Structural Maintenance of the Tension Structure Roof - Rome Olympic Stadium

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Summary

The roof of the Rome Olympic Stadium, built in the 1990, is one of the first examples of roof with tension ring, radial tension structures and external compression ring, for the covering of the stands of a stadium, a scheme that since then has spread in many recent applications. In 20 years of structural monitoring and maintenance it has been possible to compare the design assumptions with the actual behaviour. The global pre-stressing and geometry has been monitored in the time and some re-tensioning work have been carried out after the natural long term creep of the steel cables. The behaviour and the operations have been followed and simulated on numerical models. In 20 years time also the degradation of some secondary members have been detected and the maintenance, replacement and improvement works are carried out. This experience, while confirming some design decision, can provide interesting indications for the design and planning of this type of construction.

Keywords: *Tension-structure, pre-stressing, cables, creep, re-tensioning, inspection, monitoring, maintenance, stadium roof, tension ring.*

1. Introduction

The roof of the Rome Olympic Stadium designed by Prof. M. Majowiecki, was built in the years 1989-1990 during restructuring works; the roof is made by a cable tension-structure with inner tension ring and radial cable beams made by full locked coil steel cables, and external compression ring made by a steel truss; the secondary structure is made by steel frames connected to the nodes of the main tension-structure; the cladding is made by glass-PTFE membrane panels; the total covered area is about 40000 square meters. There are 78 radial cable beams, each made by one upper carrying cable and one lower stabilizing cable, connected by vertical hangers at intermediate clamps. The radial cable beams are anchored to the perimeter compression steel truss that has a triangular

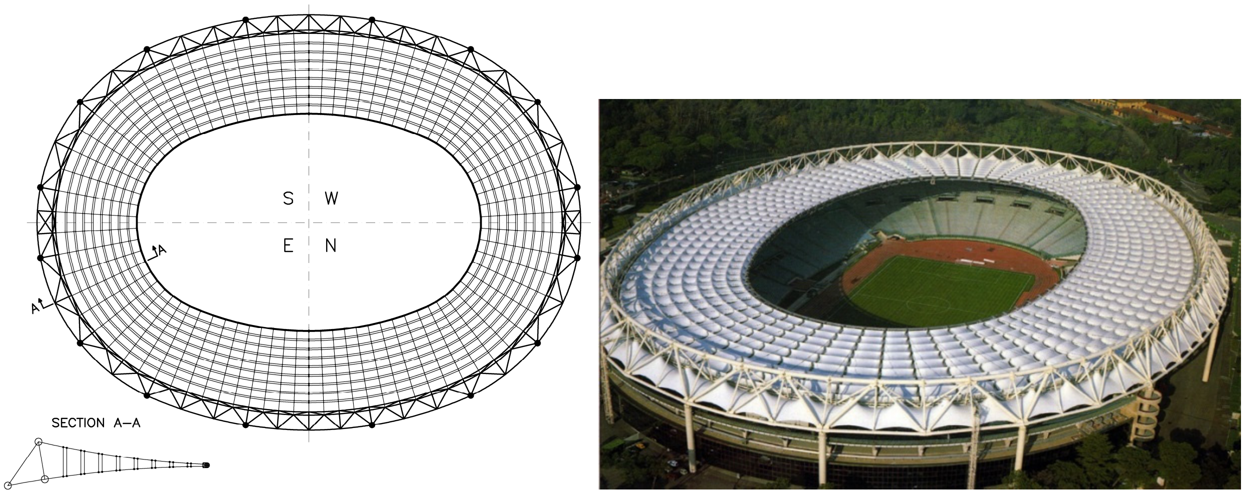

Figure 1: Scheme and aerial view of the roof

space truss scheme and to the inner tension oval ring made by a bundle of parallel cables.

The hanger connection points on the lower stabilising cables correspond to the suspension points of the secondary structure that supports the membrane panels and is made by steel trusses, with an hinged suspended scheme, with low interference with the cable structure in radial and in circumferential direction.

