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Membrane Substitution of La Cartuja Stadium Roof in Seville, Spain

Sustitución de la membrana de la cubierta del estadio de La Cartuja de Sevilla, España

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ABSTRACT

After 20 years of use, the roof membrane of the Olympic Stadium of La Cartuja in Seville showed signs of aging. This produced a certain loss of pre-stressing of the membrane-cable system that, together with a more than probable mismatch between the dead loads assumed in the original design and the current ones, made that the rainwater runoff did not drain to the appropriate points under certain rain conditions with wind downward pressure load. In March 2018, torrential rains combined with westerly winds that, in light of events, were compatible with the circumstances that led to poor roof drainage that resulted in some water ponds on the membrane. The article describes the steps that were taken to solve the pathology.

KEYWORDS: Large span roof, lightweight structures, membrane, pathology of structures, steel, cables.

RESUMEN

Tras 20 años de servicio, la membrana de la cubierta del Estadio Olímpico de La Cartuja en Sevillla mostró signos claros de envejecimiento, lo que se tradujo en una pérdida de pretensado del sistema estructural y por tanto de su rigidez. Esto, junto con un probable desajuste entre las cargas muertas asumidas en el diseño original y las actuales provocó que, bajo ciertas condiciones de lluvia y carga de viento de presión sobre la cubierta, las aguas de escorrentía no drenaran hacia los puntos adecuados.

En marzo de 2018 unas lluvias torrenciales se combinaron con vientos del oeste que, a la vista de los acontecimientos, eran compatibles con las circunstancias que provocaron un mal drenaje de la cubierta, lo cual dio lugar a estancamientos de agua en la membrana. El presente artículo describe los pasos que se dieron para solucionar la patología.

PALABRAS CLAVE: Cubiertas de gran luz, estructuras ligeras, membrana, patología de estructuras, acero, cables.

1. BACKGROUND

In this paper, the project for the refurbishment of the large span roof with structural membrane of Estadio de La Cartuja in Seville (figure 1), Spain, is described. Its aim is to go through the different phases of the project, from the appearance of the first incidents to the execution of the finally adopted solution, in order to establish conclusions and Lessons Learned to be applied in similar situations in the future.

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Figure 1. Olympic Stadium "La Cartuja" in Seville. Credit: La Cartuja Stadium SA.

2.
LA CARTUJA STADIUM ROOF

La Cartuja Stadium is a multi-purpose stadium located in Isla de la Cartuja in Seville, Spain (figure 2).

It was built to be the flagship of the Olympic dream of Seville. Inaugurated on 5 May 1999, it hosted the World Championships in Athletics in August of the same year.

The stadium was one of the largest stadiums in Spain at the time . The design provided the opportunity to, if necessary, lower the pitch and fully convert the facility into a football stadium only. In such case, a new grand-stand would occupy the space that today belongs to the athletic field. The sports facility houses offices as well as a hotel.

The roof was designed as a spoke wheel structure, with one outer four chord truss compression ring, alternating radial ridge (upper) and valley (lower)cables and a single inner tension ring. A PVC coated polyester fiber membrane was installed in between the cables, working as a climatic barrier.

There are many variants of the spoke wheel structural system applied to roof structures [1]. A very typical example is the one with two outer compression rings and one inner tension ring. This version was applied for the stadium roof of La Cartuja, featuring some particularities that are explained next [2].

The most relevant parts of the roof structure are the following:

Compression ring: A three-dimensional steel truss formed by four built-up rectangular section chords. The plan geometry of the ring in plan is formed by two tangent curves of different radius (figure 4) . The compression ring rests vertically on the building structure, and does so in an eccentric manner, as the stadium geometry does not exactly match the geometry of the compression ring.

Figure 2. La Cartuja Stadium, Inside view Credit: schlaich bergermann partner.

Tension ring: The inner edge of the roof, formed by a bundle of eight fully locked steel cables. Its geometry is homothetic to the one of the compression ring. The tangential catwalk for maintenance hangs directly from the tension ring.

a) The stadium was designed by the architectural practice Cruz y Ortiz Arquitectos that, together with the contractor ACS and the local structural consultant AYESA, won a Design and Build competition. The structural engineering for the building project was commissioned to AYESA, while the structural design of the roof was finally commissioned to schlaich bergermann partner

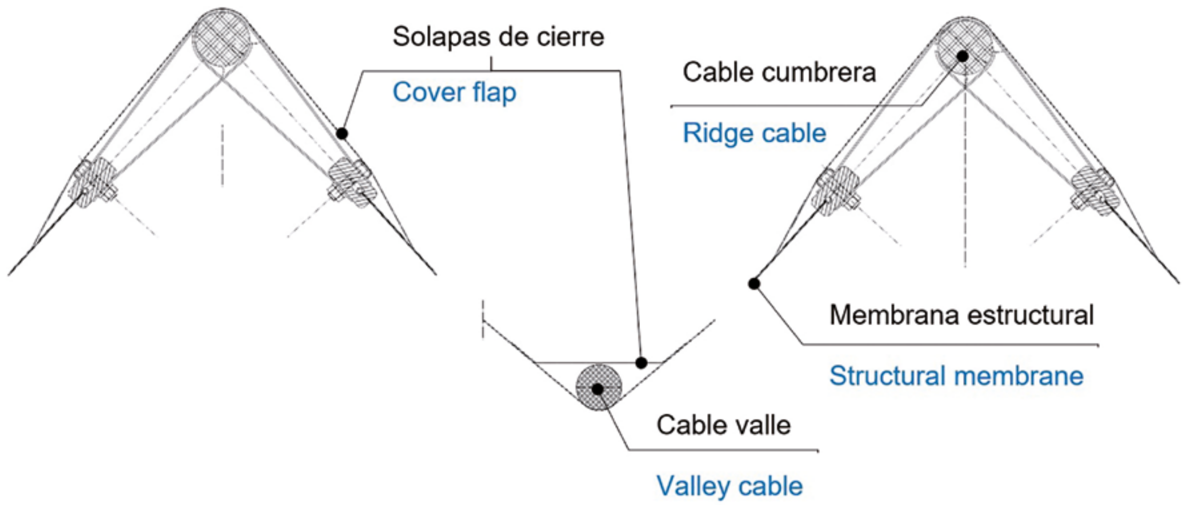

Figure 3. Tangential cut of a membrane bay. Connection to upper radial cables and interwoven with lower radial one
Credit: schlaich bergermann partner.

