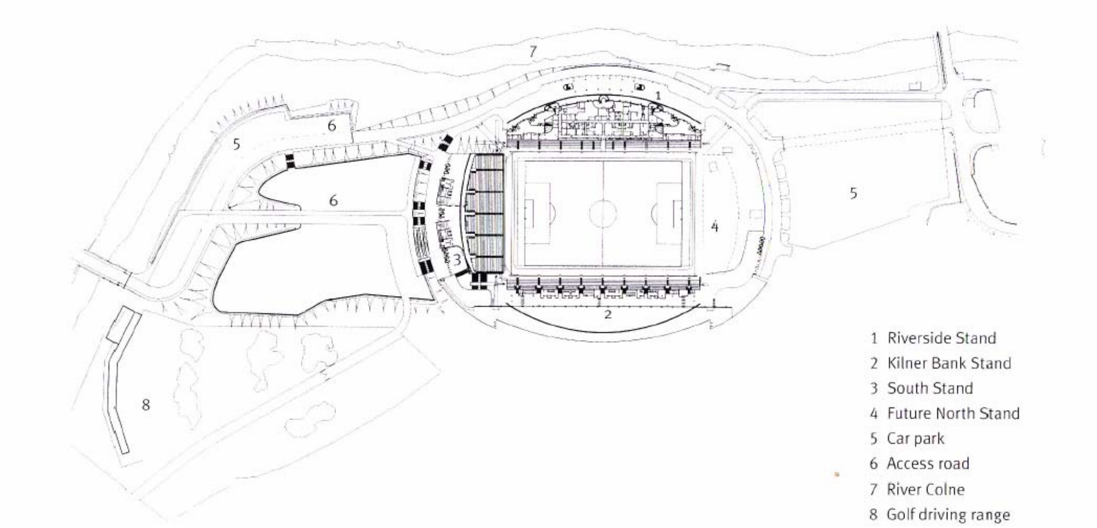


Fig. 2.1: Masterplan for the *Galpharm Stadium*, Huddersfield, UK [67]

2.3 External Planning

As already mentioned in section 2.1, the building influences the surrounding area. There are differences, if the sports venue is situated in-town or out-of-town. Historically, stadia were small buildings. Fewer people lived near the sites and attended the matches. Developments in transport made people more mobile and this led to bigger catchment areas. Hence, stadia became larger, to accommodate more spectators. [38]

Large out-of-town stadia were built in the 1960’s and the 1970’s, typically in the USA and other countries where people have high personal mobility. These buildings are often surrounded by huge car parks. The Giants Stadium at New Jersey, for example, has parking space for 30,000 cars and 400 buses [38]. In Europe, there are more venues designed as large in-town stadia, for example in the UK. For reasons of transportation both types, in-town and out-of town stadia, have advantages and disadvantages. Parking facilities, public transport, and information services have to be developed during the planning process [38]. At in-town stadia, these factors can determine the capacity of the whole ground. At *Croke Park*, in Dublin, the capacity of the stadium was determined by the capacity of the transport infrastructure. The initial desire was a capacity of 90,000 or above, but this was not possible due to urban considerations. [49]

2.4 Architectural Design

Sports stadia are architectural landmarks in their towns and cities. In addition, they have always played an important role in the civic lives of their communities. Since stadia and hippodromes in the ancient Greek and circuses and theatres in Rome, the basic form of sports venues has not changed. There are the same functional requirements today, which determine the basic form of seating tiers. For this reason, a sports stadium is a building type where *form follows fairly directly from function* [37], although, each stadium is different and has its own design within the surrounding area.

Modern sports venues are described as *Cathedrals of Sport, which are destined to become classic icons of the new millennium*. In the last century, stadia often had the image of crude, concrete monoliths. Spectator comfort was no design criterion. Stadia were places, where people gathered together, enjoyed the game, and afterwards, left the venue. Today, stadia are multi-purpose buildings that offer entertainment for the whole family, from crèches for children up to cinemas and leisure facilities for everyone. Even hotels can be included in the complexes. Hospitality boxes for the sports events can be converted into hotel rooms after the game and vice versa (see chapter 3).

Architectural design should ensure that rough, unattractive sports venues are the past. Modern stadia should be designed as exciting, stimulating, and uplifting venues of enjoyment and entertainment. These functions can provide additions to sports events and concerts, which are still the main purpose of the building. In addition, this main purpose is to provide a physical and emotional experience for spectators of sports events.

In addition, a modern stadium has the function of a television studio. There are not only spectators sitting in the stadium and forming the atmosphere of the event, but also spectators at home sitting in front of their television and watching the event. This additional function has also influenced the architectural design of stadia. [37], [67]

However, there are features that make the architectural design of stadia difficult [37]:

- Inward-looking form, a huge façade that faces the surrounding area
- Car parking, which cuts off the stadium from its surroundings
- Gigantic scale, which makes it difficult to fit the stadium into a town setting
- Inflexible elements, which make it difficult to assimilate into a traditional façade
- Tough finishes, to reduce maintenance
- Periods of disuse, which means stadia cause bleakness and lifelessness on their surroundings

Reducing the height of stadia can be achieved through dropping the pitch below ground level. The outward-looking façade is smaller and construction of seating units directly on the ground is easier. In this case, the surrounding concourse is not at pitch level, which affects the circulation elements.

Another factor in the architectural design is how to turn the corners, and hence, how to join the four sides around the pitch. Where four rectangular stands are around the activity area, four towers located in the gaps between the stands could be the solution. Another solution is to design one roof over a *bowl* stand structure. If seating tiers are deeper along the long side of the activity area, this may lead to three-dimensional shaped roof forms.

For reasons given in section 2.7.4, ramps, used as vertical circulation elements, are often big structures. Therefore, they are also important for the architectural design. [37]

Architectural concepts:

From the point of view of architectural design, usually there are two major elements: the façade and the roof. By making one of these elements dominant, harmonious architectural solutions can be achieved. The other element can then either be subdued or completely invisible. This can make the architectural design easier to handle. Therefore, possible solution could include:

- Dominant roof:

  An example is the Olympic Stadium in Munich, Germany, for the 1972 Olympics. The cable net structure is the visual element and the walls have been virtually eliminated [37].

- Dominant façade:

  At the *Mount Stand* at *Lord's Cricket Ground* in London, UK, a light membrane tent roof covers the stands, whereas there is a façade in an urban style [37].

- Dominant structure:

  Making the structure dominant (e.g. vertical structural ribs), could be the third solution, where the stadium is mostly seen from the distance. The Olympic Stadium in Athens, Greece, for the 2004 Olympics, with its dominant structure, is an example for that [37].

Stadia are intended to be an icon for the club or the owner. The icon of the New Wembley Stadium in London, for example, is a 315m spanning, 138m high arch [7]. For the Olympic Games in Beijing 2008, the icon will be the new Olympic stadium. The designers describe the massive lattice structure as a *nest*.

2.5 Activity Area

Historically, sports games were played on a natural surface. When sports became more organised and rules were defined in the last century, the surface of the activity area also had to be specified. New requirements of sports led to new developments in activity surfaces.

The first fully covered stadium in the world was the *Houston Astrodome*, USA (1966). Originally, the pitch had a natural surface, but, although the roof covering of the arena was transparent, the grass did not grow. The problems at this arena led to the development of synthetic surfaces. The first synthetic surface, which was used at the *Houston Astrodome* was called *Astroturf*, after its host venue. [37]

The determining factor for the activity area is the sports activity to be staged. Pitch dimensions, layout and boundaries of the activity area are determined by the game. They can be found in the rules of each sport activity. If the stadium is designed for different purposes, the type of surface can be difficult to choose. In addition, the layouts of different activities have to be combined.

There are three different types of surfaces available today: natural grass surfaces, artificial grass (synthetic turf) surfaces, synthetic non-turf surfaces. [37]

2.5.1 Natural grass surface

A natural grass surface is, for example, the standard for soccer or rugby. The reason is that it gives the right speed of rebound and degree of rolling resistance necessary for the type of game. It provides also the most user-friendly surface, because it provides a surface that is comfortable for running. In addition, compared to other surfaces, grass is less harmful to players who fall.

However, the use of a natural surface is limited and not always appropriate. In order to grow, grass needs sunlight, air movement, humidity, and temperature levels within strict parameters. To provide cover from the elements, seating tiers are mostly covered by huge roofs. These roofs influence the necessary conditions for healthy grow of grass. Therefore, a natural surface is not possible in totally enclosed stadia, not even if the roof covering is transparent. However, even in partly roof stadia, these conditions have to be determined and studied, to ensure good conditions for the natural grass surface. Another disadvantage of a grass surface is that it is less robust compared to artificial surfaces. This can cause problems with the number of events that can be staged at the venue. [37], [38]

To ensure both requirements, covering from the elements and a natural grass surface, movable roof structures were developed. However, the disadvantage of the less robust grass surface remains. There are lots of examples today, including the *Millennium Stadium* in Cardiff and the *New Wembley Stadium* in London, both in the UK. Movable roofs are discussed in chapter 3.

Another solution, which addresses the problems discussed above, is the concept of *pitch replacement*. This allows the grass to grow outside the stadium, when not needed for events. Another advantage of this concept is that the venue can be used with another type of surface while the grass grows outside the stadium [37]. At the *Millennium Stadium* in Cardiff, for example, the natural grass surface grows on 1m square boxes and can be transported out of the stadium, when it is used for other events than sports, where a more robust surface is required.

Modern examples, which use a natural grass surface in an enclosed stadium, are the *Sapporo Dome* in Sapporo, Japan, and the *Veltins Arena*, in Gelsenkirchen, Germany [43], [64]. In both cases, the whole pitch is moved out of the stadium, when not needed. Movable pitches are also discussed in chapter 3.

In addition, natural grass surfaces need maintenance, including: drainage, irrigation, and heating. Therefore, different types of pipes are necessary inside the pitch. [37]

2.5.2 Artificial grass (synthetic turf) surfaces

Artificial surfaces in the form of synthetic grass are often a solution for enclosed stadia, for which they were originally developed. However, like natural surfaces, they need maintenance, and the surface is not everlasting. A typical life expectancy may be six to eight years. Maintenance includes irrigation in summer, regular cleaning, and repair. For sand-filled turfs, re-sanding is necessary. However, one advantage of this type of surface is that it can be used more often, because of its higher resistance. [37]

Basic categories of synthetic grass surfaces are [37]:

- Non-filled turf
- Sand-filled turf
- Combined natural and synthetic turf and
- Temporary synthetic turf surfaces

Artificial turf is now also used for football matches. In 2004, FIFA (Fédération Internationale de Football Association) allowed artificial turf for various competitions. The *Stadium Salzburg*, in Austria, was selected by UEFA (Union of European Football Associations) as one venue to research the behaviour of synthetic grass used for football. Research in this field is still ongoing. In 2006, to ensure high quality of artificial grass surfaces, FIFA published a *Handbook of Requirements for Artificial Turf* [20].

2.5.3 Synthetic non-turf surfaces

Synthetic non-turf surfaces can be used intensively. These are the standard surface for athletic purposes and maintenance is not as high as for synthetic grass surfaces.

There are two categories of synthetic non-turf surfaces, which are polymeric systems [37]:

- Impervious finishes
- Porous finishes

2.6 Spectator Accommodation

Principally, there are differences if accommodation is designed as seating or standing accommodation. According to the regulations of the sport activity taking place, standing accommodation may be prohibited. For example, in Article 7 of the *FIFA Safety Guidelines* is found (from page 8 in [21]):

The four major FIFA tournaments (FIFA World Cup^{TM} *including qualifying matches; Confederations Cup; Club World Championship; Olympic Football Tournaments) may only be played in all-seater stadiums. For all other FIFA tournaments, standing spectators may be admitted, after seeking prior approval from the local authorities responsible for approving the respective stadium.*

On the other hand, for some sports it is usual to offer standing accommodation. For example, at *Croke Park*, in Dublin, which was designed for Gaelic Sports, a standing terrace was designed and finished in 2004. Until 1989, standing accommodation was permitted at football grounds in the UK. However, after the *Hillsborough Stadium Disaster*, at Sheffield, England, where 95 people died, standing accommodation was prohibited in the British premier league and championship. Standing areas in existing stadia had to be converted during the 1990s. [37], [82]

For reasons of safety and levels of comfort and quality, seating is the standard type of accommodation at modern sports stadia. Guidelines for design of standing accommodation are given, for example, in the *Guide to Safety at Sports Grounds* [30]. Some Sports Associations, for example the FIFA and the UEFA for football, also have safety guidelines [21], [83].

2.6.1 Capacity

The capacity of a sports venue is another important decision to be made, when developing a new project or redeveloping existing stadia. The question is [37]: What is necessary? The amount of accommodation provided influences capital costs of the development, as well as running costs afterwards. Major events, for example Olympic Games, are often the booster for new venues. The capacity needed for the Games is often much higher than for long-term use after the Games. New concepts are necessary to be able to increase or reduce the capacity if needed. (See chapter 3)

The *Guide to Safety at Sports Grounds* [30] determines the capacity as *safe capacity*, which is determined by the capacity of each of the following parts of the stadium:

- The entry capacity of the section
- The holding capacity of the section
- The exit capacity of the section
- The emergency evacuation capacity

These factors together lead to the final capacity (=*safe capacity*), which is the lowest of the above. This calculation has to be done for both seating and standing accommodation. [30]

Capacities are often set by Sports Associations themselves. For example, the capacity needed for the UEFA European Championships final matches in 2008 in Austria and Switzerland are:

Final and Opening match:	50,000 spectators, all seated
Semi-final and Quarter-final:	40,000 spectators, all seated
Group matches:	30,000 spectators, all seated

In addition, in order to provide high quality for spectators, maximum viewing distances (see next section), have to be considered. For big stadia, this may lead to a maximum number of spectators around the activity area and, thus, to a maximum capacity of the whole venue.

2.6.2 Spectator viewing

Spectator viewing is determined by two main factors, the viewing distance and sightlines.

Viewing distance:

The maximum viewing distance depends on the sport activity being staged. The size of the *ball* and the speed of the game are the determining factors. For a tennis match played with a small ball, the maximum viewing distance is around 30m, whereas the maximum viewing distance for rugby can be up to 190m. *Annex B* of *EN 13200-1:2003* [56] gives guidance on viewing distances for various sports.

This maximum distance between the spectator's eye and the diagonally opposed corner of the pitch gives a preferred viewing zone. On average, this configuration suggests a circle, the *optimum viewing circle* (see Fig. 2.2). This is just the basic configuration, which has to be modified, because the spectator is not sitting at ground level and there are preferred viewing locations for particular sports. [37]

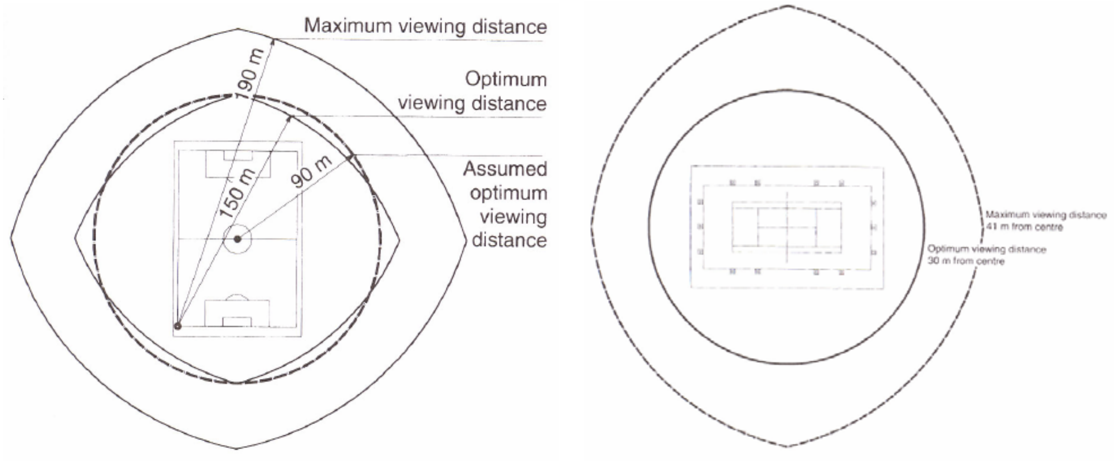


Fig. 2.2: Playing field, optimum and maximum viewing distance and a deduced *optimum viewing circle* [38]

In the UK, there was a tradition of rectangular stands around the pitch. One of the first modern football stadia where theoretical viewing distances were considered was the *Galpharm Stadium* (former *McAlpine Stadium*) in Huddersfield. The ground section in Fig. 2.3 shows the resulting oval shaped form of the stadium. The design was based on a theoretical concept called *Stadium for the Nineties* by the LOBB partnership. This concept allowed constructing a venue in different phase, from a single grandstand as first phase up to a fully enclosed stadium with a retractable roof in the last phase. The *Galpharm Stadium* was constructed in three phases. The first was finished in 1994, providing two long-side stands with 20,000 seats. The last was finished in 1998. [67]

Fig. 2.3: Galpharm Stadium, Huddersfield, UK [67]

Sightlines:

Spectators should sit as close to the activity area as possible and should have an unobstructed view from every seat in the stadium. Sightlines show the ability of a spectator to see over the spectator in front, down to the nearest point of interest at the pitch. It depends on the game, if the *ball* in the game is kept on the ground or in the air, and if the action takes place close to the stands or more in the centre of the pitch. The sightline of a spectator is also determined by the spectator in front. If this spectator wears a hat, a higher *step* is necessary. [37]

The quality of sightlines is internationally defined as 'C' value (see Fig. 2.4). The theoretical profile of seating rows can be determined according to [30] with the following equation:

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

Or according to [16], [22], [37], and [38] by:

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

C = 'C' value

D = horizontal distance from the eye to the point of focus

N = riser height

R = vertical height to the point of focus

T = seating row depth

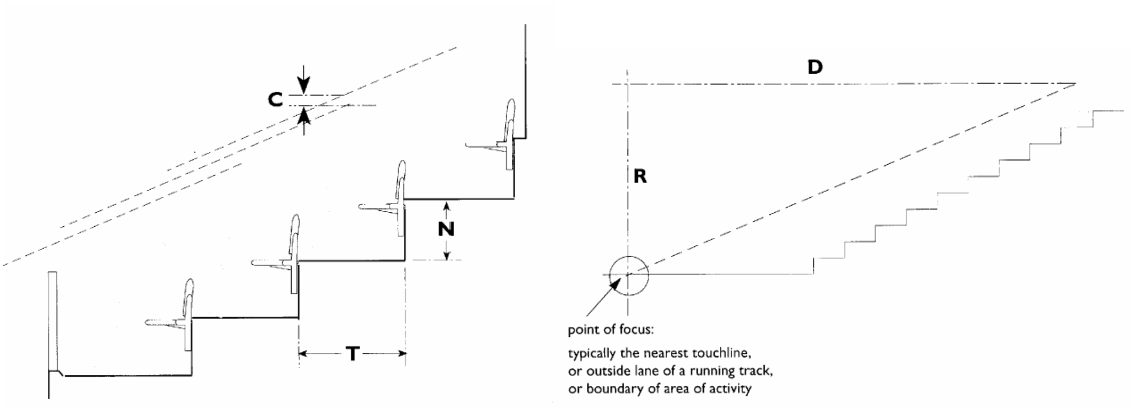


Fig. 2.4: Sightlines for seated spectators [30]

According to the Football Stadium Advisory Design Council, an excellent 'C' value would be 150mm; 120mm are very good and 90mm are reasonable [22]. *EN 13200-1* [56] recommends 120mm and an acceptable 'C' value of 90mm. However, due to practical limitations, high 'C' values are difficult to achieve in stadia with a high capacity. The calculation above gives the theoretical sightlines, which means a different riser height for each step. This in turn means that the angle of rake becomes steeper in higher areas of seating. The distance between the pitch and the first row, as well as the height of the first row relative to the pitch, also influences sightlines.

Different riser heights for each step are uneconomic as well as unpractical. In small stands the riser height may be held constant for ease of construction. This means different 'C' values. However, in large and multi-tiered stands, the riser height should vary, to provide high quality sightlines. The economic solution is to vary the riser height according to limitations of the 'C' value. This means the division of the tier into facets, so that several rows are same height.

In particular, in stadia with more levels of tiers, the angle of rake may become very high. The limitation for the maximum angle of rake given in the *Guide to Safety at Sports Grounds* [30] is 34 degrees. In Italy, a rake up to 41 degrees is allowed. However, the local codes of practice and building regulations may determine maximum angles of rake. [37]

Another point to be considered is that a stadium is a three-dimensional building with three-dimensional sightlines. Therefore, computer calculations are used to vary seating configurations and to try different options. Due to the effect of three-dimensional sightlines, the first row should ideally have a curved form. However, like different riser height, this may be difficult to design and uneconomic.

At *Croke Park*, in Dublin, for example, which has a capacity for 82,300 spectators, the design ‘C’ value is about 60mm. The ‘C’ value goes up to 80mm and down to a limiting factor. The riser height is changed, when the incremental is 15mm. The tread width at *Croke Park* is 750mm. [49]

The value of tread width also influences the angle of rake. The higher the tread width the higher is the angle of rake. In particular, more space for the spectators is necessary in order to make stadia more comfortable. A typical tread width is between 720mm and 840mm (*EN 13200-1:2003* [56] minimum tread: 700mm, recommended value for the tread: 800mm). In addition, the value of the tread width is influenced by stairs within the stand (gangways). Due to level of comfort, maybe the tread width in new stadia will be higher than it was in the past.

Preferred viewing locations:

In addition to sightlines and viewing distances, there are preferred viewing locations. They depend on the game, on the player, on the ball movements, and on the traditions of particular sports. For football, the best viewing location is along the sides of the pitch. Therefore, the capacity of stands along the pitch should be higher than behind the goals. However, to support ones team, there is a tradition to sit (or stand) behind the goals. Due to these preferred viewing locations, the *optimum viewing circle* must to be adjusted. Impressive three dimensional shaped architectural and structural forms are developed from configurations that consider those preferred viewing locations. Examples are the *City of Manchester Stadium* in Manchester, UK, or the *Telstra Stadium* in Sydney, Australia. [37]

2.7 Safety at Stadia

Safety at sports stadia is an interdisciplinary challenge. Not only the design of a stadium, but also the management of the stadium during an event, has to ensure good safety conditions.

Due to their high number, spectators are the most important group for safety at sports stadia. There are three groups of spectators. The *sports priority* spectator is primarily interested in the game itself and attends nearly all games of the club the spectator supports. On the other hand, the *social priority* spectator is primarily interested in business matters. The latter uses the boxes, lounges, and dining rooms to entertain business contacts and clients, whereas the *sports priority* spectators are sitting in the stands. The third group is interested in both, in the sporting activity, as well as in social issues. [38]

For safety reasons, it should be noted that a proportion of spectators may be familiar with the site. However, there may be a great number, who do not know the venue. In particular if one thinks about Olympic Games or World Championships in any sport, it is not the usual crowd of spectators, who are familiar with the stadium, that attend these events.

Safety is a point of major interest during the design, because stadia are designed for up to or even over one hundred thousand people. An emergency plan is essential for every venue. Zoning, crowd control, crowd circulation, fire safety, and structural safety are included in the term safety. The following presents an overview of historical disasters and how they influenced the stadia design.

2.7.1 Historical disasters and how they changed the design

After any disaster in stadia, where people were injured or killed, reasons and responsibilities were analysed and design regulations were adjusted.

This is a partial list of disasters:

1902: Twenty five people died at *Ibrox*, Glasgow, UK, when a section of wooden terrace collapsed. At least 516 more were injured, of which, according to the local newspaper *The Scotsman*, 24 were “dangerously injured” and a further 168 “seriously injured”. [34]

1971: As fans exited at the end of a match, a crush on a stairway caused the death of 66 spectators at *Ibrox*, Glasgow, UK. [34]

1985: 39 people died at the *Heysel Stadium* in Brussels, Belgium, when a retraining wall, separating the Liverpool followers from Juventus supporters, collapsed. Many were crushed or trampled when panicking Juventus fans tried to escape.

1985: 56 people died and many were badly burnt in a fire at *Valley Parade Stadium*, Bradford, UK. [38]

1989: 95 people died and many were injured, during a crowd surge into a restraining fence after kick-off at the Sheffield *Hillsborough Stadium*, UK. [75]

1991: 40 people died and 50 were injured after a referee allowed an own goal at a friendly soccer match in Johannesburg, South Africa. [38]

1992: 17 people were killed in Corsica, when a temporary grandstand collapsed in a French Cup semi-final match between Bastia and Marseille. [38]

1996: 83 people were killed and between 127 and 180 people were injured in a stadium in Guatemala City, when soccer fans stampeded before a World Cup qualifying match. Angry fans kicked down an entrance door, causing spectators inside to cascade down onto lower levels. [38]

2001: 126 people were crushed to death against block exit gates in a stampede, after police fired tear gas into a crowd at the *Accra Stadium*, Ghana. [16]

2001: 43 people were crushed to death when thousands more fans tried to enter the already overcrowded stadium, *Ellis Park* at Johannesburg, South Africa. [16]

The collapse of terraces at *Ibrox* in 1902 is an interesting incident, because the main question always was and is: Who is responsible? In 1902 not the designer, but the timber merchant responsible for supplying and erecting the Ibrox terracing, was charged. The reason given was that for certain bearers of joists he used *wood of an inferior quality of yellow pine instead of red pine of the best quality*, as specified in the contract [34].

After the 1971 disaster at the *Ibrox Stadium*, there was a public inquiry, led by Lord Wheatly. This disaster led to the 1975 Safety at Sports Grounds Act in the UK. The main problem was that no guidelines for the design of sports grounds existed. Therefore, this disaster in 1971 led to the first edition of the *Guide to Safety at Sports Grounds* [30], which was published in 1973. [34], [82]

It was the disaster in 1985 at the *Heysel Stadium*, Brussels, Belgium, and at the *Valley Parade Stadium*, Bradford, UK, as well as the tragedy in 1989 at *Sheffield Hillsborough Stadium*, also in the UK, which most influenced the design of sports stadia, as we know them today.

After the *Hillsborough Disaster* in 1989, the Inquiry by Lord Justice Taylor [75], which analysed the reasons for the many victims, led to a discussion in the UK about safety at football grounds. The disaster happened on the 15 April 1989. 95 people were crushed to death at a FA Cup semi-final match between Liverpool and Nottingham Forest. Lord Justice Taylor noted in his report, that overcrowding and misbehaviour is mostly a problem of football (in the UK).

The intention of this report was not only to analyse the disaster itself, but also possible solutions for the future.

The 1985 Bradford Disaster had already led to a discussion in the UK about safety. The *Guide to Safety at Sports Grounds* from 1973 had already given design requirements for safety. However, these guidelines were not considered at Hillsborough. Two reasons were suggested in 1989 (from page 4 in [75]): *First, insufficient concern and vigilance for the safety and well-being of spectators. This was compounded by a preoccupation with measures to control hooliganism. Secondly complacency which led all parties to think that since disaster had not occurred on previous occasions it would not happen this time. But there is no point in holding inquiries or publishing guidance unless the recommendations are followed diligently. That must be the first lesson.*

However, overcrowding at sports grounds was not the only problem. There were other problems, such as old grounds, poor facilities, hooliganism, excessive drinking, and poor leadership by the national management of the game (in England for example: the Football Association and The Football League). [75]

The most important measure for more safety at sports stadia was thought to be seating accommodation. No standing should be allowed. However, this in turn, made it necessary to add a roof over the stands, because sitting in the rain is unacceptable. Hence, stadia should be turned into all-seater venues for more safety. However, only to fix seats on an existing standing terrace is not the solution. Sightlines have to be considered. The report of Lord Justice Taylor in general, urged for more quality for spectators. To ensure quality of design, the *Football Stadia Advisory Design Council* was founded to provide guidelines for the design of stadia.

However, the Technical Working Party of the inquiry said that standing *is not 'intrinsically unsafe'*. There are sports, where standing accommodation is an *essential element (horse, greyhound, motor racing, and car rallying for example).* [75]

Another outcome of the disaster at Hillsborough was the Football Spectators Act in 1989. A *Football Licensing Authority* (FLA) was established by that Act. The role of the FLA is to ensure safety at all football grounds by providing advice and guidance for the local authorities, clubs and other bodies responsible for safety issues at sports grounds. [82]

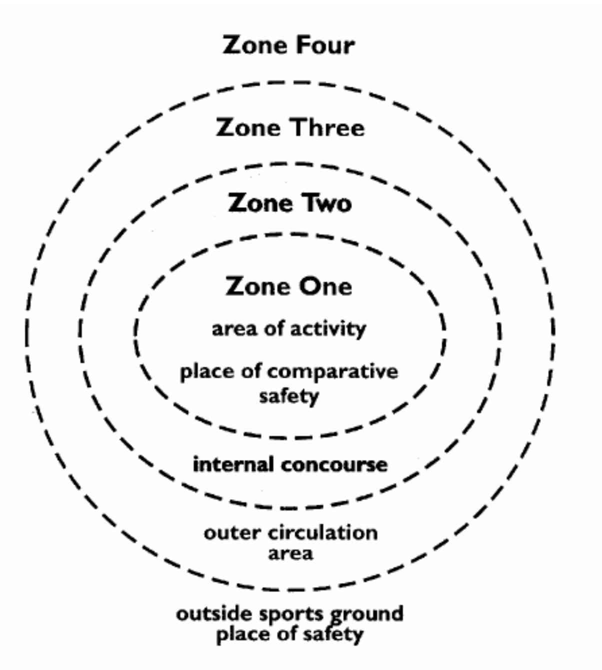
The key document in the UK for safety at stadia today is the *Guide to Safety at Sports Grounds* [30], in its fourth edition published in 1997. This paper gives information about the design and the management of sports stadia. According to this guide, the body responsible for safety is the ground management. This will normally be either the owner or the lessee of the ground, but may not necessarily be the promoter of the event [30]. The guide has had an international impact on the safety design of stadia. For example, the guide was used by the working party producing European standards for sports stadia. [82]

Design factors, regarding safety at sports stadia, are discussed in the following chapters. However, absolute safety cannot be guaranteed. *A sports ground is absolutely safe only when it is empty* (from page 188 in [82]).

2.7.2 Zoning

For safety reasons, the basis for every new project should be the design of zones. These zones are essential for safety in an emergency. The *Guide to Safety at Sports Grounds* [30] advises four zones of safety (see Fig. 2.5). The same four zones can be found in *EN 13200-1:2003* [56].

These zones determine areas of temporary or permanent safety in an emergency. Important for the design is the interrelationship between these zones. Not only for access but also for egress, for normal conditions as well as for an emergency, the flow between the zones must always be safe. Zone Four should be the designated place of safety in the event of an emergency. [30]



Zone One: the pitch or area of activity. This may be considered a place of comparative safety, to which spectators can be evacuated before using other emergency exits.

Zone Two: spectator accommodation, including internal concourses and hospitality areas. If this area needs to be evacuated in an emergency, it should preferably be to Zone Four.

Zone Three: the outer circulation area. Zone Three may, in certain situations, be considered a place of comparative safety, to which spectators can be evacuated before exiting to Zone Four.

Zone Four: a buffer zone outside the sports ground perimeter, used for the public to gather before entry and for links to car parks and public transport. The public should be able to circumnavigate the perimeter in this zone, in order to find an appropriate point of entry.

Fig. 2.5: Zonal planning for new and existing stadia [30]

2.7.3 Crowd control

As mentioned previously, the crowd of spectators must be managed to ensure safety. From the question of how spectators get to the venue to the question of how they leave after the event, spectator movement must be controlled.

Computer programmes for simulation of crowd movement are used, to ensure safe flow through the stadium and safe evacuation in the time of an emergency. Different models are available to determine the capacity of circulation elements. Computational Fluid Dynamics, for example, may therefore be used. However, simulating an emergency and how people react under these conditions is a complex issue.

In addition, modern technology is used for the crowd management. The *smart-card* system is being used in stadia. In the UK it was first introduced at the *Ibrox Stadium*, in Glasgow in 2000. Advantages are reduced administration costs and increased security, because the management responsible for safety can tell at any time exactly how many people are in the stadium. [16]

Under normal conditions, the flow of people should be comfortable and - in an emergency - should still be safe, particularly the flow between these four zones, as discussed above. Gates and barriers must be designed and operated to allow the escape of people in an emergency, but even if these gates are locked, temporary safety areas within the outer perimeter must be available. [37], [49]

One important barrier is the one between Zone One (activity area) and Zone Two (spectator accommodation). At the *Colosseum*, to give an ancient example, the barrier was in the form of a surrounding wall around the activity area, to protect the spectators from the activity. Today, it is more the other way round but, when the pitch is considered as an area of temporary safety in an emergency, people must be able to get to the pitch. [37]

There are three commonly-used solutions for this purpose: perimeter fences, moats, and change of level. Certainly, there are pros and cons for each technique and they can be combined. The governing body concerned, the local police, and safety authorities have to be involved in the decision. [37] In the UK, pitch perimeter fences must not be used in new sports grounds under any circumstances, because they can lead to dangerous situations (see 1989 Hillsborough disaster). [30]

2.7.4 Circulation

Circulation means the circulation to and from the transportation systems, as well as the circulation within the stadium. Both systems need to have the capacity to ensure safe circulation. For circulation to and from the stadium, the capacity of the transportation infrastructure (e.g. private car, public transportation system) may be the determining factor. Some 10,000 or even up to 100,000 spectators leave the stadium after an event in a very short time. Hence, the capacity of the paths (streets) to the stadium and the capacity of the public transport system have to be considered.

On the other hand, the circulation routes within the stadium have to be properly designed. The main point to be considered is that circulation of spectators in and out, as well as around the stadium, is not ensured by designing individual circulation elements. The interrelation of these and other components is critical [30]. Circulation elements are horizontal and vertical elements, discussed later on. Design regulations for dimensions of these elements can be found in *EN 13200-1:2003* [56] or in the *Guide to safety at Sports Grounds* [30], though regional building regulations have to be considered.

For egress two design scenarios are differentiated: egress under normal conditions and emergency evacuation. Four factors influence the design (from page 78 in [30]):

- *The* **widths** *of each part of the exit, or emergency exit route*
- *The* **rate of passage** *of people through the exit, or emergency exit system. This is a pre-determined figure.*
- *The* **egress time**. *This is normally a maximum of eight minutes for circulation purposes.*
- *The* **emergency evacuation time**. *This is a variable, maximum time between two and a half minutes and eight minutes, based on a number of factors.* It largely depends on the level of fire risk.

The ground capacity should be subdivided into smaller units of about 2,500 to 3,000 spectators. Each of these sectors should have its own circulation routes as well as its own supply of toilets, bars, and suchlike. The access into and between the zones is of special interest. Separation of spectators may be necessary, when *home* and *away* fans have to be segregated. This is not usual in all sports activities. At rugby matches, for example, it is common practice that *home* and *away* fans sit next to each other, mixing throughout the whole stadium. Segregation of spectators is needed, when they tend to be strongly partisan and maybe even aggressive. This is, for example, common practice at football grounds in the UK. [37]

Horizontal circulation elements [37]:

- Entrances:

  The determining factor for the entrance is the capacity of the turnstiles.