The shape of the main tension structure and of the secondary membrane has been generated according to the usual equilibrium form finding procedures. The pre-stressing forces of the main tension structure were calibrated to give adequate stiffness in the operating conditions, with resulting forces, in permanent condition (G+P), in a range from 350 to 1900 kN in the stabilising cables and from 1150 to 2700 kN in the carrying cables, depending by the position (lower force in the main stands zone with low curvature of the inner oval and higher force in the curves zone with higher curvature of the inner oval); the (G+P) force in the inner oval cable bundle is about 36000 kN.

The level of the permanent forces is in ranges from the 16 % to the 37 % of the MBF (Minimum Breaking Force) for the stabilising cables, from the 30 % to the 37 % of the MBF for the carrying cables and about 41 % of the MBF for the inner ring cables. These are typical force levels for the permanent condition in these types of construction, in an allowable range also according to the most recent codes and standards. The forces and the geometry of the structure were surveyed during the erection and tensioning and then in service. The comparison of the combined force and geometry surveys on the real structure, compared to the numerical models, gives a very good correspondence

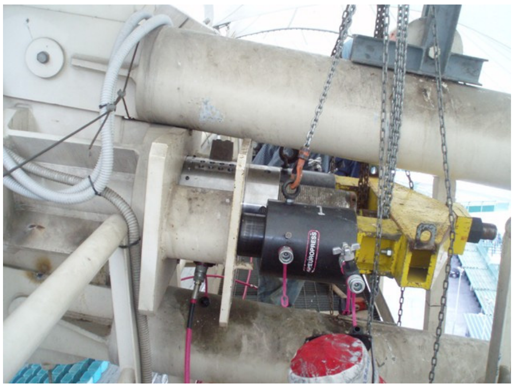

Figure 2: Jacking equipment

2. Monitoring in service

The static and geometric condition of the tension structure has been surveyed since the first years of service, with on site measurement of the forces in the cables and of the geometry. The monitored points are the outer anchorages of the carrying and stabilising cables for the forces and the inner tension ring and the outer compression truss for the geometry.

As the on-site measuring operation, specially for the forces in the cables, is demanding, with heavy jacking equipment used at height (Figure 3), to optimise the cost and efficiency of the monitoring the force surveys have been carried out on different samples in the years following the construction.

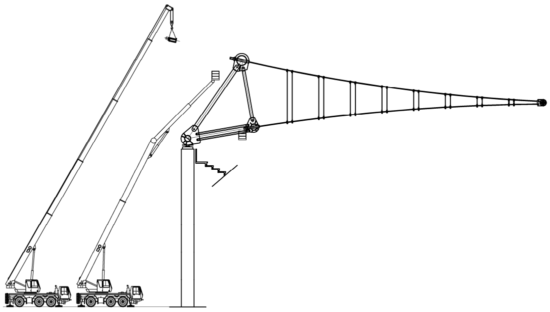

Figure 3: Access with cranes for jacks

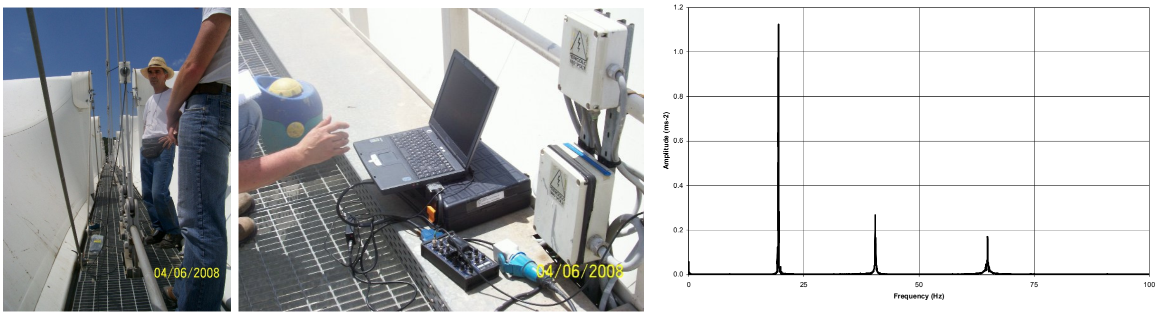

Figure 4: Dynamic measurement of natural frequencies for the force determination

The force measurement was made also on the inner ring cables, that are spliced to form a continuous ring, with no jacking accommodation in the end termination, by dynamic vibration method. The results, obtained by the measurement of the free vibration frequencies of segments of cables between the clamps, have provided force estimates coherent with the values obtained by the other measurements and this method appears suitable to be used for comparison and for the monitoring of the global pre-stressing force variation, when carried out at successive time intervals.

