VIII International Conference on Textile Composites and Inflatable Structures
STRUCTURAL MEMBRANES 2017
K.-U.Bletzinger, E. Oñate and B. Kröplin (Eds)

WIMBLEDON NO.1 COURT RETRACTABLE ROOF – A CASE STUDY

Michael J. Roberts CEng MICE

Thornton Tomasetti
Exmouth House, 3-11 Pine Street
London, EC1R 0JH, UK
e-mail: mroberts@thorntontomasetti.com web page: www.thorntontomasetti.com

Key Words: Retractable, Adaptable, Long span, Lightweight, Movement, Tolerance.

Summary: This paper presents the design of the new retractable roof for No.1 Court, AELTC, Wimbledon. Specifically, the engineering response, and the challenges of designing for movements, deflections and tolerances of the moveable long span structures supported on new and existing structure.

1 INTRODUCTION

Wimbledon No.1 Court retractable roof is a lightweight structure comprising concertinaed, tensioned fabric fields spanning between long span prismatic steel trusses. These prismatic trusses are supported on flexible long span primary steel trusses, which in turn are supported on new and existing structures of varying stiffness. Movement and relative deflection at interfaces were key to the design, construction and performance of this project.

The All England Lawn Tennis Club (AELTC) is a world class, high profile venue that has a global news access audience estimated at over 1 billion people[1]. The retractable roof is a structure that must work first time, every time. The engineering response must be robust and carefully considered to ensure all the relative movements of the various components, under varying loading conditions, work within the operational requirements of the roof.

This paper will present aspects of the design for No.1 Court operable roof, focusing on some of the key engineering challenges associated with supporting a long span operable roof on a long span flexible structure, supported on a combination of new and existing structure, using mechanisation components with very small tolerance to movement.

2 OVERVIEW OF NO.1 COURT

2.1 Retractable roof

The new roof structure for No.1 Court covers a total area of approximately 12,000m2.

Figure 1: Render showing final No.1 Court retractable roof (Image courtesy AELTC)

The retractable component, which makes up just over half of this area, traverses a distance of 84 metres and takes the form of 6.7m wide tensioned fabric fields spanning between eleven prismatic trusses, 75m in length, which deploy and retract in a concertina fashion.

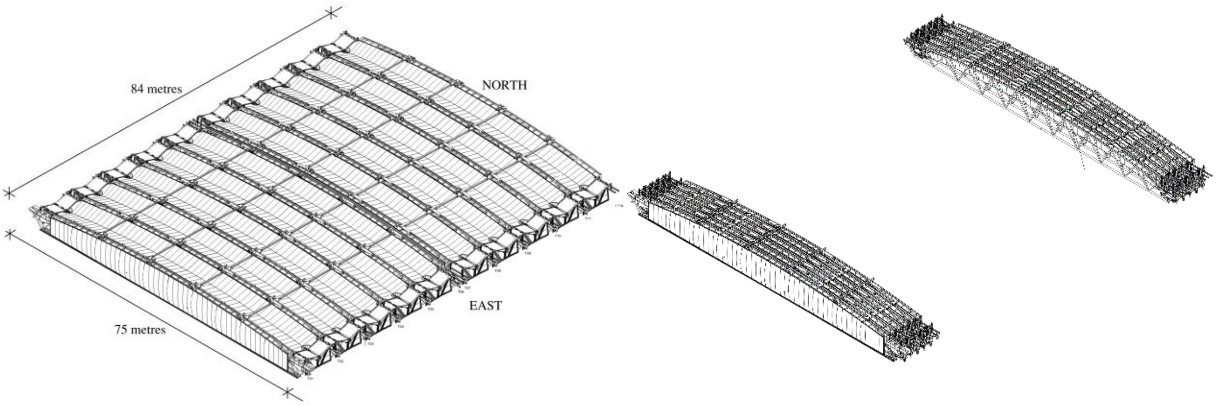

Figure 2: Image of retractable roof – deployed and retracted (image courtesy Tong Hogg Design)

The moveable roof structure is divided into 2 groups; the south group comprising 6 trusses and 5 fabric fields, and the north group comprising 5 trusses and 5 fabric fields. The roof takes up 3 primary positions: deployed, retracted and parked north. This parked north position is to maximise the amount of photosynthetically active radiation (PAR) reaching the grass playing surface when the roof is not in use. The transitions between these three states induce varying amounts of movement in the supporting structure that must be accommodated at the interfaces with the operable roof.