- Exits:

  These gates must ensure high flow of people under normal conditions after a game, and safe evacuation under an emergency.

- Concourses, corridors, and other passageways:

  The required width is determined by the calculation known as *timed exit analysis* (TEA).

- Areas of particular congestion:

  These are areas, where a change of gradient may slow people down, or areas where queues are likely. Additional space is necessary to avoid dangerous pressure from fast moving people to the rear of slower moving people at the front.

Vertical circulation elements:

For emergency egress, there are only two elements, connecting horizontal circulation ways of different levels: stairs and ramps. For normal conditions, escalators and elevators are also a possible solution, though their capacity is low compared to stairs and ramps. Circular ramps are often used at new stadia, because they have particular advantages [37]. For example, at the *City of Manchester Stadium*, eight circular ramps were designed.

- Stairs:

  They are compact in form and easy to design. For greater safety, they should be planned in pairs, to allow an alternative route, if one stair is blocked. Any sudden change of direction is a disadvantage compared to circular ramps. [37]

- Ramps:

  For safety reasons, ramps have several advantages compared to stairs. Any falling of people is less dangerous than at stairs. It is the only possible solution for service vehicles to change levels; this also applies to disabled people with wheel-chairs.

  Circular ramps are a common form with particular advantages. The circular form allows a person to select either a steeper or shallower, in other words an easier or faster, route. It also means the view down the ramp is less forbidding than down a long straight ramp. In contrast to straight ramps, circular ramps may not necessarily need landings at intervals. However, regional building regulations have to be considered.

  A disadvantage is that they allow only a low gradient (maximum 1:12 [30]), which results in big structures. Hence, they are difficult to handle from the architectural point of view. At the *City of Manchester Stadium*, the ramps also support the masts of the tension structure. [37]

Circulation at the stands:

Lateral and radial gangways are the circulation routes for spectators within areas of spectator accommodation. Due to the reasons discussed in section 2.6.2, the riser height of the seating units is different. For circulation at the stands, steps are needed to form stairs, called radial gangways. However, these steps must fit in the space provided by the seating units. A typical seating row depth for seating units is 720mm to 760mm and one step with a tread of 360mm to 370mm can be added. However, when the riser becomes higher, three steps are needed and the tread provided is only 240mm to 250mm. The limit for the risers of steps is a maximum of 190mm and for the tread a minimum of 280mm. These limits determine a minimum of 840mm, when three steps are needed due to the angle of rake. [30]

For ramps or stairs, handrails and barriers are necessary. Design parameters can be found in the *Guide to Safety at Sports Grounds* [30], as well as in regional building regulations and standards.

2.7.5 Structural safety and fire safety

Structural safety:

To quote the *Guide to Safety at Sports Grounds* (from page 48 in [30]):

All structures should be safe, serviceable, and durable at all times during their use and, where necessary, fire-resistant. ... In order to be safe, structures should be capable of resisting all loads imposed by their foreseeable use (including non-sporting use), with adequate margins of safety. ... Designers should pay particular attention both to minimise the risk of progressive or disproportionate collapse from unforeseen incidents, and to the dynamic response of structures. In doing so designers should:

- *Systematically assess conceivable hazards to structures and design the structures to be stable and robust in the light of a risk assessment*
- *Adopt structural forms which minimise the effects of the hazards identified*
- *Provide ground management with manuals which define the key elements and components of the structure requiring regular inspection and maintenance*

Structural safety is discussed in the form of structural design of stadia in chapter 4.

Structural fire engineering

Fire safety design is essential to avoid dangerous situations and to minimize fire risks. Therefore, the first step to fire safety is a fire risk assessment. This should be carried out to identify the existing level of fire risk. The determined risks have then to be reduced as much as possible. The *Guide to Safety at Sports Grounds* [30] knows three levels of fire risk: low, normal, and high risk. According to the level of risk, appropriate safety methods must be installed. In addition, the evacuation time, in case of an emergency, depends on the level of fire risks (see section 2.7.4).

Structural fire engineering is generally used for new projects to determine the risks and to minimize them. The UK Building Regulations 1991 say (from page 38 in [16]):

The building shall be designed and constructed so that, in the event of fire, its stability will be maintained for a reasonable period. The Government published Approved Document B which interprets the requirements of the Building Regulations and states that the stability criterion will be satisfied if 'the load bearing elements of the structure of the building are capable of withstanding the effects of fire for an appropriate period without loss of stability.

The aim of structural fire engineering is to produce a safe structure during a fire event. This is done by calculating the inherent fire resistance of parts of the structure. This resistance is set in relation to the temperature caused by the fire scenario. Reduced fire protection might be a consequence of optimal and careful design. No fire protection is needed, when the resistance of the structural element is sufficient [16]. When the intended use of the stadium is multi-purpose, the fire-engineering design has to ensure fire safety for each of these various events.

Where protection is needed, solutions to ensure fire safety could include:

- Fire compartments around endangered zones, for the required fire resistance
- Fire protection coat
- Stairs and concourses could be designed as safe areas
- Fire fighting lifts and dry-rising mains
- Fire resisting glassing (e.g. for lounges)
- Ventilation systems to clear smoke in the event of fire
- Automatic fire detection systems
- Automatic sprinkler systems

Blast engineering

Sports events bring together many spectators, and have high media penetration. Recent disasters (not necessarily at sports events) show that it is necessary to analyse additional extreme scenarios. Such a scenario could be an explosion. These considerations should not lead to designing a stadium that looks like a fortress. It would be neither an economical solution, nor a way that would make sense. However, effects on structural elements caused by extreme scenarios have to be considered, especially effects that could cause progressive structural collapse.

Explosions can occur accidentally or deliberately. The risks for the structure can be [16]:

- Local structural collapse: This could cause problems with evacuation, if a circulation way is blocked by collapsed structural elements.
- Total collapse: This could be caused by a mechanism of progressive structural collapse.

Though methods are available to consider such scenarios in the design, specialist advice is necessary.

2.8 Services

Facilities for players and for officials, private boxes, media accommodation, offices for administration and management, and facilities for spectators are essential parts of the building. Just as for any other building, there are a lot of services necessary to operate a stadium. These services include [16], [37]:

- Water supply and drainage services
- Ventilation and cooling
- Heating
- Lighting systems
- Closed-circuit television systems
- Fire detection and fighting systems
- Sound systems.

In order to ensure high quality, specialist design is required. Hence, the design team needs to consist of many specialists. These services also have an impact on the structural design and, thus, need to be considered. In particular for these services, but as well as for the structural design, life cycle costs have to be analysed to ensure a long-term success.

Two examples of services influencing the structural design are video screens or electronic scoreboards and stadium climate control.

Video screens and electronic scoreboards:

For the design, the size of a screen is determined by the maximum viewing distance [37]. Their impact on the structural design is caused by the massive loads they apply on the structure. Therefore, the position has to be determined by considering the supporting structural elements. Video screens are often hung from a stadium roof. In particular, in existing stadia, where video screens are added, the additional weight on the structure has to be considered.

Climate control:

In enclosed sports venues, it is necessary to control the climate to create comfortable conditions for athletes and spectators. Controlling the climate in such an arena can be achieved by heating and cooling. It should create comfortable conditions at any point of the stadium; on the track (e.g. ice rink) or on the pitch, as well as on the stands.

CFD (computational fluid dynamics) studies are used to study the internal environment to ensure acceptable conditions. Two main external factors that influence the climate are temperature and wind pressure. Another factor with major influence is the enclosed air volume. This volume has to be heated or cooled, and is, therefore, important for the running costs. In order to reduce the running costs for heating, transparent roof covering elements and windows can be used. These elements allow daylight, which means energy, into the building.

An example of cooling is an arena with an ice rink. There are different temperatures required within the arena: the athlete needs a comfort temperature of 15.6°C; the required temperature for racing conditions is 10°C; the ice has to be held at -6.6°C; the spectator wants a comfortable temperature to watch the races [16].

New technologies, like moving roofs, present new opportunities and challenges in controlling climate [16].

2.9 Maintenance

As well as everything discussed before, maintenance needs to be considered during the design process. If it is not, this may lead to unacceptable maintenance works and costs. The intensity of maintenance depends also on the climate. Each stadium should have a *Maintenance Manual*, for reasons of safety and management.

Continuous maintenance includes:

- Pitch maintenance:
    - ➢ For natural grass surfaces: mowing, fertilization, irrigation, drainage, repair and maintenance, cleaning, and protection
    - ➢ For artificial surfaces: repair, cleaning, irrigation, and protection
- Stand maintenance: cleaning, repair, and maintenance [38]

The *Maintenance Manual* should also include the structural elements:

- Maintenance of the roof
- Maintenance of the stands
- Maintenance of finishes and claddings

These maintenance works on the structure, are mainly influenced by the designed lifetime of the elements. Load bearing elements (columns, beams, and trusses) will always have the longest replacement cycle.

Typical replacement times:

- Load bearing structure: 50 years [23], [37]
- Roof coverings: 15-20 years [37]

3 ADAPTABILITY OF STADIA

3.1 Introduction

As discussed in section 1.5, to design a venue that is usable for a greater variety of events adaptability of the stadia is necessary. This means that a multi-purpose stadium has to be flexible in terms of use. Flexibility in arenas or stadia can mean:

- Flexible use of the stadium, for a variety of events, not only for sports activities
- Flexible seating capacity with flexible seating configurations
- Variable pitch size and form
- Different pitch surfaces for various uses
- Moving, sliding or retractable elements to create either an open or enclosed venue

A flexible venue has to fulfil different requirements for different uses. Financial requirements, especially, led to this development during the last two decades. Any venue has to be able to hold different events to maximize event days; this increases financial efficiency. However, different sports activities require different sight-lines, different pitch sizes and forms, different viewing distances, and different preferred viewing locations. Hence, not all sports are compatible, and not all sport can be combined without loss of quality. These requirements in turn, affect the geometry and, furthermore, the structure of the venue. [37]

The change from single-sport venues to multi-purpose venues began in the USA in the 1960s. The *Houston Astrodome*, in 1965, was one of the first multi-purpose stadia. The aim was to attract a wider range of spectators. [67]

During the development of a new project or a redevelopment of an existing stadium, there has to be a decision about what the stadium should be designed for. Not every stadium needs to be as flexible as possible. It may be better to design the stadium for the use of only one sport. Most of the football stadia in the UK are only used for football. However, to make these football grounds economically reliable, ancillary uses are required. For the Soccer World Cup in Germany 2006, twelve new stadia were built. Most of them are only used for one sports activity: football. However, even when one sport can mobilize a huge group of spectators, multi-purpose use is needed for financial reasons. For football, for example, about 20 match-days for major football matches per year are typical. For the rest of the year, the stadium would be *empty* and unused. The aim of modern venues in Europe is to provide up to 250 event-days. Hence, additional uses are required to make the stadium attractive for owners. These additional uses can either be sporting or non-sporting, either on or around the activity area or within the stand structure. Sporting or non-sporting facilities, for instance, could include exhibition halls, cinemas, health centres, squash courts, swimming pools, and hotels. The problem with including such facilities and uses within stadia is that they sometimes need large spaces, which may be difficult to design into the inflexible supporting structure of stadia. Hence, their inclusion in the design from the very beginning is vital. An alternative for additional spaces at sports grounds is to house ancillary uses in a building adjacent to the stadium structure. [37]

Examples of these can be found throughout the UK. At the *Galpharm Stadium* in Huddersfield, for example, there is a business and leisure complex with a swimming pool adjacent to the north stand. There are also some examples of hotels included or adjacent to the stadium. At the *Reebok Stadium* in Bolton, for instance, a hotel is situated within the south stand. Another hotel can be found at the *Ricoh Arena* in Coventry, where it is also situated within the stand structure. In addition, adjacent to the stadium at Coventry there is an exhibition hall (Jaguar exhibition hall) which can be subdivided into various units.

Hotel rooms, that face the inside of the stadium, are often designed to be converted into hospitality boxes for sports events (see Fig. 3.1). This offers the opportunity for a more intensive use of the stadium as a building for various purposes.

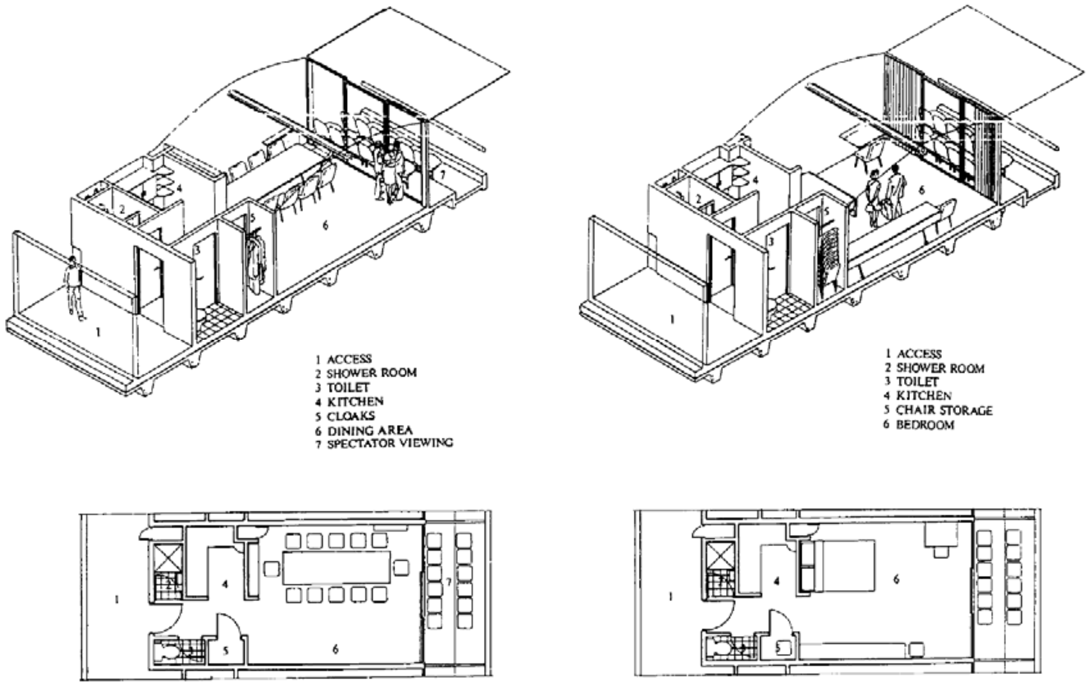


Fig. 3.1: left: Hospitality box for events; right: hotel room [38]

On the other side, a sports venue can also be designed to host various sports events. One solution could be to design the stadium for more than one club of the same sport, which would increase the number of sports event-days per year. Another opportunity is to design a stadium for sports with similar pitch sizes and forms. Due to a similar pitch form and size, football and rugby, for example, are a typical combination in the UK. [37]

In addition, new technologies – as discussed later – can be used to increase and to optimize the variety of uses. However, when a stadium is intended to host various sports activities, there are some essential points to be considered. Firstly, the playing field, with its form and size must be suitable for all intended uses. Furthermore, there has to be a decision about the surface of the pitch, which needs to be strong enough to survive the higher intensity and frequency of use. Viewing requirements for the intended sports are another point to be considered in the design. Each sport has its own requirements, as well as preferred viewing locations. All these points have to be considered and their impact has to be determined to ensure high quality for spectators. [37]

The capacity of stadia is another determining factor in the design. Sports venues designed for a major event like the Olympic Games need to have a predetermined capacity. However, this stadium capacity can be too high for long-term use of the venue. At the end of the last century stadia use after major events like the Olympic Games became more and more of a problem. As discussed in section 1.5, the European Football Championship in Portugal is a typical example. This Football Championship was held in ten stadia around the country. In five of these stadia only two games were played, and now the municipality or the local clubs (which do no attract a large crowd of fans) have to handle the running costs of these big stadia. There were some venues in the past, where this issue was considered during the design.

The Olympic Stadium in Sydney for the 2000 Olympic Games was designed for 110,000 spectators for the Games and to be converted into an 80,000 spectator venue for long-term use. However, there may even be the need for a higher capacity after Games, as it was the case at the City of Manchester Stadium in the UK. This stadium was designed as a 38,000 spectator venue for the Commonwealth Games. After the Games, it was reconfigured and a lower seating tier was added to increase the capacity to 50,000 for a long-term use as a football stadium.

The problem is to design a stadium which can provide both configurations: a high capacity for the Games and a lower long-term capacity for the intended long-term user, or vice versa. This affects not only the number of seats provided in the stadium, but also additional facilities for spectators, officials, the media, and athletes.

From the structural point of view, there are different categories of stadia to provide more flexibility in terms of use:

- *Stadia with demountable elements:*

  Temporary demountable structures are often used to increase the capacity of stadia for a major event, but to have a basic (or long-term) capacity for usual requirements. Such a major event can be Olympic Games or a championship in various sports. This category can vary from additional temporary, demountable structures, used to cover a running track to increase the capacity and to get spectators closer to the pitch, up to fully temporary, demountable stadia. For existing venues, temporary seating tiers built into existing structures can be used.

  Demountable stadia require a reconfiguration of the structure. Therefore, it has to be considered in the structural design. There are different phases of construction, which means different loads on load bearing elements.

- *Stadia with moveable elements:*

  Movable elements of stadia can be used for the seats or seating tiers, the pitch, or for the roof. These are the main elements of a stadium and the design of these elements is influenced by the requirements of the events taking place. Seats or seating tiers, pitches, or roofs can be made of movable elements, either rigid or telescopic elements.

  In particular, the wish to be isolated from the elements, as well as the requirements of media, led to the development of fully enclosed stadia. However, this was not consistent with a natural pitch surface. One possible solution is to design a moveable roof, to meet both requirements. On the other hand, a moveable pitch can also be a solution. This would allow the arena to also be used for events that need a more robust surface. Retractable seating can be a solution to cover, for example, a running track during a football match.

3.2 Stadia with demountable elements

Demountable means that a part of a venue, or the whole venue, can be erected at different places. This also means that the structure is only temporary in use. Demountable elements can vary from being re-erected only once, through to temporary structures which are erected and dismantled many times. The structural requirements will vary depending on how often the structure is reused.

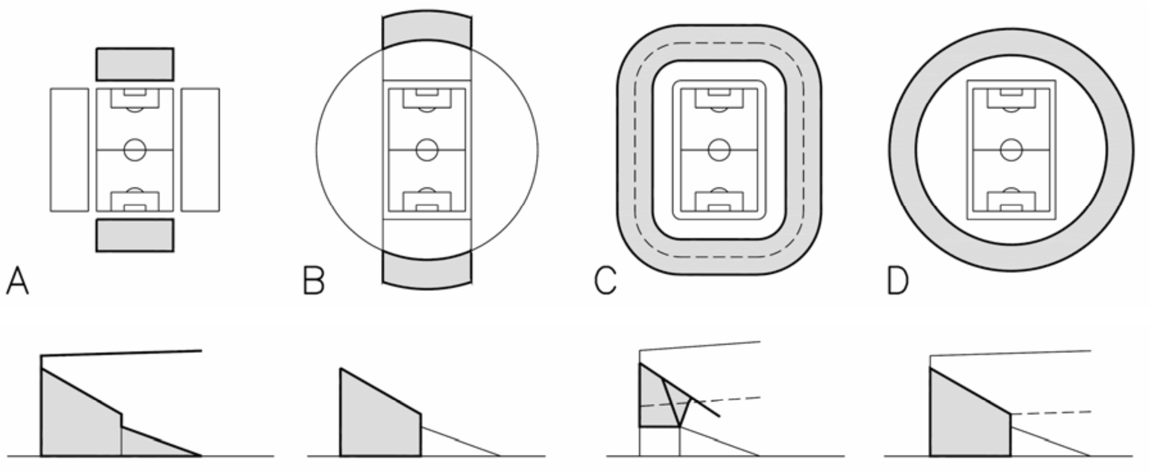


Fig. 3.2: Configurations of temporary spectator accommodation

Fig. 3.2 shows different geometries of temporary structures for stadia. An entire demountable stand, supported on temporary foundations can be added to a venue to increase temporary the capacity (compare A in Fig. 3.2). Such a stand was used, for instance, at the *City of Manchester Stadium* in the UK, which was designed for the Commonwealth Games 2002.

Another opportunity for a stadium is shown in image B in Fig. 3.2. An example was the *Stadium Australia* (*Telstra Stadium*) in Sydney for the Summer Olympic Games 2000 in Australia. In order to provide the higher capacity of 110,000 spectators for the Games, there were additionally, uncovered, temporary seating tiers at both ends of the stadium (compare B in Fig. 3.2). After the Olympics, the stadium was reconfigured to an 80,000 capacity venue for a long-term use for rugby, soccer and Australian Rules football.

There were temporary seating tiers in both quoted stadia. However, they were unprotected during the Games. The roof structure was closed to a continuous shelter over the seats during the reconfigurations of the venues. In contrast to these stadia, there are three stadia in Austria under construction for the European Football Championship 2008 (EURO 2008). These three stadia were designed to provide an increased capacity for the Championship and to be converted afterwards for a long-term use with a lower capacity. In both configurations, all spectators are protected from the elements by a roof. Hence, there are two roof configurations required and the temporary structure is added to the permanent structure (compare C in Fig. 3.2).

Image D in Fig. 3.2 shows a temporary upper seating tier with a roof over both configurations. However, in contrast to image C, the structural system of the roof for both configurations is different.

3.2.1 Use of temporary structures

Generally, there are various structures that are used many times at various sites; for example: stands, stages, tents, or marquees. In a stadium that is used for pop concerts, stages are usually temporary elements. Tents and marquees, for instance, can be used to house additionally required areas for shops or for hospitality purposes. In particular, for stadia, temporary stands with or without a roof are important and, thus, they are discussed for the purpose of increasing the capacity of a venue.

To ensure safety for spectators, there are guides for the design, as well as for the use. In the UK, the *Guide to Safety at Sports Grounds* [30] gives guidance for spectator accommodation on temporary demountable structures. In addition, there is a guide from The Institution of Structural Engineers: *Temporary demountable structures – Guidance on design, procurement and use* [80]. For European countries, there is *ÖNORM EN 13200-6:2006* [58], which also gives information for the design, procurement, and erection and dismantling of *demountable (temporary) stands*.

As mentioned previously, there are systems, which are dismantled and re-erected only once and systems, which are dismantled and re-erected many times. Generally, both are suitable for the discussed purpose in stadia. The guides quoted above define a temporary demountable structure as (from page 10 in [80]):

Structures which are in place for a short time, generally no more than 28 days, that are designed to be erected and dismantled manually many times. They are usually made from lightweight components and are used for a wide variety of functions at public and private events. However, the duration of use of 28 days is not a definitive one.

The guides quoted above developed due to accidents where people were killed. In 1992, in Corsica, such a disaster happened and 17 spectators were killed (see section 2.7.1). In October 1994, at Earls Court in London, there was another incident. A temporary grandstand with 1200 spectators collapse during a pop concert and 50 spectators were injured. Thus, temporary stands at sports grounds may be prohibited for specific events. In the UEFA Binding Safety and Security Instruction of 2004, for example, one finds (from page 2 in [83]):

For the purpose of these instructions, temporary seating shall be defined as seating which, by its substance, design and construction is clearly intended for use for a very limited period of time, and which could not in any sense be considered suitable for use over a lengthy period of time. Such temporary stands are prohibited in all UEFA competition matches.

Nevertheless, the requirements for temporary structures are the same as for permanent structures. Thus, the design of these elements has to ensure the same margin of safety, although, there are some specific characteristics that must be considered. For reasons of time and ease of construction, such structures need to be lightweight. Therefore, they are more sensitive to dynamic effects, as well as to horizontal loads induced by the crowd of spectators or by wind. In addition, temporary elements are usually required at short notice and, thus, decisions have to be made rapidly.

For practical reasons, temporary structures are usually made of steel, aluminium, or timber. There may be some larger elements, such as hospitality boxes or toilet units that can be pre-cast and be erected as one element. All these structures need to be supported by temporary foundations. The required foundation depends on the site conditions, especially on the allowable bearing pressure. Differential settlements due to loads from temporary elements may be different to long term differential settlements. The allowable pressure must be determined by a geotechnical investigation. Recommended values for allowable bearing pressures for foundations of temporary structures can, for instance, be found in *Temporary demountable structures – Guidance on design, procurement and use* [80].

Foundations are usually formed by baseplates made of metal. However, there may be some larger structures, such as video screens, which need another type of foundation. For example, timber spreads are used to transfer the loads through the baseplates to the foundation ground. In addition, concrete pads can be used as foundations for heavy loads. Temporary structures may be subjected to uplift forces and, thus, ground anchors can be used to resist these forces. [30], [80]

3.2.2 Loads and external forces

- Dead loads:

Due to practical reasons, the dead load of the structure should be low.

- Live loads, wind loads, snow loads, temperature change effects, lateral loads on barriers:

Live loads on temporary seating tiers are the same as for permanent seating tiers. However, it has to be considered that a temporary structure may be used for various events on various sites.

- Dynamic performance of seating tiers:

Due to the use of lightweight elements for temporary demountable structures, they are more sensitive to dynamic excitation. The dynamic behaviour due to crowd action has to be considered and determined in the same way as for permanent structures (see section 4.4.2).

- Wind loads:

Due to the nature of demountable structures, they can be erected at many sites. Thus, the structure can be subjected to different wind action environments. The design, as well as the use of demountable elements must ensure safety for spectators and, thus, there are design approaches to meet these requirements.

The first opportunity is to design the elements for the worst wind loading environment. This has the advantage of a maximum variety of use, but, obviously, a disadvantage from the view of economic viability. Therefore, there are other solutions:

- Designing for a defined zone or region, in which the structure should be used
- Designing each structure of a range for the site of intended use
- Designing a structure up to a defined wind speed for events and a defined maximum wind speed without crowd loading

The last opportunity takes into account, that events may be cancelled due to bad weather conditions. In addition, this approach needs a continuous monitoring of wind speed during the use.

- Overturning as a result of wind action:

In contrast to permanent structures, overturning as a result of wind should be determined. The worst case load combination is caused by dead, imposed, and wind loading. There should be a margin of safety not less than 1.5 (1.5 x overturning moment > 1.0 x restoring moment). [80]

- Notional horizontal loads:

Notional horizontal loads are intended to ensure resistance against dynamic effects (as discussed in section 4.2.2). Additional notional horizontal loads on temporary demountable structures intend to ensure effects from geometrical imperfections of frames. These effects can, for example, be caused by a lack of alignment of structural members. Recommended values of notional horizontal loads can be found in Table 10 in *Temporary demountable structures – Guidance on design, procurement and use* [80].

3.2.3 Independent temporary structures

Examples of structures re-used many times at various sites include temporary grandstands for golf-championships or for ski-championships. The latter can also be used in stadia to cover a running track and, therefore, to increase the capacity of the venue. Such structural systems are usually separate structures on temporary foundations.

The supporting structure of temporary stands is usually formed by a space frame. In order to achieve low self-weight, seating units can be made of aluminium or timber.

An example of a temporary stand that is dismantled and re-erected many times is shown in Fig. 3.3. For the *Military Tattoo* in Edinburgh, UK, there are stands erected every year to accommodate spectators of the event. However, this structure is used at only one site.

Fully demountable venues are also possible. The concepts for the Olympic Games in London in 2012 include such venues. Some of them may be re-used at other sites in the UK. Due to different building sites, these concepts have to consider different requirements from the point of view of structural engineering.

Fig. 3.3: Temporary stand structure for the *Military Tattoo* in Edinburgh, UK

3.2.4 Temporary structures built in permanent structures

In contrast to the structures discussed above, there are temporary structures that are built in the permanent structure of the venue to increase the capacity for major events. Such developments are not only interesting for the duration of a major event. If an existing stadium is intended to be redeveloped to increase the capacity, there is the question of how to add a new structure to the existing one. However, this section only discusses the design of temporary structures.

As discussed in chapter 2, uncovered seating accommodation is not acceptable and, thus, usually, a roof over the permanent and temporary stands is necessary. Hence, the design has to solve the problem to use a roof in the temporary as well as in the permanent state. A main factor that influences the design process is, whether a venue is newly designed or an existing venue is redeveloped. Another decision to be made is whether the temporary structure should be re-used at another site or not. The problem in this context, for instance, is the geometry of the seating tier, as well as the geometry of the roof structure.

Examples for demountable structures added to permanent structure include the Austrian venues for the European Football Championship 2008 in Austria and Switzerland. The design of temporary elements in these stadia is discussed in the following.

3.2.4.1 ***Wörtherseestadion*****, Klagenfurt**

The *Wörtherseestadion* in Klagenfurt is currently under construction. It was designed to be constructed in a Championship-mode with a capacity of 32,000. After the Championship, the capacity will be reduced to a 12,000 spectator stadium. During the major event, spectators are accommodated in two tiers. The supporting structure and the seating elements of the lower tier are made of concrete. The west stand houses the required under-terrace accommodation for players, officials, the clubs, hospitality areas, and the media. In order to achieve an adaptable structure, the upper tier is made of steel and is going to be dismantled after the Championship (see Fig. 3.4). A concourse for all spectators is situated between the upper and the lower tier. For the duration of the EURO, there are additional kiosks, toilettes, and other spectator facilities situated on this concourse.

During both configurations, all seats must be covered by a roof and, thus, there are two roof configurations necessary. In the case of the Wörtherseestadion, the roof structure is newly constructed in the EURO-mode and will be dismantled and re-erected after the Games for a long-term state. The connection to achieve this is situated at the level of the concourse. A temporary trussed steel element is used to hold the roof structure on the required level for the EURO and to allow a second tier inside the stadium (see Fig. 3.5). This element is going to be removed afterwards and the roof structure (trusses) is going to be re-erected on the level of the concourse.

However, due to differences in the geometry of these configurations, the roof in the higher position would be too short to provide an acceptable protection for the first rows of seats. Thus, there is a temporary steel structure hung down from the trusses to stretch the roof towards the pitch. In order to avoid additional snow loads, this temporary roof parts are just covered during the EURO (out of snow-season) (see Fig. 3.5). [90]

Fig. 3.4: left: Permanent concrete structure of lower tier; right: Temporary upper tier and roof

Fig. 3.5: left: Concourse level with temporary steel element at the back; right: Roof trusses above the temporary second tier with a temporary roof extension at the front

3.2.4.2 *Stadion Salzburg*, Salzburg

The *Stadion Salzburg* was inaugurated in 2003 and constructed with a capacity of 18,200. Spectator accommodation is not only in the form of seating accommodation, but also as standing accommodation. However, for the EURO all stadia must be all-seater venues. The brief was to design a stadium suitable for the use of the EURO 2008 with a predetermined higher capacity. Thus, the stadium was constructed as a basis stadium that can be expanded for the Championship. The pitch level is below ground level to reduce the impact of the stadium on the surrounding townscape. Due to the lower pitch level, the lower tier structure is supported directly on the ground. Facilities for all users and visitors of the stadium are situated in a building behind the lower tier. The roof is formed by a cantilever structure made of steel trusses as primary structural elements.

In the configuration for the EURO, the stadium will provide space for 30,000 spectators. Spectator accommodation must be seated and, thus, the terraces must be converted into seating areas. The temporary expansion of the stadium is achieved through building a second tier in the permanent structure (see Fig. 3.6 and Fig. 3.7). These elements are made of steel and supported on the permanent elements. The foundations were built large enough to bear the additionally applied loads. The space for the upper tier was achieved through lifting the roof structure 10.5m higher than in the basis configuration. For spectator circulation, there is a lower concourse for the lower tier and an upper temporary concourse for the second, temporary tier. Additionally, temporary facilities for spectators (kiosks, toilettes, and suchlike) are situated on the upper concourse above the stadium structure. Temporary stairwells are used as vertical circulation elements to allow access to the upper concourse. [66], [71]

Fig. 3.6: lelft: Permanent lower tier and temporary upper tier with roof lifted into a higher position; right: Temporary upper tier made of steel with aluminium seating rows

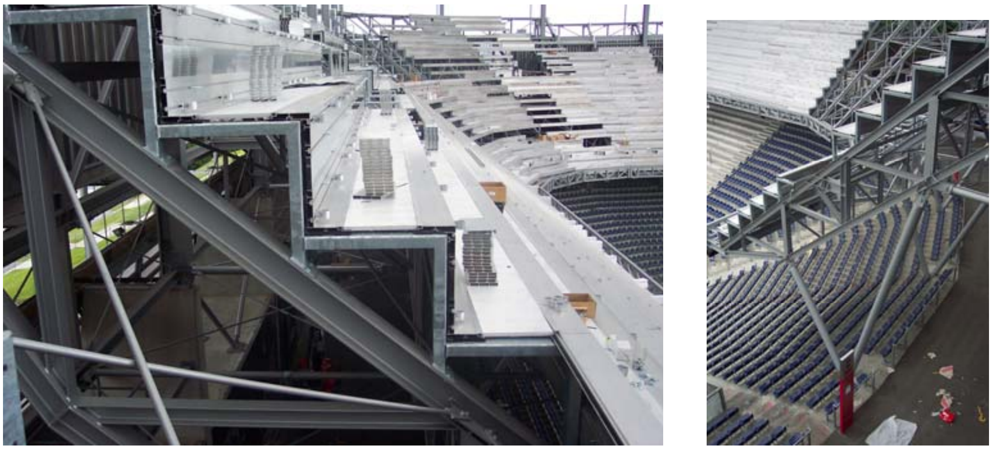


Fig. 3.7: left: Detail of rakers and seating elements of the temporary upper tier; right: Rafter and V-column of the temporary upper tier

3.3 Stadia with a movable element

Movable bridges, for example the Tower Bridge in London, were first steps in the development. Movable systems developed from manually operated small structures to computerised controlled, automatically operated longspan structures. As mentioned previously, for stadia, there are different elements that can be designed to be movable: the roof, seating tiers, or the pitch. (See Fig. 3.8) All of them can increase the use of a stadium. In addition, there are different systems in use to move the structures. All these different concepts for rigid movable structures have in common that there has to be a space, where the retracted elements can be stored. In addition, there may be dynamic loads to be considered in the design. Furthermore, the design has to ensure safe, repeated operation of the systems over the whole lifetime with minimal supervision and maintenance effort [44]. This section discusses the design of movable structures in stadia and their impact on the structural design of the permanent structure.