Radial cables: The roof has 88 radial cables. Half of them are connected from the upper inner chord of the compression ring, being these the ridge cables. The other half of the cables are connected from the lower inner chord of the compression ring, these being the valley cables. What makes this roof very particular is that the radial cables, ridge and valley cables, are alternating and never coincide on the same radial axis. The radial cables span 40 m between the inner edge of the compression ring and the tension ring.

Tension ring node: The intersection between the tension ring and the radial cables, either valley or ridge cables, are materialized by a high resistance steel casting node. These elements are transferring the deviation forces from the tension ring to the radial cable.

Membrane: Woven between the radial cables, the membrane is the element to shade and protect the spectators from sun and rain. It is a polyester textile membrane coated with PVC. The membrane panels go from ridge cable to ridge cable through the corresponding intermediate valley cable. In this way, the runoff rainwater is naturally conducted by the lower radial cable to the drainage point at the lower inner chord of the compression ring.

The membrane panels are continuous between two upper radial cables (ridge), joined to them by stainless steel straps attached to the membrane edge by an aluminum profile called a “keder”. The membrane is intertwined with the lower radial cable (valley) without any mechanical means. In this way, the lower radial cable (valley) can slide freely in relation to the membrane (figure 3). This makes the membrane easier to install since the number of stainless-steel belts and keder profiles (aluminum profile edges) is reduced significantly. This is not necessarily a structural or mechanical advantage, but it is economical.

The inner and outer edges of each membrane panel are materialized by edge catenary cables. In the case of the inner edge, next to the tension ring, the catenary cable goes from one tension node to the next. In the case of the outer edge, the catenary cable connects the anchorage points of an upper radial cable and a lower one at its junction with the compression ring.

The roof structure of the La Cartuja Stadium is an example of a very efficient and economical application of the spoke wheel system to cover large spans.

3. STRUCTURAL PATHOLOGY

At the beginning of March 2018 there were torrential rains in Seville combined with strong west winds. On March 4th, La Cartuja Stadium maintenance management warned of large water accumulations in the membrane with associated plastic strains. At this point, the roof had been in use for 20 years without any incidents, but now a problem related with an abnormal drainage on the roof was reported. This was immediately notified to the architects, who forwarded the issue to the engineers of the roof. [2]

There were eight ponds located at the valleys of the five membrane panels on the west side of the roof (figure 5). The water ponds occurred at a variable distance between 3m and 10m from the tension ring, in any case, at the third of the span of the roof closest to the tension ring.

After the notification of the problem and the preliminary analysis of the photographs received, it was determined that the drainage problem would not compromise the global structural integrity of the roof, although it could lead to a local failure of the membrane. Therefore, a series of immediate measures to be carried out on the roof were communicated (figure 6), consisting of:

1. To cordon off the west grandstand.
2. To install lifelines to secure the maintenance personnel on the roof with harnesses.

2 schlaich bergermann partner.

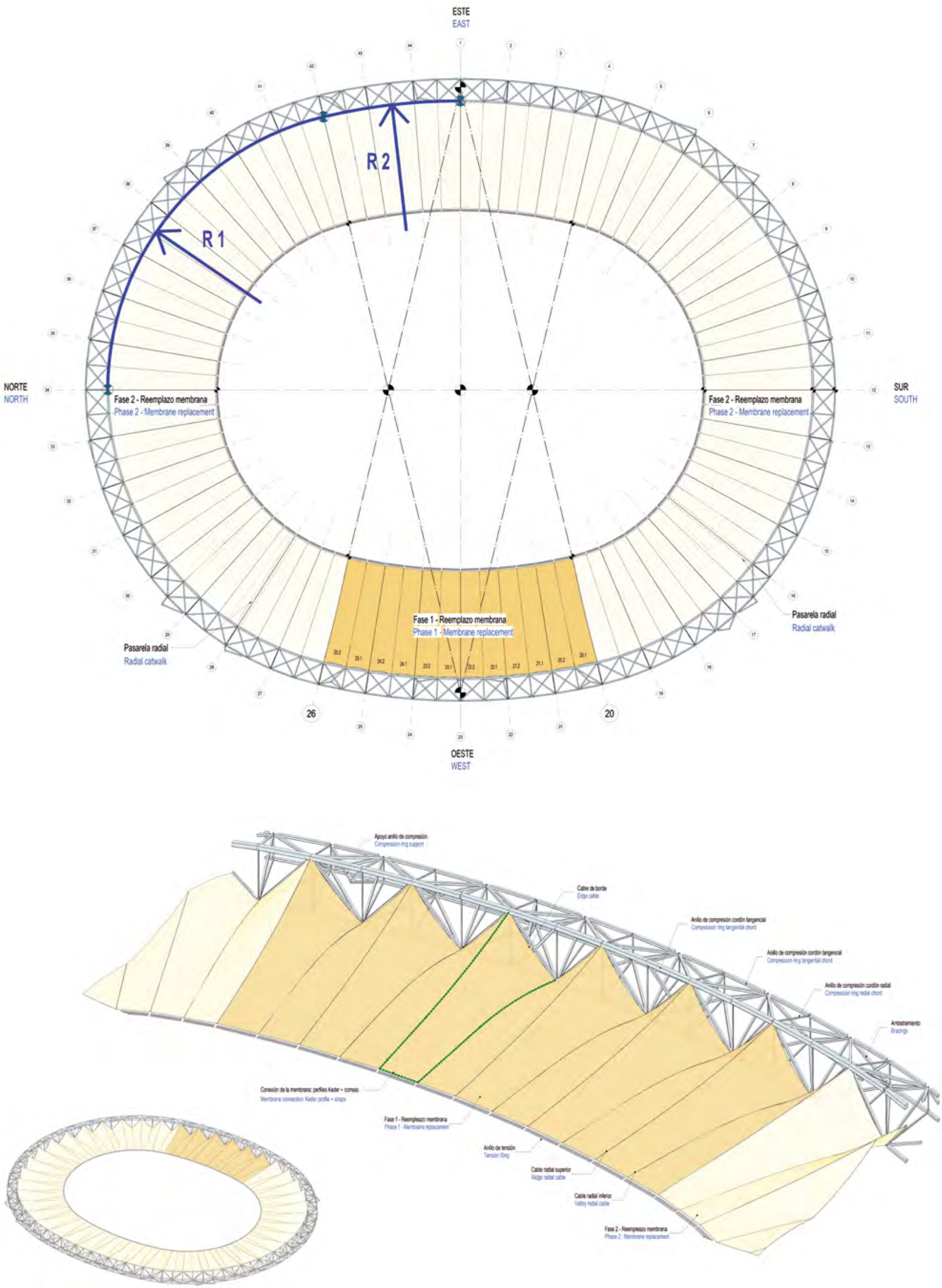

Figure 4. Elements of La Cartuja Stadium Roof Credit: schlaich bergermann partner.