The same dynamic method has been used also on the vertical hangers, that have no adjustment, but the measurement on these elements, that also should theoretically provide an indication of the actual existing pre-stressing, is more affected by local effects and dispersion, while the measurement on the inner ring can provide integral data (sum of all the radial cable beams) and effective information.

3. Re-tensioning operation

Loss of pre-stress forces, due to the creep of the cables, appeared from the monitoring, with reduction of the forces in the radial cable beams to values lower than the design pre-stress; in a conservative approach and wanting to preserve the stiffness characteristics of the structure, it has been decided to carry out re-tensioning operations. The first re-tensioning was done after 7 years from the construction and a second after 17 years.

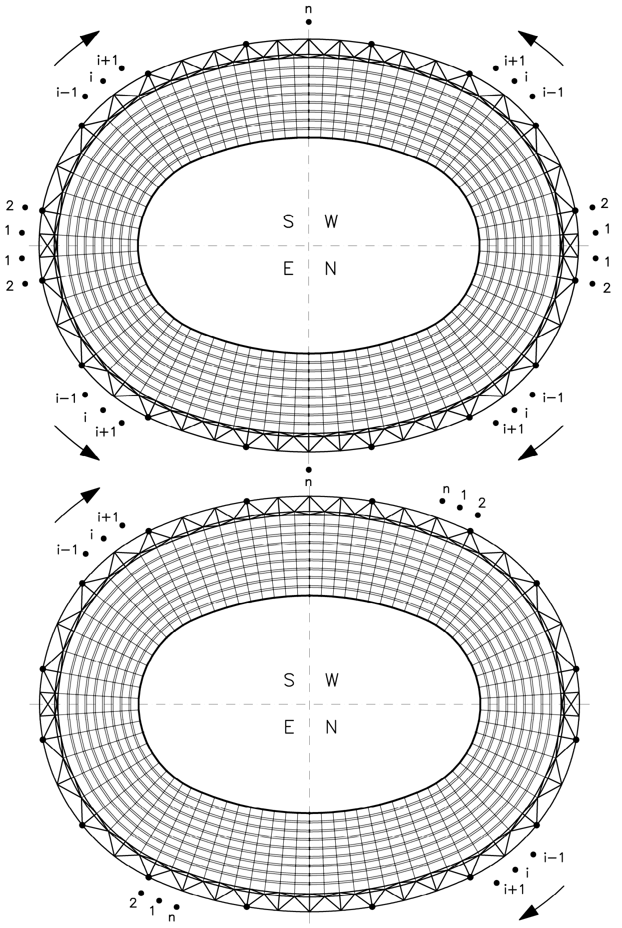

Figure 5: Scheme of re-tensioning sequences 4 fronts or 2 fronts

To carry out the re-tensioning in a consistent way, the following sequence of operation has been adopted:

- general survey of the forces at the cable anchorages
- general survey of the geometry
- simulation, on numerical model, of the structure with the actual dispersed values of the forces measured; a specially in house developed numerical procedure, integrated in the numerical analysis software, has been used to reproduce with sufficient precision the surveyed force condition
- simulation, on numerical model, of the re-tensioning operation, carried out in several steps, operating in symmetry on the construction, with determination at each step of the force variation to be applied to the cable anchorage operated at the step, of the extension at the anchorage, of the force variation in all the other cables, of the geometry variation at all the joints; the Figure 5 shows two possible symmetries of sequence adopted, with 4 fronts on the 4 opposite sectors or 2 fronts on 2 opposite sectors, in rotation around the construction
- execution of the re-tensioning, acting with different teams, with the designed sequence; during the sequence the measured forces and extension, as well as the geometry variation are registered and compared with the theoretical values from the model
- at the end of the sequences, measurement of the forces on sample cables in the different sectors and general geometrical survey

We have observed that the distribution and variation of the forces is rather accurate and near to that predicted by the numerical model; the general displacements have the same behaviour but with smaller values; the reason of the smaller displacements can be interpreted as higher global stiffness due to the presence and partial collaboration of the secondary elements, as supported steel frames and catwalks.