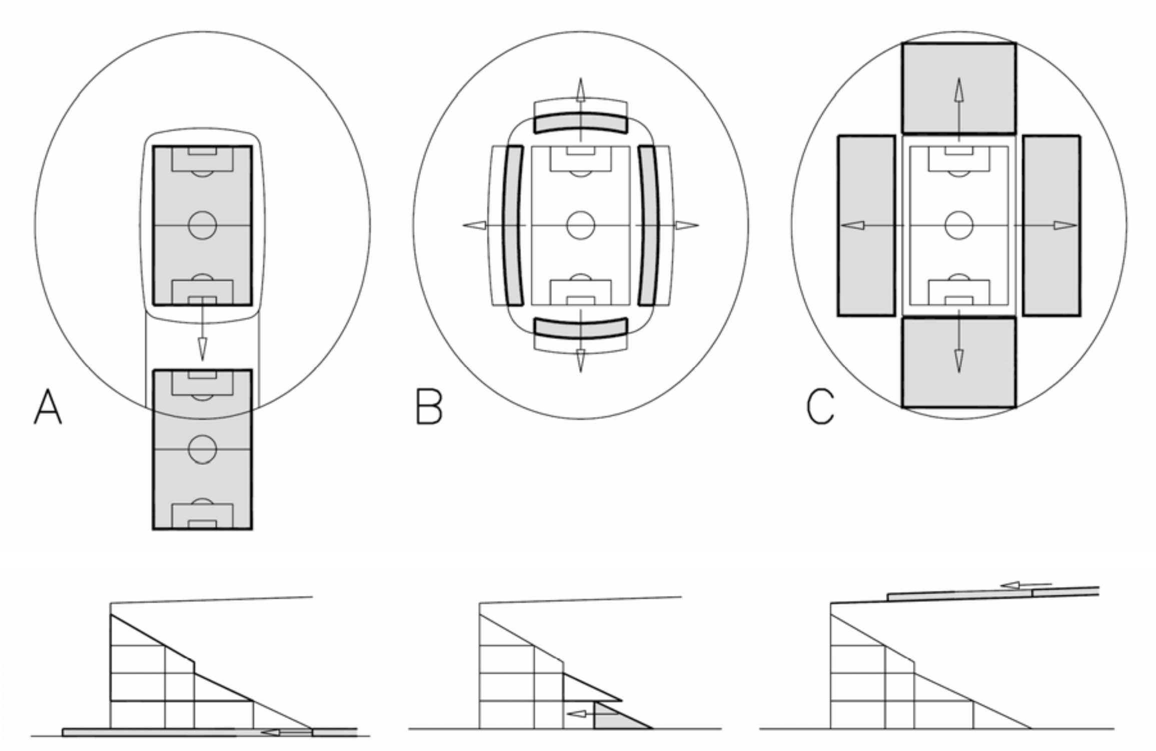


Fig. 3.8: Movable elements in stadia: movable pitch (A), seating tiers (B), roof (C)

3.3.1 Retractable roof structures

Movable roofs developed out of needs of multi-purpose stadia. A venue with a moveable roof can either be used as an open stadium or as an enclosed arena. When the roof is closed, spectators and the activity area are completely covered and the event is independent of weather conditions. Another reason for movable roofs is that natural pitch surfaces need sunlight and air circulation for healthy growth. Therefore, natural surfaces are still incompatible with enclosed arenas. [37]

Definition (from page 3 in [35]):

A retractable roof structure is a type of structure in which a part of or the entire roof structure can be moved or retracted within a short period of time so that the building can be used both in an open state or in a closed state of the roof.

An ancient example of a venue with a retractable roof was the *Colosseum*, where the roof over the audience could either be opened or closed with a sun shade. Remains of this structure can still be seen at the *Colosseum*. Since the 1930s, small retractable roof structures were designed and built. The technology for retractable roofs developed from cranes, because there were already standards and specifications for cranes. In particular, during the last three decades, longspan, retractable roofs for stadia developed. However, there are still problems in the use [35]. One of the first examples was the roof for the *Montreal Olympic Stadium*, where a fabric roof, supported by cables from a high reinforced concrete tower was designed (see Fig. 3.9). The idea was to retract the foldable membrane to the tower to allow sunlight into the venue. For changing to the enclosed configuration, the membrane would have been driven down on the cables and would have span over the gap in the permanent roof structure. However, the intended retractable system proved too ambitious. Therefore, the retractable roof was replaced by a fixed permanent roof structure.

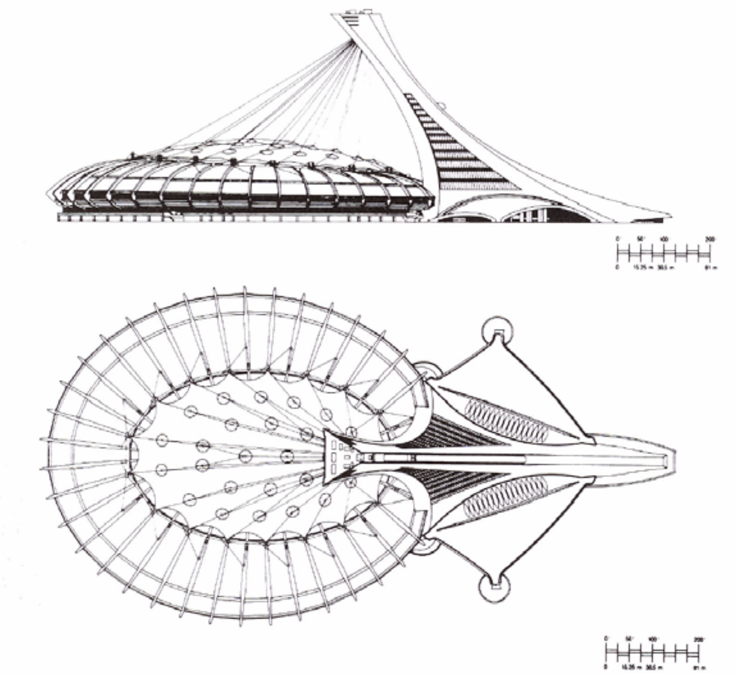


Fig. 3.9: Montreal Olympic Stadium retractable fabric roof [38]

The first differentiation is between two types of retractable roof structures from the point of view of operation [35]:

- Roofs that are closed most of the time and are only opening for certain events under good weather conditions
- Roofs that are open most of the time and are only closing for certain events under poor weather conditions (i.e. rain, or extreme cold/heat)

For the design of movable roofs, it is important whether the system is used only frequently or just once or twice a year. The frequency of opening and closing depends on the purpose of the roof.

In addition, retractable roof structures can be classified by the moving system used [35]:

- **Sliding system**
    - Roof is opened by horizontally moving/overlapping roof elements
        - Parallel movement system
        - Rotary movement system
        - Structural frame fixed type
        - Structural frame moving type
    - Roof is opened by vertically (up and down) moving/overlapping roof elements
        - Parallel movement system
        - Rotary movement system
        - Structural frame fixed type
        - Structural frame moving type
- **Pivoted moving system**
    - Roof is opened by rotatable roof panels on their axes
- **Folding system**
    - Roof surface is folded or wound up using various folding methods
        - Horizontal folding type
        - Rotary folding type
        - Vertical folding type
        - Structural frame fixed type
        - Structural frame moving type
- **Expandable system**
    - Truss frames are expandable/retractable
- **Combined system**
    - Combination of the above systems

Typical opening and closing methods used for stadium roofs can be seen in Fig. 3.10. Various geometric forms are possible.

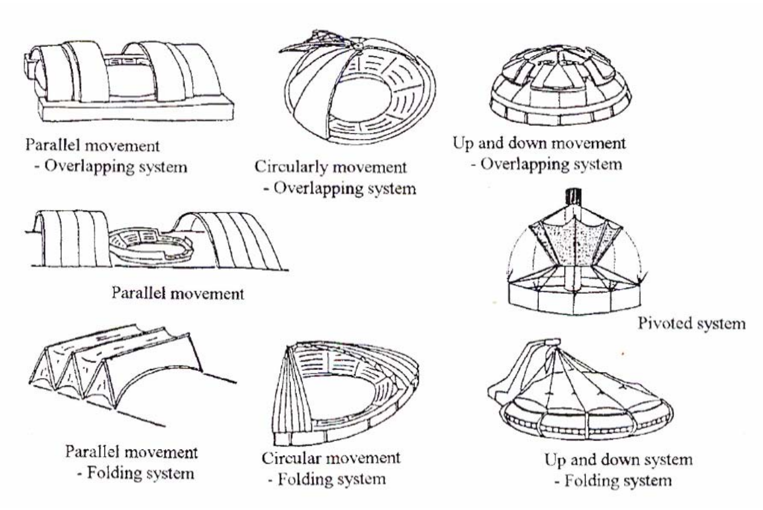


Fig. 3.10: Typical opening and closing methods [35]

Of these, two types of systems are typically used for retractable roof structures of stadia at the moment:

- Frame structures, where a covered, rigid frame is the moving element
- Membrane structures, where a membrane is used to open or close the roof by folding the membrane, either in combination with a stationary or a movable supporting structure

Other methods, like expandable or foldable trusses and supplying/releasing air in pneumatic structures are still in planning stage. They have not been used for stadium roof structures. However, small air-membrane structures have already been built, and are considered to be important in the future development of retractable roofs. [35]

Frame structures:

Rigid frame structures are used to design retractable rigid elements that can be moved between an open and an enclosed configuration. Options for the movement of these rigid elements are shown in Fig. 3.11. However, not all possible solutions are suitable for retractable stadia roofs.

Each rigid movable element has its own independent structure and transfers loads to the supporting structure. However, the supporting structure is the same for all panels. Therefore, there is an interaction between these elements. Such panels are usually dome-shaped in form. From the structural point of view, a shell effect may be difficult to obtain due to the division of these elements and, thus, the arch effect may become dominant. However, loads and external forces on panels vary form element to element.

Due to these separate panels, there are gaps between them that need to be closed in the close state of the roof. Flexible seals can be used for this purpose. In addition, these seals can be designed stiff enough to transfer loads from one panel to the adjacent one. [35]

Membrane structures:

Retractable membrane structures use the foldability of the material, which is often PVC-coated polyester fibre. Movement of membrane structures results in various geometries of folding and movement of the supporting structures (see Fig. 3.12). Such structures developed with the development of the material. Research was initially carried out by Professor Otto (University of Stuttgart). The first project was a plan for an open-air theatre at Stuttgart in 1954. However, the design of retractable membrane structures for stadia is still a challenge.

The working group of the *International Association for Shell and Spatial Structures* (IASS), who published a guide for the *Structural Design of Retractable Roof Structures* in 2000 stated (from page 42 and 43 in [35]): …, *however, no large retractable membrane roof (stadium size) has yet been realized, although several plans exist. Currently membrane materials are used in roofs of rigid retractable structures but they are not folded* However, the development of such structures continued and a retractable membrane roof (stadium size) was built at the *Waldstadion* in Frankfurt for the Football World Cup in 2006 in Germany [81]. Generally, there are membrane systems with a stationary supporting structure and systems with a movable supporting structure. The first uses the foldability of a membrane to bunch or to roll the membrane. The latter retracts through folding the membrane between movable structural elements.

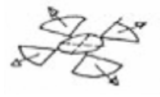
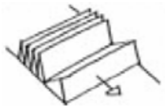
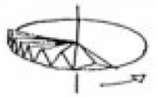
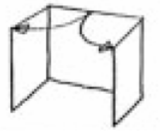
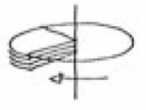
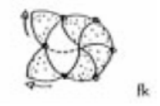
Type of movement		Parallel	Central	Circular	Peripheral
Supporting structure	Sliding				
	Folding				
	Rotating				

Fig. 3.11: Movement options for retractable **rigid frame** roof structures [29]

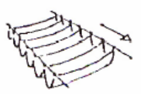
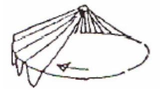
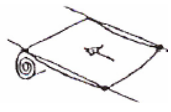
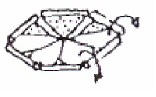
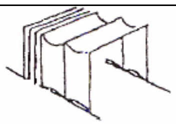
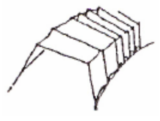
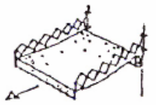
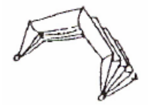
	Type of movement		Parallel	Central	Circular	Peripheral
Supporting structure stationary	Membrane	Bunching				
		Rolling				
Supporting structure movable	Supporting structure	Sliding				
		Folding				
		Rotating				

Fig. 3.12: Movement options for retractable **membrane** roof structures [35]

3.3.1.1 Standards and design guides

Standards for retractable roof structures are mostly based on references to crane structures. Cranes are used worldwide, and they have been designed for a long time. Bridge cranes with a frame structure and cable cranes on a support cable were used as references. Standards and references for cranes are available, whereas for retractable roof structures, there are internationally a relatively small number of standards and design guides. If design guides and standards for retractable roof structures are not available, the designer has to prepare sufficient design data (including references) for the planning authority. It has to be demonstrated that the design ensures public safety. [35]

Guidelines for the structural design of retractable roof structures can be found in *Structural Design of Retractable Roof Structures* [35]. This is the result of a working group of the IASS, who worked on a state-of-the-art report and guidelines for retractable roofs.

3.3.1.2 Opening and closing conditions

The position the roof will be used in is important for the structural design. Through this, design conditions can be determined. In addition to an open and closed position, there can be semi-open states in which the roof will be used. This is important for the evaluation of loads and the design of the driving mechanism. Another determining factor for the design is whether the roof will be designed to resist strong winds in the closed or in the open state. This depends on the driving mechanism, the retractable structure, and the intended use of the venue. However, this is an important decision and should be made at an initial stage of the design. Tab. 3.1 gives an overview over these two conditions [35]:

Strong-wind condition	Closing the roof (closed state)	The entire structure resists and excludes wind	The roof is closed when wind velocity exceeds a certain value. This plan is selected when the opening and closing method and open shape of the structure are disadvantageous against wind loads, or when the interior should not be subjected to wind and rain.
	Retracting the roof (open state)	The movable roof should be retracted to release wind loads from the roof surface	The interior structure will be subjected to strong wind and rain. This plan is selected when the closed-state structure is disadvantageous for resisting strong wind or storms, for economic reasons or in cases where the structure should be open because the wind velocity exceeds a predetermined value.

Tab. 3.1: Opening and closing control in strong wind conditions [35]

3.3.1.3 Driving mechanism

Designing retractable roof structures is a multi-disciplinary challenge. The driving mechanism of a retractable roof structure has to ensure smoothly function of the movement and various solutions are possible. Any defect or error can lead to serious accidents with a large influence on the entire structure. The driving mechanism has the function of moving the structure and transferring loads to the supporting structure.

Rigid frame retractable roof structures move along a track. This track can either be formed by straight horizontal rails, or rails which are curved and ascending or descending in form, depending on the entire roof form. In the case of ascending or descending rails, it is difficult to move the roof elements only by means of friction forces, generated from running wheels on rails [35]. Various driving mechanisms are possible (from page 29 in [35]):

- *Self-running wheel method: Power wheels run on horizontal rails*
- *Cable traction method: Wheels run on rails pulled by cables*
- *Rack and pinion method (Rack and gear method): Driving gear runs on rails which have convex and concave parts*
- *Jack method: A jack is used as a special method*

As shown in Fig. 3.13, the driving mechanism for rigid frame retractable roofs consists of: running wheel, rail track, driving device, fixing device, stopper and buffer, brake, and auxiliary power device and power supply [35].

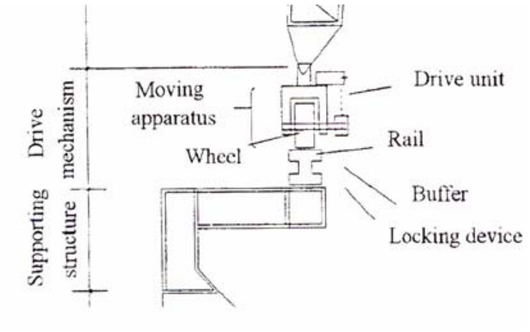


Fig. 3.13: Driving mechanism for a rigid frame retractable roof [35]

The driving mechanism for retractable membrane structures is different to those with rigid elements. The driving mechanism for such structures consists of a cable trolley or a tractor. A trolley is a pulley, which runs on a cable and has no power system. The trolley is pulled by a rope along the cable. On the other hand, the tractor uses a built-in motor and suspends the membrane by means of wheels or caterpillars. A combination of both systems is used for some structures. For the movement, the frictional force is the determining factor. However, a one-wheeled tractor cannot move, except if the cable is stretched horizontally. For this reason, frictional force is increased by various options (from page 38 in [35]):

- *To increase frictional force, rope is wound around the wheel*
- *To increase frictional resistance on the surface of the cable, wire is wound around it*
- *The surface of the cable is irregularly wrapped*
- *The tractor moves with a caterpillar along a cam or a chain attached to the cable*

An example of a cable-trolley and a tractor is shown in Fig. 3.14.

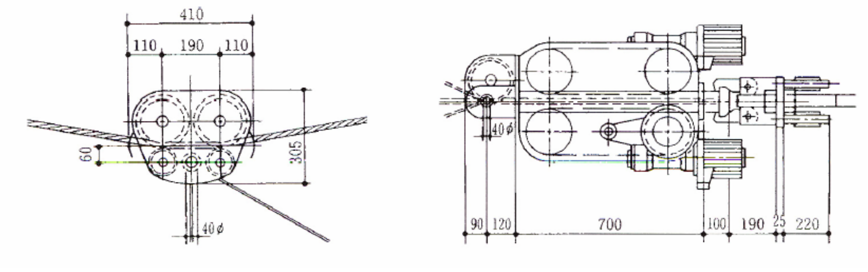


Fig. 3.14: Examples of cable-trolley (left) and tractor (right) [35]

3.3.1.4 Loads and external forces

Various loads and external forces need to be considered for retractable roof structures. Specific attributes of these are discussed in the following section [35]:

- Dead loads:

As for any other longspan roof structures, the dead load is a main design criteria. Thus, it should be held as low as possible. For the supporting structure, the dead load from the retractable part changes when the roof is under operation. Hence, the dead load of the retractable elements is a moving load for the supporting structure.

- Live loads:

Live loads on roofs arise from maintenance and repair work, such as changing or painting roof structure elements. Loads should be set in accordance with the required work and the maintenance plan.

- Wind loads:

The usual design of retractable roofs is to provide a shelter against bad weather conditions. In addition, the roof can be designed either to close or to open, when a predetermined wind velocity is exceeded. When the roof is designed to withstand wind in a closed state, then wind load under this condition is a maximum.

Due to the long span of retractable roof structures, as well as lightweight structural systems, wind on the roof has a high impact on the behaviour of the structure and dynamic effects from wind must also be considered. However, safe closing or opening of the roof is required within a predetermined wind velocity of winds that occur with relatively high frequency, but of a small magnitude that can be forecast. By setting a wind velocity limit for retracting the roof, it can be possible to reduce the maximum wind loads on the structure in the open or semi-open condition. For determining the wind pressure, high wind speed, which occurs relatively frequently and for which storm warnings are issued in many countries, should be used. In addition, loads on parts of the roof suspended from cables and frames have to be considered. Due to the fact that retractable roof structures are often lightweight, effects of fluctuation of wind pressure cannot be ignored, especially when membrane fabric materials are used. These variations depend on the roof opening and closing condition and the roof shape.

- Temperature change effects:

Due to long spans of retractable roofs and due to being exposed to direct sunlight, changes in temperature can cause large deformations that have to be considered. These deformations can affect the operation of retractable roofs. Abnormal operations, like play, squeal, and jamming can occur.

- Snow loads:

It is dangerous to design a structure that moves to avoid snow accumulation. From the view of safety, during the snow-fall season, retractable roofs should be left closed. Hence, snow loads in open or semi-open states, as well as in moving conditions, have not to be considered.

- Earthquake loads (depending on the site)
- Ice loads and rain loads (if necessary)

Special loads for designing retractable roofs

Special loads are those from wheels and rails [35]:

- Horizontal load during operation and closing:

  A Lateral force on the rails depends on the clearance between the rail and horizontal wheel, the rail alignment accuracy, the angle of the retractable roof, the meandering of the line, etc. Due to the lateral force, a bending moment occurs, which has to be considered. The impact of the lateral force on the supporting points is important.

- Impact force during opening and closing

  Forces in vertical and horizontal direction during running are also caused by rail joints and unevenness of the running path.

- Inertia force and braking force

  The inertia and the braking force depend on the running speed and on the brake characteristics. As with cranes, consideration of the loads can either be done as β –times the running part weight, or as the acceleration α.

- Impact load buffer

  Depending on the performance of shock absorbers, impacts of running retractable roofs must be considered.

3.3.1.5 Supporting structure

The supporting structure is the basis for the retractable roof. There needs to be a connection that transfers the loads from the retractable elements to the supporting structure. For example, the supporting structure can be formed by the fixed elements of the roof, which are mostly steel structures. This in turn, has to be supported by a lower structure, for example the stand structure, which can either be made of steel or concrete.

Fig. 3.15 shows a typical supporting structure for a rigid retractable frame roof (left image) and for a retractable membrane roof (right image) with a stationary supporting structure. For rigid structures, the connection between the movable panels and the supporting structure is the rail. The supporting structure either can be formed by a permanent canopy roof structure or by a separate supporting structure for the moving roof. [35]

The main determining factor, which influences the retractable roof, is the deformation in the supporting and base structure. Deformations can be caused by stress, but also by temperature change effects. In addition, when using reinforced concrete, creep and shrinkage have to be considered.

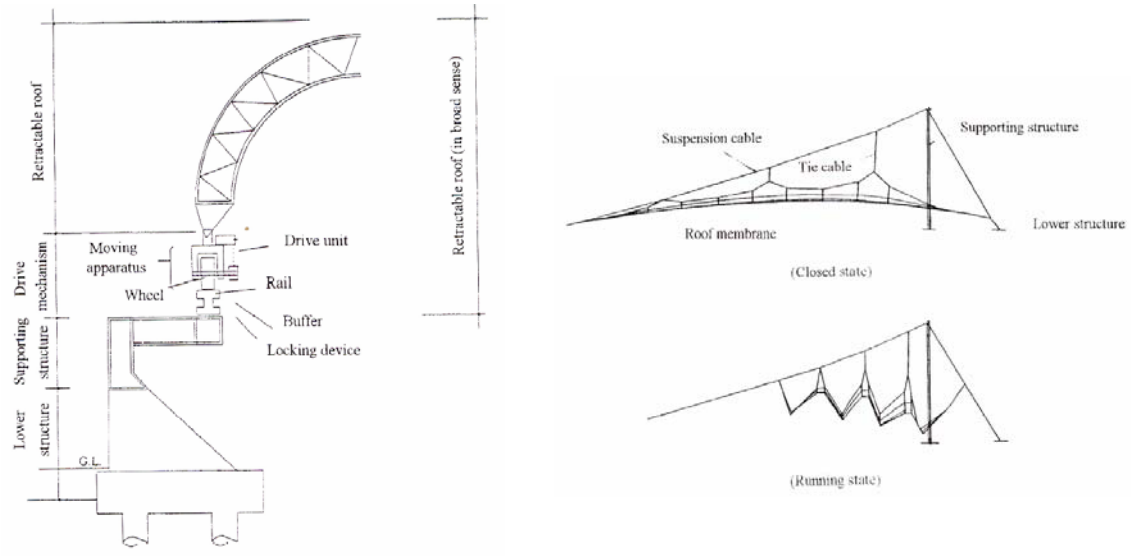


Fig. 3.15: Supporting and lower structure of retractable roofs [35]

Due to the dynamic behaviour caused by repeatedly moving loads from the moving elements, structural fatigue needs to be analysed. Another specific in the case of moving loads for retractable roofs are effects of geometrical imperfections of the running tracks. These imperfections can be caused by elastic deformation, thermal effects, shrinkage, no uniform settlement, and construction tolerances. Furthermore, they change during the lifetime of the running track.

Due to these moving loads, as well as due to the variation of these loads, there is an impact on the design of the supporting structure, which, for this reason, needs to be rigid and strength enough to resist all applied loads. In addition, the operation of the retractable elements must be safe under all conditions. Deformations of the supporting and the base structure influence the running track and, thus, this interaction is important.

For membrane retractable roofs, there are the same points to be considered. However, in addition, the supporting structure is subjected to pre-tensioning forces and roof hoisting loads from the membrane. [35])

3.3.1.6 Examples of retractable roof structure

The following is a partial list of retractable roof structures:

- *Retractable rigid frame structure*
  - Millennium Stadium, Cardiff, UK
  - Wembley Stadium, London, UK
  - Amsterdam Arena, Amsterdam, Netherlands
  - Skydome, Toronto, Canada
  - Bank one Ballpark, Phoenix, USA
  - Miller Park, Milwaukee, USA
  - Reliant Park Stadium, Houston, USA
  - Oita Sports Park Main Stadium, Oita City, Japan
- *Membrane with a stationary supporting structure*
  - Neues Waldstadion Frankfurt, Frankfurt, Germany
  - Bull fight arena Zaragoza, Zaragoza, Spain
- *Membrane with moving supporting structure*
  - Toyota Stadium, Toyota City, Japan
  - Wimbledon Centre court, London, UK (retractable roof under construction)

3.3.2 Movable seats

Movable and retractable seating can be an opportunity to design a stadium that allows two pitch configurations. This is the case, when venues are intended to stage different sports, as well as perhaps other events. The greater the variety of events and required configurations, the greater is the amount of movable seating required. For example, football (soccer) is played on a rectangular pitch. However, Australian Rules football is played on an oval shaped pitch. To provide good viewing standards and an enclosed atmosphere for both sports in the stadium, movable or retractable seating tiers can be used. [37]

3.3.2.1 Types of movable seats

Generally, there are different types of seats in a sports venue [68]:

- *Permanent fixed seats*
- *Variable seats: retractable or telescopic seats*
- *Demountable seating in temporary tiers*

Demountable elements are discussed in section 3.2. For variable seats the usual systems for sports stadia include [37]:

- *Rigid seating tiers mounted on steel tracks*
- *Rigid seating tires with large retractable wheels*
- *Rigid banks of seats moved about on air or water cushions*
- *Retractable seats on folding or telescopic frames*

Movement of the systems is achieved either by pushing the elements manually or mechanically to change the configuration. The advantage of telescopic (or foldable) types is that they can be compactly stacked or folded, when they are not in use. Hence, there is less space needed for storing the movable elements [37]. The space required for storage of rigid structures is large.

3.3.2.2 Loads and external forces

Guidance for the design of *telescopic stands* can be found in *ÖNORM EN 13200-5:2006* [57].

- Dead loads:

  In contrast to longspan roof structures, the dead load of retractable seating elements is not of major concern. However, it has to be considered that it is the dead load that needs to be moved from one configuration to the other. Thus, the dead load is a determining factor for the moving mechanism.

- Live loads, wind loads, snow loads, temperature change effects, lateral loads on barriers:

  These loads on a movable seating tier are the same as for permanent seating tiers. However, it has to be considered that there are two configurations in which the seating tier can be.

- Dynamic performance of seating tiers:

  Rigid elements in particular have an impact on the structural design of the stands. Due to the large space that is required to push back the movable structure, there may result a large cantilever structure for the next higher seating tier. The problem with cantilever seating tiers is that such structures are more sensitive to dynamic excitation by spectators. In order to achieve the required natural frequency of the structure for the intended use, there are limits for the deformation of the structure under dead weight (see section 4.4.2).

3.3.2.3 Development and examples of retractable seating

First concepts for *flexible* venues, which can stage various types of events developed in North America. One of the first concepts for a combination of sports, in the 1960s, was to host American football (rectangular pitch) and baseball (diamond shaped pitch) in the same venue. However, these concepts were often thought unacceptable [37].

In 1989, Toronto Skydome, Canada, was opened. It was designed to be adaptable for different uses such as (from page 104 in [37]):

- *Auditorium configurations to allow 10,000 to 30,000 seats as desired*
- *A hockey or basketball configuration of 30,000 seats*
- *A baseball configuration of up to 50,000 seats*
- *A football configuration of up to 54,000 seats*
- *Various configurations allowing up to 68,000 spectators for rock concerts or other entertainments*

However, from the point of view of capital costs, retractable elements for stadia, especially retractable seating tiers, are expensive. In addition, sightlines and viewing distances for all intended configurations need to be calculated. Spectator viewing quality should be ensured for all intended events. [37]

In Australia, there are two examples of stadia with retractable seating tiers: the *Telstra Dom*e in Melbourne and the *Telstra Stadium* in Sydney. They allow two configurations: one for football with a rectangular pitch and one for Australia Rules football with an oval shaped pitch. Fig. 3.16 shows these two configurations.

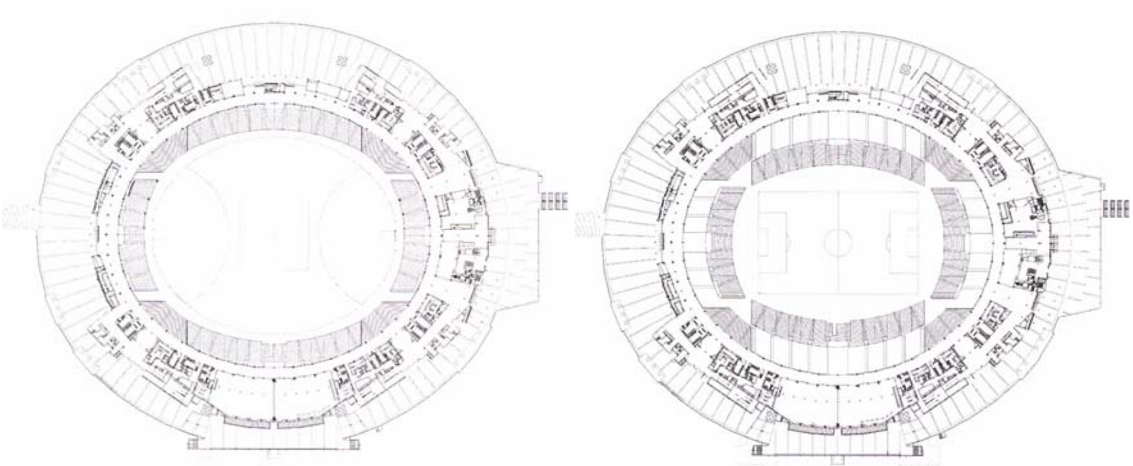


Fig. 3.16: *Telstra Dome*: left: Australian Rules football configuration; right: football configuration [37]

The *Telstra Dome* (former *Colonial Stadium*) in Melbourne is designed for international standard rugby union, rugby league, soccer, and Australian Rules football. Additional uses include entertainment events, like pop concerts and shows. Due to different pitch configurations needed for the intended sports, the lower seating tier is designed to retract on tracks. Therefore, a rectangular pitch for soccer, as well as an oval formed pitch for Australian Rules football, can be provided. The side tiers move 18m overall, and the end tiers 14m, when reconfiguring from one to the other configuration. 12,800 spectators can be seated on the movable lower tiers. The structure is made of steel sections, and runs on tracks sunk in trenches below pitch level. In the oval configuration, the tracks are covered by palletised turf sections. In addition, the stadium has a retractable roof structure. [67]

Another example of a stadium with retractable seating tiers is the *Telstra Stadium* in Sydney, where similar to the *Telstra Dome* in Melbourne, the lower tier is retractable. The stadium was designed for the Olympic Games 2000 in Sydney, as well as for a long-term use for football and Australian Rules football. A cross section of the stadium is shown in Fig. 3.17. The movable tier structure is made of in situ concrete with main raker beams at 7.2m centres. As a whole, it is a 100m long x 31m wide x 12m high stiff diaphragm, monolithic structure with no movement joints. The structure moves on rails, which are constructed under the pitch. Post-tensioned concrete for the movable structure had the advantage of pulling together the whole structure, which due to its size could not be poured in one hit. Due to pulling the structure together, there are no movements at planned construction joints.