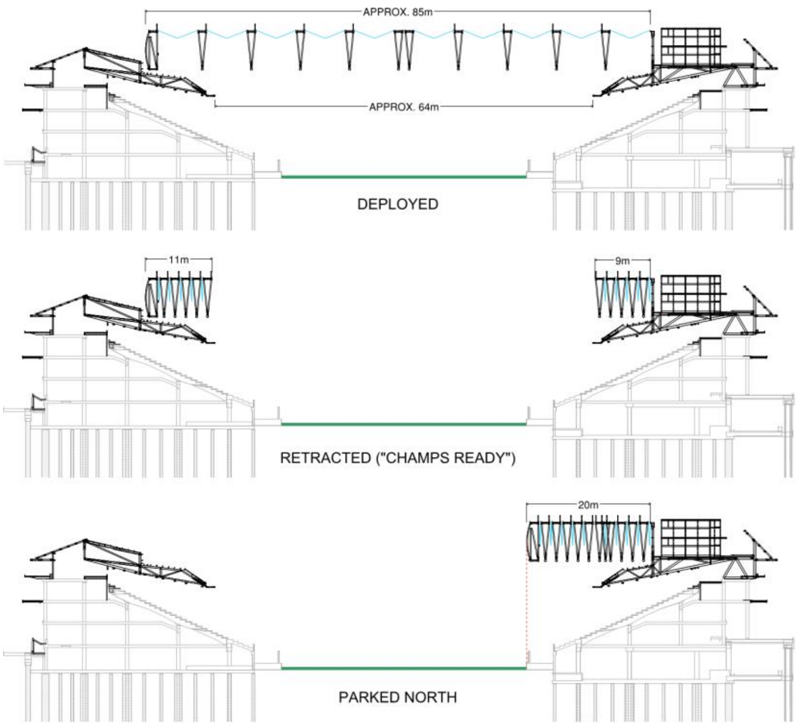

Figure 3: Retractable roof positions

The main structure for the retractable roof utilises eleven trusses. Ten prismatic Warren trusses and one box truss, all 74m long, formed from tubular steel, and symmetrical about both axis on plan. The main trusses have a single horizontal bottom chord, with the top chords curved to a constant radius to ensure that water is channelled to either side. The trusses are1.5m in width and 6.6m deep in the middle. The prismatic shape allows for a minimal visual appearance when viewed from below, but provides the necessary width at the top to provide lateral stiffness to the truss and to provide sufficient area to mount the mechanisation equipment.