Figure 5. Ponding on the roof. Credit: schlaich bergermann partner

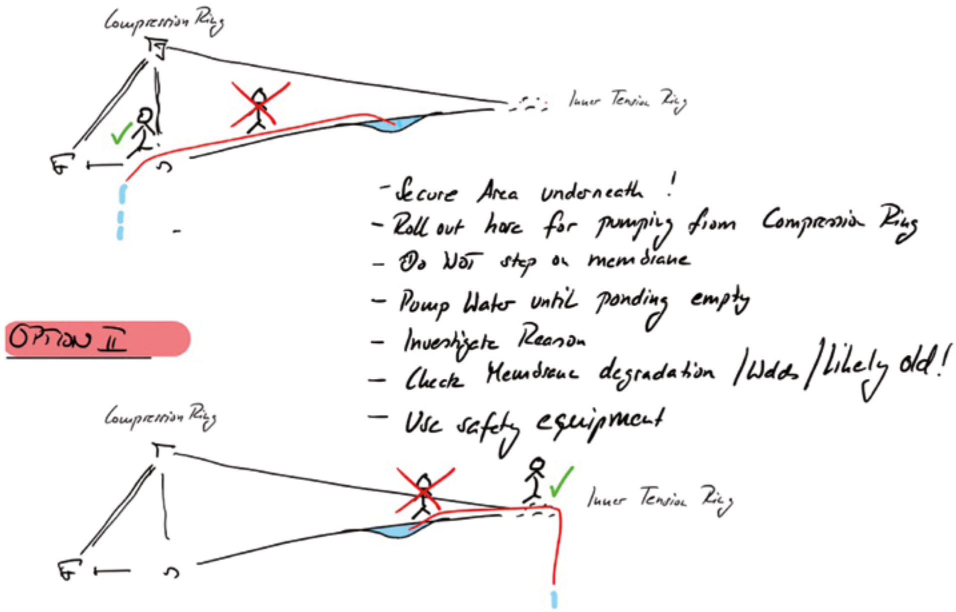

Figure 6. Immediate instructions given right after notification of the issue. Credit: schlaich bergermann partner.

3. To pump the water out from the ponds with of conventional pumps.
4. Do not step on the membrane.

It was appropriate to advice not to host any event in the stadium until the causes of the problem were analyzed and corrective measures were taken. The stadium had been used only for concerts and some punctual soccer matches, but it had no continuous use. However, the decision to temporarily close the stadium had a certain impact in the local media.

Figure 7. Some evidence in lack of maintenance. Credit: schlaich bergermann partner.

4. PRELIMINARY ANALYSIS OF THE PROBLEM

After 20 years of service, the roof was experiencing rainwater drainage problems. In order to determine the reasons as well as evaluate possible solutions a site visit was made. In this site visit, it was found that there was not much maintenance or inspection performed on the roof during its life span. This was evident in the accumulation of lichens and even vegetation in some points of the membranes (figure 7).

Figure 8. Drainages holes. Credit: schlaich bergermann partner.

Figure 9. Result from scanning of the membrane after postprocessing of the data. Credit: schlaich bergermann partner.

However, it was also clear that the lack of maintenance on the membrane was not the main cause of the drainage problems with the roof. It was noted that the membrane had a clear lack of tension most probably due to aging effects. The topcoat of the membrane was coming off. It could be evidenced then that the life span of the membrane was close to its end. On the other hand, it was also noted that the points where ponding happened would become a focus for water accumulation as soon as it rained again. For this reason, it was necessary to drill some holes (figure 8) in the points that, *in situ*, were detected as those with the lowest relative level (more or less the center of the ponds: these were easy to identify since the accumulated water left a clearly distinguishable patch).

To make these drains while maintaining the integrity of the membrane, two stainless steel circular headplates were first screwed on and then a cross-cut in the center was made in the membrane. A diffuser plate was also installed to prevent rainwater flowing down as a stream on rainy days. These drains, as a provisional solution, allowed, under certain conditions, the operativity of the stadium until a long term solution was found.

During the site visit, it was also detected that the tension ring was clearly depressed at the East and West side compared to other areas of the roof. This meant that the runoff water did not drain naturally to the compression ring, but partially to the tension ring, which was not prepared for it, resulting in undesirable water ponds. The reason for this circumstance could only be clarified via analytical studies. The maintenance managers of the stadium were asked to make a topographic survey of the most relevant points of the roof, including a mapping or scanning of the membrane that would be the basis for further analysis. The result of the survey was millions of points that had to be postprocessed (figure 9).

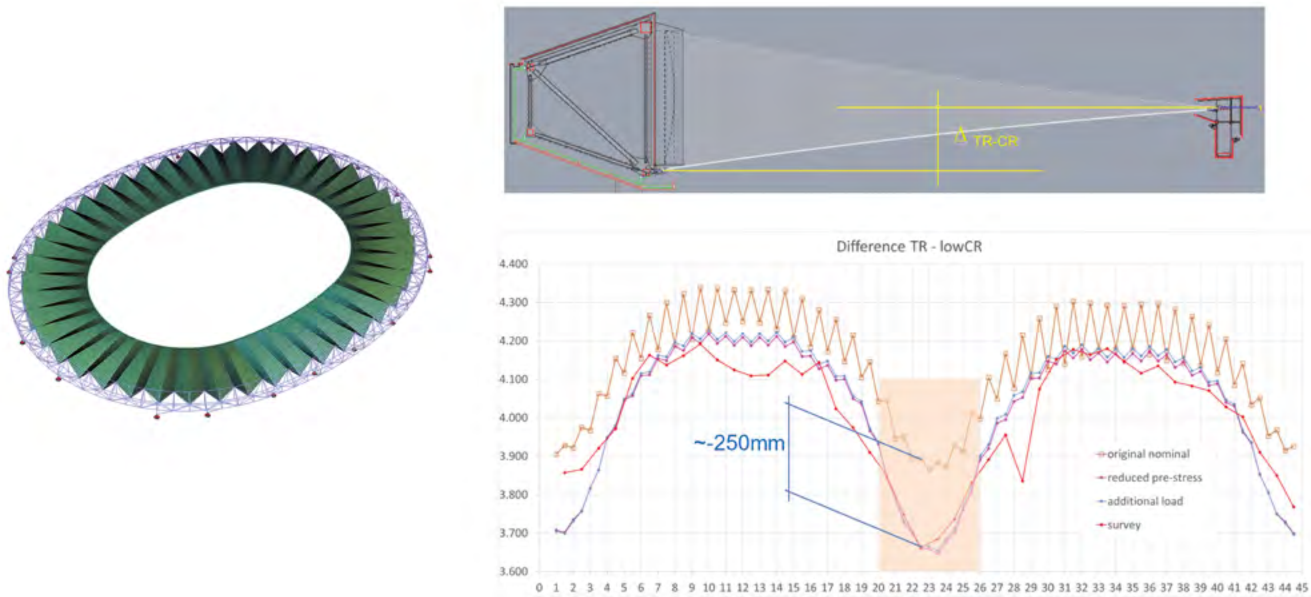

Figure 10. Calculation model and parametric study regarding level of tension ring. Credit: schlaich bergermann partner.