Due to the retractable lower seating tiers, there is a 16m cantilever mid-tier structure. It is formed by steel trusses that cantilever out of the main grandstand structure at 7.6m centres and, which are braced laterally and connected to the floor slabs of the main structure. In order to achieve the limits of dynamic requirements of the cantilever structure, the deformations needed to be as small as 20mm. The overturning moment from the cantilever seating tier is transferred through the floor slabs to four cores at the perimeter of the stadium. These cores are situated within the circular ramps for spectator circulation. In addition, these cores are vertically prestressed to withstand the high overturning moment, applied from the cantilever mid-tier structure. Two cores can be seen at the ground plan, as well as at the cross section in Fig. 3.17. [5], [37], [48]

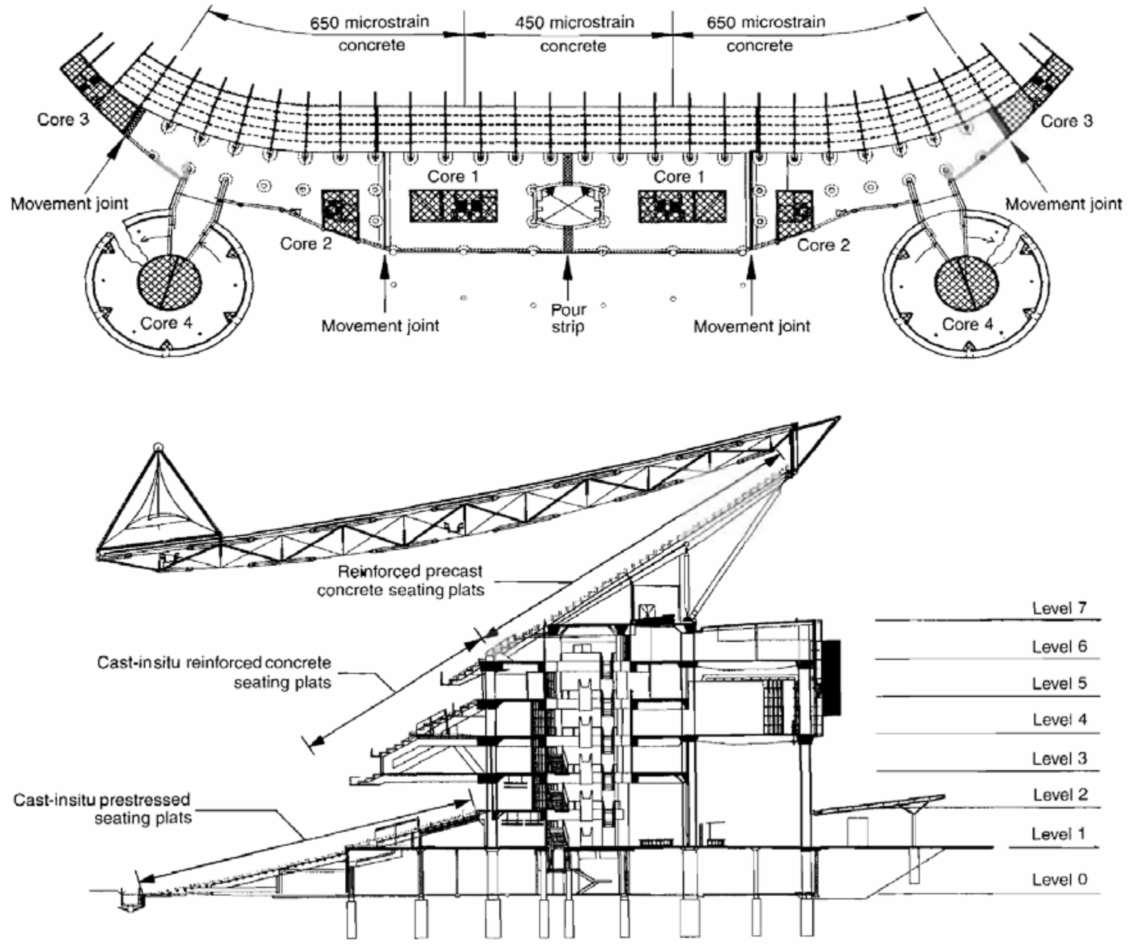


Fig. 3.17: *Telstra Stadium*: A ground plan and a cross section of a section of the lower retractable seating tier and the cantilever mid-tier. [5]

As mentioned previously, some stadia in Europe are designed for football and athletics. However, the spectators for football are further away from the pitch in the football configuration, which creates a less intimate atmosphere. Retractable seating tiers can be used to form a stadium with configurations suitable for both sports. The *Stade de France* in Paris, France, is an example of this. In order to cover the running track, the lower tier was designed to be retractable. In the case of a football event, the tier can be moved forward and, therefore, there is a more intimate atmosphere. During athletics the tier is retracted back and allows the running track to be used. A cross section of the stadium with the retractable lower seating tier is shown in Fig. 3.18. [37]

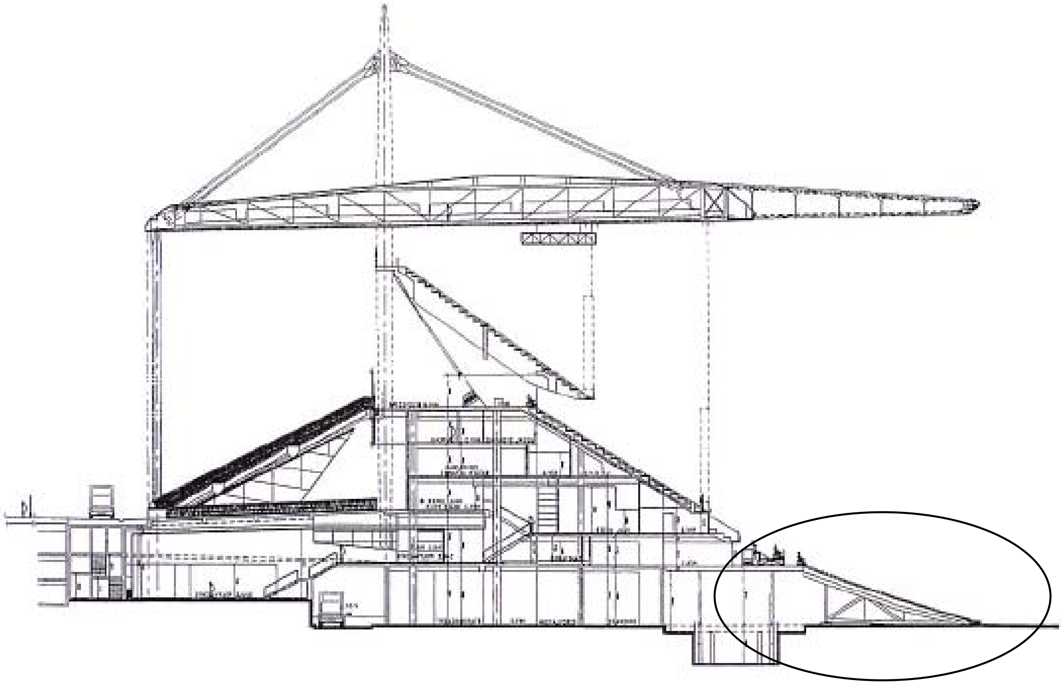


Fig. 3.18: *Stade de France*: Cross section with retractable lower seating tier [54]

In addition, retractable seating structures are used in combination with a movable pitch (see section 3.3.3), where a gate, which provides the link between the outside and the stadium, is required. During pitch operation, it needs to be free, but during events it can be used to accommodate spectators. To provide both configurations, a retractable seating system can be used. Examples are the *Veltins Arena* in Gelsenkirchen, Germany, and the *Sapporo Dome* in Sapporo, Japan. Both are discussed in section 3.3.3.

3.3.3 Movable pitch

Multi-purpose use also influences, firstly, the pitch size and form, but also the surface of the activity area. Usually, the sport determines the type of surface. Football and rugby, for example, are traditionally played on a natural grass surface, which is also determined by the regulations of the sport. However, natural grass surfaces need specific conditions for healthy growth, such as sunlight, air movement, humidity, and temperature levels within strict parameters. On the other hand, various requirements made it necessary to stage events independently of weather conditions. Enclosed arenas are one solution for providing such conditions. However, a natural grass surface is still not suitable for enclosed stadia. The reason is found in the specific conditions needed for healthy growth. Even transparent or translucent roof covering materials do not provide a solution to the problem. One possibility is to design a movable roof. However, even in partly roofed stadia, the effects of shadows and reduced air-movement can cause problems with the natural pitch surface. [37]

Another limiting factor for the use of natural grass is the intensity of the use. Therefore, *pitch replacement* concepts have been developed, to remove the grass, when not needed. Such concepts are discussed in section 2.5.1. The key of these concepts is to allow grass to grow outside the stadium when not needed for sports events. There are various concepts that could be used. For example, the turf could grow in large boxes that can then be moved out of the stadium. Another concept, though still un-built, is to raise the pitch with a natural grass surface by jacks into the roof area after sports events. Such a concept is the *Turfdome* concept by Geiger Engineers, New York, USA. [37]

A system already in use is a movable pitch. The entire pitch is moved outside the stadium when not needed. The open air outside the stadium provides the necessary conditions for grass. The obvious disadvantage is the large additional space required. In fact, there needs to be an area of the size of the pitch outside the stadium, where the whole pitch structure can be moved to. Fig. 3.19 shows the ground plan of the *Sapporo Dome* in Japan with the pitch parked outside the stadium (shaded area).

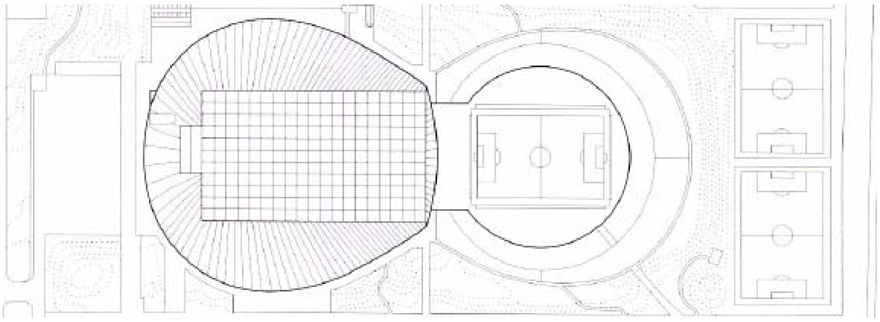


Fig. 3.19: *Sapporo Dome*, Japan: Ground plan [64]

As discussed in section 2.5.1 the pitch consists of various elements. The movable pitch structure has to ensure the same conditions and, hence, it consists of the same elements: the grass-soil matrix as well as drainage, irrigation, heating, and other installations. This results in a large tray, which moves in or out of the venue. The connections for the installation systems in the activity area are of special consideration.

From the point of view of structural engineering, there are effects on the structure caused by the design of a movable pitch. First of all, there has to be a gate, where the pitch can move out of the venue, with a minimum width of the small side of the pitch. This in turn influences the structural design of seating rows above the gate. Girders with spans of about 90m are required to span the gate and to provide support for the seating rows. In addition, the dynamic behaviour of these *bridge* structures has to be considered. Furthermore, there needs to be a solution to provide the gate, as well as seating rows during events. This can be found in retractable seating.

The movable seating structure can move on the same surface as the pitch and retract during pitch operation. A combination of retractable seating in the lower tier and a *bridge* structure for supporting upper tiers can be required for stadia with a high capacity. During an event, when the spectator accommodation areas are used, there is usually the pitch inside or outside the stadium. Thus, there can be temporary props for the *bridge* structure. This has advantages for both, the static as well as the dynamic behaviour.

A surface and *tracks* are required for the movement of the pitch. Technology used for moving the pitch includes (from page 37 in [62]):

- *Discrete air pads*
- *Discrete bogies on wheels*
- *Discrete sliding bearings*
- *Air cushion*

3.3.3.1 Examples of movable pitches

Veltins Arena, Gelsenkirchen, Germany

A movable pitch structure can be found at the *Veltins Arena*, in Gelsenkirchen, Germany. The stadium opened in 2001. The movable activity area has a size of 118m x 79m, a weight of 11,400t and is transported in a 1.50m tall concrete tray. The movement is achieved by four gripper-jacks, which push the structure. The surface for the movement is formed by a 120m x 80m reinforced concrete slab. For horizontal control during the operation, coated rails are used. During motion, they are subjected to high lateral loads. The tray for the activity area is made of pre-stressed reinforced concrete and has 400 PTFE coated foots (coefficient of friction = 0.08). For the link between the two pitch configurations, a gate is provided at the south stand. Three steel trusses form the *bridge* structure, which supports the upper concrete tier. The lower tier is made of a retractable steel structure. During operation of the pitch, the steel trusses act as single span girders. However, during an event, when the structure is subjected to live loads, retractable props are set to convert the single-span system into a three-span system. Fig. 3.20 and Fig. 3.21 show this *gate* from the outside and during construction (see Fig. 3.21, right image).

During events with the grass pitch inside the arena, the concrete slab outside is used as car park. In addition, the stadium has a movable roof. [42], [43]

Fig. 3.20: *Veltins Arena*: pitch outside the stadium and the stand that provides the gate

Fig. 3.21: *Veltins Arena*: left: Gate for movable pitch; right: Under construction [42], [43]

Gelredome, Arnhem, the Netherlands

The *Gelredome* is a multi-purpose arena in Arnhem, in the Netherlands. In order to be independent of weather conditions, a retractable roof structure with two rigid panels was constructed. Furthermore, in order to increase healthy grow of the natural grass surface, a movable pitch is used (see Fig. 3.22). Due to the retractable pitch, the stadium can be used for concerts and other events with a more robust surface. The stadium was one of the host venues of the European Football Championship 2000 in the Netherlands and Belgium.

One stand provides the gate for the movable pitch structure. A space frame made of steel supports this stand structure. During pitch operation, the stand structure is just under self-weight. However, during an event, there are temporary props that support the stand and that reduce the span of the structure (see Fig. 3.23).

The entire 115m long and 72m wide tray for the pitch has a weight of 11,000t and is operated with a speed of 90cm per minute. [28]

Fig. 3.22: *Gelredome*: pitch outside the stadium and the stand that provides the gate

Fig. 3.23: *Gelredome*: temporary props for the stand structure and the pitch outside the stadium

***Sapporo Dome*, Sapporo, Japan**

The *Sapporo Dome* is an enclosed stadium in Japan, built for the Soccer World Cup 2002 in Japan. In order to provide a natural grass surface in the enclosed arena, the stadium got a movable pitch. The brief required a multi-purpose arena suitable for various purposes and independent of weather conditions. However, due to high snow loads in winter, a movable roof was considered inappropriate for the stadium. To provide a natural grass surface, although the roof is fixed, there is a movable pitch with a size of 85m x 120m and a height of 1.38m. The whole pitch structure has a weight of 8,300t. At the rear of the stadium, a 90m wide gate provides the link between the surface of the enclosed arena and the outside. During events, this gate can be closed by retractable seating elements (see Fig. 3.24) and, vice-versa, opened for pitch operation. The gate from the outside, as well as from the inside can be seen in Fig. 3.25. In addition, the pitch makes a 90° rotation within the stadium for the football-configuration (see Fig. 3.26). The pitch structure moves on 34 electrically operated wheels and can be raised 7.5cm by an air cushion system. An operation speed of four meters per minute is achieved. [64]

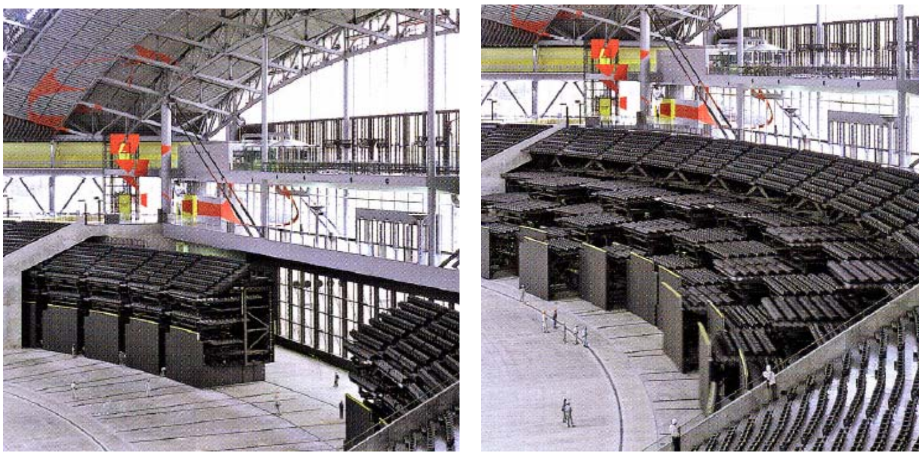


Fig. 3.24: Telescopic seating at the *Sapporo Dome* [64]

Fig. 3.25: *Sapporo Dome*: gate for movable pitch [64]

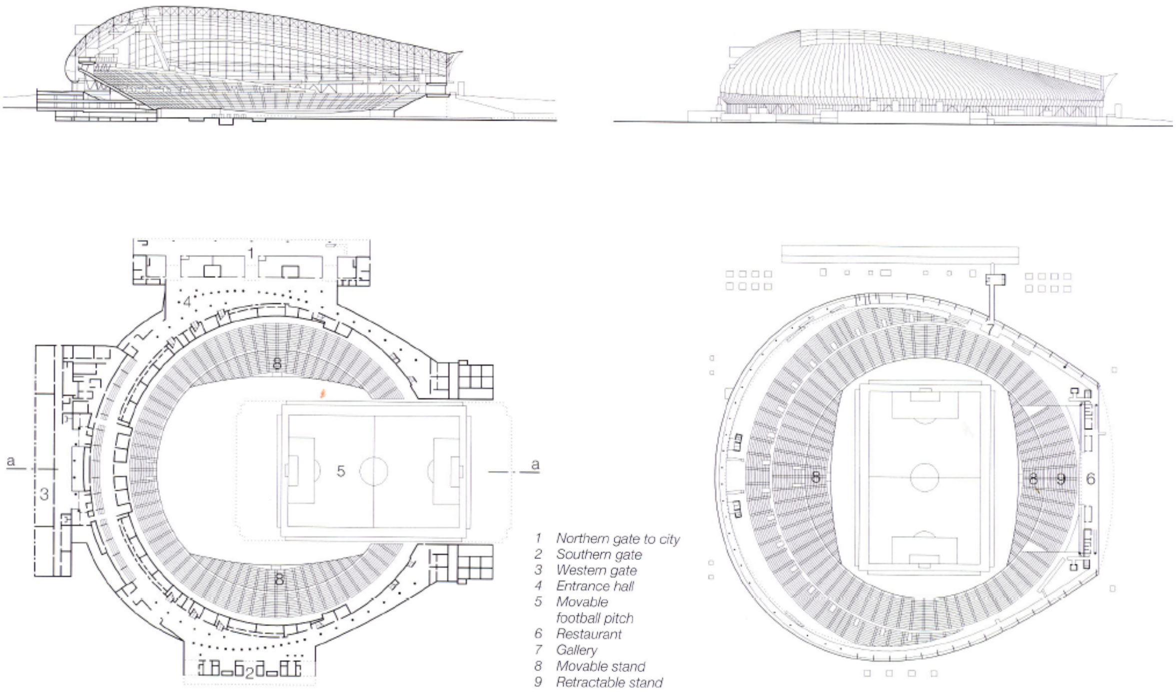


Fig. 3.26: *Sapporo Dome*: pitch operation [64]

4 STRUCTURAL DESIGN OF STADIA

4.1 Introduction

The structural design itself has to ensure stability and fitness for the intended use. Loads applied on the structure, have to be safely transferred to foundations and, furthermore, to the foundation ground. The form of a stadium is determined by the parameters, as listed in chapter 2, as well as by the adaptability requirements discussed in chapter 3. During the architectural design, forms of the building are developed. These forms of stands, terraces, roofs, and other elements determine the structural design. Hence, during the architectural design, the structural engineer should already play an active part. Section 4.2 gives an overview of typical forms of stadia.

Various materials can be used for the construction of the structural elements of stadia. Section 4.3 gives an overview of these materials as well as of advantages and disadvantages.

The main structural elements of stadia are roofs and stands, which are discussed in section 4.4 and section 4.5. Most of the facilities needed for spectators, players, club offices, and suchlike are accommodated in the stands. Hence, the supporting structure for the seating tiers is also the load bearing structure for other facilities. In addition, there are structural elements, such as stairs and ramps, required for vertical circulation of spectators.

Not only the structure of the building itself, but also its interaction with the foundation soil is part of the structural design (see section 4.6).

4.2 Geometry

The form of a stadium is mostly defined by requirements of spectator viewing, as discussed in section 2.6.2. Maximum and recommended viewing distances define the area of spectator accommodation, although three-dimensional effects must be considered. In addition, the form of the stadium is also determined by an architectural design. The optimum of spectator accommodation would be in a circle (*optimum viewing circle*) around the pitch (see image A in Fig. 4.1). For football stadium in the UK, for example, there was (is) a tradition to design stands as rectangular structures parallel to the sidelines of the pitch (see image B inFig. 4.1). This configuration provides the advantage of adding or dismantling stands, as needed. Other options for the form of stands are shown in image C and image D in Fig. 4.1. The first is the accommodation in an ellipse (a modification of the circle), the latter an extension of rectangular stands with seats in the corners. These are just some principal examples, various other configurations are possible.

Not only the ground configuration, but also the configuration of the stands in the view of a cross section is important. Spectators can be accommodated in single tier stands or in multi-tier stands (see Fig. 4.2). The form of the tiers itself is determined by sightlines, as discussed in section 2.6.2. In the case of a multi-tier stand, the change from one tier to another one can either be formed by a single *super riser* or by a cantilever tier (see Fig. 4.2). The impact on the entire structure is that, due to the cantilever, spectators are closer to the pitch. In addition, this reduces the span of the canopy roof structure. The change between tiers is usually used for hospitality areas and private boxes, either with adjacent seating rows or not.

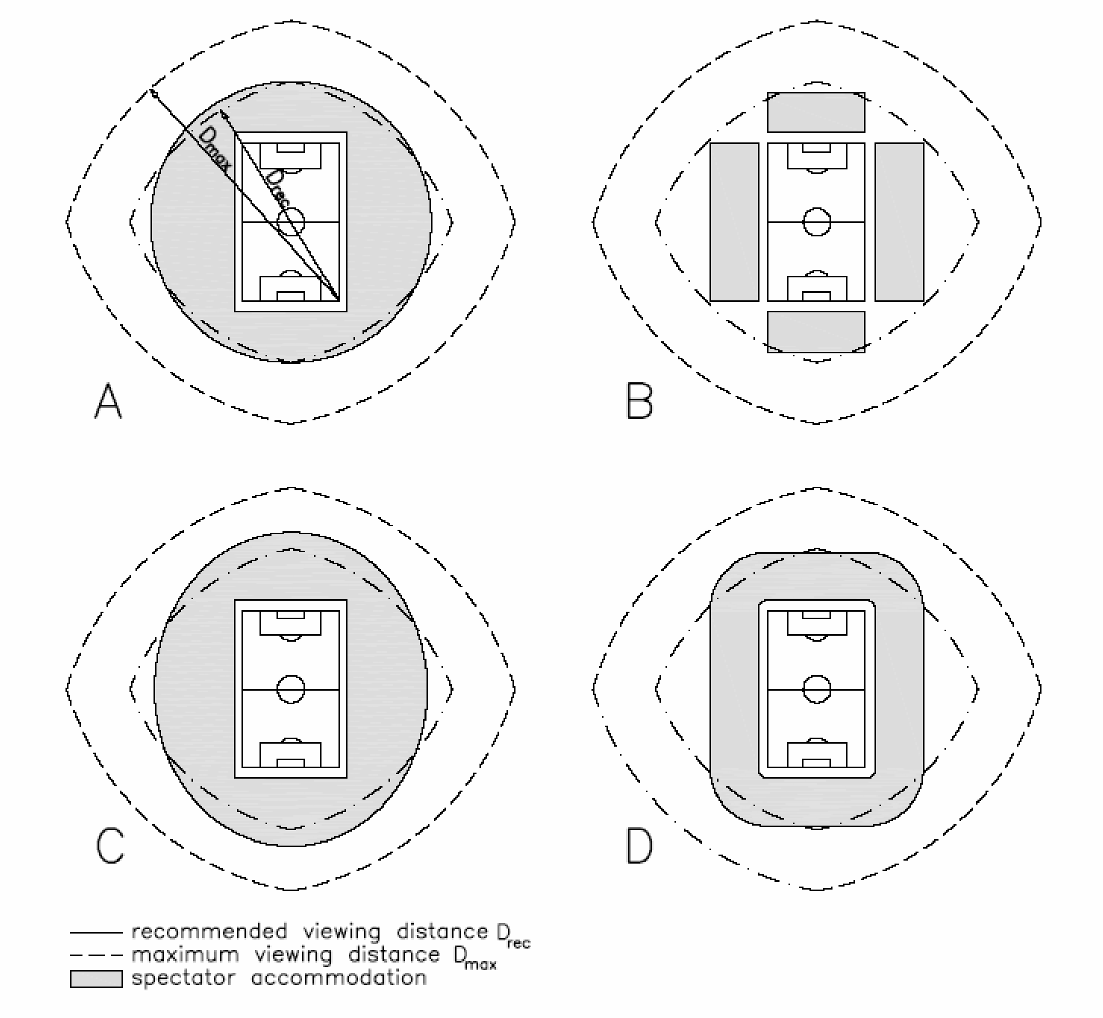


Fig. 4.1: Ground plan configurations for spectator accommodation

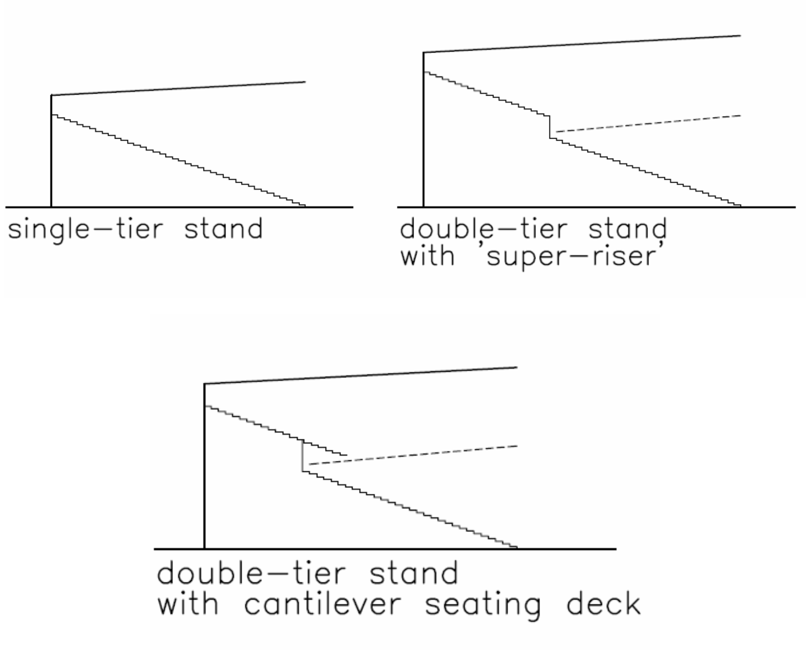


Fig. 4.2: Cross sections shows various stand configurations

4.3 Materials

Various construction materials, as well as various cladding materials for roofs and walls are used for the construction of stadia. Each one of these materials has certain advantages.

The last century brought new materials for applications needed at stadia. Because structures for sports stadia are often longspan, the dead weight of materials needs to be low. However, other technical aspects like fire resistance and durability have also to be considered. Superstructure and substructure build a main part of the total capital costs [38]. Therefore, costs of materials are a major factor for the success of a project. [37]

In the past, venues have been built using materials like brick and stone. The materials for the main structural elements of modern stadia are steel and concrete. The use of timber, brickwork, aluminium, and plastic fabrics can be appropriate in special applications.

Not only technical aspects, but also the surfaces, which determine the visual effect of the building, are of interest. Various cladding materials and finishes are used. Cladding materials, by their dead weights, also influence the structural design. They transfer loads to the main structural elements.

4.3.1 Steel

Due to its many advantages, steel is a material often used for structures of sports stadia. However, there are situations, where the use of other materials could be more satisfactory.

Advantages of steel include higher quality and better time-management, as well as functional advantages for the architectural design. Steel is a manufactured product, which means the quality control is high. Various types with various properties are available. In addition, compared to structures made of concrete, in some countries there might be a cost advantage for steel. [37]

For better time and site management, prefabrication off-site is used. At stadia, where the construction time often needs to be short, high construction speed and prefabrication is necessary. Functional advantages result from the high strength-to-weight ratio of steel. Therefore, steel structures can gracefully span long distances without internal columns for support. This is necessary in stadia, because the view of spectators has to be unobstructed and, thus, there can only be supports at the perimeter of the stands.

Due to the lower weight of the structure, cheaper foundation is also an advantage. In particular, in poor ground conditions, this can lead to savings. In addition, steel is a ductile material, which is of advantage for long-term integrity when dynamic loads are applied. Various forms of structures can be constructed with steel without formwork as it is needed for in-situ concrete structures. Due to various forms of steel elements, impressive and attractive structures can be achieved. [16]

These are all reasons, why steel is often chosen for roof structures and steel may also be chosen for the supporting structure of stands. However, there are disadvantages to steel.

The fire resistance of unprotected steel structures may be insufficient. To achieve the required fire resistance, protective coatings may be necessary. Solutions include encasing the steel elements, spraying the elements with mineral fibre of vermiculite cement, or thin-film intumescent coating. If protection is necessary, cost advantages may be lost. The main danger, in the event of a fire, is not of the structural collapse but smoke suffocation. As discussed in section 2.7.5, *fire-engineering* can be used to ensure a high level of safety in the event of a fire. Unprotected steel can be used, provided that spectators can escape safely from the stadium within a defined time, or other provision for safety of spectators is made. [37]

Another point to be considered for steel structures is the prevention of the formation of rust on low-carbon equivalent steels. A form of protective coating must be applied. The choice of solution influences the required maintenance. The protection can be a combination of metal spray and a paint system, or galvanizing.

Weathering steel, which has a higher corrosion resistance, could be used for roof structures. Its certain advantage is that maintenance effort would be lower. The rate of specific elements like chromium, copper, vanadium, and phosphorus is higher in weathering steel. Rust is produced in the same way as for low-carbon equivalent steel, but the rate of rust growth reduces considerably. This reduction occurs because the access of oxygen and moisture to the steel surface is impeded by these elements. However, the oxidation is not stopped, but continues over the whole lifetime. This has to be considered in the design, as well as in the maintenance. [16]

Fabrication influences the properties of steel. Various forms of hot rolled shapes are used for structural elements. High-grade steel (e.g. S355 J2) has a better cost to strength ratio, compared with lower-grade steel (e.g. S275 J2). For this reason, it is generally economic to use high-grade steel and it leads typically to a 20% cost advantage. Where deflection limitations are the criteria, lower grade steel could be more economical. [16]

Tolerances, especially when structures are prefabricated, are of major consideration during the design. Though steel structures are prefabricated at manufacturing sites, close tolerances may be expensive.

For connection the prefabricated elements at site, welding and bolting can be used. If welding is used for profiles or connections, distortion can cause dimensional variations. Distortion arises due to the shrinkage of the molten metal as it cools. [16]

Steel is sometimes chosen as material for the supporting structure of stands. Where stadia are used for pop concerts, a high natural frequency of the structure is necessary. However, steel is a flexible material. Another construction material, like concrete, may be more suitable for a more rigid structure.

Steel and concrete have virtually identical coefficients of thermal expansion. Therefore, the combination of both materials is no problem. For grandstands, a combination of concrete and steel elements is often used.

4.3.2 Concrete

In the design of stadium structures, concrete is as important as steel. It is a versatile material used for seating units, supporting structures of stands, as well as in some cases for roof structures.

An advantage of concrete is that it is inherently more robust in a fire than steel. This can make concrete economical compared to steel, if high fire resistance is necessary. Components for concrete are available nearly everywhere. Steel on the other hand, may have to be transported a considerable distance. Hence, in some regions, concrete may be cheaper than steel.

Usually, concrete structures are left unfinished without any protecting façade. Design and detailing must ensure a high quality of unfinished concrete structures, to avoid streaks and stains on the surface. If an unfinished concrete surface is not wanted, cladding materials or finishes could be added.

Due to its characteristics, concrete is the only practical material for the construction of seating units of a stadium. However, concrete can also be used to design and construct impressive roof structures.

In situ concrete or pre-cast elements, as well as pre-stressed and post-tensioned concrete are used. [37]

In situ concrete:

A disadvantage of in situ concrete is the formwork required. Though in situ concrete was used to build architectural and structural impressive roofs like the *Palazzetto dello Sport* in Rome, Italy, its use for roof structures has diminished since the development of lightweight structural forms. However, in situ concrete is still important and can be used for all structural elements of a stadium. [37]

Pre-cast concrete:

The advantages of pre-cast concrete are similar to advantages of pre-fabricated steel elements. These are off-site construction in a controlled climate and, therefore, better time-management. Pre-fabrication is necessary, when a short construction time is required to reduce the effects on the operation of the stadium. Pre-cast concrete is the standard solution for seating units. [37]

Pre-stressed and post-tensioned concrete:

Pre-stressing and post-tensioning allow concrete structures to be thin and light. Special consideration is necessary for their jointing. Both are useful techniques for stadium structures. Thermal movement of the structure is important, because stadia are long buildings. Usually, expansion joints are designed to allow thermal movement. If post-tensioning is used, these joints can be reduced, or may even be unnecessary. The entire structure is held together by the tensioned reinforcement rods. Two examples in the UK for this technique are the South Stand at *Twickenham Rugby Football Ground*, London and the West Stand (also known as the Sir Stanley Rous Stand) at *Waterford Football Club*. [37]

4.3.3 Other construction materials

Timber:

The *Football Stadia Advisory Design Council* (FSADC) recommended timber should only be used for the roof supporting structure of a small stand. Timber structures for longer spans are normally too expensive. Another reason is the required protection against fire, insect attack and fungal decay. In addition, these result in continuous maintenance works.

Usually softwoods are used for structural elements. With larger sections, made of glue-laminated timber (glulam), longer spans can be achieved. [23]

Nevertheless, timber can be used to design attractive buildings and stands for sports venues. These structures can be more attractive ecologically than other materials, because timber is a natural construction material with low energy use in production.

There are various examples of sports grounds in Austria, where timber structures were used. However, these are small stadia. A recent example is *Stattegg Sports and Leisure Facility* in Styria (designers: Hohensinn Architektur). [37]

Aluminium:

Aluminium is more expensive, but has a higher strength-to-weight ratio than steel. For this reason, it is only used as structural element for special purposes, where a higher strength-to-weight ratio offers advantages [23]. For temporary demountable structures, aluminium can be used to reduce the dead weight and, thus, make the structure easier to handle.

4.3.4 Materials for roof covering

Roof covering materials are required to close the gaps between the structural elements of the roof structure. Various materials are used for this purpose (from page 20 in [23]): *Materials need to be lightweight, tough, incombustible, aesthetically acceptable, cost-effective, and durable enough to withstand the effects of outdoor weathering, including ultra-violet light. They should also be strong and stiff enough to span between primary and secondary elements, supporting snow and other superimposed loads, including wind forces. Over the facility areas of stands and stadia, such as private boxes, kitchens, restaurants and toilets, the roof construction may require additional thermal and/or acoustic insulation.*

The roof covering material may be required to allow sunlight onto the pitch, for reasons as discussed in section 2.5.1. Other determining factors for the roof surface could include better conditions for media purposes. Transparent or translucent materials can be used for these reasons. Where this is not a problem, opaque covering materials are a cheap solution and, therefore, commonly used.

Materials used for roof covering include [23]:

- Metal sheeting
- Concrete
- Timber
- Rigid plastics
- Fabrics

Another decision to be made is how to fix the roof covering material onto the main structural elements. There are two options, either above or beneath the structural elements. The problem is that pigeons would be able to nest in the structure, if the roof covering was fixed above the elements. However if the covering is beneath the structure they would be unable to nest in the structure. In addition, painting the structural elements is easier from above, than building a scaffold, which, in addition, may be difficult to erect due to the steps in the seating tiers.

4.4 Stand structure

The stands have not only the function of providing spectators accommodation and good views onto the pitch, but also the function of providing *under terrace* accommodation. Therefore, the stand structure is discussed in two parts: the *seating elements* and the *supporting main stand structure*. In this context, various loads have to be considered in the assessment of stand structures.

4.4.1 Loads

- Dead loads:

Stand structures are usually made of reinforced concrete, steel or of a combination of both materials. Dead loads are permanently acting and, therefore, must be considered in all load combinations.

- Live loads:

Live loads are caused by spectator circulation, as well as by the intended additional uses. In particular, for multi-purpose stadia with secondary uses, various live loads are to be considered. However, live loads caused by spectators of events are usually the highest. Live loads for sports use are defined in *ÖNORM B 1991-1-1* [55]:

Live load on floor slabs:	Category C5: $q_k = 5.0\text{kN/m}^2$
Live load on concourses:	Category C5: $q_k = 6.0\text{kN/m}^2$
Live loads on stairs and ramps:	Category C5: $q_k = 6.0\text{kN/m}^2$
Live loads in areas of seating accommodation:	Category C2: $q_k = 4.0\text{kN/m}^2$

- Snow loads:

Spectator seating rows in partly roofed stadia are exposed to the elements. In this case, the structure can be subjected to snow loads. However, spectator accommodation and snow on the structure is an unlikely combination of loads.

- Wind loads:

For stand structures wind loads, especially lateral wind loads, must be considered. In particular, lateral stability is affected by these loads.

- Temperature change effects:

Stadium structures are long exposed buildings, subjected to high temperature changes. Expansion joints are required to allow movements of the structure.

- Earthquake loads (depending on the site)
- Loads from supported structures:

Stand structures can be subjected to loads from roof structures and other supported structures. In particular, roof structures transfer high loads to structural elements of stands. Due to wind loads on the roof and depending on the type of roof structure, these supported loads may change in direction. These effects have to be considered in the assessment of stand structures. In addition, high lateral loads and overturning moments can be transferred from the roof structure to the stand structure, which affects the lateral stability of the structure.