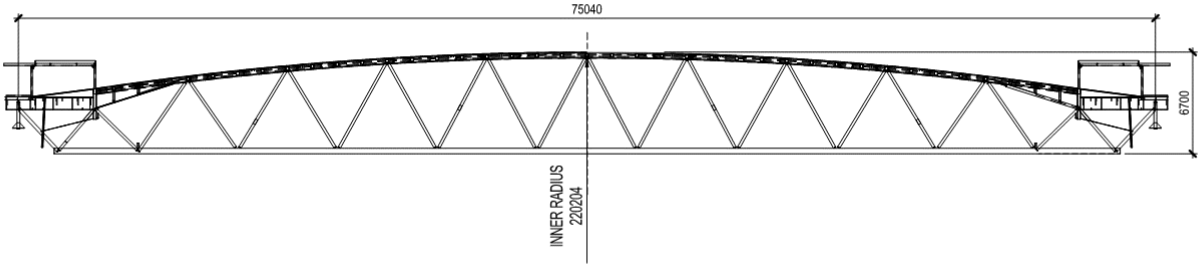

Figure 4: Elevation of steel truss

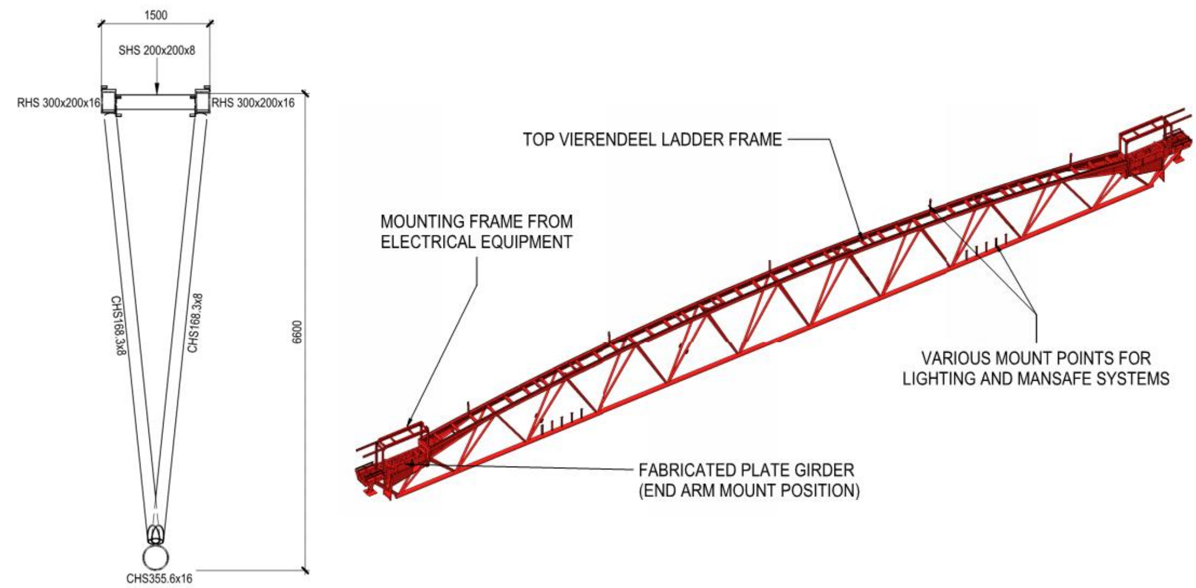

Figure 5: Typical truss elevation, section and isometric

One of the three principle mechanised systems are the bogeys which support each endof the trusses. These run on rails supported by the primary fixed roof structure. The detailing of this interface must accommodate the varying displacements of the supporting structure, the expansion and contraction of the moving trusses, and the fabrication and erection tolerances of the various components. This is discussed further in Section 3.

At the ends of each truss, mounted on the fabricated plate girder elements, are the mechanised end arms. These are hinged structures driven by 4 actuators arranged around a pivot. This arrangement provides fixity between the end arm and the truss, forming a portal structure that stabilises the trusses.

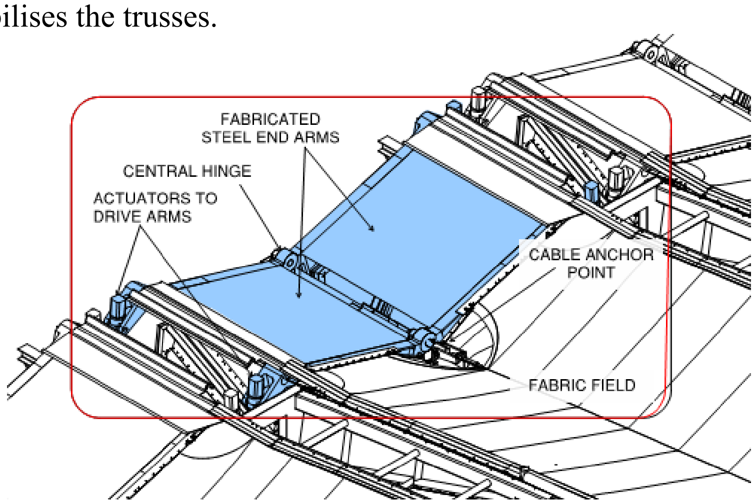

Figure 6: End arm arrangement (base image courtesy Tong Hogg Design)

Four sets of actuator driven restraint arms, equally spaced across the width of the trusses, ensure the trusses remain restrained at all stages of deployment.

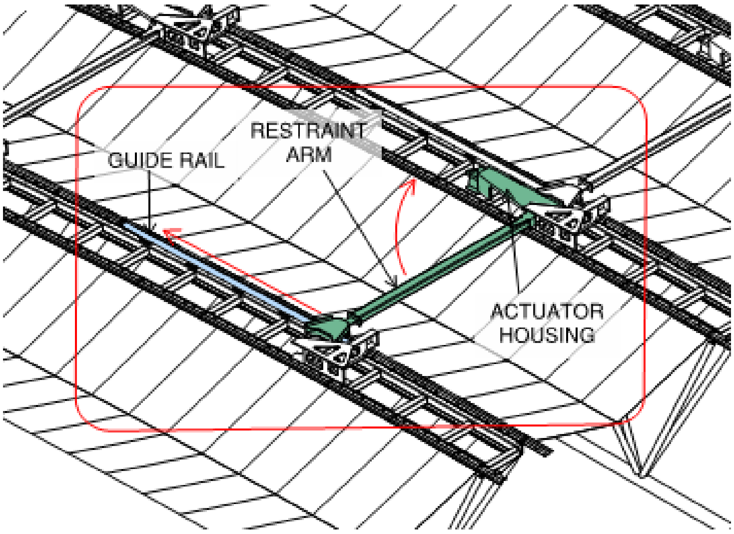

Figure 7: End arm assembly (base image courtesy Tony Hogg Design)

The forces induced in the restraint arms are resolved back along the roof in a north-south direction to points of connectivity with the fixed roof structure. In the north there is a direct connection to the fixed roof, whilst in the south, connectivity is achieved via a deployable locking mechanism. Both of these are key interfaces with the fixed roof, and the detailing must accommodate the differential movements between the moveable and fixed roof structures.