To have a uniform condition of the structure as much as possible consistent with the numerical model, the re-tensioning operations were carried out in night time, to avoid the presence of the direct sun heat with consequent possible differential temperature conditions that would alter the distribution of the forces. Also the geometrical surveys of sample nodes, to monitor the re-tensioning operation, were carried out preferably in early morning, before the sun radiation. The complete surveys of the structure, due to the large dimension, requires longer time than few hours in early morning, and were carried out preferably in cloudy weather conditions.

The operation carried out in night time allows also to minimise the impact on the regular activities in the stadium, with no disruption of the access to the structure; in particular in the building of the stadium, under the stands, there are office facilities, with hundreds of people working and there are also daily gymnasium activities. During all the phases of the re-tensioning the structure has been maintained in full service and operation, without any interruption of the activities. In the events with large access of public the works were suspended for one or more days, as in the weekends, leaving the plant in safe regular condition.

4. Interpretation of the monitored data, estimate of the cable creep

The decay of the permanent forces in the cables, starting in the first years and progressing in the time, is due to the long term relaxation of the full locked coil cables, that, even if pre-stretched during the pre-fabrication, had a significant creep under the service forces. The amount of creep to which this type of cables can be subject is not well defined and known, and there are not indications in the standards or in the data provided by the manufacturers. According to the author’s experience the creep is sometime tested in laboratory for projects with special requirements, but the duration of the laboratory tests is of the order of one hundred or of some hundred hours only and the information about the long term effects, in operating conditions, is not a common available data and can only be supposed, even if with ingenious extrapolation, from the short term tests.

The effect of the natural creep of the cables has been observed by the authors also in other structures of large or of small size, and can have a real influence on the behaviour of the structure. In order to provide some indicative data from the real case, some analyses and simulation on numerical models have been carried out, simulating different creep levels in the cables.

Looking at the results of the force monitoring and of the geometrical surveys, there was also the intention to understand if the creep were evidently higher in some group of cables.

Different creep conditions have been analysed on numerical models (Figure 6); for the particular case the permanent force in a set of stabilising cables in the zone of low curvature of the inner tension ring is rather low, and the simulation of the creep, at higher levels, generates singularities in the numerical model due to slackening. To avoid singularities and trying to follow a possible physical behaviour of the structure, the following conditions have been simulated, including some cases to check the effect of higher creep in the inner tension ring:

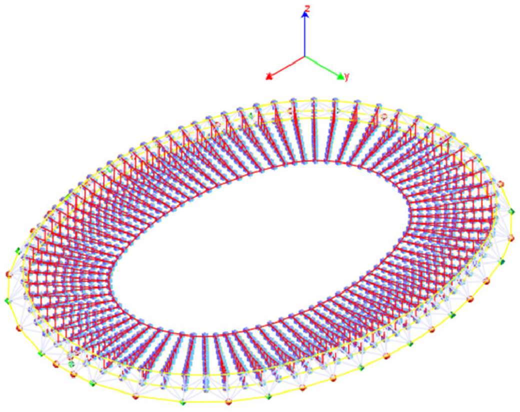

Figure 6: Numerical model scheme

a1) creep in all cables 0,24/1000;

a2) creep in carrying and inner ring cables 0,48/1000, creep in stabilising cables 0,24/1000;

a2) creep in carrying and inner ring cables 0,72/1000, creep in stabilising cables 0,24/1000;

b1-2-3) inner ring cables only 0,24/1000 - 0,48/1000 - 0,72/1000 creep.

The results of the numerical simulation have been compared to the results of the force monitoring, considering the average values of the force ratios N/$N_{(G+P)}$ obtained, calculated on different groups of elements: stabilising or carrying cables in the two zones between alignments T1-T10 and T11-T20 of the 4 sectors (Table 1).