- Lateral loads on barriers:

  Lateral loads on barriers are also defined in ÖNORM B 1991-1-1 [55]:

  For Category C2: $q_k = 1.0$kN/m (in areas with seated accommodation)

  For Category C5: $q_k = 3.0$kN/m

  The *Guide to Safety at Sports Grounds* [30] gives lateral loads, depending on the type of barrier between 1.0kN/m and 5.0kN/m (see page 87 ff in [30]).

4.4.2 Dynamic performance of stands

In addition to static loads there are dynamic load effects to be considered in the design of stadia, especially in the design and assessment of stands. General dynamic load effects on stadia structures can be caused by [30]:

- Excitation by wind
- Excitation by the activity of spectators

Excitation by wind is to be considered in roof structures, but is not relevant for the stand structure. Hence, the excitation of grandstand structures by the activity of spectators is much more important in this context. Due to an increasing use of sports venues for events like pop and rock concerts, stadia structures are subjected to rhythmic dynamic loads caused by spectators. In addition, longer spans of stand structure and reduced supports for larger spaces within the structures increases the consideration of these dynamic effects. Cantilever seating tiers are designed to offer unobstructed views without columns between the rows of spectators. Longspan, lightweight structures, as well as cantilever structures are consequently more sensitive to dynamic effects, due to lower natural frequencies than more massive structures.

Dynamic effects in properly designed, robust grandstand structures are usually not a problem of structural failure. It is more a problem of motions that could cause discomfort to spectators. Hence, structural design limits and serviceability limits are required to avoid such motions.

The increased importance of such effects in stadia was also caused by venues, which required structural modification due to motions that caused concerns to spectators (e.g. *Millennium Stadium*, Cardiff, UK). Therefore, design guides and standards were needed, which took various events at sports venues into account and provided guidance for the structural design. However, due to the materials used and structural solutions, there are differences between permanent and temporary structures.

Guidance for dynamic performance of grandstands and design limits can be found in:

- *Dynamic performance requirements for permanent grandstands subject to crowd action, Interim guidance on assessment and design* by The Institution of Structural Engineers, 2001 [79]:

  The guide refers to permanent grandstand structures with seating decks in steel, concrete or composite construction, with supported spans greater than 6.0m or cantilever spans greater than 2.5m. It sets *trigger values* for natural frequencies, depending on different categories of intended use, as a precursor to a requirement for a more detailed dynamic evaluation.

- *Guide to safety at Sports Grounds, 4th Edition*, by The Stationary Office, 1997 [30]:

  The guide gives *trigger values* for natural frequencies of permanent seating decks, as a precursor to a requirement for a more detailed dynamic evaluation.

- Standards and Building Regulations:

  BS 6399: *Loadings for Buildings, Part 1: Code of practice for dead and imposed loads*, British Standard Institution, 1996

Dynamic forces and dynamic structural response:

Dynamic forces induced by crowd behaviour at stadia depend on many parameters. First of all, there are two types of action: a sudden concerted single action and a repeated action. The first is generally not of serious concern, because it dies away relative quickly. Such an action, can be spectators standing up when a goal is scored. The second type, when spectators are inducing repeated action can be rhythmic jumping, bobbing (sometimes referred to as bouncing), or swaying, during pop concerts for instance, where a musical beat can excite coordinated spectator movement. From the view of structural safety, repeated dynamic forces are of concern, when the excitation frequency is close to the natural frequency of a mode of the structure, because it can lead to resonance. [87]

Repeated dynamic forces can be expressed as harmonic forces, which vary with time as a sine wave. The forces induced by a crowd of spectators can be expressed as a sum of harmonic forces, each with is own magnitude and phase. The force acting at the basic rate of the activity is the first harmonic or fundamental frequency. The second harmonic is acting at twice the basic rate, the third at three times the basic rate, and so on. The magnitude decreases for higher harmonics and hence, the first is the largest. Repeated dynamic forces can be set in relation to a *dynamic load factor*. [87]

To achieve higher frequencies the coordination has to be better. This is less likely for a crowd of spectators than for individuals and, therefore, only low frequencies should be considered. However, as the coordination caused by the event increases, there can be higher frequencies required to be considered (from page 11 in [79]):

- *Spectator event with no singing or music played; first harmonic dominant*
- *Event with singing, but without musical accompaniment; some influence of second harmonic*
- *Event with some audience participation with singing to musical accompaniment but without impacting motion; first and second harmonics significant*
- *Dedicated pop or rock concert with audience participation and likelihood of jumping; first and second harmonics very important with the third harmonic becoming influential only if the audience reaction were unusually well synchronised*

The natural modes are the free vibration frequencies of the structure. Only the lower modes of natural frequencies of a structure are to be considered for the dynamic behaviour induced by crowds of spectators. The reason lies in the coordination of the group as discussed above.

Vertical and horizontal modes are defined as (from page 12 in [79]):

- *A 'vertical' mode is one that has a significant component of vertical displacement at the seating deck, such that it may be excited by the vertical dynamic load due to the crowd.*
- *A 'horizontal' mode is one that has a significant component of horizontal displacement in the front-to-back ('lateral') or side-to-side ('longitudinal') directions at the seating deck, such that it may be excited by a horizontal dynamic load introduced by the crowd.*

The structural response due to dynamic excitation depends on both the excitation frequency and the natural frequency of the structure. In the case of a much higher excitation frequency as the mode of the structure, as well as in the case of a much lower excitation frequency as the mode of the structure, the cyclical deflection of the structure is not more than the statically deflection due to the peak force. However, when both frequencies are close together, resonance can occur. In this case, the response can build up cycle by cycle up to a limiting response, which can be much higher than the statically response. The highest deflection is caused when the excitation frequency is equal the natural frequency (see Fig. 4.3 left image). In this case, the dynamic amplification factor is $1 / (2\xi)$, where ξ is the damping ratio [87].

The highest forces due to dynamic excitation in stadia are caused by coordinated jumping or bobbing during pop concerts. In addition, the spectators may stamp, clap, or sway in time to the music. Higher dynamic excitation is achieved by jumping. However, jumping in raked rows of spectator accommodation in stands is difficult and uncomfortable due to fixed seats and less space. Therefore, bobbing due to the musical beat at pop concerts can be seen as the more relevant action. Bobbing is described as *rhythmic activity causing vertical motion during which contact with the structure is maintained at all times* (from page 32 in [17]). The coordination of spectators is the essential factor. Individuals can achieve vertical excitation frequencies of up to 3.5Hz or 4Hz but, due to the problem of coordination of crowds of people, such groups can hardly achieve frequencies above 2.75Hz. Dynamic load factors achieved by groups of people are shown in Fig. 4.3 (right image). In addition, the dynamic load factor for people jumping depends on the contact time ratio (ratio of time(s) in contact with structure to period of jumping(s)) [87].

The DLF at frequency f (>3.5Hz) for a group of 20 jumping people can be expressed as (from page 48 in [87])

$$\mathrm{DLF}_{20} = 0.011 \bullet (11.0 - \mathrm{f})^{2.1} \leq 0.60$$

For larger groups of N people

$$\mathrm{DF}_{\mathrm{LN}} = \mathrm{DLF}_{20} \bullet (\frac{20}{\mathrm{N}})^{\gamma} \quad \textit{where} \quad \gamma = 0.24 + 0.03 \bullet (\mathrm{f} - 4.0)$$

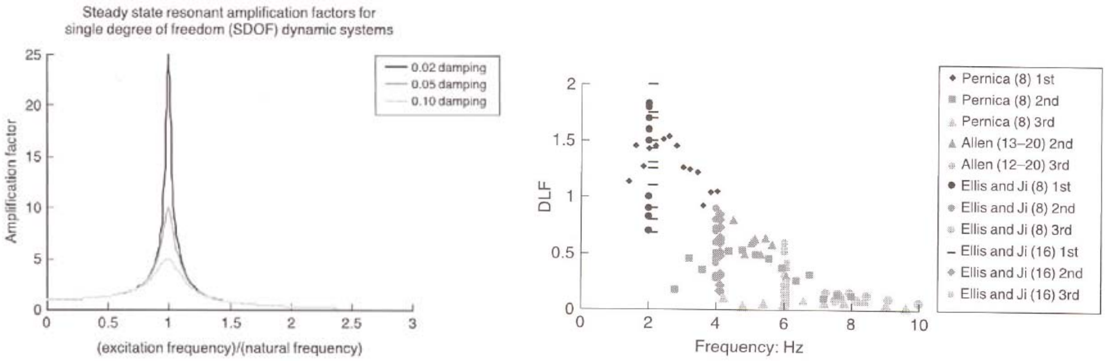


Fig. 4.3: left:Resonance amplification curves; right: Measured DLFs for group jumping [87]

In addition to vertical dynamic forces, lateral dynamic effects can be caused by spectators. Side-to-side action can be induced by swaying. Back-to-back excitation by spectators is generally small and not of concern. Frequencies and dynamic load factors for lateral dynamic effects are shown in Tab. 4.1.

Direction of sway	Frequency range: Hz	Dynamic load factor (1^{st} harmonic)
Left – right	0.5 – 1.5	0.25
Front – back	0.5 – 1.5	0.05

Tab. 4.1: Dynamic load factors assumed for swaying [87]

Various types of events:

As mentioned previously, the excitation frequency depends on the crowd of spectators. Hence different events with different behaviour of spectators require different limiting natural frequencies of the structure. The design has to ensure adequate conditions for the intended variety of uses of the stadium. The worst case for the dynamic behaviour induced by a jumping crowd may occur during pop or rock concerts. Structures for use in events where crowds induce dynamic loads through jumping generally require natural vertical frequencies higher than 6Hz (see [30] and [79]). As already stated, a crowd of people hardly achieves excitation frequencies above 2.75Hz. However, twice the frequency is 5.5Hz and the natural frequency should be above that. In the case of sports events, the required natural frequency of the structure is lower, because the induced excitation frequency is lower. This difference is also considered in the design guides.

Dynamic design requirements:

The design of grandstands has to ensure structural safety, as well as motions which do not cause discomfort or panic to spectators. The dynamic design requirements for grandstands are expressed by fundamental natural frequencies for vibration in vertical and lateral direction. When the natural frequency of the structure is lower than the minimum frequencies required by the guides, the structure can cause problems for the intended use and additional action may be required. Depending on the nature of the event, dynamic requirements for grandstands are [79]:

- Grandstands used solely for viewing events including sport:

  In the case of sports, resonance at the first harmonic should be avoided, which means a minimum vertical natural frequency above 3.5Hz or even 3.0Hz for an empty stand.

- Incidental music:

  Incidental music should not lead to any problems when the vertical fundamental frequency is above 5.0Hz for an empty stand. However, the management should ensure safety of spectators through monitoring and through the selection of incidental music.

- Pop concerts and their requirements:

  Due to better coordination by the beat of the music, the second harmonic of crowd jumping can be seen as the determining factor. Hence, a vertical fundamental frequency above 6.0Hz for an empty stand should avoid discomfort to spectators.

Fig. 4.4 and Fig. 4.5 show the limits discussed above and the required actions for permanent grandstands (empty stands) according to the Institution of Structural Engineers guide *Dynamic performance requirements for permanent grandstands subject to crowd action* [79]. The first figure shows the limits depending on the nature of the event. Stands with a vertical natural frequency less than 3.0Hz require immediate action. Existing stands with a vertical frequency between 3.0Hz and 3.5Hz can be used for sports events, but this depends on past experiences with the structure. For stands with a frequency higher than 3.5Hz there could still be problems serviceability and, thus, there might be a restriction to the use for sports events. Structures with vertical frequencies above 6.0Hz can be seen as suitable for all types of events. [79]

Fig. 4.5 is a flow diagram for the management of stadia and it should provide the outcome that the frequency of the structure is high enough for the intended use. Otherwise, there is information which action must be undertaken by the management.

In addition, the horizontal dynamic behaviour must be determined. For permanent grandstands, the horizontal behaviour should be ensured by the required limits of vertical fundamental frequencies. However, the horizontal dynamic behaviour may be of interest for temporary demountable grandstand structures. In such structures, stiffness for adequate horizontal response is to be considered. [79]

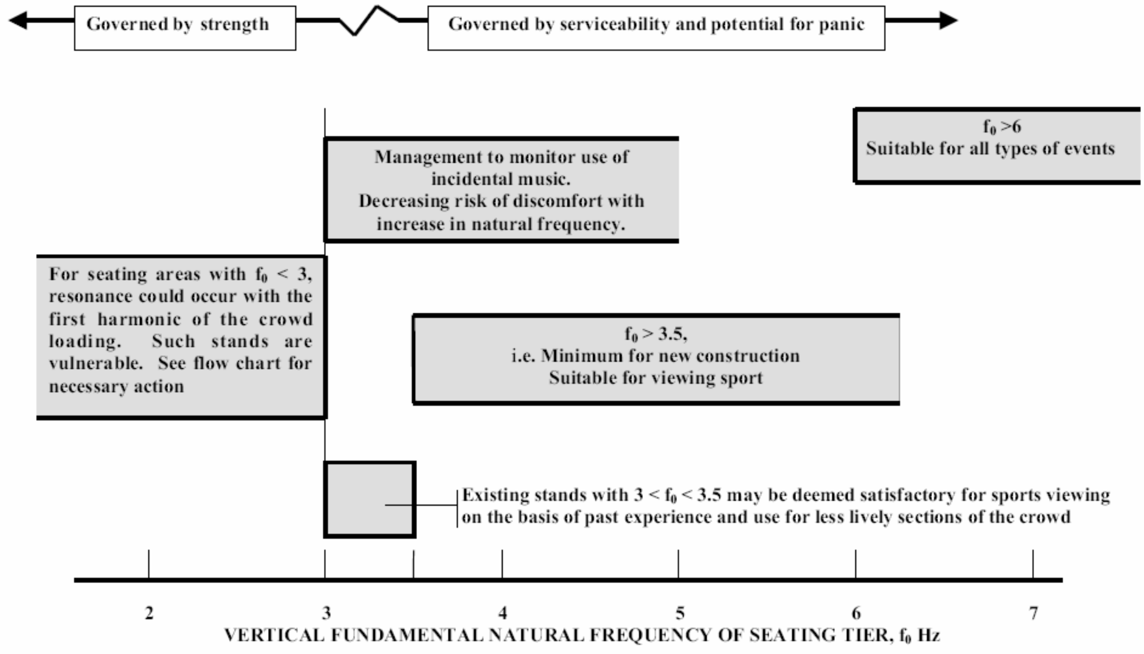


Figure 1 Frequency criteria for assessment and design

Fig. 4.4: Frequency criteria for assessment and design [79]

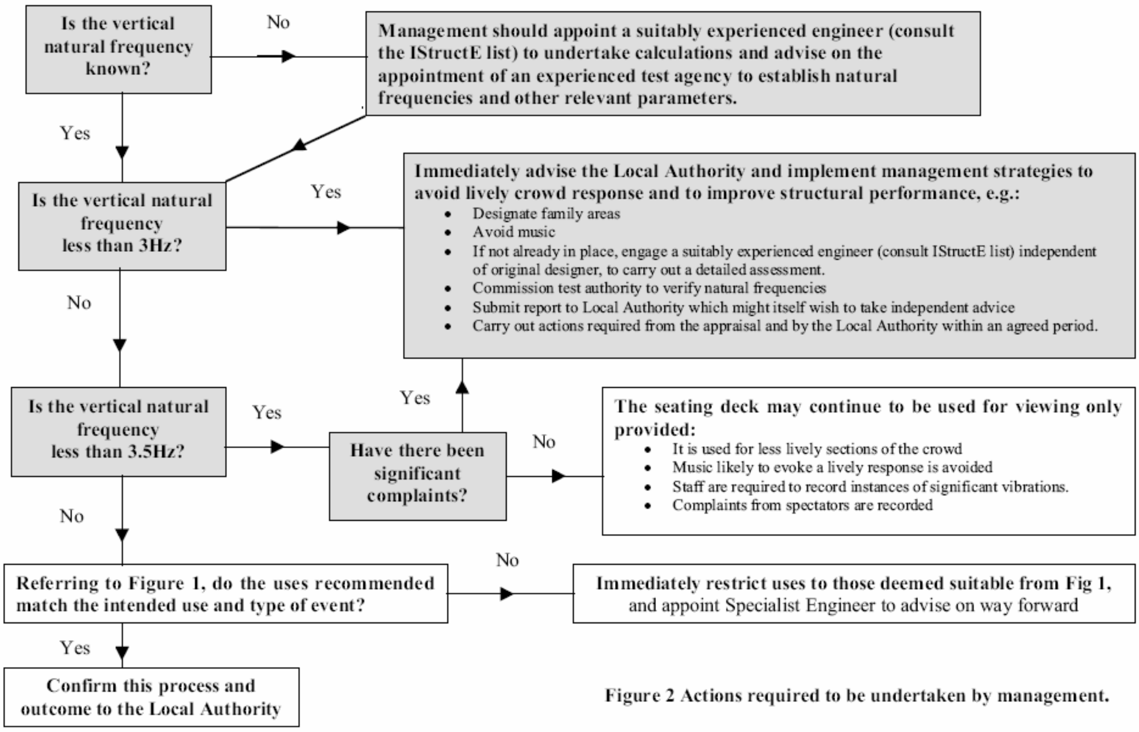


Figure 2 Actions required to be undertaken by management.

Fig. 4.5: Actions required to be undertaken by management [79]

In existing stadia with intended additional uses such as pop concerts, and structures with low natural frequencies, temporary measures may be required to stage these types of events. These can be either measures to stiffen the structure or measures provided by the management of the event. Measures to control vibration of the structure during certain events can be (from page 53 in [87]):

- Introduce temporary or retractable props for lively events
- Provide vibration dampers
- Keep the first few rows of seats (of cantilevers tier) empty when lively activity is anticipated
- Provide stewarding to control audience activities
- Disconnect the sound system if vibrations exceed a determined level

At the *Millennium Stadium* in Cardiff, UK, for example, the long cantilever seating deck of the second tier was subjected to excitations, which caused discomfort for spectators during pop concerts. However, it was not a problem during sports events. The solution was found in a temporary, retractable prop (see Fig. 4.6), which is used during concerts and folded back during sports events.

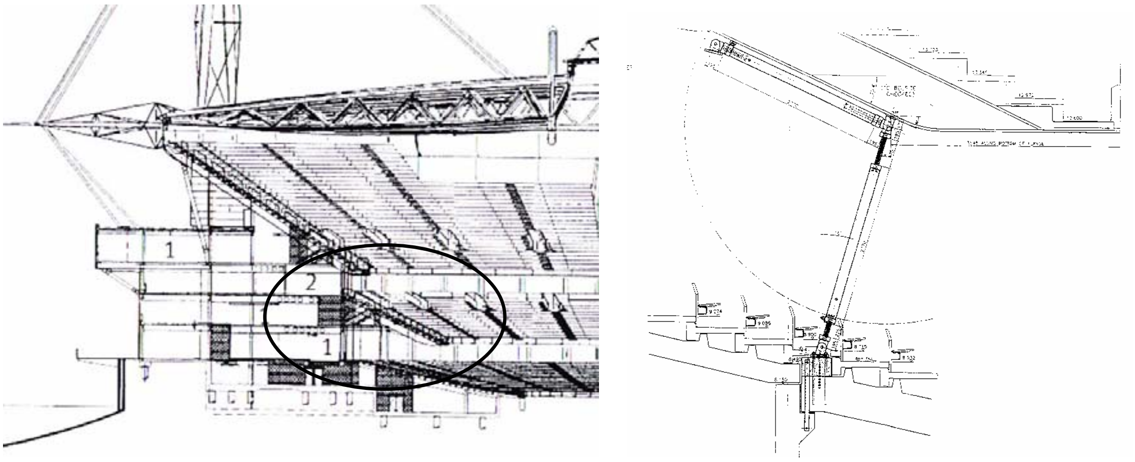


Fig. 4.6: *Millennium Stadium*, Cardiff, UK: left: Cross section; right: Temporary, retractable prop of the cantilever seating tier [62]

Determination of natural frequencies:

As the guides recommend limiting natural frequencies, they are the key parameters and have to be determined either by calculation or, for existing stands, by testing. The easiest method of calculating natural frequencies is by hand, which has the advantage of being easy. However, in general, the calculation is done by finite element calculation. Two dimensional or even three dimensional models can be used depending on the structure. Three dimensional effects can be caused by a non-uniform stiffness across the frames of the stand. In addition, effects from supported roofs, foundation flexibility, and non-structural elements should also be considered.

The natural frequency can also be determined by the self-weight deflection of the structure. However, it must be noted that such a short cut method can be used to estimate the natural frequency, but can also be misleading and is therefore not an adequate calculation for the evaluation for the dynamic performance of grandstand structures [79].

Ongoing research:

Research in the dynamic behaviour of grandstands due to dynamic effects by spectators is still ongoing. In the UK, a joint working group is preparing improved recommendations for design and assessment of stadia and seating decks subjected to dynamic crowd loading (see page 38 in [17]). The joint working group states that (from page 38 in [17]): *For practical grandstands and dense crowd loading, the currently recommended method of analysing performance is inadequate as omitting the effect of human structure interaction leads to a substantial overestimating of structure response*. Current recommendations are based on tests of people jumping or bobbing on a very stiff base, like *force plates*, (with thin, very stiff platform dynamometers), or stiff, structural elements. Due to the arguments that the behaviour on a flexible seating deck is the same and people could only react to large displacements of the structure, human structure interaction is currently omitted. However, there is an interaction due to *mechanical* properties of the body and the structure. This can be described with an idealised human body/structure system, which is shown in Fig. 4.7. The supporting structure, as well as the human body, is represented by a single degree-of-freedom system. For stadium structures, the contact force is the important force in the design. [17]

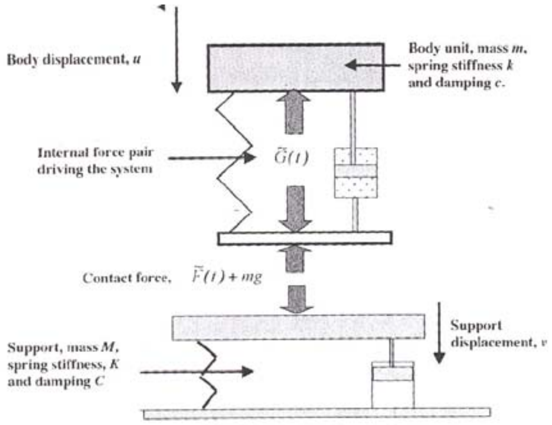


Fig. 4.7: Idealised human body/structure system [17]

4.4.3 Seating elements and main stand structure

From the point of view of structural engineering, stand structures consist of two main elements: the seating elements and the supporting structure. The main function of the stands is to accommodate spectators and provide high quality views onto the pitch. However, there are additional functions, sometimes referred to as *under terrace accommodation*, which use the large spaces under the spectator accommodation areas. The structural solution is mostly a skeleton construction, which provides the large spaces needed under the terraces.

The form of the steps for the area of spectator accommodation is determined by sightlines, which ensure high quality for spectators, as discussed in section 2.6.2. In theory, the riser height of the steps is different for each riser. However, this would be uneconomic from the point of view of construction. Therefore, the riser height is constant for some steps to allow design for economic pre-cast elements. For the supporting elements, a polygonal form results.

For the structure of supporting elements, there would either be the opportunity to span the elements from the perimeter of the stadium towards the pitch or parallel to the sides of the pitch. The first would create large spans for the seating elements. Hence, the usual solution is a structural system, which consists of main frames orthogonally to the sides of the pitch. In this case, the seating elements span between these frames, either over a single span or over two or more spans.

Due to its properties and behaviour during fire, concrete is the usual material used for seating units. Pre-stressed concrete can be used for designing lighter elements. However, the dynamic behaviour of the elements, which is influenced by the mass of the element, has to be considered.

Usual structural forms vary from single span elements to multi-span elements with spans between 6m to 8m, but sometimes even larger spans are found. However, the dynamic behaviour of the seating units has to be determined and can be critical for larger spans. The seating accommodation is usually exposed to weather conditions. Therefore, the seating elements should provide a water tight *roof* for the *under terrace uses*. The load bearing system of seating elements is one of beams and slabs. However, if an adjacent element fails, the elements is subjected to a consequential introduction of torsional moments [49]. Typical cross sections of seating units are shown in Fig. 4.8.

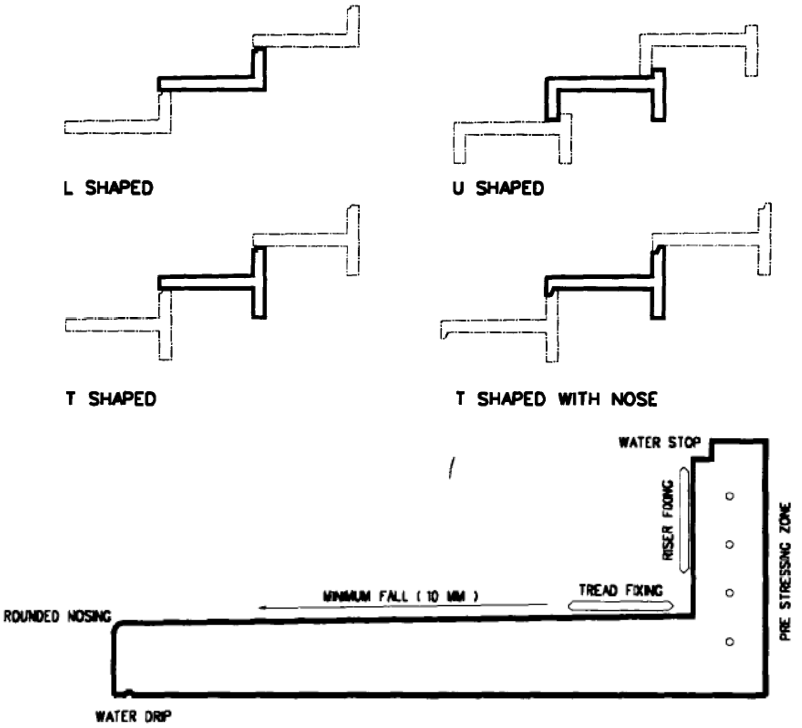


Fig. 4.8: Typical cross sections of seating units [38]

The supporting main frames can either be made of steel or concrete. In-plane stability of the main frames is achieved either by rigid frames or by bracing. The latter has the disadvantage of dividing the space within the stands. Cantilever supporting structures can, for example, result at the step between two tiers. For large cantilever spans, the dynamic behaviour has to be determined and can be critical.

The supporting structure transfers the loads applied directly to the foundations. Due to the skeleton construction, there are usually high concentrated loads. These loads are usually transferred to piled foundations. At *Croke Park* in Dublin, Ireland, the structural solution for the supporting structure is a rigid concrete frame in the form of a *Y* (see Fig. 4.9). This has the advantage of concentrating the loads on one structural element. A secondary column on the pitch side of the stand and a beam from the main concourse provide in-plane stability of the frame [50]. Overall stability of the stand structure is achieved either through a rigid frame system or through bracing. Both solutions are possible for stadia structures and sometimes a combination can be adequate. In addition, stability is required during construction.

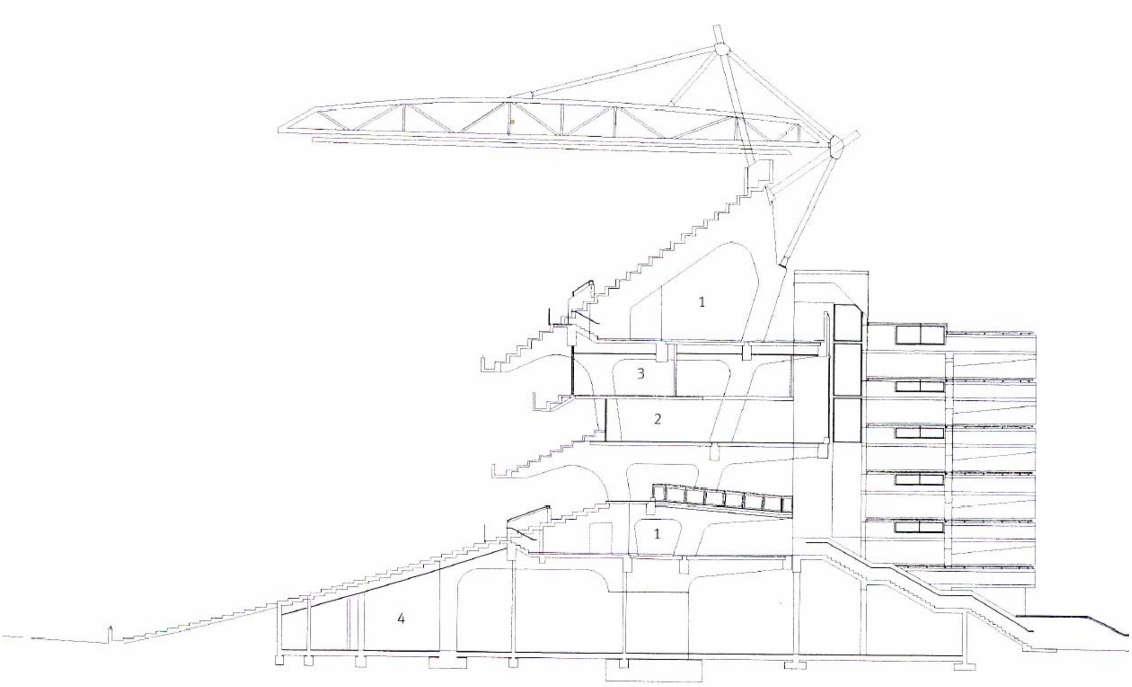


Fig. 4.9: Cross-section with ‘Y’-frame at *Croke Park*, Dublin, Ireland [67]

4.4.4 Stairs and ramps

As discussed in section 2.7.4, stairs and ramps provide vertical circulation for spectators. From the view of structural engineering, stairs and ramps are subjected to high vertical live loads due to spectator circulation. Live loads are defined in *ÖNORM B 19991-1-1* [55]:

Live loads on stairs and ramps in stadia: Category C5: $q_k = 6.0\text{kN/m}^2$

Lateral loads on barriers: Category C5: $q_k = 3.0\text{kN/m}$

The *Guide to Safety at Sports Grounds* [30] gives lateral loads, depending on the type of barrier between 1.0kN/m and 5.0kN/m (see page 87 ff in [30]).

Stairs and ramps are either found within the main stand structure or are designed as adjacent structures. The latter is often the solution for ramps due to the large spaces needed. In addition, these elements are often designed as cantilever structures. Due to the cantilever and spectator safety in circulation, the dynamic behaviour must be determined. Rigid stairwells, as well as rigid ramps can be used to increase lateral stability of a stand structure.

4.5 Roof structure

4.5.1 Roof form

From the structural point of view, the roof of a stadium is a challenge, not only due to its size but also to its form. Roof structures of stadia are mostly longspan and lightweight canopy structures in various shapes. In addition to architectural factors and in finding an appropriate form of the roof, there are functional factors to be considered.

Firstly, the roof is a shelter from the elements. It should provide protection from rain, sun, and wind. Depending on the degree of enclosure, four zones can be identified in a covered stand: A zone of good protection, moderate protection, partial protection, and an exposed zone (see Fig. 4.10). [37]

For reasons discussed in section 2.5.1, effects of the roof on the pitch should be considered when the surface of the activity area is natural grass. Shadows and reduced wind flow have an adverse effect on the durability and quality of grass. For these reasons, it may be necessary to use transparent or translucent roof covering materials. Effects of shadows on the pitch can be studied in a computer model. Such modelling should also consider any reduced wind flow, especially in continuous roofs arranged in a circle or ellipse. However, closed configurations have the advantage of creating more comfortable conditions for spectators and athletes. Stadia with gaps between the stands are better for drying of the pitch after a rain. In addition to these effects, there are other design parameters, such as regional requirements, as well as the architectural design of the roof structure to be considered. [37]

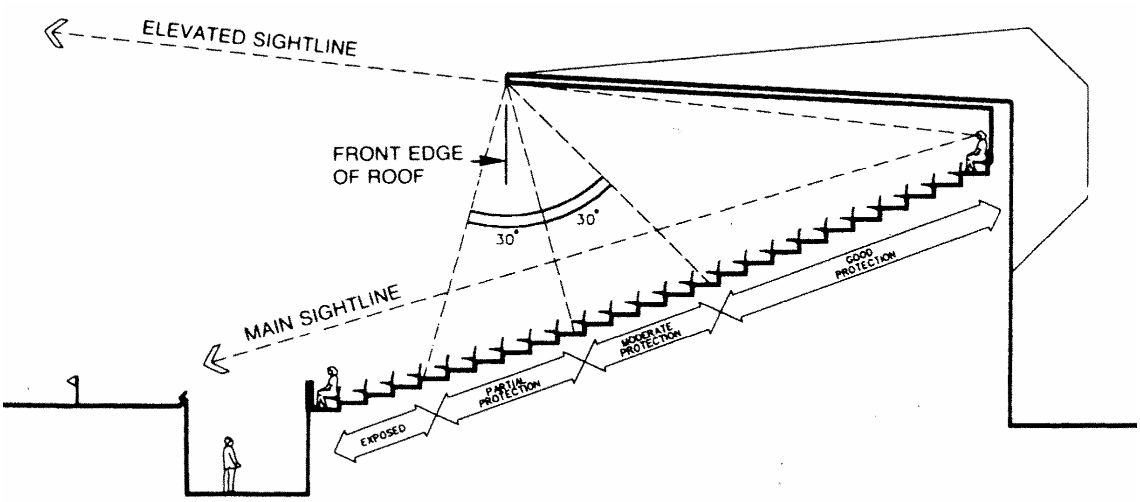


Fig. 4.10: Degree of protection offered by a stadium canopy [38]

The roof line near the pitch determines the elevated sightline (see Fig. 4.10). Spectators view at the top row of the stand should be unobstructed when the *ball* of the game is kicked high into the air. For football in the UK, the *Football Stadia Advisory Design Council* advices the elevated sightline should allow viewing to 12m (ideally 18m) above the centre circle [23]. *ÖNORM EN 13200-1:2006* [56] recommends 15m (for open air sports) above the centre of the pitch. Elevated sightlines need also to be considered at cantilever seating tiers.

In addition, the form of the roof and the roof covering material affects the acoustic within the stadium. On the other hand, if the stadium is enclosed and can be heated or cooled, the air volume within the stadium may be a determining factor. All these factors have to be considered in finding an appropriate form of the roof. [37]

4.5.2 Loads

- **Dead loads:**

Due to wide spans of the structure, the dead load is a determining factor. The self-weight is high compared to other loads.