5.
DIAGNOSIS: ANALYSIS OF THE PROBLEM AND ITS CAUSES

Once the data was collected and analyzed, a 6-step action program was set up as described below:

1. To compare the current geometry of the roof with the nominal one of the project.
2. To simulate the existing situation.
3. To establish the causes of the problem.
4. To study possible solutions.
5. To develop the preferred solution.

6.
RESULTS OF THE ANALYSIS

As mentioned, the data provided by the company that scanned the roof structure consisted of millions of dots that had to be postprocessed in order to understand the existing situation of the rood. The reasons behind the drainage problems were to be revealed by the geometry of the tension ring and the radial valley cables, as was suspected during the site visit. In the meantime, the calculation model, with which the roof was calculated and designed 20 years ago, was also retrieved. This was going to be extremely useful to give the nominal or reference geometry of the structure.

By comparing the nominal project geometry with the geometry measured *in situ* (scanned geometry), it was possible to verify that in general the tension ring was lower in elevation than expected from the nominal geometry. This fact was more pronounced on the west side of the tension ring, where the difference was up to 25 cm (figure 10).

This could be part of the explanation of the pathology as the drainage of the cover is determined by the difference in height between the tension ring and the bottom of the compression ring. The comparison of the valley cable geometry of the roof also pointed out that, in the current situation, the radial cable had practically no slope in the vicinity of the tension ring.

The next step was to try to depict a situation for permanent loads in the calculation model in which a geometry, such as the one measured *in situ*, was obtained. Different hypotheses to explain the geometrical differences found had to be made:

a. A reduction in the pre-stressing of the cables that, assuming that they were manufactured properly, could have its origin in the creep of the cables. With this hypothesis, the pretension of the cables was a parameter to manipulate in the calculation model the elevation of the tension ring.
b. A reduction of the pre-stressing of the membrane due to the degradation of its properties over time. With this hypothesis, the pretension of the membrane was a parameter of the calculation model to mainly manipulate the geometry of the radial cables and in particular the geometry of the lower ones (valley cables), which was the greatest interest since they are the channels for drainage towards the compression ring.
c. An excessive load on the tension ring, more specifically on the tangential maintenance catwalk. With this hypothesis, the weight of the tension ring catwalk became as parameter to manipulate the height of the tension ring.

The structural model is basically a mechanism in equilibrium thanks to the imposed internal forces of the system (pretension) found in a form finding process for the desired geometry of the roof, the project geometry [3].

With the appropriate analysis /manipulation of the parameters that were determined for each hypothesis (pre-stress and weight), and combining them accordingly, it was possible to reach a geometry very similar to the one surveyed.

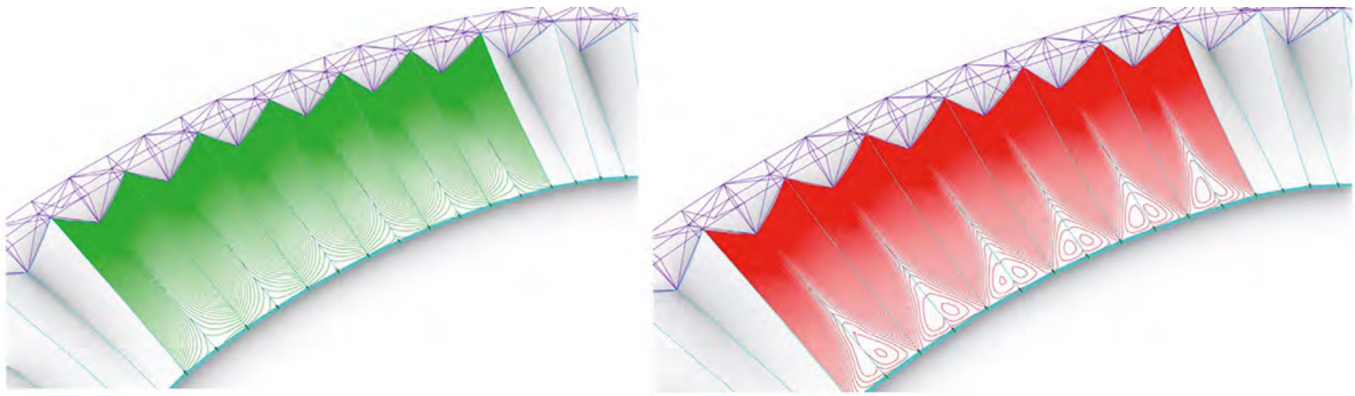

Figure 11. Iso lines under permanent conditions (green).Iso lines under permanent conditions combined with uniform load 0.15kN/m^2 (red). Credit: schlaich bergermann partner.

In particular, it was found that either:

– with a 20% reduction of pre-stressing in cables combined with a 48% prestressed reduction in the membrane,

or

– with an extra weight of 250 kg/m on the maintenance catwalk in combination with a 20% reduction in the pre-stressing of the membrane,

a quite accurate approximation of the geometry surveyed could be reached. Since there were different paths to reach the existing geometry, it could be stated that the cause of the pathology was not unique and it probably was the result of a combination of certain unfavorable scenarios.

Once the current situation of the roof was simulated, it was possible to verify how the drainage would work in future situations. It could be noted that, under permanent conditions, the level isolines showed an appropriate slope towards the compression ring at the valley cable. It could also be noted that, at East and West sides, the level iso-line were getting closed about themselves next to the tension ring as soon a pressure load is acting on the membrane (figure 11). This would create water accumulation in case of rain (now mitigated with the drainage holes that were made).

West component winds, predominant in Seville due to the directionality imposed by the Guadalquivir River, cause pressure loads (downwards) on the roof. This fact combined with heavy rain, a lack of pre-stressing of the system due to clear evidence of aging and a more than likely increased load on the maintenance catwalk caused the drainage problem reported in March 2018.