Both the end arms and the restraint arms are fabricated to tighter tolerances than the main truss steelwork, to ensure the mechanised components function correctly. They must also be aligned accurately across the length of the roof. Section 3 discusses the careful detailing and erection methodology required at the interfaces.

The main roof covering comprises ten primary fabric fields, tensioned with a steel valley cable, and formed from Sefar Tenara fabric. Tenara uses a base fabric of woven high strength expanded PTFE fibres with additional coatings for waterproofing. This particular fabric was chosen over more traditional PTFE/glass or PTFE/fibreglass fabrics because of its ability to flex and fold repeatedly without cracking or losing strength. Its other properties of reflectivity, and light transmittance were also key to ensure the playing environment feels as natural as possible. The fabric has interfaces with the moving trusses, the mechanised components, and the static roof structure. This not only generates varying load conditions as the roof deploys, but adds further parameters to be considered as part of the overall movement and tolerance strategy.

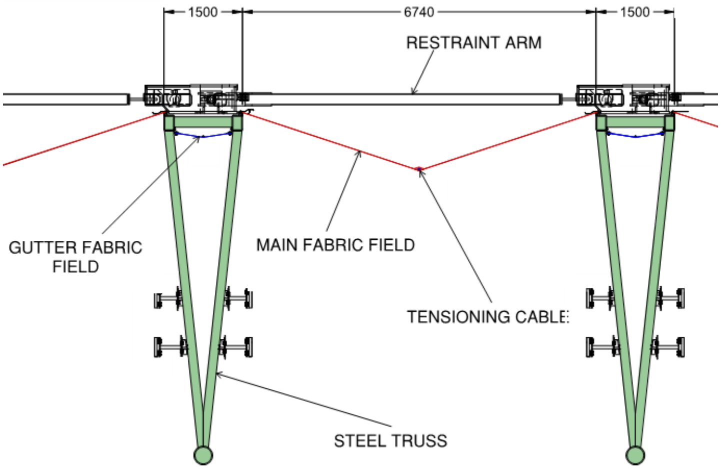

Figure 8: Fabric field arrangement

2.2 The Static Roof

The static roof provides support for the moving roof, provides the necessary cover to the seating bowl, and houses the mechanical and electrical equipment necessary to both condition the bowl space when the roof deploys, and service the hospitality spaces below. The structure comprises a series of 80m span prismatic trusses in the east and west, and a series of long span planar trusses up to 77m in length in the north and south. The inner section of the roof is comprised of simple cantilever planar trusses, supported from the main long span trusses. The static roof structure is supported on the 8 existing concrete cores, and also 3 new “super” columns carefully integrated into three corners of the existing building.

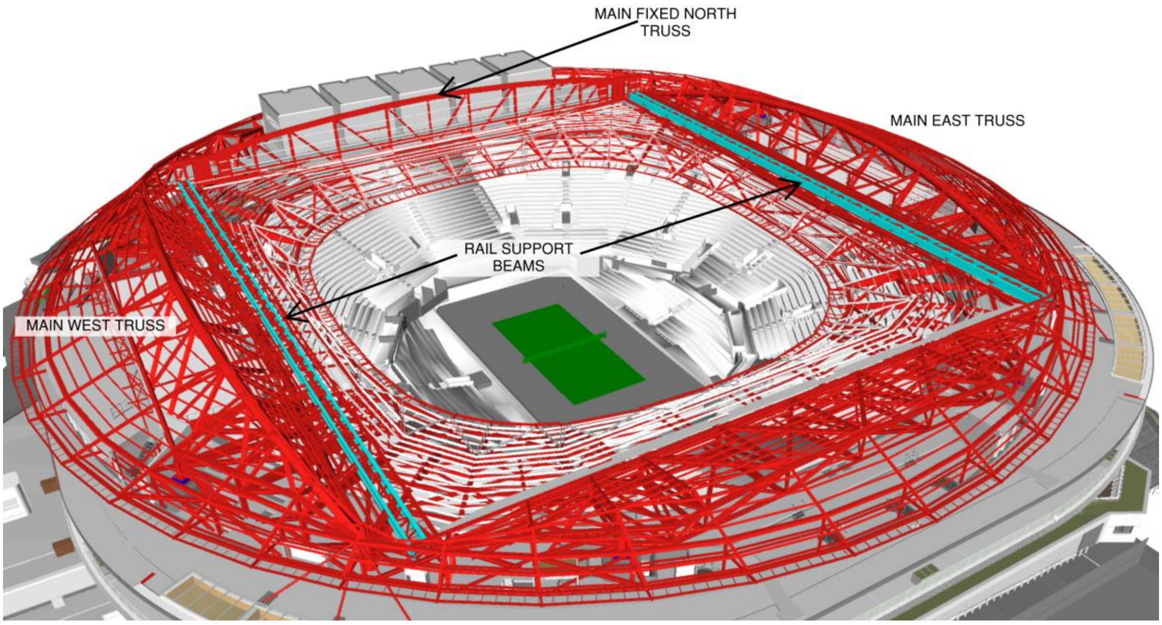

Figure 9: Overview of roof structure

The main east and west trusses support a pair of deep beams that sit eccentrically to the centroid of the truss. These deep beams form the main rail supports upon which the retractable roof bogeys travel.