Dead loads can also be applied by user equipment for the stadium. Such equipment can be floodlights, TV-cameras, loudspeakers, commentary boxes, or video screens. However, these loads might be applied years after construction. Video screens, for example, which have high self-weight, developed through the last two decades and, thus, they needed to be retrofitted into stadia. [23]

- **Live loads:**

Live loads are 1.0 kN/m² on a maximum area of 18m² in unfavourable position, when the roof is just accessible for maintenance works. It is not necessary to combine this load with wind and snow loads (see *ÖNORM B 1991-1-1*, *ÖNORM EN 1991-1-1*) [55]. However, live loads should be set in accordance with the required maintenance works. Maintaining the roof, or changing roof elements, can result in higher local live loads on the roof structure.

- **Snow:**

In addition to the usual snow loads, snowdrift can cause higher regional loads on the roof structure. These effects can be determined by wind tunnel tests.

- **Wind:**

Wind loads are of major consideration for the design of a roof, especially of a longspan and lightweight canopy roof for a stadium. In addition to horizontal wind loads and vertical wind pressure, the roof has to be resistant against wind-uplift. Hence, the roof has to be tied down, in addition to the support for holding it up. *Stadium Roofs* is quoted to show how important those forces are (from page 7 in [23]): *These forces should not be underestimated. Of the few grandstand roofs which have failed, more have blown away than have collapsed.*

Lightweight structures are more sensitive to wind-uplift. In addition these uplift-forces can set up oscillation of the roof beams, which must be dampened by the structure. Natural damping is determined by self-weight, which is low in lightweight structures. One solution to withstand wind-uplift is to increase the self-weight of the structure, making the roof heavy enough to withstand wind-uplift forces. This is a possible solution, though often disproportional expensive. The reason is that wind-uplift forces occur only occasionally, whereas the self-weight is permanent. Another solution to stiffen lightweight structures is to add special braces. [23], [37]

Wind forces act on roof covering or cladding elements, which can be used semi-structurally, to transmit loads to the main structural elements. Hence, they can be used to create a stiffer, less sensitive structure. This can help to control oscillation of the roof beams. The reversal in the direction of the forces also occurs on the covering and cladding elements.

Wind tunnel tests on a model are usually carried out to determine wind loads on the structure. In addition, the impact of the stadium on the surrounding area can be studied. Therefore, disruptions on the environment can be minimized. Wind tunnel tests usually take two to three months [23], [37].

In addition to values of wind forces on the structure, and impacts of the stadium on its environment, investigations in wind tunnel test can include [37], [86]:

- Wind directions and velocities
- Air temperatures, and whether winds at match times are likely to contain rain or snow
- Local patterns of air turbulence caused by surrounding buildings and by the stadium structure
- Microclimate investigations to ensure optimal circumstances for a natural grass pitch
- User's comfort investigations

In addition to static wind loads on stadia roofs, there are dynamic effects that must be investigated. Usually, the natural frequency of a stadium roof is between 1Hz and 2Hz and the excitation frequency is about 0.1Hz to 0.05Hz. Dynamic effects are usually considered as equivalent static loads. [86]

- **User equipment:**

The roof structure may be subjected to high loads from user equipment, especially from video screens and electronic score boards. In addition to vertical loads, wind loads may result in high lateral loads transferred from the user equipment to the roof structure. As mentioned previously, user equipment may be changed or added during the lifetime of the structure. Therefore, the effects have to be considered in the design. Additional user equipment can make it necessary to strengthen the structure.

At *Croke Park* in Dublin, Ireland, there were two video screens added into the stadium during 2006. One screen hangs down from the roof structure at the southwest corner and a second one stands on a building at the north side of the stadium. Video screens are generally very heavy, the hanging screen has a weight of 20t, and the other one has a weight of 35t. In particular, the one hanging from the roof transfers high loads to the roof structure. The location in the corner of the stadium is chosen, because the structure of the main frame and the roof structure are the same over the stadium, which means the area of load is smaller in the corner. Hence, there were reserves for additional loads.

4.5.3 Structural systems for roof structures

Various structural systems for roof structures of stadia are possible. Each structure is a three-dimensional system. Thus, from the point of view of load bearing characteristics of the structure, there are plane structures and spatial structure (see Tab. 4.2.). In the following, structural systems for open air venues are discussed. The sections are shown in Tab. 4.2 [23], [26], [37], [61] and [65]:

PLANE STRUCTURES	SPATIAL STRUCTURES
4.5.3.1 Post and beam structures	4.5.3.5 Cable net structures
4.5.3.2 Goal post structure	4.5.3.6 Membrane structures
4.5.3.3 Cantilever structures	4.5.3.7 Compression/tension ring structures
4.5.3.4 Catenary cable and cable girder structures	4.5.3.8 Shell structures
	4.5.3.9 Air supported roof structures
	4.5.3.10 Space frame

Tab. 4.2: Structural systems for stadia roofs

4.5.3.1 Post and beam structures

Historically, post and beam structures were used for the first roofs to cover stands or terraces. Columns were situated at the perimeter, as well as at the front of the first row. There were rafters, for example steel trusses, that span between these columns. Fig. 4.11 shows a stand in Edinburgh, UK, where such a system is used.

Fig. 4.11: Stand at Stewart's Melville F.R.C., Edinburgh, UK

Structures of modern sports stadia that provide seats for tens of thousands of people should not be made of a post and beam structure supported on columns within the stands. The reason is that columns within the stands obstruct spectators view on the pitch. The obstruction can be reduced by situating the columns further back to the perimeter of the structure. Another solution to improve the sightlines of spectators is to use angled or raked columns. They have the disadvantage in being less efficient structurally. [23], [37]

Nevertheless, as the oldest form of roof structures for stadia, post and beam structures are still found at various sports grounds. However, there are new stadia, where columns are accepted for architectural reasons. Wherever such solutions are thought, there should be as few columns as possible. [23]

A recent example is the redevelopment of the Olympic Stadium in Berlin for the 2006 Football World Cup in Germany. The new added roof structure rests on 132 columns at the outer edge and on 20 tree-columns situated at the upper tier. 76 trussed beams span between those two supports and the cantilever out to the pitch is 49m. A trussed beam at the outer edge and a triangular shaped trussed beam over the tree-columns, together with the radial trusses form the primary structural system. Fig. 4.12 shows the roof structure. [74]

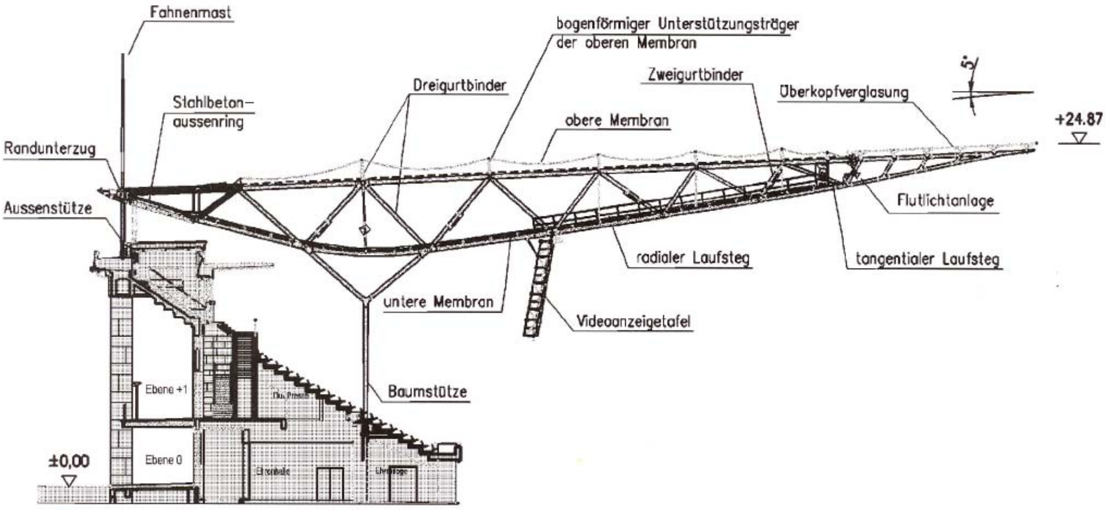


Fig. 4.12: Cross section of the roof at the Olympic Stadium Berlin, Germany (explanation in German) [74]

4.5.3.2 Goal post structures

The primary structure of this system spans along the sides of the pitch and is supported at the ends. For the main element, there are various structural systems possible. The secondary trusses span between the primary element and the edge of the stand structure [23], [37]. Goal post structures developed from post and beam structures. Columns at the front, as discussed in section 4.5.3.1, were the support for a structural element parallel to the pitch. In the UK, there are still stands with a goal post structure with various columns.

For modern goal post structures, one solution is a girder supported by two columns at the ends. An example in the UK is *Ibrox Park* in Glasgow. Trussed beams form the main structural elements of the roof for each of the four rectangular stands. Two of the corner gaps are now closed to create an enclosed atmosphere [37]. Another solution is an arch, acting as main structural element at the front of the roof. Such a structure was used, for example, at the *Galpharm Stadium* in Huddersfield, UK [37].

The advantages of a goal post structure lie in the unobstructed view of spectators and moderate costs. However, it is difficult to design a continuous bowl of seating with that structure due to the required supports at the corners. [37]

Another recently built example is the Olympic Stadium in Athens, Greece, for the 2004 Olympic Games. There are two arches, spanning 304m with the highest point 60m above the stadium, as main structural elements parallel to the pitch. Each of the arches has a lower compression arch hung on steel cables. The secondary beams cantilever out from the compression arch with a length of 50m. In addition, the beams are supported from the upper arch by secondary cable stays. [45]

Arsenal's new *Emirates Stadium* roof is an example of a goal post structure over a continuous bowl seating configuration. Fig. 4.13 shows the roof structure. Two primary triangular trusses along the sides of the pitch are supported by 11m high tripods. These 15m deep trusses span 204m over the whole length of the stadium. In addition, they support two 100m long secondary girders. Primary and secondary girders create the main structure. 32 tertiary trusses span back from the main trusses to the perimeter of the stadium. At the perimeter of the stadium they are connected to a continuous ring truss. [77]

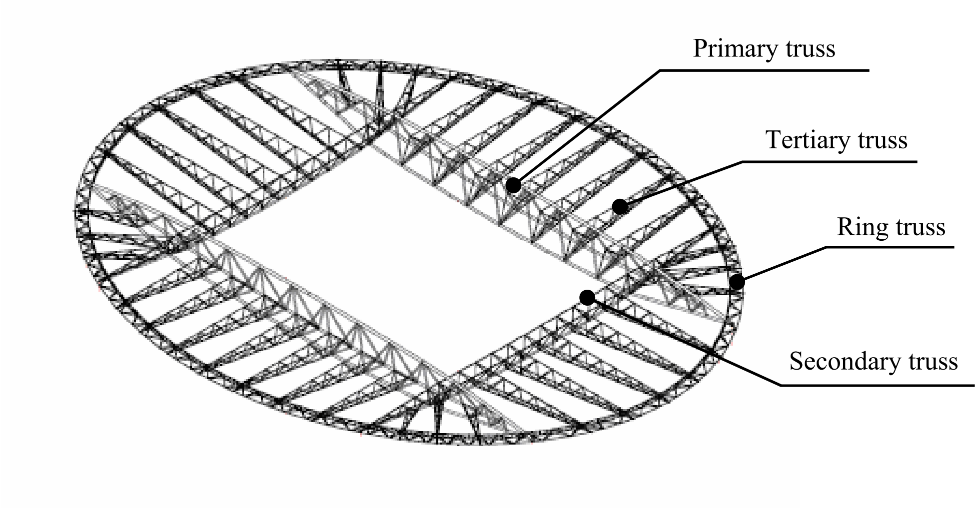


Fig. 4.13: Roof structure of the *Emirates Stadium*, London, UK [88]

4.5.3.3 Cantilever structures

Cantilever structures are the standard solution for designing a canopy roof, which can only be supported at the perimeter of the stadium. However, to create a stable structure, it is necessary either to build a rigid angle at the rear, or to support the cantilever beam from above. The advantage of cantilever structures is the unobstructed view from the stands, due to no supporting columns within the seating areas. In addition, it can be used either to design a separate rectangular stand, or a continuous bowl around the pitch. Due to supports only at the back of the structure, it may require more space than other solutions. In addition, the structure may become visually intrusive for the same reason. Cantilever lengths at stadia, achieved with such a structure, can be up to 64m (*St. James Park*, Newcastle, UK). However, other solutions may be more economical. [23], [37]

Cantilever structures are usually plane structures. However, there are cantilever structures, made of spatial cantilever elements, as well as cantilever structures, that support a main structural element parallel to the pitch. Fig. 4.14 shows examples of cantilevers structures in the UK. Simple plane cantilever structures can be formed with two columns at the perimeter (e.g. *Kingston Community Stadium*, Hull). Another solution for large cantilever is to support the rafters from above (e.g. *St. James Park*, Newcastle, or *Riverside Stadium*, Middlesbrough). There is also the opportunity to design a rigid angle, usually with a trussed structure, at the edge of the stand (e.g. *Twickenham*, London, or *Murrayfield Stadium,* Edinburgh).

On the other side, there can be spatial elements used to design a cantilever roof structure. Such elements, for example, are used at the Kingston Community Stadium, Hull (see Fig. 4.14). Another spatial structure is formed by a plane cantilever structure, supporting a *goal post* structural element that forms a support for the rafters (e.g. *Walkers Stadium*, Leicester). At the *Millennium stadium*, Cardiff, for example, the cantilever structure is used to provide additional supports for a *goal post* truss, whereas at the *Madejski Stadium*, Reading, the cantilever structure supports a *goal pos*t frame (see Fig. 4.14).

Plane structures, as well as a structures made of spatial cantilever elements, must be stabilised by bracing bars. Generally, the advantage of this structure is that it can be adjusted to any intended form of the roof, with straight secondary elements.

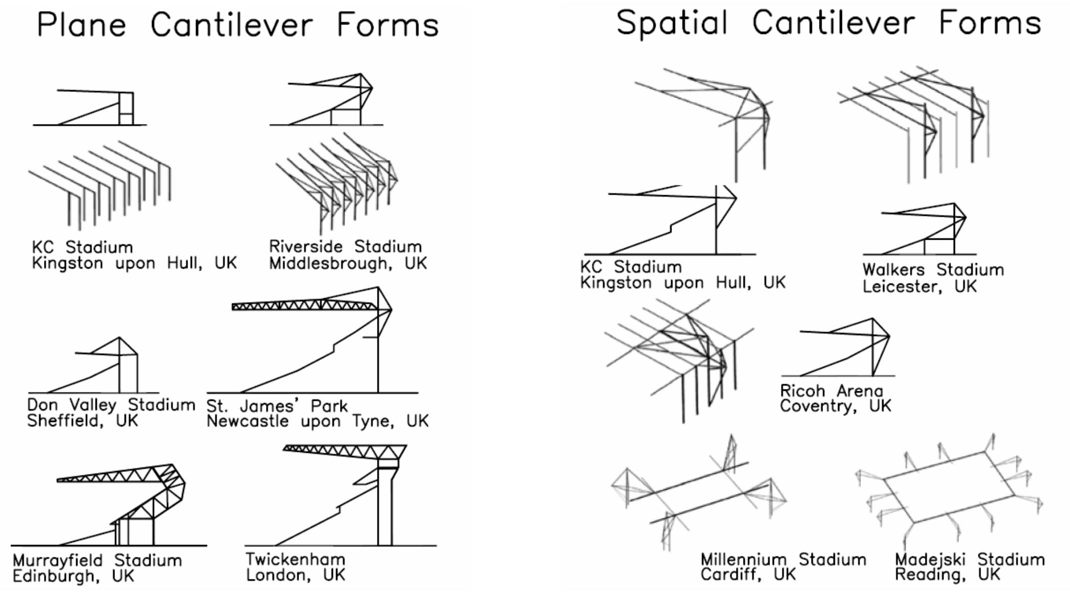


Fig. 4.14: Principal forms of cantilever roof structures

Forces on the support of the cantilever structure change from downward to uplift forces due to the wind. Under normal conditions, the *holding-down* stays of the cantilever girder are subjected to tension. However they have to be stiff enough to withstand compression forces, caused by wind uplift forces on the roof. For this reason, small diameter, high strength cables may not work as support of the cantilever girder. [23], [37]

Another example of a cantilever roof is the one at *Croke Park* in Dublin, Ireland. The roof structure consists of cantilever main trusses and a secondary structure between. Each main truss is supported by twin compression posts fixed to a complex concrete knuckle at the rear of the top deck of the stand. Tension members are tied to the rear leg of the Y-frame just above the upper concourse level. This means the supporting structures that carry the loads of the roof to the foundations are the concrete main frames. The secondary structure between the main frames is arch-shaped for architectural reasons (see Fig. 4.15). [49], [50]

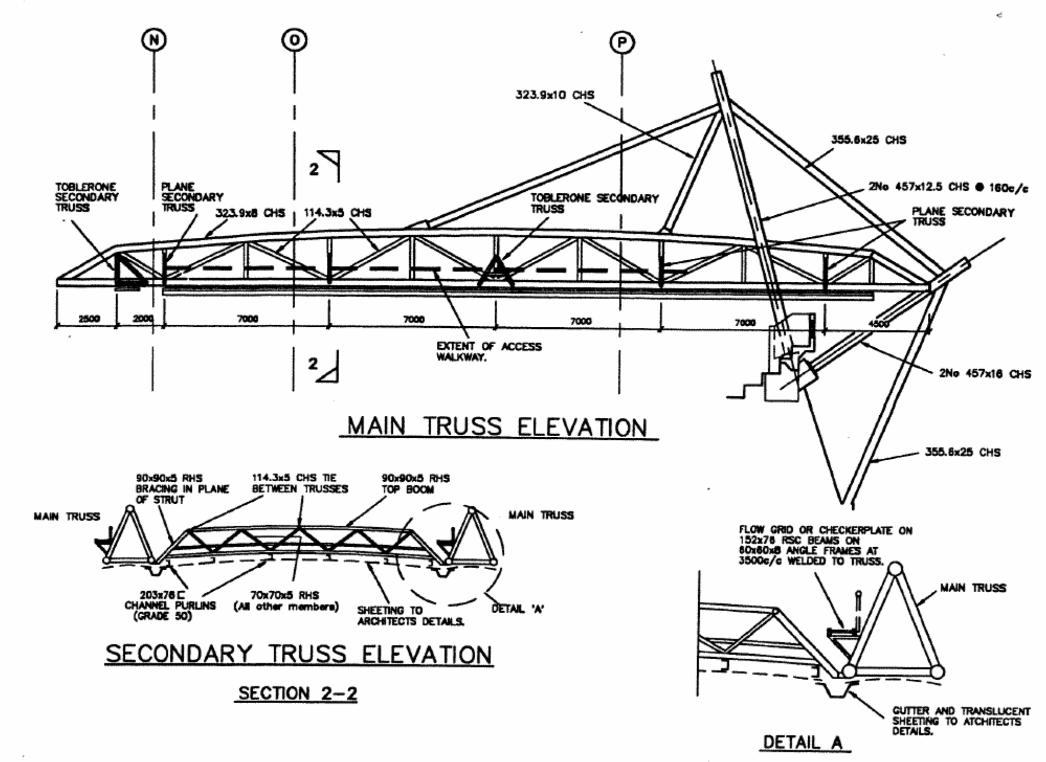


Fig. 4.15: Cantilever roof at *Croke Park*, Dublin, Ireland [49]

4.5.3.4 Catenary cable structures

Catenary cable structures are a form of tension structures. Generally, tension structures are another opportunity for lightweight roofs. The main structural elements are pure tension members. However, such a structure has to be stabilised against loads that could cause compression in members that are normally under tension. Such circumstances could occur due to deformation. Another advantage is that this type of structure is suitable for different forms of stadia. However, such structures need more systematic and intensive maintenance than other solutions. For stadia roofs, there are three forms of tension structures: catenary cable structures, cable net structures, and membrane structures. [37], [68]

Catenary cable structures are sometimes heavy structures compared to other tension structures. There is a main structural element (e.g. an arch or even arches), from which cables are hanging down in a catenary shape. These cables support the roof. A historically important and impressive example is the twin gymnasia for the 1964 Olympic Games in Japan. The roof is formed by concrete slabs, which are supported by the catenary cable structure. The structure is stabilized against wind uplift, due to high self-weight [37]. High point loadings are critical for tension structure, due to large deformations. Hence, catenary cable structures are unsuitable for heavy loads from user equipment (such as video screens). [68]

The roof of the *Football Stadium* in Braga, Portugal, is a more recent and lighter catenary cable structure. The stadium was built for the European Football Championship in Portugal in 2004. The architectural solution is different to other stadia, because stands are only situated on the long sides of the pitch. Due to this configuration, it was possible to span the roof over just one direction. Pre-stressed catenary cables, as the main structural elements that form the suspension structure, are supported on the upper edge of the concrete main frames of the stand structure (see Fig. 4.16). The roof slab is built of concrete elements on ribbed metal sheeting, which were laid on the cables over the areas of spectator accommodation. On both sides, at the edge of the roof slab, there are space frames to stabilise the structure. In addition, these triangular shaped trusses are used as support for lighting and loudspeakers. The 1m thick main frames, which support the seating areas, are built of concrete with a modular grid of 7.5m. [24]

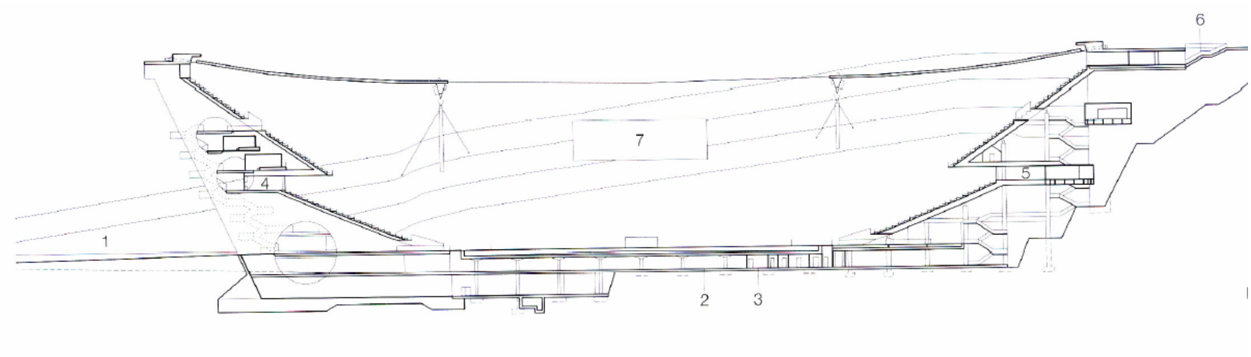


Fig. 4.16: Cross-section of the *Football Stadium* in Braga, Portugal [24]

4.5.3.5 Cable net structures

Cable net structures are formed by a three-dimensional double-curved net of steel cables. The roof covering is supported by the cable net. Cable net structures are pre-stressed to ensure as little deformation as possible [37]. Historically important is the cable net structure at the Olympic Stadium in Munich, Germany (see chapter 1).

The roof of the *City of Manchester Stadium*, UK, was designed and constructed as a cable net structure. The cable net structure is supported by twelve masts. Eight masts are supported on concrete cores and four masts at a plinth at ground level. The cable net structure is formed by forestay cables to the roof and backstay cables to the ground. Tension from the cables is transferred into compression in the masts. At the end of the forestay cables, a *catenary cable* links them all together (see Fig. 4.17). [69]

Of major consideration in tension structures are roof uplift forces. Due to the lightweight form of tension structures, it is necessary to stabilise them. The method used for the *City of Manchester Stadium* roof is referred to as a *grounded tension ring*. The catenary cable is tied back to the ground by four *corner tie cables*. In addition, through these corner tie cables, tension can be induced into the cable net. To ensure that they do not slack, the design of these cables was determined by the maximum wind uplift forces. [69]

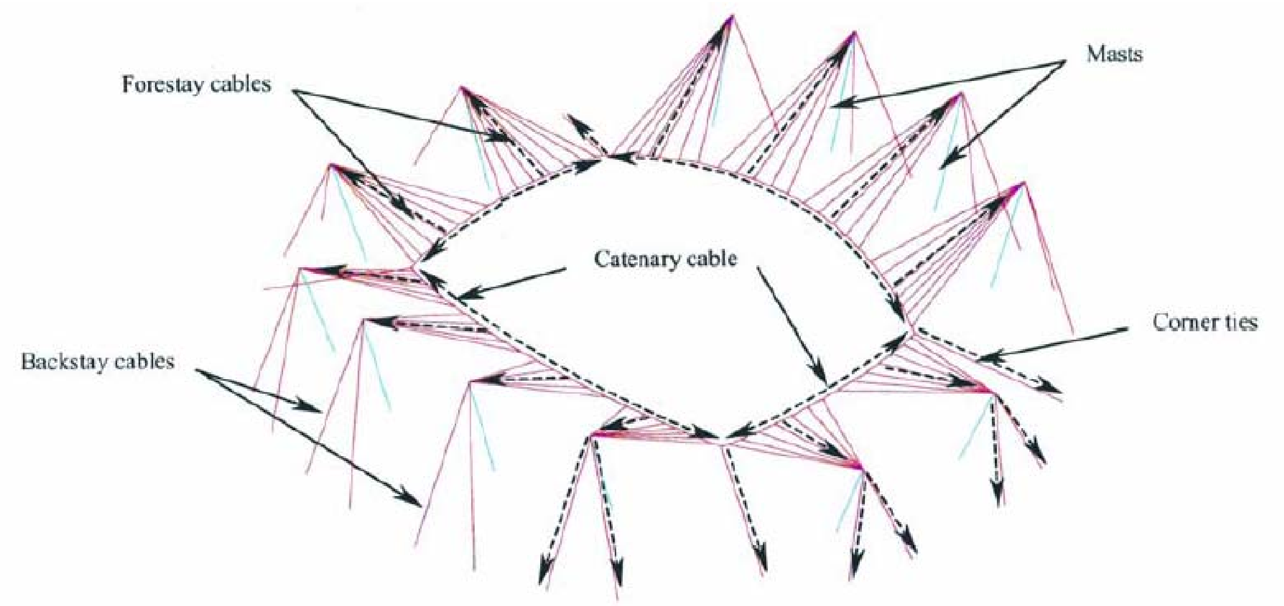


Fig. 4.17: Cable net structure of the *City of Manchester Stadium*, Manchester, UK [69]

4.5.3.6 Membrane structures

Unlike the two tension structures discussed above, a membrane forms not only the structural element but also the surface of the roof covering. Membranes for stadium structures are PVC-coated polyester fabric and PTFE coated glass fibre fabric. The first is the cheaper one, but has a life of only 15 years. The second is more expensive, but has a longer life time. In addition, the behaviour of Teflon coated glass fibre fabric must be considered, because of a tendency to produce toxic fumes in a fire. [37]

Examples for membrane structures are the *Algarve Stadium* in Faro, Portugal and the *Oita Stadium* in Japan [37]. In the UK, a membrane is used as structural, as well as covering material for the roof of the *Don Valley Stadium*, Sheffield.

4.5.3.7 Compression/tension ring structures

Compression/tension ring structures were often the solution for new roofs over existing bowl stadia. The structural system consists of an outer, an inner ring, and radial elements between them. The outer ring is subjected to compression and the inner ring to tension. Therefore, the outer ring is often a trussed structures and the inner ring made of cables. Aesthetically lightweight forms result, because columns are only needed at the perimeter to support the compression ring. The view of spectators onto the pitch is free of obstructions and wide distances of spans can be achieved. At the *Prater Stadium* in Vienna, Austria, for example, the span between the outer and inner ring, is 48m. However, there is the disadvantage that the roof forms a bowl and does not fit over a rectangular shaped stadium. In addition, wind uplift has to be considered and, for this reason, the lightweight structure needs support against those loads. [23], [37]

The roof at the *Prater Stadium* in Vienna, Austria was built in 1986, over the existing concrete bowl stadium. The compression/tension ring structure has the form of an ellipse with a size of 270m by 215m.

For the 1990 Soccer World Cup, a new roof was designed for the Olympic Stadium in Rome, Italy. The roof depth is 52m. [23], [37]

4.5.3.8 Shell structures

Concrete shell structures for stadia have been built in a variety of different shapes. Most of them were designed for enclosed arenas. However, there are examples of open stadia. The *Zarzuela racecourse* near Madrid, Spain, by Eduardo Torroja, built in 1935 and the *Palazzetto dello Sport* in Rome, Italy, are two examples. Internal forces of shell structures are mainly membrane forces and, therefore, they are mostly normal forces. The strength of thin shell structures is derived from their geometric shape, which can be cylindrical, domed, conoid, or hyperbolic. Various elegant curved roof forms can be realised with thin shell structures.

When in situ concrete is used, formwork costs may be very high. Therefore, pre-cast concrete solutions should be considered. In addition, ground conditions and foundations are important for shell structures. [37], [68]

An alternative to concrete shell structures are *grid shell structures*. Such an example of a grid shell structure is the roof of *No. 1 Tennis Court* stadium at Wimbledon, UK, finished in 1997. This roof is formed by a curved circular steel grid, which is supported on 72 double inclined columns at the perimeter. The structure is pre-stressed by its own weight. The inner members are in tension and the outer roof members are in compression, due to shell membrane forces. Another advantage of such structures is that there is little bending, when the loads remain generally in a balanced load pattern. However, unbalanced loads would cause local bending of the structural members. No in-plan cross bracing was needed because in-plan moments were insignificant. [13]

4.5.3.9 Air supported roof structures

There are different systems of air supported roofs [41]: air supported space structures, air cushion structures, and air tube structures. Air supported roof structures are commonly used for enclosed stadia. The roof is formed by a plastic membrane, which is supported by positive internal pressure provided by fans. The pressure needed is generally low (e.g. 2.5mbar [68]). In addition, a perimeter wall structure subjected to compressions must be the support for the roof structure. For larger roofs, cable reinforcement is needed. The common material for membranes is PVC polyester. Though the capital costs are low, running costs are high due to the necessity of a continual internal pressure. Mechanical failure or the loss of air tightness can cause deflection of the roof. Cable reinforcement of the fabrics is needed to ensure temporary stability when the roof is hanging down as a catenary in such a situation. Air supported roofs are not suitable for heavy point loads from user equipment (such as video screens). As mentioned previously, the lifetime of membranes must be considered in the design (see section 4.5.3.6). [37], [68]

An example of air supported roof is *BC Place* in Vancouver, Canada, with a capacity of 60,000 seats. The stadium was constructed in 1983 and the opening and closing ceremony of the 2010 Olympic Games in Vancouver will be held there. The roof membrane material is PTFE coated fibreglass, which covers an elliptical area of the stadium of 190m by 231m. To hold the membrane 27m above the perimeter support in position, an internal pressure of 2,4mbar is required. At the perimeter there is a reinforced concrete compression ring as support for the tension in the membrane. In January 2007, due to tears in the membrane, controlled deflating of the roof structure was required. At this time, the membrane was already 24 years old and, as discussed previously, it was at the end of its lifetime. In addition, usually, the roof surface is stabilised by internal pressure. However, snow loads act against this pressure, therefore, reduces the tension in the membrane and, make the roof more sensitive to wind loads. Furthermore, during the last 24 years, due to new buildings, there were changes in the surrounding area that can cause turbulences and, thus, increase wind loads. These circumstances are believed to have caused the incident in January 2007. [37], [47]

4.5.3.10 Space frame

A space frame is a structural element formed by a grid of structural members. Stability is provided through the three-dimensional shape and three-dimensional bracing. The commonly used material is steel. Space frames are capable of spanning large distances and need only support at the perimeter. However, plan proportions should provide a length-to-width ratio of 1.5 to 1. The reason is that a space frame should span over two directions to be efficient and sensible. Such space frames for stadia can be expensive solutions. [37]

The primary structure of the roof at *San Siro Stadium* in Milan, Italy, is a space frame roof structure. This is made of an aluminium deck supported from steel lattice beams. [37]

4.6 Foundations and Substructure

Foundations act as connection between the structure of the building and the ground. Hence, ground conditions influence the construction of foundations. The allowable ground pressure is the critical factor. As sports grounds are often located on sites with poor soil, construction risks have to be determined in a full geotechnical report. The reason for these poor soil conditions is that stadia need large areas of land, which are often found in former industrial districts, in urban areas. At these sites, groundwater and soil can be contaminated. The determination of ground conditions is also needed for financial reasons, because ground improvement measures and foundation works, as well as the treatment of contaminated soil, can have a high impact on the construction budget. [14], [37]

Special features of foundations for stadia structures (from page 3 in [14]):

- *Some columns tend to be exceptionally heavily loaded*
- *Due to large cantilever roofs (and sometimes supporting arches), the foundation system is subject to high horizontal loads and large overturning moments*
- *A high proportion of the loads are live, either induced by crowds or by wind. These dynamic effects have to be considered in the design of the structure and its foundations. A related issue is that the consequences of structural failure in a stadium can be horrendous, with the potential to kill hundreds of people. Therefore a higher margin against failure is appropriate than for most other structures*

A feature of foundations, in general, is that they are buried under the ground and can not be investigated easily. However, an investigation of the foundations is required, when an existing stadium is to be extended. For the extension of an existing structure, the determination of loads, which can be additionally applied on foundations, can prove difficult.

The chosen pitch level also influences earthworks. Ground excavation can be needed to lower the pitch level under the level of the surrounding area. In this case, the seating units near to the pitch can be situated on foundations directly on the ground. However, retaining walls are necessary and ground conditions dictate when they can be designed either as gravity or embedded retaining walls.

In addition to vertical loads and due to large cantilever roofs, some foundations are subjected to high horizontal loads. For this reason, large thrust blocks may be required to use the passive capacity of the shallow soils. However, this in turn can influence construction cost, if more ground excavation is required.

There are geotechnical risks. They can lead to significant construction delay and higher costs. Therefore, they have to be determined in the form of a desk study and a site investigation, in a timely manner, and reduced wherever possible. Hazards can be risks to service pipes and cables above or under the ground. The first may be obvious and the latter can be difficult to determine. The outcome of a ground investigation for a stadium project should provide appropriate factors for the design. [14]

Loads are transferred from the structure to foundations, and then to the ground. For this reason, foundations are the most heavily loaded parts of the structure. The design of the foundations has to ensure that the applied loads are supported without significant risk of failure, and with sufficiently small movements of the foundations. These two design criteria in the assessment are known as *ultimate limit state* and *serviceability limit state.*

Types of foundations:

Generally, there are two types of foundations: *shallow foundations* and *deep foundations*.