6. STUDY OF SOLUTIONS AND FINAL SOLUTION ADOPTED

With the data available so far, it was possible to establish a series of primary measures that could be carried out regardless of what the integral and final solution to the problem would be:

1. To replace the entire roof membrane with a new one. The existing membrane showed signs of degradation and 20 years is a life in the range of what is expected for a PVC membrane.
2. To provide to the new membrane with an updated pre-stressing of 5k N/m and comparatively more than what current membrane has.
3. To attach the inner edge of the new membrane to the tension ring directly and not to a catenary cable as was previously the case. This would make the inner edge of the membrane stiffer in the vertical direction.
4. The new membrane panels would be subdivided between ridge cable and valley cable and not, as before between consecutive ridge cables, intertwining without mechanical means over the valley cable.

The calculation model, adjusted to the real situation, enabled the analysis of how the roof would behave when applying these four measures. It was possible to verify that, although these measures improved the situation, the risk of ponding in the vicinity of the tension ring persisted. It was therefore necessary to establish additional measures to ensure drainage towards the compression ring in all possible scenarios.

The additional measures to be considered would have to be effective and economical, as the budget for membrane replacement was very tight. They would also have to meet tight deadlines given that La Cartuja's intention was to reopen the stadium as soon as possible, having already committed to a series of events for the end of 2020. Thus, the deadline for implementing the solution could not go beyond November 2020.

The additional measures that were considered were the following (figure 12):

Opt. 1: To add an additional over-coverage on top of the area with increased ponding risk. This additional coverage would aim to provide a sufficient slope towards the compression ring at the problematic areas. Here, the space between both membranes could be guaranteed with some stiff foam or Porexpan.

Opt. 2: To join the valley cables with the ridge cables by means of rigid struts as a way of trying to freeze the shape (geometry) of the valley cable with the desired slope.

***Opt.* 3**: To provide an additional pre-stressing to the valley cable. While the cable was already made and in place, in theory, it could be uninstalled, shortened in the workshop, and be reinstalled.

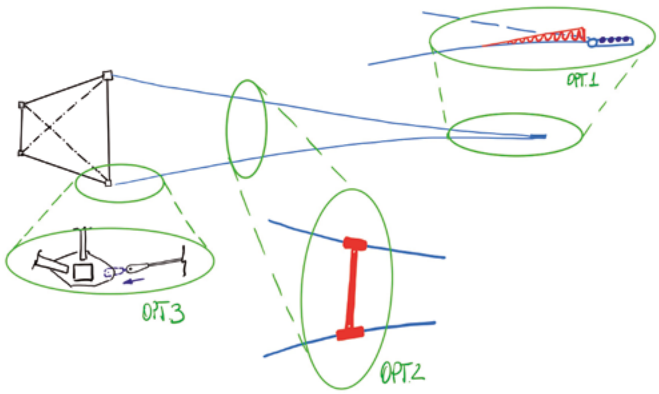

Figure 12. Solution Studies. Credit: schlaich bergermann partner.

After evaluating all the options, it was clear that none would meet the financial or time constraints of the project. Furthermore:

- Option 1 solution would solve the drainage problem, but it was very expensive due to the additional square meters of membrane that would be needed. It was difficult to guarantee that it would be well executed and not affecting the interior view of the stadium, as the double-layer part was clearly more opaque, and would contrast with the rest of the roof that would always let a small fraction of light through.
- Option 2 solution was not entirely effective since it was found that the points, where the props were placed, could be a source of water accumulation.
- Option 3 solution, although effective, was not feasible due to the time constraints.

Finally, given the circumstances, it was concluded that the only way to solve the problem with the existing time and budget was to provide the roof with a new drainage system in the area of the tension ring, collecting the water at that point and conducting it towards the compression ring under the valley cable using radial drainage pipes (figure 13).

The idea was that a stainless-steel funnel, connected to each radial cable and to the tension ring, would collect the rainwater that could go to the inner edge of the roof. A tangential pipe, running along the tangential maintenance catwalk, would connect all the funnels. At two specific points, radial pipelines would carry the total runoff water towards the compression ring. The funnels at the tension ring were demonstrated to be needed at the east and west side of the roof only. On the other hand, a stainless-steel funnel was also installed at the compression ring at all valley cables of the roof (figure 14).

The project to replace the stadium's membrane was designed to be executed in two phases. In the first phase, the panels between axes 20 and 26 of the roof (6 roof modules = 12 single panels on the side, please see figure 4) would be replaced on the west side only. All other membrane modules would be replaced in a later phase. This phasing would lower the financial efforts that had to be made for the complete replacement of the membrane.

7. STAGE CONSTRUCTION

One of the key issues of the project was to clearly define how the membrane replacement process would be carried out. This question was not easy to solve, given that the actions required were to be taken on an existing roof. The new membrane had to be made and patterned taking into account the existing boundaries.

The project of membrane replacement was submitted in mid-June 2020 and tendered out one month later (d). The construction company respected the project and the proposed

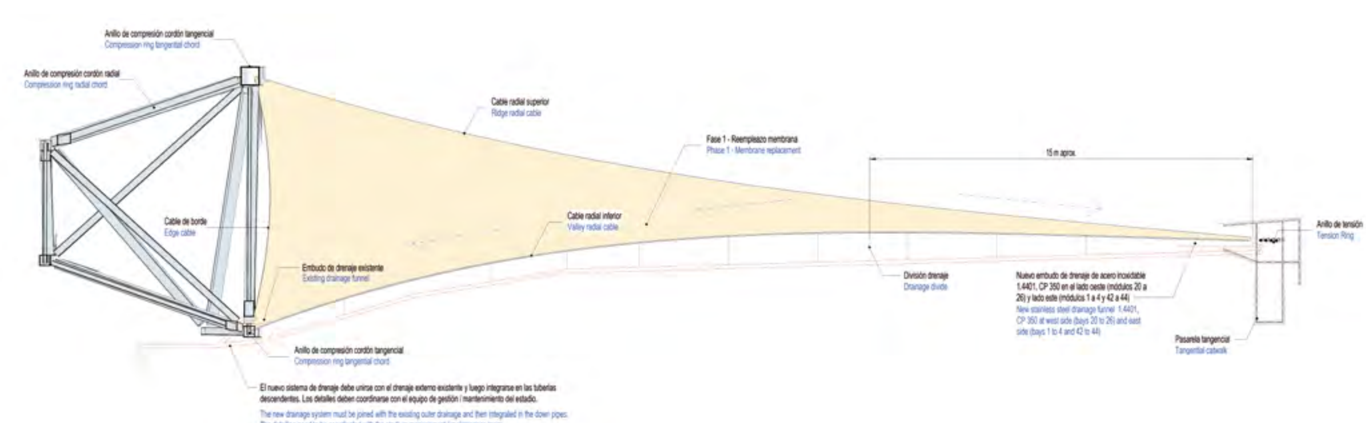

Figure 13. Final solution adopted. Rainwater collected at the tension ring area. Credit: schlaich bergermann partner.