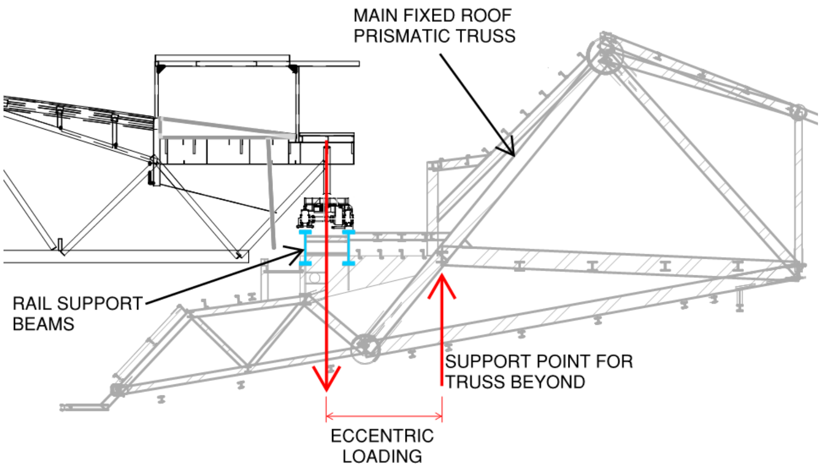

Figure 10: Section through main east support truss

The long span nature of the trusses, the eccentricity of the moving roof support, the transfer elements, the mix of new and existing support structure are significant factors influencing movement and tolerances.

3 MOVEMENTS AND TOLERANCES

All buildings move, the degree of which is governed by stiffness and applied force. It is generally not feasible to completely prevent the movement, it's about understanding how the structure moves, to what degree, and then designing for it.

In the case of the No.1 Court development, the challenge of understanding the movement is compounded by the fact that there is moving structure that can take up multiple positions, applying forces in different ways, inducing a varying response in the supporting structure. For the moving roof, it is also important to ensure that there is a direct load path back through the structure that can be resolved back the main stability elements with the building. The mechanised components also need to be fabricated, installed and operated to much tighter tolerances that standard steelwork.

3.1 Primary Support Structure

The moving roof is supported on the long span east and west trusses. These undergo varying degrees of movement as the roof is deployed and retracted. When designing the long span trusses it was important to consider overall magnitude of vertical and horizontal deflection, deflection profile – in particular the gradient that the moving roof must traverse, relative movements between adjacent rails, and relative movements between the east and west rails.

Survey data for the Centre Court retractable roof shows that the supporting structure for moving roof deflects approximately 116mm vertically (span/630) at the rail locations. The spacing between the east rails and west rails increased by up to 69mm during deployment due to rotation of the supporting structure. Discussions with the mechanisation consultant agreed that the No.1 Court supporting structure should achieve at least the equivalent of span/630 for the vertical deflection, and should not exceed the lateral displacements observed at Centre Court. It was also agreed that the supporting structure should be pre-cambered such that when the roof is deployed, the entire structure is "level" and achieves the theoretical design position.

The design of the long span support trusses evolved to minimise the eccentricity of the rail support beams from the bottom chord of the truss to control the lateral deflections. The stiffness of the truss was then tuned to ensure the vertical deflection criteria was achieved.

The following graphs, normalised against the deployed case, show the deflection performance of the supporting structure measured at the rail locations.