Shallow foundations are cheaper than deep foundations. However, they need a strong ground near the surface and the groundwater level should be deep. They are an economic solution, especially for smaller stadium stands. Ground improvement measures could be used to stiffen soil. Types of shallow foundations are (from page 10 in [14]):

- Trenchfill – for the lightest loads
- Pad footings
- Strip footings
- Raft – for heavier loads

The second solution for foundations, appropriate for higher loads, is to design *deep foundations* usually in the form of piled foundations. There are various types of bored or driven piles. Driven piles have the disadvantage of noise and vibrations during construction, which especially for extension of existing stadia can be a determining factor. However, on the other hand, driven precast concrete piles can be very economical, if a new stadium is located outside an urban area, away from other structures. [14]

Substructure:

The design of a basement for various uses, like car parking, storage, and delivery areas, can be appropriate for new stadia. Retaining walls around the basement are required to hold back the soil and groundwater. In addition, they can be subjected to loads from the superstructure. Water pressure in accordance to groundwater level, in temporary and permanent conditions, determines the choice of wall, as well as the construction method. Floor plates in the basement can be used as horizontal propping elements. Ground movement is the determining factor in urban areas, where the influence on neighbouring buildings is critical. [14]

At the *St. Jakob-Park-Stadion* in Basel, Switzerland, a two-storey basement under the whole stadium was built. The level of the raft is 9m under the ground level and the highest groundwater level is 7m above the raft level. Due to the high groundwater level, high hydrostatic uplift forces would occur. The solution to avoid these forces was found in *cutting off* the groundwater. An 80cm thick surrounding wall, penetrating 4m into the watertight rock, was constructed. However, there is still water flowing through that system, but this small amount of water is collected with a drainage system and flows into a sump shaft. In-situ concrete piles with a diameter from 90cm to 150cm were constructed to carry the high vertical forces of the stadium structure and the adjacent nine-storey building. [10]

In the case of the *Stade de Suisse* in Bern, Switzerland, a basement was also constructed. However, this basement structure is subjected to groundwater pressure. The highest groundwater level is 2.6m above the raft level. The 45.000m² raft is 60cm thick and was constructed in 72 sections. Water impermeability is achieved through bentonite mats under the raft and expanding joint tapes in the working joints. The bottom slab is supported by 8m to 42m long bored piles with a diameter of 72cm to 150cm. [9]

When a basement is designed under the activity area, the slab over the basement is the basis for the activity area. This slab may be subjected to high vertical loads, depending on the intended use. The vertical forces on the top slab of the substructure at the *St. Jakob-Park-Stadion* in Bern are 26kN/m² and the slab was designed as flat mushroom construction. The mushroom head is 2.7m to 2.7m and 56cm thick, whereas the slab has a minimum thickness of 28cm. [10]

The slab above the basement at the *Stade de Suisse in Bern* was designed as an in-situ concrete flat ceiling with a column grid of 8.0m to 8.0m. Due to high vertical loads, because mobile cranes are needed for construction works inside the stadium, and to compensate hydrostatic uplift forces, the slab is 55cm to 60cm thick. [9]

5 SUMMARY AND CONCLUSION

Stadia of today are much more than just sports stadia. They developed from ancient Greek running tracks to modern multi-purpose arenas for various uses, not only sports uses. The form of stands and terraces for spectators has not changed basically; there are the same requirements as for ancient stadia. However, due to a higher quality for spectators, new requirements developed.

In particular, there are new requirements out of multi-purpose reasons to avoid unused venues. A wider use of stadia for various sports, as well as for non-sporting events, with increasing number of event days brought new challenges for the architectural and structural design. Adaptability of stadia is required to achieve venues that can be converted into various states to provide an optimal scene for various uses. From the point of view of structural engineering, for adaptability of multi-purpose stadia, there are movable structure for spectator accommodation, movable structures for pitches and, movable structure for roofs.

Firstly, a stadium must be comfortable for spectators, who are an active part of an event. The function of a roof is to provide the shelter against the elements. Retractable roofs are an opportunity to allow two configurations: an open stadium with protection for the spectators and an enclosed arena with additional protection for the activity area. Movable roofs also developed to allow a natural grass surface within an (for events) enclosed arena. Generally, there are two types of retractable roofs: movable rigid elements and membranes. Rigid elements move along a track from an open to a close state, whereas membranes have the advantage of being foldable. The foldability of a membrane allows to bunch it and to store it in a small space. Another opportunity of membranes is to use them between movable rigid supporting elements, in which case the membrane is folded parallel. First retractable roofs developed since the 1930s, although longspan retractable roofs suitable for stadia were first built at the end of the last century.

From the point of view of structural engineering, retractable roofs apply high static as well as dynamic forces on the permanent elements of the stadium structure, especially if the movable elements are supported at the edge of a large canopy roof structure. Guidance can, for example, be found in *Structural Design of Retractable Roof Structures* [35], a guide from the *International Association for Shell and Spatial Structures* (IASS).

The size and form of the activity area is determined by the event taking place. In the case of various events, there are maybe different forms and sizes required. Movable seating elements are an opportunity to solve this problem and to create two different configurations of the activity area. Generally, there are rigid or telescopic elements that can be used. Usually, although they need a larger space to be stored, due to the size and a more robust structure, rigid movable seating tiers are constructed.

Loads and external forces on movable seating tiers are the same as for permanent structures. However, rigid elements in particular have an impact on the structural design of the stands. Due to the large space that is required to push back the movable structure, there may result a large cantilever structure for the next higher seating tier. The problem with cantilever seating tiers is that such structures are more sensitive to dynamic excitation by spectators. In order to achieve the required natural frequency of the structure for the intended use, there are limits for the deformation of the structure under dead weight.

The activity area, especially the surface of the activity area, is the third main element of a stadium. It is determined by the intended events that should be staged. In a stadium for various events, the surface of the activity area must be robust and suitable for all intended uses. However, natural grass, as it is required for soccer or rugby, can not be described as robust. Movable pitches, although they provide an opportunity to stage events on a more robust lower surface, mainly developed for reasons of healthier grow of grass.

Not only enclosed arenas, but also large canopy roofs over the stands have a major impact on the conditions for the grass. Thus, movable pitches allow the grass to grow outside under optimal conditions, whereas the venue can be used for events with a more robust surface

Due to the large gap in a stand to move the pitch outside the stadium, movable pitches have an impact on the stand structure. The gap required in one stand is about 80m to 90m. This is also the span for the supporting *bridge* structure, if spectator accommodation above the gap is needed. However, operation of the movable pitch is just needed between events and, therefore, during events the *bridge* structure can be supported by temporary retractable props.

On the other side, major events, like Olympic Games or championships in any sport, have always been the booster for the construction of new stadia, as well as the redevelopment of existing stadia. However, such stadia for major events have a short lifetime and a long-term use must be considered to ensure that the stadium will not become a disused venue with high running costs. Therefore, new solutions are required to make a stadium and, thus, the stadium structure itself, adaptable in terms of use. Temporary structures can be an opportunity to solve this problem.

The use of temporary structures can vary from independent structures, erected on temporary foundations, to structures integrated in the permanent, long-term structure. On the other side, temporary structures can be re-used many times after an event or just re-erected once. The structural design depends on these circumstances.

If there is not a continuous bowl of spectator accommodation around an activity area, temporary separate structures can be used. In addition, depending on the geometry of a stadium, such structures can be erected adjacent to an existing stand. Furthermore, temporary stands can either be covered by a roof or not. At the *Ernst Happel Stadion* in Vienna, Austria, there is a temporary structure used to cover the running track and to increase the capacity of the stadium during the EURO 2008. This structure is supported on temporary foundations and will be removed after the Games.

The Austrian stadia for the EURO 2008 in Klagenfurt, Salzburg, and Innsbruck are ideal examples for increasing the capacity of existing or newly designed stadia temporary, for the duration of a major event. In contrast to temporary structures in stadia for major events before, in both configurations all spectators are protected by a roof. Hence, there are two roof configurations required and the temporary structure is added to the permanent structure.

The stadium in Salzburg was inaugurated in 2003 for 17,000 spectators and designed to be converted into a 30,000 spectator venue for the EURO. Thus, additional forces from temporary elements applied to the structure and to foundations, were considered. The roof was lifted 10.5m to provide space for a second tier.

In contrast to the stadium in Salzburg, the *Wörtherseestadion* in Klagenfurt was constructed for 32,000 spectators for the EURO 2008. After the Championship, the stadium will be reconfigured, the upper seating tier will be removed and the roof will be lowered above the lower seating tier. The roof will be dismantled and re-erected on a lower level. Due to a movement towards the pitch, the roof covering needs to be adjusted. A temporary structure to extend the roof during the EURO is used.

The *Tivoli Stadion* in Innsbruck was not designed and constructed with the intention to increase the capacity temporary for the Championship. Thus, the temporary structure for a second seating tier is supported at additional foundations at the perimeter of the stadium. In addition, the roof structure is not the same as for the long-term use.

London’s Olympics in 2012 will be a further step in the use of temporary structures for stadia for major events. The Olympic Stadium, as currently intended, will be constructed for a spectator capacity of 80,000, but will be reconfigured after the Games for 25,000 spectators. Some venues will even be designed to be fully demountable and re-erectable at other sites within the UK. Temporary demountable stadia are even thought to be an opportunity for smaller countries to stage major events. However, such structures must be easy to transport and handle, as well as fast to erect.

Adaptability of stadia from the structural point of view certainly has an impact on the structural design. During the last two decades, solutions developed for increasing either the capacity temporary for a major event, or for increasing the use of the venue for a longer term. For temporary structures, additional decisions, especially where and how to use the structure, have to be made and additional points, such as the dynamic behavior of large cantilever seating tiers, must be considered. In the past, temporary structures were just used to increase spectator capacity temporary, but to have a long term basic configuration. The next major events will show, if it makes sense to design fully demountable stadia, suitable for various sites.

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6.2 Table of figures

7 APPENDIX

The following is a summary of information on the structural design and references about interesting stadia in the UK. The pictures were taken during a study trip. Further pictures can be found in [6].

Stadia visisted during the work are:

7.1 *Brit Oval*, London, UK
7.2 *City of Manchester Stadium*, Manchester, UK
7.3 *Croke Park Stadium*, Dublin, Ireland
7.4 *Don Valley Stadium*, Sheffield, UK
7.5 *Emirates Stadium*, London, UK
7.6 *Galpharm Stadium*, Huddersfield, UK
7.7 *Ibrox Stadium*, Glasgow, UK
7.8 *JJB Stadium*, Wigan, UK
7.9 *Keepmoat Stadium*, Doncaster, UK
7.10 *Kingston Community Stadium*, Hull, UK
7.11 *Millennium Stadium*, Cardiff, UK
7.12 *Murrayfield Stadium*, Edinburgh, UK
7.13 *New Wembley Stadium*, London, UK
7.14 *Old Trafford*, Manchester, UK
7.15 *Reebok Stadium*, Bolton, UK
7.16 *Ricoh Arena*, Coventry, UK
7.17 *Riverside Stadium*, Middlesbrough, UK
7.18 *St. James Park*, Newcastle, UK
7.19 *Twickenham*, London, UK
7.20 *Walkers Stadium*, Leicester, UK
7.21 Other stadia visited in the UK

7.1 *Brit Oval*, London, UK

Brit Oval is a cricket stadium in London with a capacity of about 25,000. The new *OCS Stand* (see Fig. A-1) was opened in 2005. The roof above the new stand only covers the terrace but does not cover the seats; they are all unprotected. The façade is an interesting design solution. It was designed and constructed as a *living façade* and consists of a steel frame, which is connected to the stand structure and covered by wooden plates. Between the living façade and the stand structure, there is a concourse for spectators.

The roof of the new stand is three-dimensionally shaped, supported by trees, as well as by columns at the perimeter and is made of steel. Due to the three-dimensional form, there are no bracing bars necessary. Thus, the roof acts as a grid shell structure. The supporting stand structure is made of steel with pre-cast concrete seating elements. Fig. A-2 and Fig. A-3 show the structural system and details of the roof structure.

Fig. A-1: *OCS Stand* at *Brit Oval*

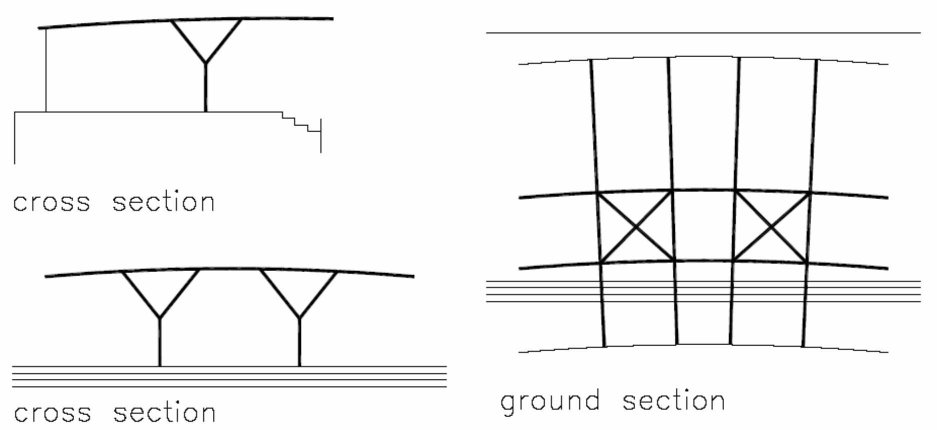

Fig. A-2: Structural system of the roof structure with trees

Fig. A-3: Roof structure of the *OCS Stand* with supporting trees and cantilever beams

7.2 *City of Manchester Stadium*, Manchester, UK

[2], [3], [4], [31], [32] [39], [69]

The *City of Manchester Stadium* was designed for the 2002 Commonwealth Games in Manchester. However, long term use of the venue was considered during the development and, thus, the stadium was designed to be reconfigured after the Games. In 2003, it became the new home of *Manchester City Football Club*.

The roof structure is made of a cable net structure (tension structure). Although, from the point of view of adaptability, this structural solution is inflexible, two configurations (for the Games and for long term use) could be created (see Fig. A-4). Due to a running track, there was a larger activity area required for the Games. In the configuration for long term use, the activity area only consists of a football pitch. Therefore, the activity area was excavated after the Games and a larger venue with additional seating in a new lower tier was created This, in turn, lowered the pitch level about 6m under the surrounding ground level. Due to spectator accommodation in three tiers (football configuration) along the sidelines and in two tiers behind the goal, a three-dimensional shaped roof form results (see Fig. A-5).

The main structure of the stands consists of concrete frames that form the supports for the pre-cast seating units. The steel rafters for the roof are suspended from a cable-net structure and supported at the rear of the stand structure.

The cable net structure is supported by twelve masts. Eight masts are supported on concrete cores and four masts at a plinth at ground level. The cable net structure is formed by forestay cables that span from the masts to the roof and backstay cables that span from the masts to the ground. Tension from the cables is transferred into compression in the masts. At the end of the forestay cables, a *catenary cable* links them all together. It is the connection from the rafters to the cable net structure.

Of major consideration in tension structures are wind uplift forces. For this reason and due to the lightweight form of tension structures, it is necessary to stabilise them. The method used for the roof of the *City of Manchester Stadium* is called a *grounded tension ring*. The catenary cable is tied back to the ground by four *corner tie cables*. In addition, through these *corner tie cables*, tension can be induced into the cable net. The design of these cables was determined by the maximum wind uplift forces to ensure that they do not slack.

Fig. A-6 and Fig. A-7 show the foundation of a corner tie, a mast and a backstay cable.

In addition, the construction of such cable net structures is a challenge. The main point to be considered is that the cables are short until they are pre-stressed. The other challenge was the construction of the lower tiers during the reconfiguration. During the Commonwealth Games, there was a temporary stand structure at one end of the stadium. At this end, the roof was not completely finished. The temporary stands were dismantled after the Games and the gap in the stand structure, as well as in the roof, was closed. However, this gap allowed access into the stadium during the reconfiguration.

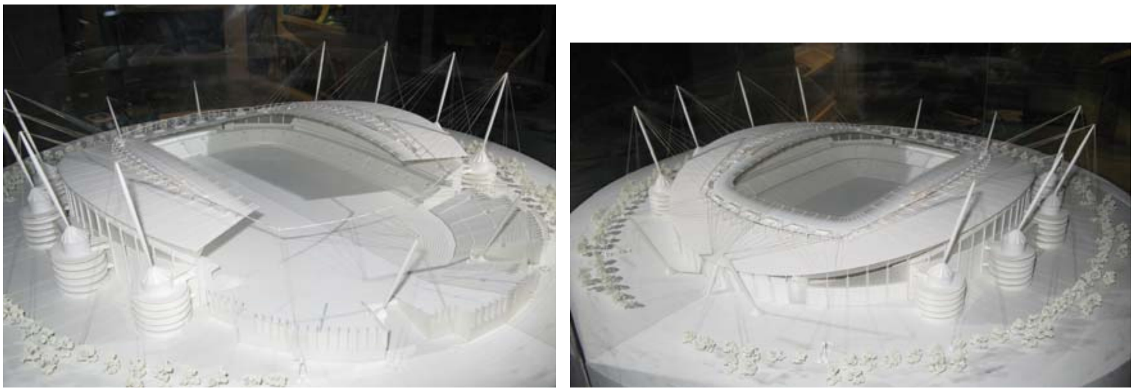

Fig. A-4: left: Configuration for the Commonwealth Games; right: Configuration for football

Fig. A-5: three-dimensional shaped form of the roof

Fig. A-6: left: foundation of the corner ties that form the grounded tension ring; right: foundation of the cigar-shaped mast

Fig. A-7: foundation of one of the backstay cables

7.3 *Croke Park Stadium*, Dublin, Ireland

[15], [36], [49], [50]

Croke Park Stadium was completed in September 2004 and has a capacity of 82,300 spectators. There were physical boundaries for the design of a new stadium. Jones Road in the west, railway lines in the north and south of the site, and the Royal Canal also south of the stadium site. Historically, the site was on the outskirts of the urban area. When the city expanded, the site was surrounded by various buildings.

The initial desire was to design a stadium for 90,000, or even more, spectators. This would have been possible at the site, but the capacity was determined by the capacity of the roads. Hence, the possible capacity for the new stadium was about 85,000 spectators, as it is today. *Croke Park* was designed for Gaelic sports, which need a larger pitch than soccer or rugby. This meant different sightlines and sight distances than in football stadia.

The stadium was constructed in several phases. The last phase of construction was the *Hill 16*, which is the tier on the north side. This tier is built for standing accommodation. For soccer games the tier could be reconfigured and seats added, to fulfil the regulations. However, the tier was not designed for this. Standing accommodation is generally used for Gaelic sports or rugby.

Seating tiers and main structure:

The main structure of the stands is formed by a concrete frame with pre-cast concrete seating units. The Royal Canal, south of the stadium, was moved during construction, to allow foundation of the main frame between the Canal and the railway line. One special frame with a greater span in the corners was necessary, because of the railway line.

The cross section of the precast seating units shows a *T* shaped form with a nose. The corporate box level is built of a steel structure hanging from the concrete main frame. This solution includes a *slim floor* ceiling. Expansion joints are necessary to allow movement of the structure, caused by temperature effects. These expansion joints are located in the concrete structure at the main frames, after every four bays, which is a distance of about 57m.

Additional loads on the main frames next to the railway line needed to be considered. Thus, additional concrete was built around the main frame to carry horizontal loads and to protect the main frame in the event of a train derailing.

Roof structure:

The solution for the roof was a cantilever structure spanning approximately 30m. Each main truss is supported by twin compression posts fixed to a complex concrete knuckle at the rear of the top deck of the stand. Tension members are tied to the rear leg of the Y-frame just above the upper concourse level. This means the supporting structures that carry the loads of the roof to the foundations are the concrete main frames. The stadium from the outside with the support of the roof on the main frame is shown in Fig. A-8. Fig. A-9 shows details of the cantilever roof structure.

For architectural reasons, the secondary structure between the main frames is arch-shaped.

Wind tunnel tests were carried out to determine loads on the structure. The results indicated that the worst condition of loading would occur during the first phase of construction. Loads after completing the stadium are now about 50% lower than those for the first phase. The wind tunnel tests were compared to the building regulations. Calculations from Standards normally give higher loads than the wind tunnel tests.

For wind loads on the stadium, also of interest is whether the surface of the façade is fully closed or not. In the case of Croke Park, a closed surface was desired by the architect but, a gap was accepted to lower effects of wind uplift on the roof. For spectators in the top level, the movement of air is not noticeable. To close the gap would cause higher loads on the roof structure.

Video screens:

Two video screens were added into the stadium during 2006. One screen is hung from the roof structure at the southwest corner and a second one stands on a building at the north side of the stadium. Generally, video screens are very heavy. The hanging screen has a weight of 20t and the other one has a weight of 35t. The location in the corner was chosen, because the main frame is the same everywhere, which means the area of load is smaller at the corners. Hence, there were reserves for additional loads.

Fig. A-8: *Croke Park* from the outside, showing the supports of the cantilever roof structure

Fig. A-9: The left image shows the cantilever roof structure, the right one the knuckle at the rear of the stadium

7.4 *Don Valley* Stadium, Sheffield, UK

The *Don Valley Stadium* is a venue for athletics and was designed for the 1991 World Student Games. The main structural frame of the roof is a cantilever form that is supported from above. The roof between these frames is formed by a membrane, which is supported by the frames and two arches between the frames. The two gaps between the three stands are covered by a membrane structure supported by the adjacent steel frames, as well as by a tension structure.

Fig. A-10 shows the stands with a membrane as roof covering between the frames. The structural system of and a view to the cantilever roof structure are shown in Fig. A-11 and in Fig. A-12.

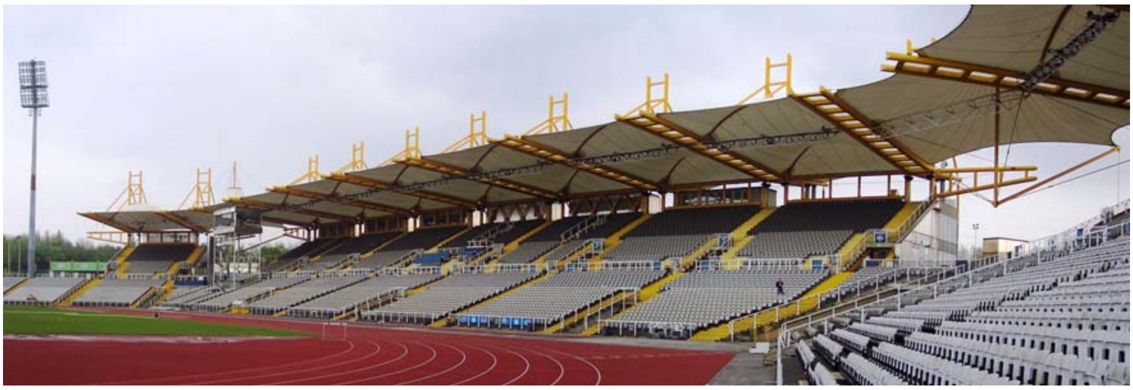

Fig. A-10: Cantilever roof with the membrane between the frames

Fig. A-11: Cantilever roof structure supported at the rear of the stand

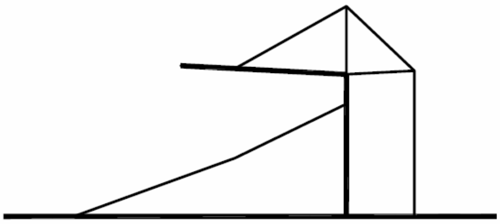

Fig. A-12: Structural system of the roof structure

7.5 *Emirates Stadium*, London, UK

[19], [25], [72], [77], [88]

The *Emirates Stadium* is the home to Arsenal Football Club and provides seating for 60,000 spectators. The stadium was inaugurated in 2006. The ground plan of the venue shows an elliptical bowl form. There were site restrictions caused by railway lines on two sides and also planning restrictions imposed on the height of the stadium. Thus, the form of the stadium, as well as the possible structural solutions, was determined by these restrictions.

The roof steelwork solution is described as a *dished* roof profile, hung from the main structure. This structure consists of two 700t parallel primary triangular trusses spanning 204m and 15m deep. Due to these primary structural elements, the roof is a goal post structure. The girders were fully welded on site because of their size. Due to stability criterion, the triangular cross section was chosen. The advantage of this form is that the trusses are inherently stable against lateral buckling effects. Overall lateral and torsional stability is achieved through their interconnectivity. These two primary trusses are resting on 11m high tripods. Two 100m secondary girders span between the primary trusses and there are two tripods at the perimeter where these secondary girders are supported. Thus, there are eight tripods, one over each core, on which the roof structure is supported. Vertical and lateral loads are transferred to the main structure through these tripods. In addition, there are 64 articulated props for the perimeter truss down to the rear of the rakers of the upper tier. Between that main structure, 32 tertiary trusses span back to the perimeter of the stadium. At the perimeter, there is a continuous ring truss.

An amazing 1360 bored, in situ, reinforced concrete piles are forming the foundation for the new stadium. They are arranged within an ellipse to support the superstructure. As mentioned previously, for the main structure, there are eight massive structural concrete cores that support the majority of the roof weight. These concrete cores are used to achieve lateral stability. In addition, there are stairwells within these cores. For thermal movement of the structure, a system of expansion joints was designed. Due to ground conditions, it was not possible to construct a basement.

Seating accommodation is arranged over four tiers. The upper and lower tiers are for general spectators, the mid tiers for hospitality boxes and restaurants. The main structure is formed by a combined reinforced concrete and steel solution. The rakers for the lower tier, the club tier, and the box tier are made of reinforced concrete, whereas the rakers for the upper tier are made of steel. The seating units are pre-cast concrete elements. In addition, reinforced concrete floors and frames are used.

The low form of the roof offers advantages for the natural grass surface of the pitch. However, sightline requirements, especially elevated sightlines, must be considered to ensure high quality for the spectators.

7.6 *Galpharm Stadium*, Huddersfield, UK

[67], [89]

The *Galpharm Stadium* (former *Alfred McAlpine Stadium*) is designed for soccer and rugby. The reason for this was the aim to design a commercially viable, multi-use venue, suitable for sports, social and community events. Additional facilities included in the 25,000 capacity, all-seater stadium development are bars, restaurants, banqueting hall, commercial offices, hotel, floodlight golf driving range, and a cinema. The stadium was built in several phases. The construction began in 1992. At the beginning of the 1990s, the LOBB Partnership developed a theoretical concept for a phased development of a stadium; it was called *Stadium for the Nineties*. For financial reasons, as well as for a short construction time between two seasons, phased construction is often needed at sports venues. The concept for the *Galpharm Stadium* was based on the *Stadium for the Nineties*.

As mentioned previously, the stadium was designed for football and rugby. Hence, the pitch is larger and has a size of 75m x 120m, suitable for both sports. The stadium is a *bowl* in plane with four separate stands around the pitch. In the corners, the stands are joined, but there are no seats. Though there are four stands around the pitch, there is a change from the traditional rectangular shaped stands to a *bowl*. Due to theoretical sightlines and viewing distances, the stands at the *Galpharm Stadium* have this form. Sightlines and viewing distances are considered, with no seats further than 150m from the furthest corner of the pitch and no seat further away than 90m from the centre of the pitch. The ‘C’ value is at least 90mm. The tread width of the seating units is 800mm.

The main structural element of the roof is a 135m (long side) *banana truss* of triangulated tubular steel. From the structural point of view, the roof is a goal post structure (see Fig. A-13), because the trusses span parallel to the long sides of the pitch. In addition, these trusses provide the visual identity of the venue. The roof rafters span between the rear of the stands and the trusses (see Fig. A-15 and Fig. A-16). The main trusses meet at the corners, where they are supported by *cigar-shaped* concrete columns (see Fig. A-16 left image). Lateral loads are supported in the corners, with a maximum value of 7,000kN. Horizontal loads result from the large horizontal and vertical loads induced by the arch-shape form of the trusses. The foundation of the corner supports is achieved by continuous flight auger piling.

The main frame of the stand structure generally consists of steel. The seating units are made of pre-cast concrete and the main floors are made of pre-cast concrete planks with an in situ topping.

The last phase was the construction of the fourth grandstand: The *Panasonic Stand* (Fig. A-14). The design of this stand considered concerts to be staged. Therefore, the lower tier is comprised of demountable and removable seating. The capacity for concerts can be up to 40,000, whereas for sports use, the capacity is 25,000. The stadium was finished in 1998 by completing the *bowl* with the third phase.

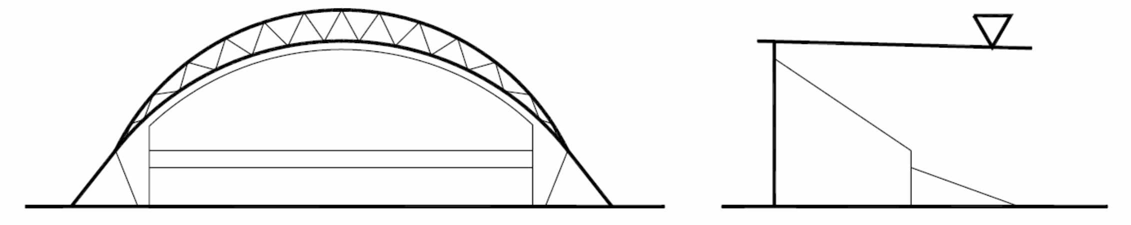

Fig. A-13: Structural system of the goal post structure for the roof

Fig. A-14: *Panasonic Stand*

Fig. A-15: The triangular shaped truss, the rafter spanning from the trusses to the rear of the stands, and the corner support.

Fig. A-16: left: Corner support; right: Detail of the roof structure

7.7 *Ibrox Stadium*, Glasgow, UK

[78]

The *Ibrox Stadium*, Glasgow, is the home of Rangers Football Club. The stadium has experienced some tragedies, which led to a redevelopment of the stadium (see section 2.7.1). Therefore, it was one of the first modern sports grounds in the UK. More comfort and safety was considered in the redevelopment. The brief in the 1980s already contained all seated accommodation and unobstructed views for spectators. In addition, the accommodation provided should be close to the pitch to create a more intimate atmosphere.

A trussed girder spans parallel to the pitch at each stand and supports the roof structure. These girders are supported at the corners by columns. Thus, the roof structure is a goal post structure. Secondary roof girders span between the rear of the stand and the main girder, at 6m centres. Bracing in three planes is used to create lateral and torsional stability. The corners were free of seats, to provide optimal viewing distances for spectators. These corners were redeveloped during the 1990s. Fig. A-17 shows the inside of the stadium. Due to the supports of the trusses, there are only a few seats in the corners. The main stand with the impressive roof structure and the triangular shaped main truss is shown in Fig. A-18.

Fig. A-17: Inside of the rectangular stands at Ibrox

Fig. A-18: Main stand of the Ibrox

7.8 *JJB Stadium*, Wigan, UK

The *JJB Stadium* in Wigan was opened in 1999 and has a capacity of about 25,000. It has a traditional form with four rectangular stands and gaps in the corners. The structural solution for the roof is a typical goal post structure (see Fig. A-20). All four roofs are supported by a triangular shaped trussed beam. The two trusses for the stands next to the side of the pitch are above the rafters and the roof covering. The trusses of the stands behind the goals are under the rafters and the roof covering. There are four concrete columns at the corners, where the trusses meet and where they are supported (see Fig. A-21). Fig. A-19 shows the stadium from inside.

Fig. A-19: East Stand, North, and South Stand; stadium from inside.

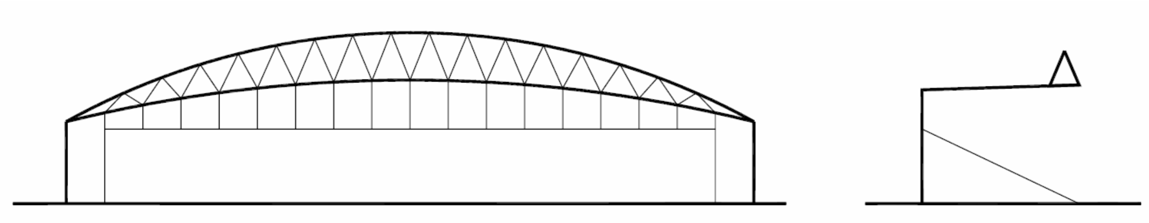

Fig. A-20: Structural system of the East and West Stand roofs

Fig. A-21: Concrete columns in the corners

7.9 *Keepmoat Stadium***, Doncaster, UK**

The stadium was opened in December 2006 and has a capacity of about 15,000. There are no visible supports for the roof structure. The roof structure is formed by a cantilever beam, supported on two columns at the back of the stadium. The structural system is shown in Fig. A-22. Between the columns at the rear of the stands, there is a concourse. This cantilever form has the advantage of a thin roof structure, with no supports above the roof level. Therefore, it keeps the façade of the stadium, as well as its impact on the surrounding townscape, or landscape, low (see Fig. A-23). The roof covering is above the structural elements and the supporting stand structure is made of steel with pre-cast concrete seating rows. Fig. A-24 shows the stadium from inside.

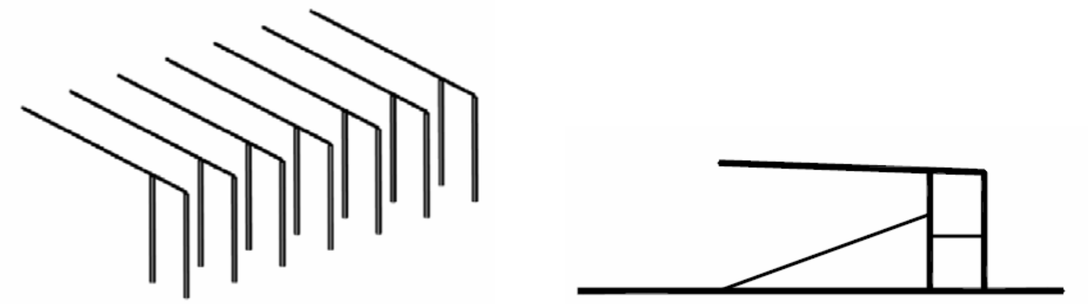

Fig. A-22: Structural system of the roof, as well as of the stand structure

Fig. A-23: Façade of the stadium

Fig. A-24: Roof structure from inside

7.10 *Kingston Community Stadium*, Hull, UK

[12], [85]

The stadium was opened in 2002 and is the home of *Hull City FC* (football) and *Hull FC* (rugby league). The architectural concept for the roof structure resulted from the asymmetric form of the stands. There are three single-tier stands and one double-tier stand. However, the configuration is in a *bowl* around the pitch. Due to the asymmetric roof form, the structural solution is described as *two stadia in one*. The main structure of the stands consists of steel. Pre-cast concrete seating units were used for the stands. Overall stability is achieved through a combination of frame action and bracing of the terracing rakers. From the structural point of view, the roof of the north, south, and east stand is a cantilever structure with a span up to 29m (see Fig. A-25 and Fig. A-28). It is supported by two columns, one at the rear of the terracing and one along the external perimeter. There is the main concourse between these columns. The west stand roof is a different solution. It is a cantilever roof with a stayed rafter solution (see Fig. A-26 and Fig. A-27).

A reason for the chosen roof structures is, if it is necessary, to allow the higher capacity of the two-tier stand to be copied to the other stands, thereby increasing the capacity of the whole stadium. The three-dimensional shaped roof form is shown in Fig. A-29.