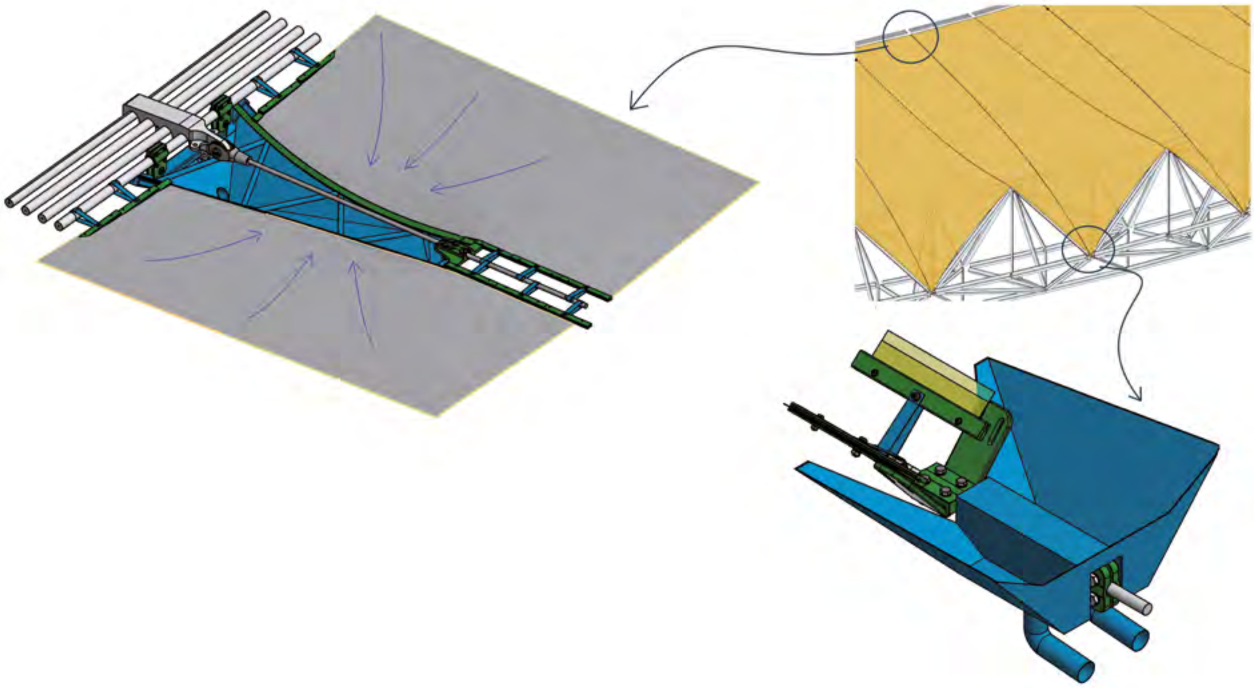

Figure 14. Funnels to collect rainwater. Credit: schlaich bergermann partner.

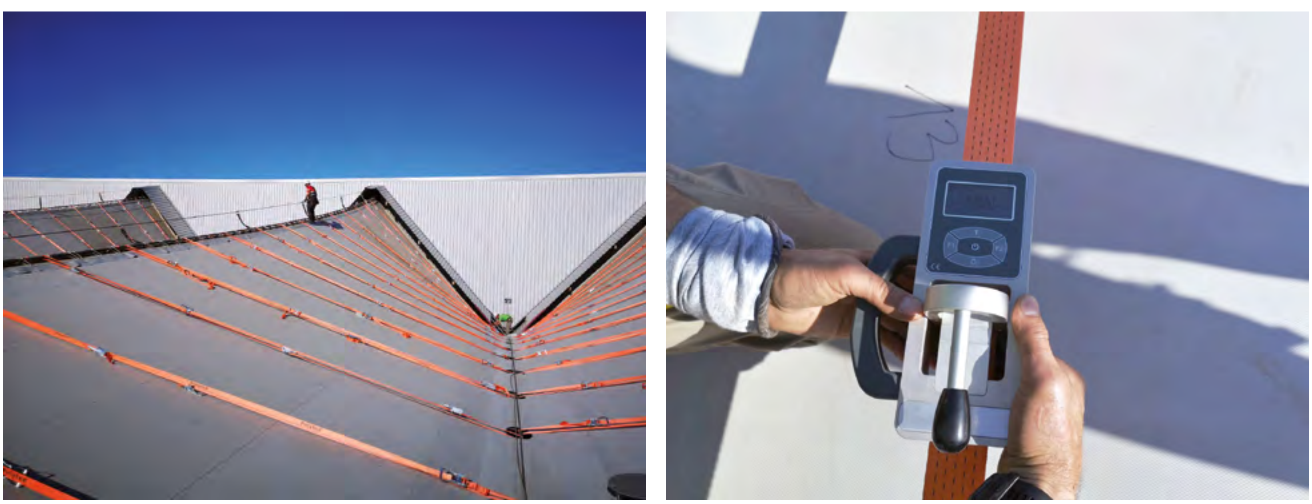

Figure 15. Ratched belts under 5kN tension every meter. Checking of the force. Credit: Pfeifer Seil- und Hebetechnik GmbH.

construction process quite faithfully and only a few subsequent improvements were introduced in a coordinated manner between all parties.

7.1. The phases of the project

The phases of the project are described below in conjunction with some pictures of the construction site.

In a first stage, the relevant safety systems (life-lines) had to be installed. Then, the membrane closing flaps (non-structural) had to be cut in both valley and ridge cables. The aim was to leave the radial cables uncovered and thus fully accessible.

The next step was to install ratchet straps, tangentially joining the radial ridge cables with the valley cables on both sides (figure 15). The straps are distributed evenly in a radial direction over a distance of one meter. These belts are tightened with a force of 5 kN each, thus trying to represent the tensional state of the future membrane that will replace the existing one.

The tensioning process of the belts had to be an iterative process since when manipulating a belt, the next ones would be misadjusted. After several iterations, it was possible to obtain the desired forces in the belts. Once the straps had the appropriate force, a topographical measurement of the geometry of the edge cables was made. This geometry was the basis for determining the geometry of the membrane in its permanent state, and thus proceed to the pattern of the membrane accordingly.