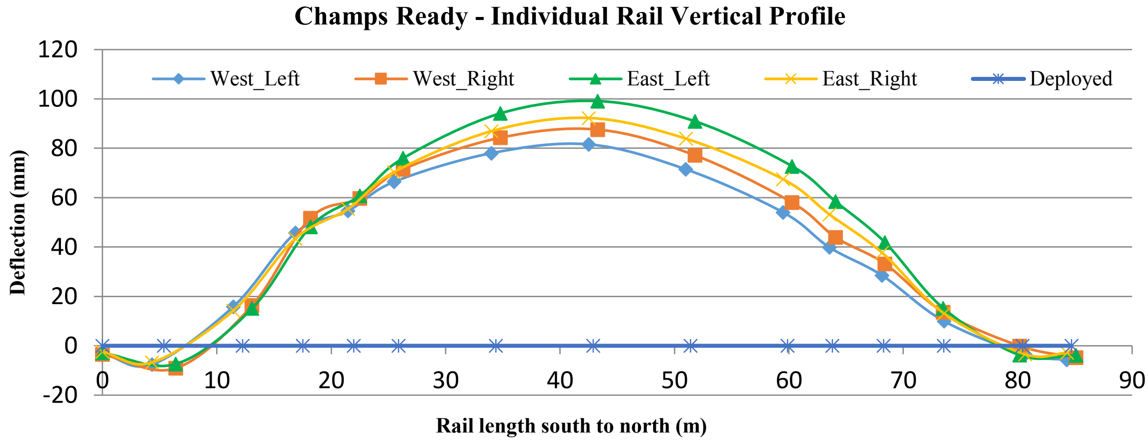

Figure 11: Vertical Rail profile in "Champs ready" position

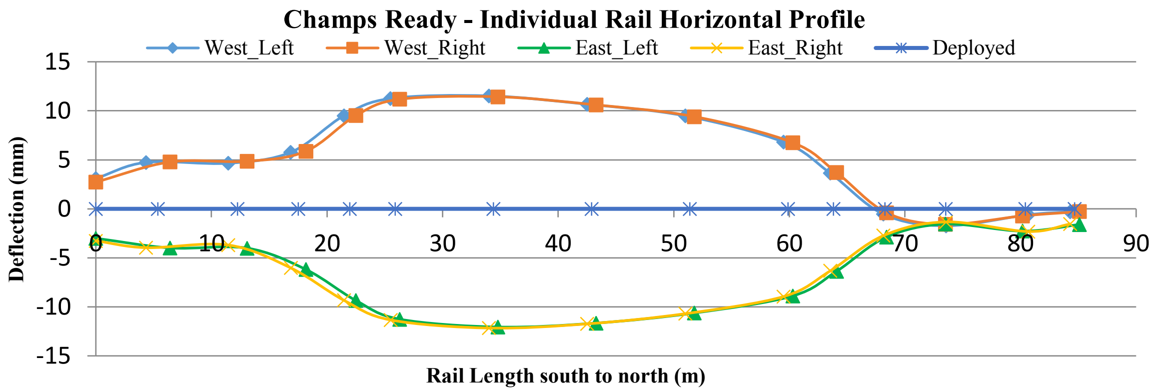

Figure 12: Horizontal rail profile in "champs ready" position

The predicted deflections also account for the varying differential settlements and displacements of the supporting structure. Since the aim is to achieve a level rail structure when the roof is deployed, the rail support structure hogs in the retracted and parked-north cases. The peak vertical deflection of the rail support structure when the roof is deployed is 100mm which is the equivalent of approximately span/850. It can also be seen that that change in distance between the east and west rails peaks at 25mm, well within the agreed criteria.

This movement must be accommodated at the interface with the moving roof, otherwise there is the risk of either the bogey guidance rollers being damaged, or the moving roof structure acting as a prop to the fixed roof. The solution to this is to use bearings between the bogeys and the moving roof trusses. No.1 court uses bearings that allow a displacement of up to 150mm on the west side, and 50mm on the east side. As well as accounting for the change in rail spacing, these bearing also permit the moving roof trusses to expand and contract freely under thermal loading without imposing lateral forces onto the bogeys.

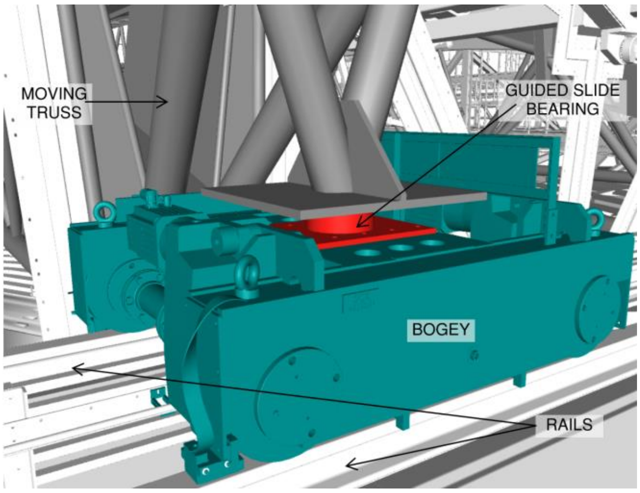

Figure 13: Bearing detail

The bearing arrangement requires some consideration though, as there is still a requirement to achieve some restraint in certain locations to ensure the moving roof structure remains stable. The following diagram illustrates the bearing release strategy:

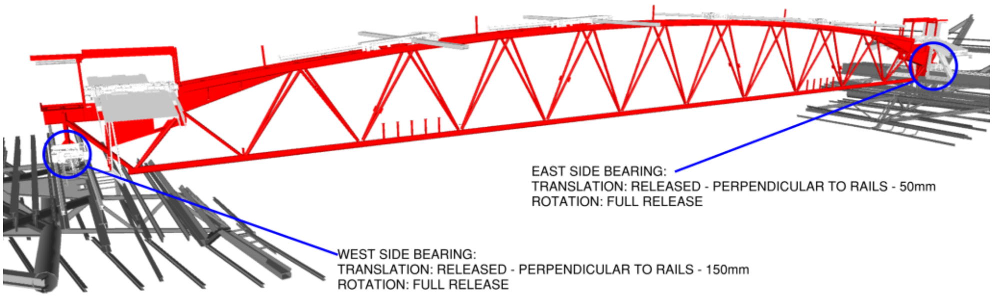

Figure 14: Typical bearing release strategy

The east side bearings on the leading trusses of the south group (truss 1 and truss 6), and the leading truss of the north group (truss 7) have full restraint in an east-west direction to provide a plan rotational restraint to the truss group.

3.2 Primary interface at north end

The connection of the moving roof structure to the fixed roof structure in the north forms a critical interface. At this junction, the engineering solution must deal with differential movements of the fixed and moving roof structure, the interfaces of the mechanisation equipment, the fabric connection, and water tightness.

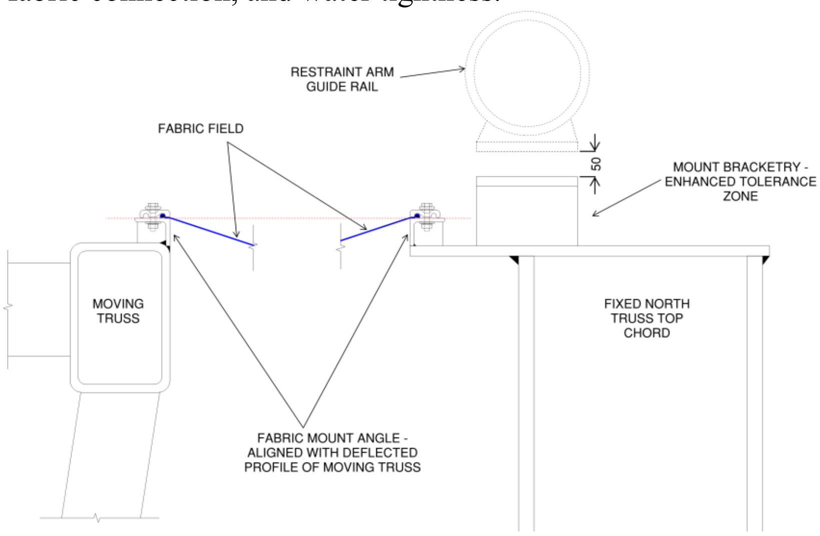

Figure 15: North Truss interface

The moving roof trusses are not pre-cambered so the profile of the fixed structure (the fixed north truss) was profiled to match the deflected geometry of the moving roof trusses. This was important to ensure a consistent fabric interface detail on both the fixed roof and the moving roof. This also ensures that the cutting pattern for the fabric remains consistent for each fabric field. The mechanisation mounting points were lowered an additional 50mm to provide an enhanced tolerance zone for mounting the mechanisation equipment. Differential movements are accommodated in the rotation of the restraint arm, and the general flexibility of the fabric.

Since the moving roof trusses utilise bearings at the interface with the bogeys, they are free to expand and contract under thermal loads. There is then the potential for the end arms mechanisms, which are fixed onto both the moving truss and the fixed roof structure, to act as a restraint to the thermal loads, which may lead to potential over stress. A simple solution of using a bearing detail at the interface of the end arms with the fixed roof structure was not feasible due to the tension forces in the main fabric field cable. The fixed north truss was also not easily divorced from the supporting structure to integrate a bearing either. The final solution was to expose the fixed north truss to same environmental conditions as the moving truss to minimise the potential differential thermal expansion. Whilst there is still some differential, the forces this induces in the both the structure and the mechanisation equipment are within the acceptable limits.

3.3 Tolerances

Understanding the tolerances has been a key part of the design process. The steel fabricator, who is responsible for fabricating and erecting both the fixed roof steelwork and the moving roof steelwork is typically working to National Structural Steelwork Specification recommended tolerances. The mechanisation consultant who is responsible for fabricating and installing the mechanisation components is working to a much tighter set of tolerances. The fabric consultant who is responsible for the final design of the interface connection and the installation of the fabric is working to another set of tolerances. Ensuring these are compatible at the interfaces has been one of the key challenges.