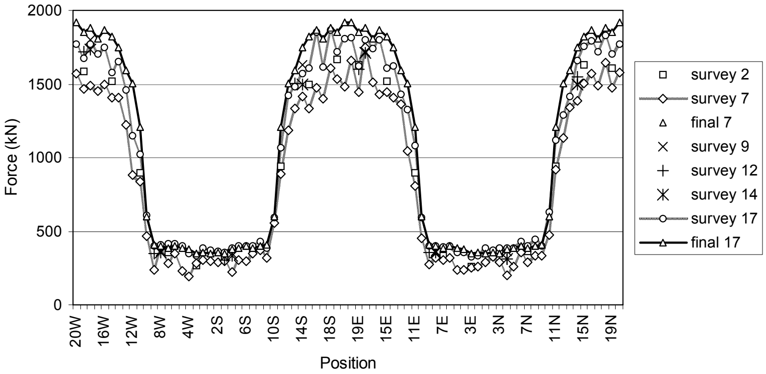

Figure 7: Measured forces in the stabilising cables

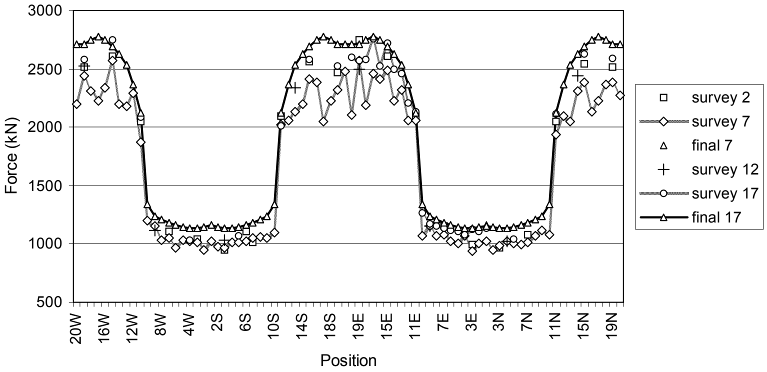

Figure 8: Measured forces in the carrying cables

The diagrams of the forces measured on site are shown in the Figure 7 and Figure 8 and the average force ratios from the measurements are given in the Table 2

There is a dispersion of the measured data, reasonably due also to the initial tolerances during construction, to measurements precision and to differences of configuration as example for thermal effects.

From the comparison of the average force ratios from the calculation and from the measurements, the following values of creep more fit to the measured data, in the averages. Years 0-7: 0,57/1000 for the stabilising cables and 1,04/1000 for the carrying cables, average value 0,80/1000; years 7-17 0,05/1000 for the stabilising cables and 0,32/1000 for the carrying cables, average value 0,19/1000; the average total value of the creep that would fit to the force decay after 17 years is about 1,0/1000.

Table 1: Simulated creep, ratios calculated force N/$N_{(G+P)}$

case	Stabilising cables, average T1-T10	Stabilising cables, average T11-T20	Stabilising cables, average all	Carrying cables, average T1-T10	Carrying cables, average T11-T20	Carrying cables, average all
a1)	0,86	0,92	0,89	0,97	0,96	0,97
a2)	0,77	0,86	0,81	0,95	0,93	0,94
a3)	0,67	0,80	0,73	0,92	0,89	0,91
b1)	0,91	0,95	0,93	0,98	0,98	0,98
b2)	0,83	0,89	0,86	0,96	0,95	0,96
b3)	0,74	0,84	0,79	0,95	0,93	0,94

In the interpretation of the data obtained it must be considered that the load level is not uniform in the different groups of cables; the different average values of the ratio $N_{(G+P)}$/MBF are in stabilising cables T1-T10: 0,19, T11-T20: 0,33, in carrying cables T1-T10: 0,31, T11-T20: 0,35, in inner tension ring cables: 0,41; the group with lower load level is the stabilising T1-T10.