The to-be-replaced membrane, which was practically stress free when the belts are tightened, remained installed at all times, acting as a safety net. It was eventually removed at the end of the whole process when the new membrane was fully installed. This simplified the process significantly.

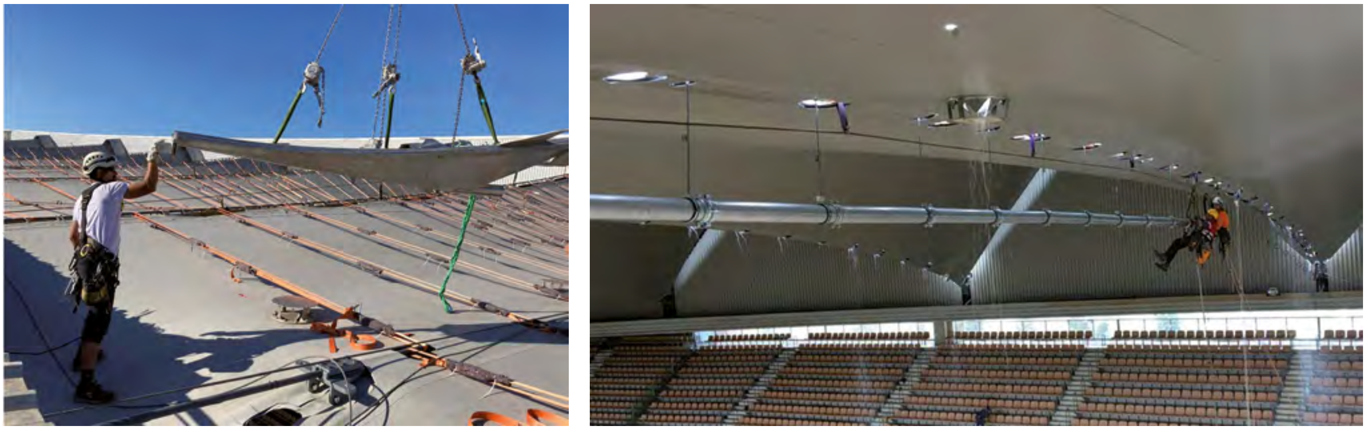

Figure 16. Radial drainage pipes and funnels at Tension Ring installation. Credit: Pfeifer Seil- und Hebetechnik GmbH.

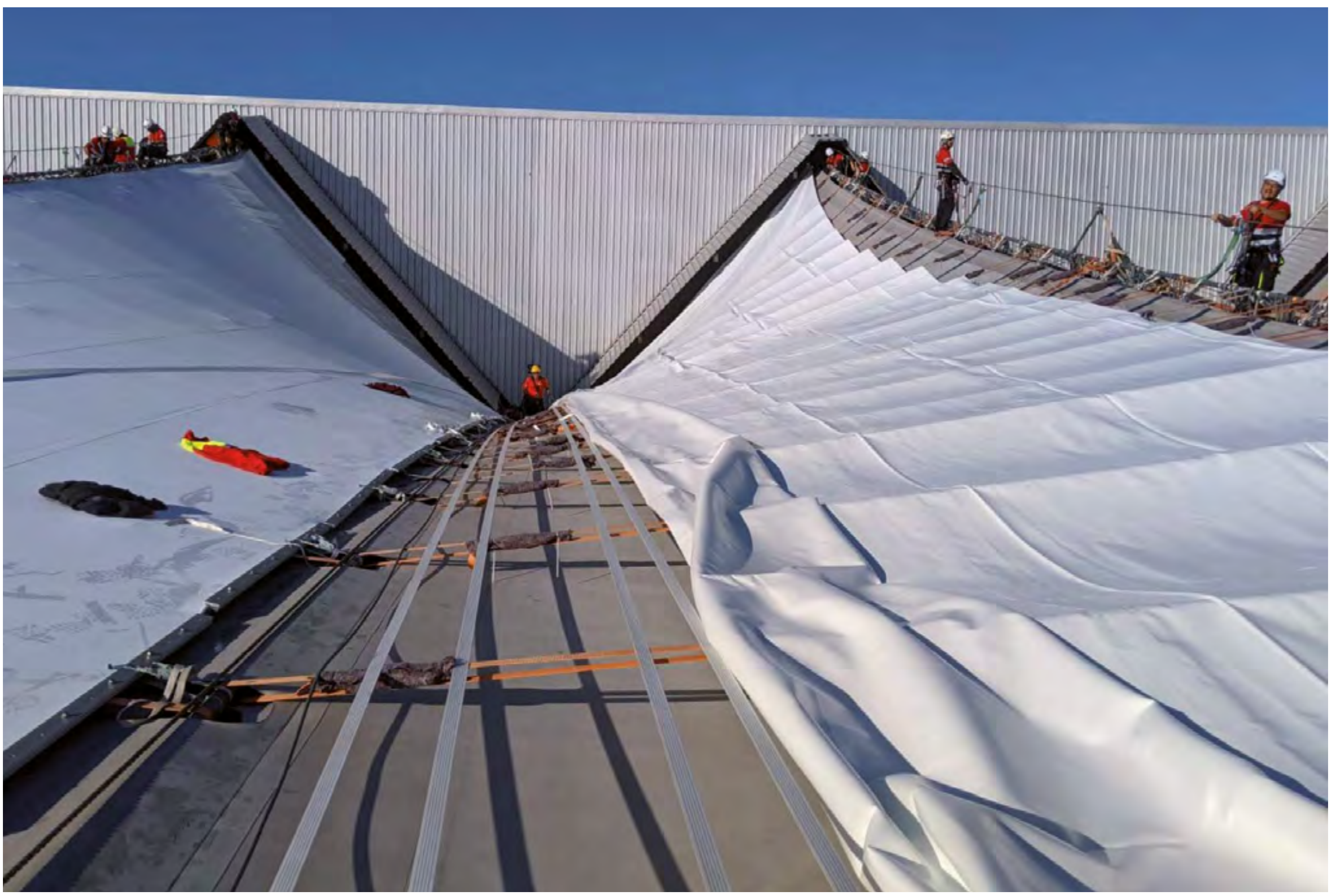

Figure 17. Membrane Installation. Credit: Pfeifer Seil- und Hebetechnik GmbH.

The necessary holes for the installation of the funnels at the tension ring and at the compression ring were opened in the existing membrane. The radial drainage pipes at the two selected locations and the tangential pipes along the tangential catwalk were also installed (figure 16). The last step was the installation of the new membrane panels on the existing cables (figure 17). During the construction process the stadium was operational under certain limitations. For example, in late October and mid-November 2020, it hosted two UEFA matches behind closed doors due to pandemic restrictions.