The mechanisation consultant uses “BS ISO 12488-1:2012 – Cranes – Tolerance for wheels and travel and traversing tracks” as the basis for the permissible movement and tolerances for the rails and the supporting structure. The moving roof mechanisation has been defined as Class 2 installation. This code puts very tight controls on the positioning and profile of the rails. The entire supporting long span truss structure is being pre-cambered to ensure that once constructed, and the moving roof is deployed, the entire structure is in the theoretical designed “level” position. When dealing with long span structures and pre-sets, there are many factors that can influence how the deflection response of the structure will manifest. Variation in connection fixity between the theoretical design and actual performance, variations in calculated loadings, thermal effects, and connection “slip” are just some of the factors. By considering each of these and generating a potential movement envelope, the deflection performance of the supporting structure could be estimated. Using this envelope informs how much permissible adjustment needs to be designed into certain connections to allow adjustment to meet the required tolerance. In the case of the main bogey rails, the primary support beams had full lateral and vertical adjustment to ensure they could be positioned correctly. The rail connections then had further adjustment for fine tuning.

For the mounting of the mechanisation equipment, the interfaces were dealt with primarily by providing oversize or slotted holes, together with adequate shim zones. In certain locations, for instance the fixed north truss, enhanced shim zones were provided to provide for potential lack of pre-set “drop-out”.

For the mechanised end arms, the alignment is critical to ensure the smooth deployment of the roof. Lack of alignment has the potential to cause the end arms to lock up, potentially generating high stresses in both the structure and the equipment. The ends arms must be consistently spaced between the east and west ends, and be aligned on an axis parallel to the rails. As the moving trusses are sequentially erected on the supporting structure, along with the end arms, the supporting structure deflects both vertically and laterally. Providing oversize or slotted holes for the mounting does not give sufficient adjustment. In this case, the mount positions on the moving roof trusses are drilled off site for the east side, but are site drilled in the west once the alignment has been set. Where the end arms mount onto the fixed north truss, direct site drilling is not feasible into the fabricated box girder which forms the top chord. In this instance an interface plate has been utilised which can fixed directly to the top chord, and be site drilled and tapped to suit the end arm position.

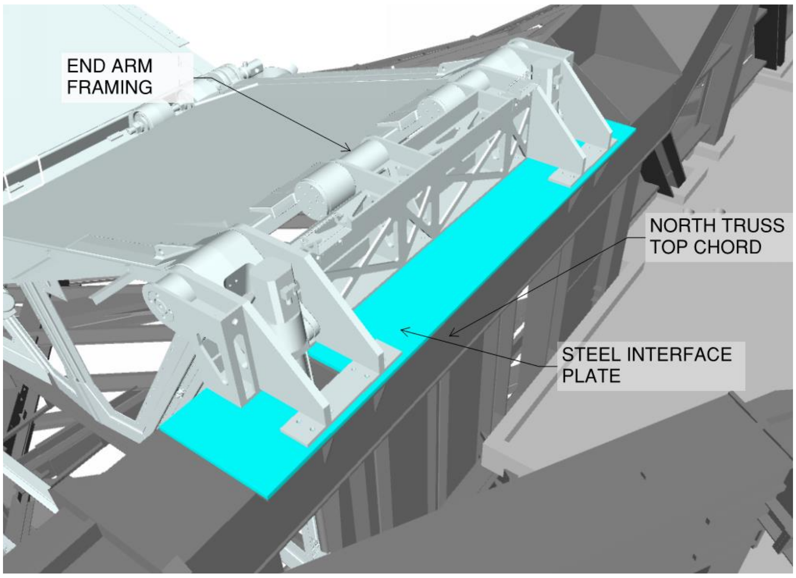

Figure 16: North truss interface plate

The fabric fields have interfaces with both the primary steelwork and mechanisation equipment. The fixing detail comprises a clamp plate detail with bolt fixings at regular centres. For these interfaces, the steel fabricator has ensured that the fabrication tolerances match the requirements of the fabric consultant.

4 CONCLUSIONS

Whilst there are many different moving roof typologies that are a response to a specific brief and constraints, there are many common engineering challenges. Movement, relative deflection and tolerance are one of the most important aspects to understand, and correctly design for. The varying load cases induced by a deployable structure adds further complexity and misalignments and lack of tolerance to movement have the possibility of causing the moving roof structure to “lock-up”. For No.1 Court roof and Centre Court roof, which are the only significant moving roof structures in the UK that can be operated during stadium occupation, a deployment failure is unacceptable.

[1] Facts and Figures / FAQ, http://www.wimbledon.com/en_GB/atoz/faq_and_facts_and_figures.html, 12th April 2017