Table 2: Ratios measured forces $N/N_{(G+P)}$; re-tensioning has been carried out in year 7; in years 9, 12, 14 limited data measured

year	Stabilising cables, average T1-T10	Stabilising cables, average T11-T20	Stabilising cables, average all	Carrying cables, average T1-T10	Carrying cables, average T11-T20	Carrying cables, average all
2	0,89	0,83	0,85	0,90	0,96	0,94
7 before re-tensoning	0,77	0,79	0,78	0,87	0,87	0,87
7 re-tensioning	1,00	1,00	1,00	1,00	1,00	1,00
9	(0,93)	(0,92)				
12	(0,85)	(0,91)	.	(0,91)	(0,93)	
14	(0,87)	(0,89)				
17 before re-tensioning	1,01	0,92	0,97	0,95	0,97	0,96

The comparison of the vertical displacements data obtained from the calculation with simulated creep (Table 3) to those from the geometrical surveys (Table 4) has been done for the nodes at the main alignments on the longer and on the shorter axis in plan, at alignments 1 and 20 of the 4 sectors. From this comparison, there are the following values of creep that more fit to the measured data: years 0-2: 0,29/1000; year 7 recovered at re-tensioning 0,56/1000; years 7-14 0,12/1000; year 17 at re-tensioning 0,21/1000; the average total value of the creep that would better fit after 17 years is about 0,7/1000. It must also be considered that the measured vertical displacements are disturbed by thermal effects that can generate displacements of some centimetres in case of not uniform temperature distribution.

Table 3: Simulated creep cases, vertical displacements Dz

case	Node 1 Dz (mm)	Node 20 Dz (mm)
a1)	-69	-38
a2)	-157	-101
a3)	-247	-165
b1)	-42	-22
b2)	-85	-45
b3)	-128	-67

Table 4: Measured vertical displacements, limited data is available for some years

Years	Average Nodes 1 Dz (mm)	Average Nodes 20 Dz (mm)
0-2	-77	-51
7 at re-tensioning	+213	+104
7-14	-40	-15
17 re-tensioning	-29	-62

In consideration of the fact that at the re-tensioning in year 17 the adjustment has been done to the stabilising cables only, the displacements at that stage were downwards and in the following years some creep upwards is appearing.

Also the actual take-up extension at the anchorages, during the re-tensioning operations, has been considered for the estimate of the creep; the take-up applied at the re-tensioning can be considered an almost direct measurement, but also this is disturbed by possible interaction with the secondary structures, increasing apparently the stiffness of the primary structure.

The values of the creep obtained from the average measured extensions are: at year 7 stabilising cables 0,19 - 0,46/1000, carrying cables 0,53 - 0,57/1000; at year 17 stabilising cables 0 - 0,16/1000, with total 0,20 - 0,62/1000. The different values obtained for different group of cables depends also by the different load levels to whom each group of cables is subject, and this has a mutually cross-influenced effect in the whole structure.

The creep estimated using the comparison of the forces is higher that that estimated from the comparison of displacements of from the extensions; an interpretation of this can be the fact that the secondary structures fixed to the cables increase the stiffness and partially collaborate with the main cable structure for the additional loads applied by jacking, that are rather small if compared to the total capacity of the elements.

The comparison of the results of the different models and of the different effects, leads to values of the creep, that approximately reproduce the various measurements carried out, in a range of about 0,50 - 0,80/1000 in the first 7 years and an additional of about 0,10 - 0,20/1000 in the following 10 years. It is usually expected that the creep is also related to the load level, the indicative values obtained does not provide yet this relation, so they can provide a limited information, that could anyway be used for comparison or for sensitivity analyses on other similar structures.

We enhance that the effect of the creep should not be disregarded and that adequate design provisions, with sensitivity analyses and simulations, even if not completely accurate, should be carried out, also for differential creep, with prediction of the possible static and geometric effects, and if necessary details and systems that allow the re-tensioning after some years of operation should be provided. In our case the details and the solution chosen during the design of the stadium roof allow for integral monitoring and adjustment operations for the preservation of the condition.

5. Secondary elements and details

The general condition of the roof structure, after 20 years of service, is good, with the main elements in adequate condition, not affected by main damages or by corrosion.

Deterioration was found and required specific maintenance works on some secondary elements; these deteriorations can be considered natural, in the environmental conditions, and observing them could help in improving decisions in detailing and in selection of materials, that even if giving higher initial cost, would help in providing lower and more practicable maintenance costs in future.