For thermal movement of the structure, expansion joints are located as pairs at all four corners of the stadium.

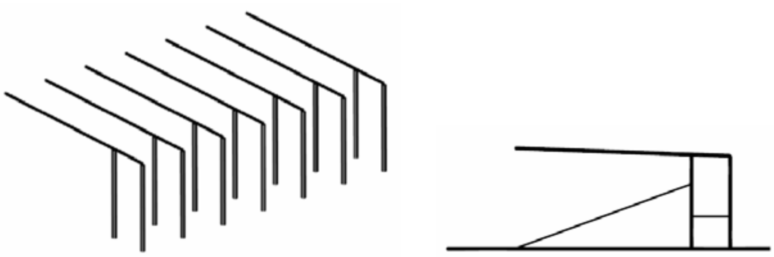

Fig. A-25: Structural system of North, South, and East stand

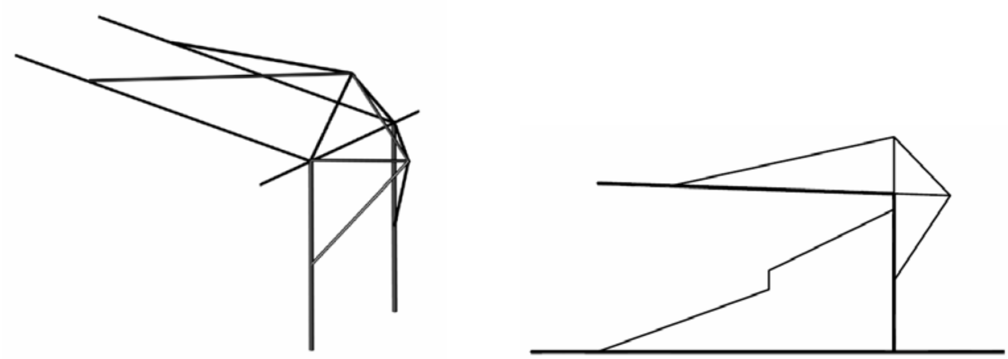

Fig. A-26: Structural system of the West Stand roof

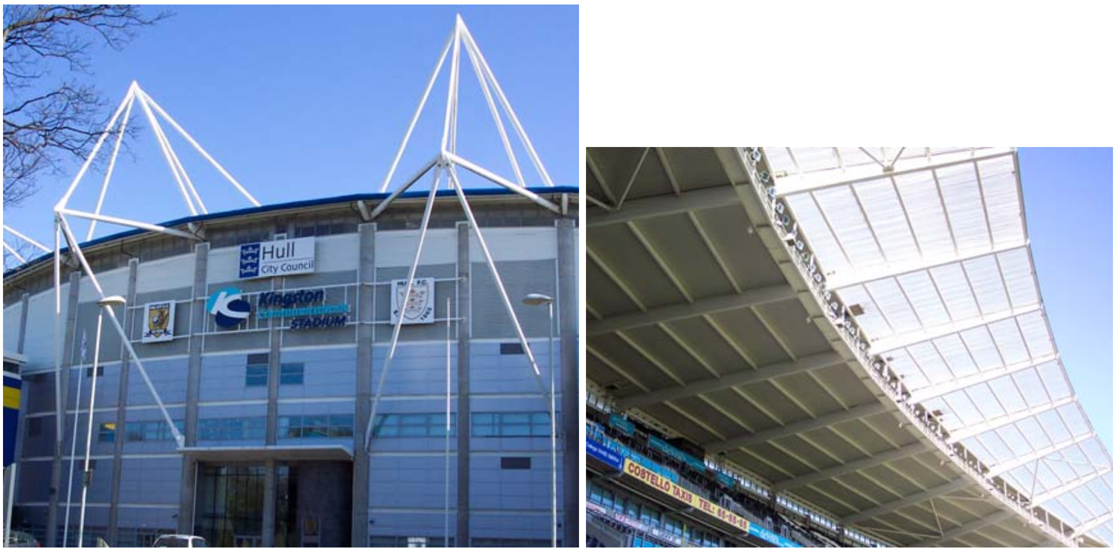

Fig. A-27: left: West Stand façade, right: West Stand cantilever roof structure

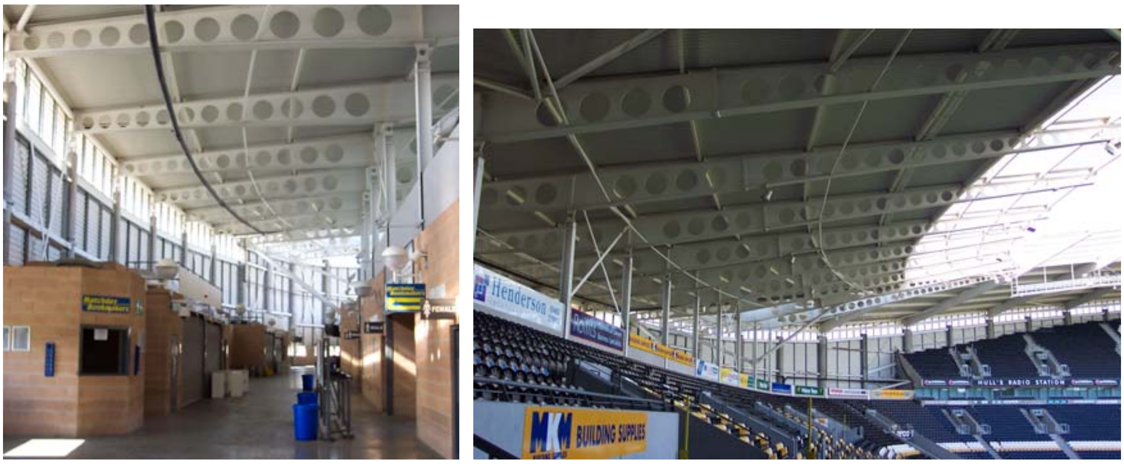

Fig. A-28: left: Main concourse, right: roof of South Stand

Fig. A-29: View from the East to the West Stand

7.11 *Millennium Stadium*, Cardiff, UK

[67], [59], [60]

The *Millennium Stadium* was built for the 1999 Rugby World Cup in Wales. It is a multi-purpose stadium with a retractable roof and provides seating for 72,500 spectators.

The impressive spatial roof structure is supported by four masts in the corners (see Fig. A-31). However, they are not symmetric because of land restrictions. The fixed roof is made of three different types of main trusses – the primary, the secondary, and the tertiary trusses. The two primary lattice trusses span over 220m (full length of the stadium) (see Fig. A-32). They are supported by cables from the corner masts, at the two quarter points (at the corners of the opening of the retractable roof). The trusses provide support and rigidity for the continuous runway beam which supports the moving roof, as well as support for the fixed roof on the east and west of the opening. The secondary trusses span over 180m orthogonal to the primary trusses. Tertiary trusses span over 50m and are spaced at 14.6m centres to support the roof deck purlins. Bracing in the roof structure is necessary at both levels to form lateral stability and to resist torsion effects on loads from the moving roof. The structural system is shown in Fig. A-30.

The four corner masts provide vertical support, as well as horizontal stability of the roof structure. The masts consists of a pair of lower columns (concrete filled steel tubes), which sit upon a fabricated steel tensioning chamber. Cables support the primary trusses as tension system from the masts.

For the retractable roof, there are two rigid roof sections (76 x 55m), each made of five 11m wide units, which are linked together with vertically orientated sliding bearings. The roof moves along rails at both sides.

For the supporting stand structure, frames are typically at 7.3m centres. The stand structure from the concourse level upwards is made of steelwork in CHS, RHS, open sections and plate girders. The stand structure at ground level (substructure) is made of reinforced concrete.

Due to the large cantilever solution for the upper tier, the dynamic behaviour of the structure was a problem, especially for concert use. The solution was found in a temporary prop of the cantilever (see Fig. A-33). In the concert configuration, this prop is used and, for football or rugby use, the prop is not needed and clicked back.

In addition, there is an interesting solution for the pitch. A natural grass pitch surface is needed for rugby. The movable roof was designed to ensure sunlight and wind flow for healthy growth of the grass. However, for an all-year use of the activity area the solution was found in a fully palletised system of interlocking turf modules. They can be lifted and replaced if damaged or worn.

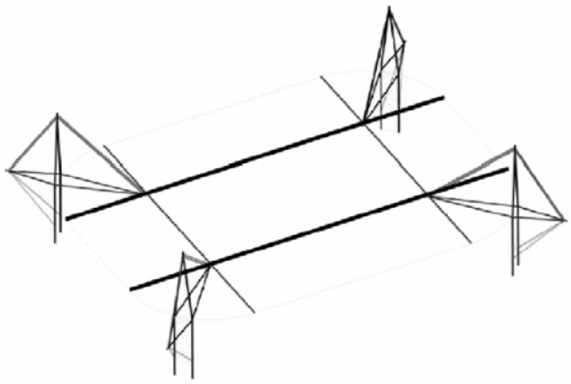

Fig. A-30: Structural system of the roof structure

Fig. A-31: Corner mast of roof structure

Fig. A-32: Main truss (the support for the retractable roof elements) with the tops of the corner masts

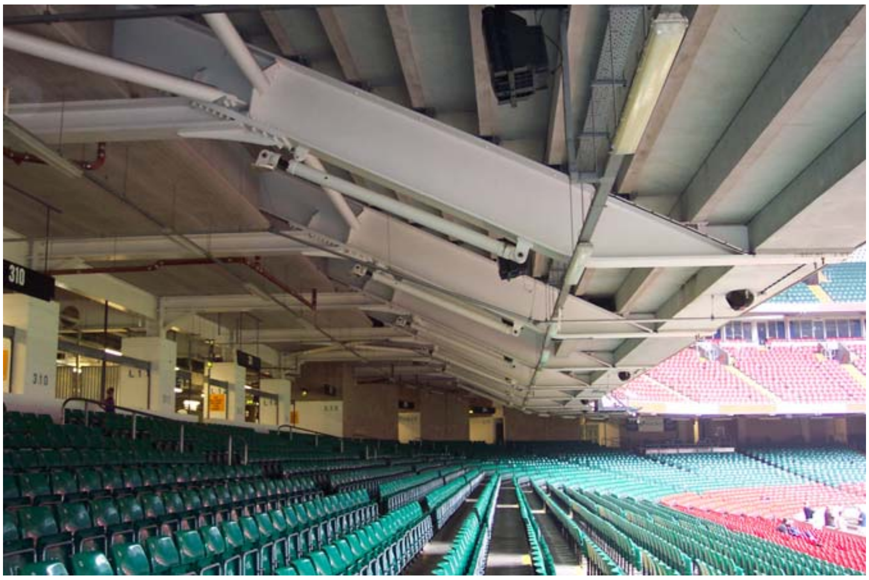

Fig. A-33: Cantilever structure of the second tier; temporary props beneath the steel rakers

7.12 ***Murrayfield Stadium*, Edinburgh, UK**

[63]

The *Murrayfield Stadium* was designed to stage rugby union matches. However, football, as well as American football matches, music concerts, and other events were also held at the venue.

The redevelopment started in 1979, with the decision to construct a stand with seated accommodation on the upper tier and a standing terrace on the lower level. Three similar stands would have been added to form a final stadium with a capacity of 67,000. However, the Hillsborough disaster and the changes in stadium design afterwards, required a new concept for the stadium. In order to achieve the required all-seater configuration prior to the 1995 season, a new design was carried out and approved in 1991. Construction followed in three phases.

Computer simulation and wind tunnel tests were carried out to ensure good conditions for the natural pitch surface. As a result, the front edge of the roof (over the pitch) became a transparent roof covering.

The structural solution consists of a cantilever roof structure (see Fig. A-34). Materials used are concrete and steel, to achieve the strength and stiffness requirements of the structure. Driven pre-cast concrete piles are used for the foundations. Trusses form the cantilever structure of the roof, with cantilever spans of up to 48.5m. Profiled steel cladding spans about 6.8m between the main trusses and is supported by structural gutters, suspended beneath the trusses. The main trusses are made of self-weathering steel, which gives the opportunity of an essentially maintenance free main structure.

Data from the wind tunnel tests was used for the structural analysis of the roof. The natural frequency of greater than 1Hz was considered stiff enough to avoid wind excitation.

Due to the intended use of the stadium for music concerts, dynamic effects were also considered for the stand structure. The limits used were 6Hz vertically and 3Hz horizontally. Bracing bars were designed on that basis.

Furthermore, thermal movements need to be considered, especially in such big structures as stadia. For the structure of the Murrayfield Stadium, thermal movements are allowed locally at the bolted joints. This has the advantage that expansion joints, where relatively large deformations occur, can be avoided. Smaller, local deformations at the joints are more efficient to design.

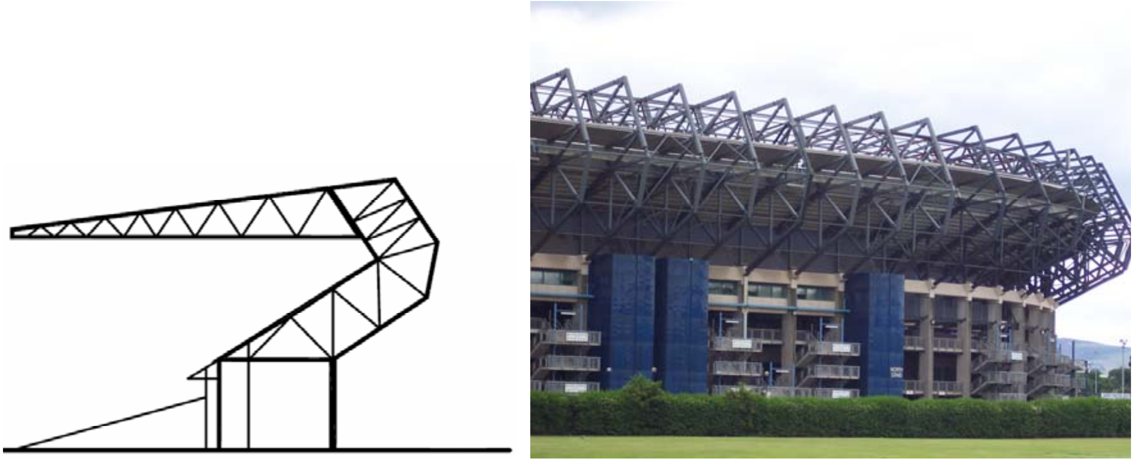

Fig. A-34: left: Structural system of the roof; right: Roof structure from outside

7.13 *New Wembley Stadium*, London, UK

[7], [53]

The *Wembley Stadium* is and was the national stadium of England and hosts major sport events for football, rugby, and athletics. The old stadium was demolished and a new stadium was inaugurated in 2007. It provides seating for 90,000 spectators.

The roof is very large even for a stadium, because it is designed to cover not only the spectator areas but also the huge additional facilities (hotel, museum, offices, etc.) in one. Hence, one of the largest roofs in the world, which contains long clear internal spans, resulted.

At the *old Wembley Stadium*, there was a running track between the pitch and the seating tiers. Therefore, sunlight and fresh air required for the natural grass playing surface was no problem. At the *New Wembley Stadium* the seating tiers are much closer to the pitch and the roof causes more shadows. However, conditions for the television cameras are also influenced by the configuration of the roof. To address these problems to allow more sunlight onto the pitch, sliding roof panels on the south side of the roof were developed.

A massive arch, supporting the roof and spanning from East to West over the whole building, was the solution for both the architectural and the structural design (see Fig. A-35). This arch is the new icon for the stadium.

For this chosen structure of the roof, a model was tested in the wind tunnel to determine wind loads and highlight specific effects on the roof and arch.

The arch spans over 315m, is 138m high, has 7m in diameter, and consists of a *basket weave* unclad lattice structure. Intensive iterative analysis was necessary to ensure that the arch acts as far as possible in direct compression, which is the most efficient state for the arch. However, wind uplift forces needed to be considered. One solution would have been to increase the dead weight of the roof. However, this would have been uneconomic. For this reason, there is a secondary structural system, a second lower arch. Nearly the entire roof is supported by the arch. Thus, safety and security issues had to be considered. The arch has an expected maintenance period of 30 years (first repainting). The cables for the stays have a guaranteed life of 60 years.

The roof plate main structure runs north south. The longest trusses, spanning to the south edge of the bowl, span over 155m. They carry the rails for the moving roof panels and the main southern roof. Lateral stability for these main trusses is provided by a series of horizontal cable ties.

Athletic events can be staged at the *New Wembley*, though the intimate atmosphere at football games can also be achieved. This is done by a temporary demountable structure for the running track. The platform will be built over the seats of the first rows. It will take a few weeks to install or remove this structure.

Construction process started in September 2002, when the existing stadium was demolished.

Fig. A-35: Arch as main structural element of the roof

7.14 *Old Trafford*, Manchester, UK

[27]

Old Trafford is the home of Manchester United Football Club. The stadium provides seating for 76,000 spectators.

The stadium stand structure is made of steel with concrete seating elements. The roof structure was developed and realised in phases. Though the roof covering is beneath the main structural elements, there are pigeons nesting in the roof. The form of the roof intends to create a low edge over the pitch to reduce negative impacts on the natural grass surface and to increase the protection against the elements.

The roof structure is a cantilever form with trussed structural elements. The cantilever span of 58.5m (at the North Stand) is one of the largest in the UK. The structural system of the North Stand roof is shown in Fig. A-36. Fig. A-37 shows the North Stand from inside. Fig. A-38 shows the roof structure of the East and West Stand, where cantilever trusses support a space frame.

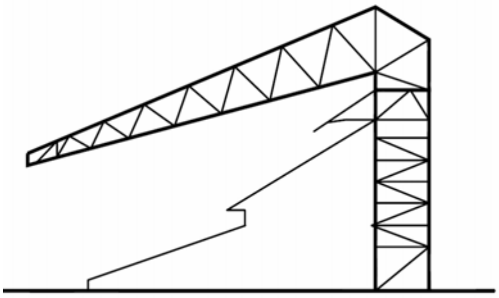

Fig. A-36: Structural system of North Stand roof

Fig. A-37: North Stand

Fig. A-38: East and West Stand structure

7.15 *Reebok Stadium*, Bolton, UK

[18], [52], [67]

The *Reebok Stadium* was designed as multi-functional venue for about 28,000 spectators and was inaugurated in 1997. Therefore, it can be used for activities other then football. For the main purpose, football, the stadium offers 28,000 seats for spectators. As regards viewing distance, all seats are within 90m from the centre of the pitch. The minimum 'C' value is 90mm and the tread width of the seating elements is 800mm. Seating configuration around the pitch is in a *bowl* shape with seats in the corner.

The architectural design is achieved through a dramatic roof structure formed by the trusses, the main structural elements of the roof. The form of the trusses is curved at the top and at the bottom (see Fig. A-39). The structural system is shown in Fig. A-40.

The roof consists of four segmental elliptical shell elements, which are suspended from the main structural elements: four lattice girders. These girders are in turn supported by four masts in the corners. The first step in the design of the lattice girders was to decide the geometry. Due to high impacts on the load transfer, the geometry was important for the behaviour of the girders and the masts. In addition, the main girders, as well as the masts, were inclined at about 20° to the vertical. The beams for the roof covering span between the rear of the stands to the main girders and cantilever out to the pitch (see Fig. A-42). Another design issue was the stability of the girders upper chords. In order to avoid buckling due to compression in the upper chord, tie bar stays are used. Two tie bar stays link each roof beam with the upper chord. Stability of the lower chord is achieved through the roof beams. In addition, bracing in the girder plan is used to stabilize vertically. A stiff arching effect is achieved through the bottom chord. Hence, most of the loads are carried by this effect.

The supporting masts in the corners are made of tubular cross sections (see Fig. A-41). In addition, these towers are the supporting structure for the floodlighting.

Fig. A-39: Reebok Stadium inside

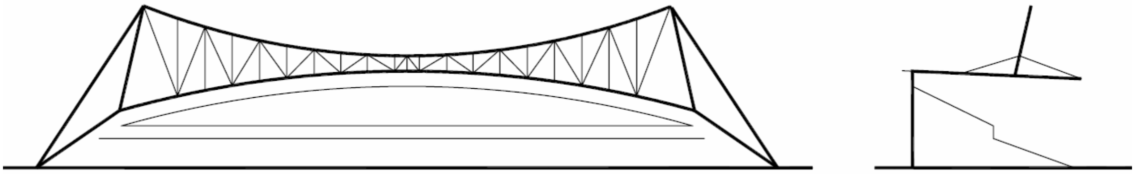

Fig. A-40: Structural system of goal post roof

Fig. A-41: Corner masts; left: from inside; right: from outside

Fig. A-42: left: Stadium from outside, right: Roof structure from inside

7.16 ***Ricoh Arena*, Coventry, UK**

Ricoh Arena is a multi purpose venue, not only for sports events. There is a conference and exhibition hall adjacent to the sports stadium. For this reason, there is a hotel included, with hotel rooms that can be converted into hospitality boxes for sports events. *Ricoh Arena* was inaugurated in 2005. The total capacity of the stadium is about 32,000.

The structural solution for the roof is a frame roof structure, held up by stays from a spatial cantilever structure (see Fig. A-43). These elements support a steel frame that consists of a beam that spans parallel to the pitch and beams (rafters) that span from the perimeter to the pitch. The cantilever elements are made of steel. Fig. A-44 shows pictures of the roof structure.

The supporting stand structure is made of steel and pre-cast concrete seating elements. The gap between the exhibition hall and the stadium is closed and provides space for the reception, as well as for spectator circulation. One of the disadvantages of a cantilever structure is the space required at the perimeter of the roof. In the case of the Ricoh Arena, this was a point to be considered at the link from the stadium to the exhibition hall. Therefore, the supporting structural elements of the roof are different at this side of the stadium.

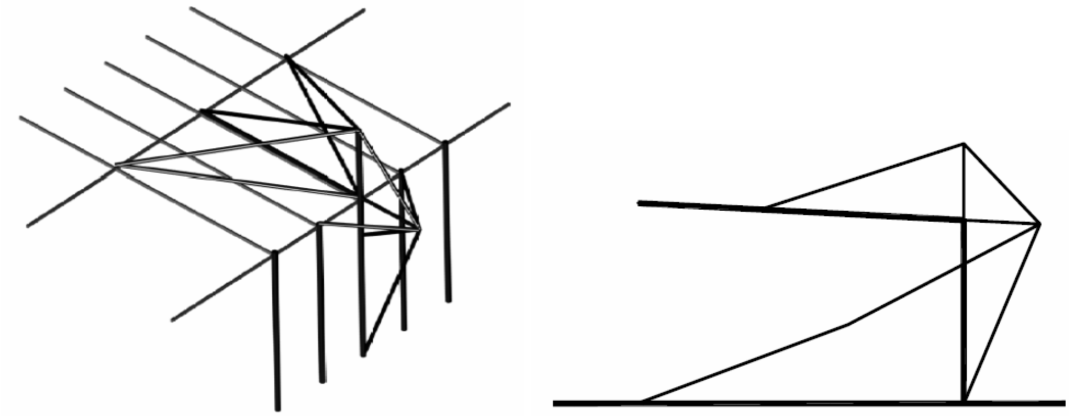

Fig. A-43: left: Spatial cantilever element of roof structure; right: cross section of structure

Fig. A-44: left: Stadium façade; right: Detail of the connection between stays and roof frame

7.17 *Riverside Stadium*, Middlesbrough, UK

The *Riverside Stadium* was inaugurated in 1995 and provides seating for about 35,000 spectators. There are single-tier stands on the east, north, and south sides of the stadium, whereas the West Stand has two tiers.

The supporting stand structure is made of a steel frame with pre-cast concrete seating elements. The roof structure is formed by a plane cantilever supported back to the perimeter (see Fig. A-45). Fig. A-46 show the roof structure from outside. Lateral stability is achieved through bracing bars. The roof covering is beneath the structural elements. Due to the change from a single-tier stand to a double-tier stand, there is a change of level in the roof. The gap between the two adjacent cantilever elements is closed with a trussed structure (see Fig. A-47).

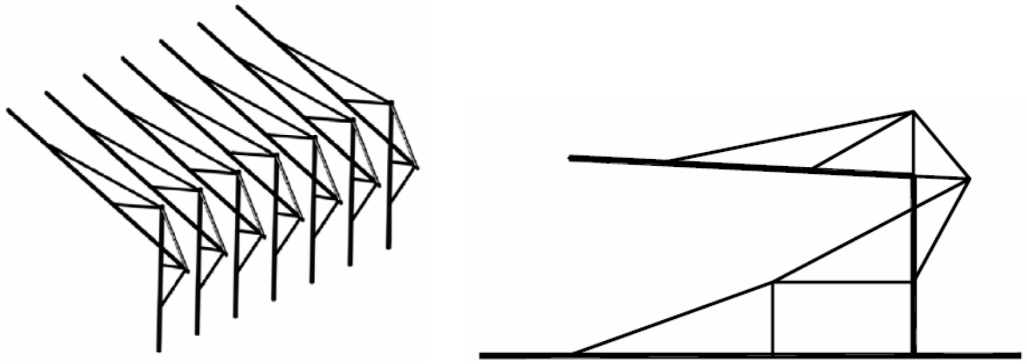

Fig. A-45: Structural system of the cantilever roof

Fig. A-46: West Stand roof from outside

Fig. A-47: Change of level in the roof between the South and West Stand.

7.18 *St. James Park*, Newcastle, UK

[70]

St. James Park holds about 52,000 spectators in four rectangular stands. However, most spectators are accommodated in the two *new* stands. The stadium was redeveloped and opened in 2000. The new roof structure for the Sir John Hall Stand and the Milburn Stand is an impressive cantilever with a span of 64m (see Fig. A-48 and Fig. A-49). The gaps between the *new* stands and the old ones (the Gallowgate End and the East Stand) are closed by a steel structure with a transparent covering. The roof structures of the older stands are also cantilever structures. However, one is formed by a trussed beam with the roof covering above the trusses. The other is made of steel trusses supported on concrete columns with the roof covering beneath the structural elements.

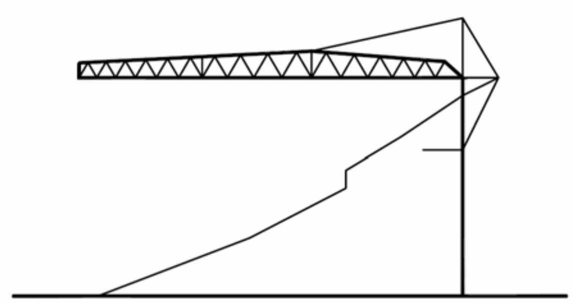

Fig. A-48: Structural system of the Sir John Hall Stand and the Milburn Stand

Fig. A-49: Roof structure of the Milburn Stand

7.19 *Twickenham*, London, UK

[33], [73]

Twickenham is England's national rugby stadium. The redevelopment of the venue started in 1991 with the rebuilding of the north, east and west stands and, it is going to be finished in 2007 with the completion of the south stand. The final capacity will be about 80,000, with spectator accommodation in three tiers. Thus, it is going to be the largest rugby stadium in the world. The last phase includes a hotel, a conference centre, a health and fitness club, and an arts centre. All these additional uses will be situated within the new south stand.

The supporting stand structure is made of steel and concrete. The third tier is made of a cantilever structure and supported by the concrete columns at the back. For the roof, there is a cantilever structure (trussed elements with bracing) (see Fig. A-50 and Fig. A-51). The roof covering elements are beneath the structural elements. The 41m cantilever trusses are supported on an in-situ concrete Vierendeel sway frame.

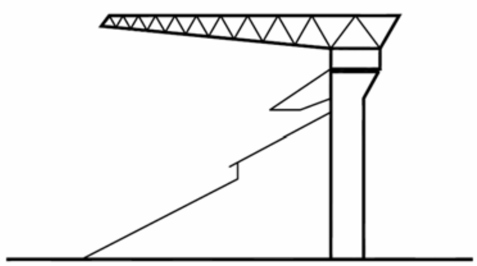

Fig. A-50: Structural system of the roof

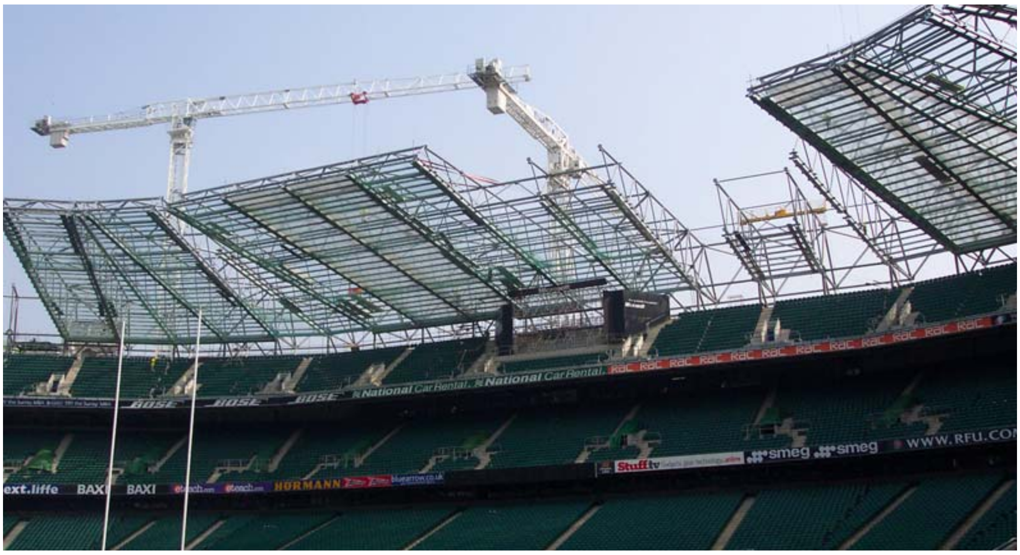

Fig. A-51: Roof of the south stand under construction.

7.20 *Walkers Stadium*, Leicester, UK

Walkers Stadium in Leicester was opened in 2002 and provides accommodation for 32,000 spectators.

The structural solution is one of a steel structure with pre-cast concrete seating rows. The roof is supported by plane cantilever elements with in plane supporting stays. However, there is a second structural element parallel to the pitch. This beam provides support for rafters between the cantilever elements, and the beam is supported after every third or fourth bay (app. 20m to 25m). The structural system is shown in Fig. A-52. For lateral stability, there are bracing elements in the roof plane, as well as at the perimeter. Under one stand, there is accommodation for the club, as well as for hospitality. In this part of the stadium, the structural solution for the roof is the same. However, the supporting stays are different and included in the supporting stand structure. The roof covering is above the structural elements. Therefore, birds are able to nest in the structure. Fig. A-53 shows the roof structure from outside and from inside.

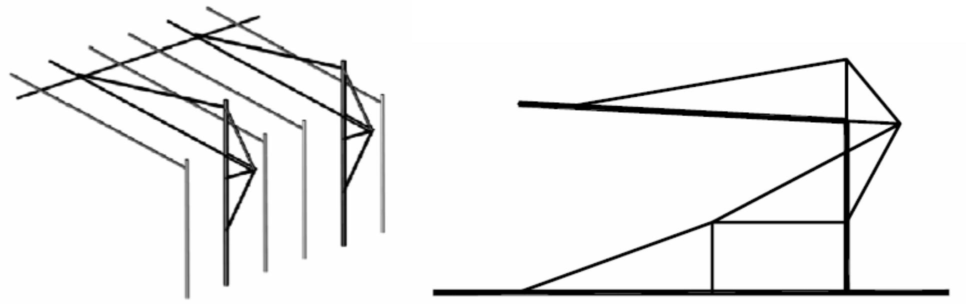

Fig. A-52: Structural system of cantilever roof

Fig. A-53: Roof structure from outside (left) and inside (right)

7.21 Other stadia visited in the UK

- ***Anfield Road*, Liverpool, UK (mostly goal post roof structures)**

Anfield Road is one of Liverpool's football grounds, home to Liverpool FC. At *Anfield*, there is a typical goal post structure solution for the roof over the four rectangular stands. Hence, the main structural elements are trusses supported by trussed columns at the corners. Due to these supports, there are few seats in the corners. The supporting stand structure is either made of steel or of concrete with concrete seating rows. The newer stands are made of concrete.

There is discussion about a new football ground for Liverpool FC at Stanley Park with a capacity of 60,000 to 90,000.

- ***Celtic Park, Glasgow, UK (cantilever and goal post roof structure)***

Celtic Park in Glasgow is the stadium of Celtic Football Club and provides seating for roughly 60,000 spectators. As with any other football ground in the UK, due to the Hillsborough disaster and *The Taylor Report*, *Celtic Park* needed to be redeveloped in the 1990s to fulfil the requirements for more safety at sports grounds. The roofs for the *Jock Stein Stand* and the *Lisbon Lions Stand* are formed by a trussed cantilever structure. In contrast to them, the main stand roof (which is an older structure) is supported by a goal post system with columns within the seating tiers. The north stand roof is also formed by a cantilever structure. However, at the seating tiers, there are columns that support the cantilever beams.

- ***Easter Road, Edinburgh, UK (cantilever roof structure)***

Easter Road is the stadium for the Hibernian Football Club in Edinburgh. It was renovated during the 1990s. There are three modern stands that provide unobstructed views for spectators. However, the older east stand roof consists of a post and beam structure. The last stand to be constructed was the west stand, which was built in 2001.

- ***Falkirk Stadium, Falkirk, UK (cantilever roof structure)***

Falkirk Football Club plays at *Falkirk stadium*. The venue, with a capacity of roughly 7,000, is a smaller one and consists of two rectangular stands. For both stands, there is a cantilever roof structure.

- ***Hampden Park, Glasgow, UK (cantilever roof structure)***

Hampden Park is Scotland's national football stadium and was redeveloped in the 1990s. As the national stadium for football, it provides seating for roughly 52,000 spectators with accommodation in a bowl around the pitch. At the south stand only, there is a second tier, but the other stands are designed as one tier seating. The roof was designed as a cantilever structure with the roof covering material fixed beneath the structural members.

- ***Pittodrie Stadium, Aberdeen, UK (goal post and cantilever roof structure)***

Pittodrie Stadium is the home of Aberdeen Football Club. There are four rectangular stands around the pitch with seating for roughly 22,000 spectators. From the structural point of view, there are three systems. A goal post structure is used for the main stand roof and a cantilever form for the south stand. For the older west and north stand, there is goal post beam with some columns at the front of the stand.

- ***Stamford Bridge, London, UK (cantilever roof structure)***

Stamford Bridge is a football stadium in London and home of Chelsea Football Club. There are four rectangular stands around the pitch, each with different structural solutions.

- ***Tulloch Caledonian Stadium, Inverness, UK (cantilever roof structure)***

The *Tulloch Caledonian Stadium* at Inverness is used for football and provides seating for about 7,500 spectators. The stadium was constructed in 1996 and expanded in 2004. The roof is formed by a cantilever roof structure.