8.
CONCLUSIONS

The article has described the steps that were taken to solve the pathology:

- Emergency measures.
- Provisional Measures.
- Definitive measures.

Emergency measures do not solve the problems, although they prevent them from getting worse. With the provisional measu-

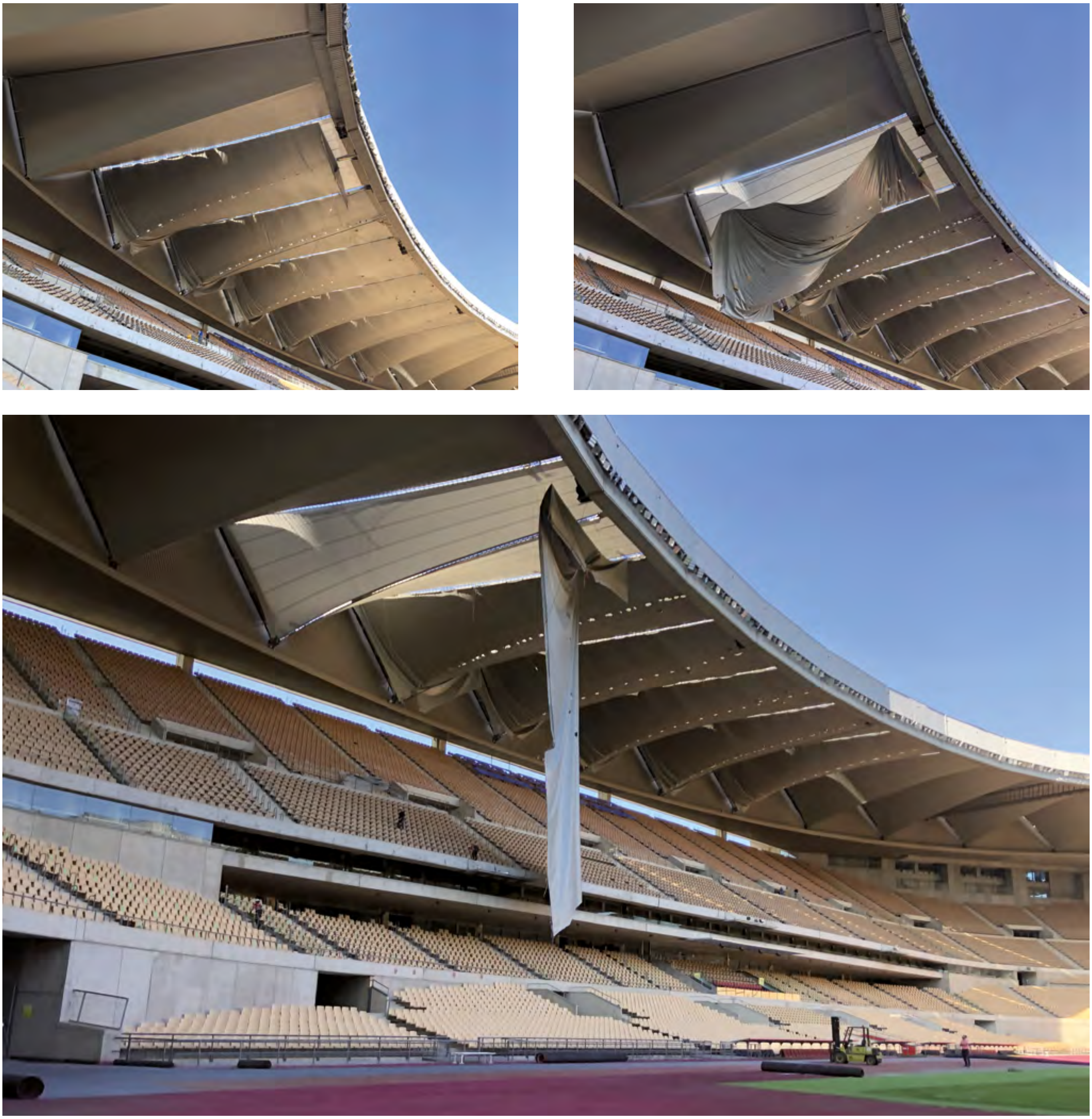

Figure 18. controlled detachment of the existing membrane after installation of membrane modules. Credit: schlaich bergermann partner.

res, a solution is adopted that, although it solves the problem, it does not maintain the conditions that allow the correct use of the facility. The chosen solution solves the problem and allows the normal use of the facility.

Each problem of structural pathology is different, and it is not always necessary to go through these three phases, although in this project it was.

After 20 years of service, the rainwater was not draining properly from the roof of the At the La Cartuja Olympic Stadium. In the article it has been described the way in which the solution to this pathology was approached.

- Data collection to investigate the problem.
- Analysis of the data to identify the causes.
- Replicate in an analytical way the current situation and thus be able to simulate the solution to be adopted.
- Study of solutions since an objective can be achieved in different ways.
- Final solution as the one that solves the problem taking into account the restrictions imposed by the project, in this case, temporary and economic.

From the analysis of the pathology, it can be concluded that the origin of the drainage problem was not unique and it was a combination of loss of membrane pretension due to aging effects together with a creeping of the main radial cables and a more than likely increase of facilities weight at the tension ring catwalk.

After having considered different options for a long term solution to the pathology, providing a funnel at the tension ring at the affected areas of the roof was demonstrated to be the most economic and effective one, taking into account the budget and time constraints of the project.

Finally, it is important to highlight the need for periodic inspection and maintenance of such structures. This helps to avoid problems or to anticipate them, respectively. It is necessary, it should even be prescriptive, that every project is provided with a maintenance manual indicating the critical points to be inspected, specifying what the inspection consists of and how often it should be carried out.

9. GENERAL DATA AND MAIN PARTIES INVOLVED IN THE PROJECT

The result of the project is the product of the work of a team of experienced specialists, for whose work we would like to thank in this article.

On the part of schlaich bergermann partner:

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- Project Manager: Enrique Goberna Pérez.
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- Analytical studies: Thomas Moschner, Florian Market, Roberto Piñol.
- BIM and 3D Modeling: Bernd Ruhnke, Alberto Sánchez, Fernando Escamilla.

Other agents:

- Client: La Cartuja Stadium SA.
- Stadium Infrastructure Director and Construction Manager: Daniel F. Oviedo Barrera.
- Contractor: PFEIFER Seil und Hebetechnik GmbH.

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Rehabilitation and pathology of structures is an engineering field in which the late Luis Ortega Basagoiti was a recognized expert. We are honored to participate in this publication honoring his memory.

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