Bolts of some connections, not galvanised or protected by zinc plating only, were subject to oxidation, that after years assumed the aspect of corrosion and required replacement works. Being the access to the bolts not simple, even if near to the permanent catwalks installed for inspection and maintenance, the replacement work requires special access, with a team of absailors, or with the use of platform on crane. The replacement of the bolts in a node is done starting with a general view of the condition, and then with dismantling and replacing the bolts one by one, starting from the ones in worst appearance, maintaining the connections in service. The bolts used for the replacement are hot dip galvanised, overcoated by anticorrosion paint, to provide longer corrosion resistance. Stainless steel bolts are used for the replacement until 14 mm of diameter, with cleaning and re-protection of the connected steel parts around the bolts. Some gaps in the connections are cleaned and filled with sealants, to prevent the penetration of water and of aggressive elements.

Figure 9: Corroded wire ropes, replacement with stainless steel wire ropes

Other components that were found subject to corrosion, are small wire ropes that hold in tension the membrane panels pulling their edge pipes (Figure 9); at the construction the material used for these small components with diameter 8 mm was hot dip galvanised steel. After about 10 years, in the exposition to the rainwater, with the pollution from the urban traffic, the zinc coating appeared deteriorated and oxidised, and after some more years extended corrosion affecting the wire ropes and their sockets was detected. Specially in zones subjected to water traps, a quantity of wires were completely corroded and a complete replacement is carried out, after 20 years. The new elements installed are stainless steel wire ropes, with stainless steel swaged socket and nut, with copper ferrule; the diameter of the new wire ropes has been increased to 10 mm, to have, with a material that has a little lower mechanical properties, a strength higher than the initial. Also for the replacement of these components it has been necessary to define a method and a sequence of operation that allows to maintain in full operation the structure during all the works, without dismantling complete panels of membrane, that would limit the access to some zones of the stands during the works. The replacement is done one by one, with de-tensioning and cutting of the old rope, installation of the new one, with swaging of the ferrule on site and then re-tensioning. This work is done from the permanent catwalks, with some additional provision for the access.

Also some other wire ropes, made by galvanised steel, with larger diameters, up to 30 mm, show some oxidation and corrosion, but the condition is still acceptable and it appears that with additional corrosion protection the condition can be maintained for more years. The replacement of these ropes, that pass inside pockets and sleeves of the membrane, would require different works to have limited impact on the regular operation and use of the structure.

Other elements showing deterioration are rubber cushions installed in anti-uplift posts. These components are deteriorated by the exposition to the sun light and to the relatively high temperatures on the upper zone of the roof. The new cushions are made by neoprene, added with carbon black and stabilizers to protect from ultraviolet radiation, that should be stable longer than 20 years; the fixation to the saddles is made with two component chloroprenic glue. The replacement of these components is relatively simple, using for access the permanent catwalks.

The replacement of thousands of elements (bolts, ropes, cushions or others), sometime with special access, requires many months and is distributed on some years; proper care must be adopted to maintain safety and to have no interference with the regular use of the construction.

After some years of service also the re-tightening of the bolts of the cable clamps was necessary, the reduction of the force in the bolts can also be related to long term effects on the cables, with reduction of the diameter due to geometrical and material setting.

6. Conclusion

Some values of long term creep on the cable structure have been estimated, after force and geometry measurements in real scale, in medium-long term, in comparison with calculations on numerical models. Values from measurements on other constructions, also with different structural schemes, would also be useful in providing information for future design.

Some indications for future design, may be redundant and surely not new, are:

- use materials with intrinsic anticorrosion, specially on small elements; long term protection provided by coatings should be maintainable; galvanised surfaces should be overcoated;
- small and medium wire ropes and spiral strands should be made by stainless steel;
- bolts should be made by stainless steel where possible for the steel grade required, specially for small sizes; where stainless steel is not possible, hot dip galvanised elements should be used, with additional coating applied after the installation;
- care must be taken to have no water traps and good ventilation, specially in high temperature climates that accelerate the corrosion process; drainage grooves must be capable to be checked and cleaned, as debris can enter; avoid or protect holes or details from bird nests;
- consider repair and replacement of “secondary” elements, with possibility to replace components without interruption of disruption of the regular use of the construction;
- consider long term creep of cable structures with elements made by locked coil or spiral strands, and consider the necessity of future adjustment;
- maintenance and replacement works should be foreseen and designed in a way suitable to maintain the safety and service of the construction during all the operations, with minimum impact on the regular use of the structure.