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Large structures in motion

Summary

Innovative architectural projects often have included methods for moving structural elements. These moving elements can be driven using wire ropes.

The paper presents different technologies that have been used for this purpose and focuses on the moving roof of the new Singapore Sport Hub stadium. The stadium is the world's largest domed structure. This roof contains two movable panels of 10,000 m², each of which traverses a 20° slope. Each panel is driven by 8 wire ropes of 50 mm diameter. The authors describe the driving mechanism which has been devised as a safety system permitting the roof panels to be moved above 55,000 spectators while they are seated in the arena.

1 Preface

Mankind has been answering the challenge of launching large structures into motion for thousands of years. The motive for conceiving such labour-intensive jobs has varied from artistic, decorative, or religious urges to the commercial necessities of real estate transactions. In a few cases, geophysical changes of the location itself have mandated a relocation. Regardless of when or why the work is performed, gravitational inertia and friction are the primary forces to be overcome when causing a large structure to move on the surface of the earth. For many centuries ropes have served as an excellent tool for controlling and moving enormous weights.

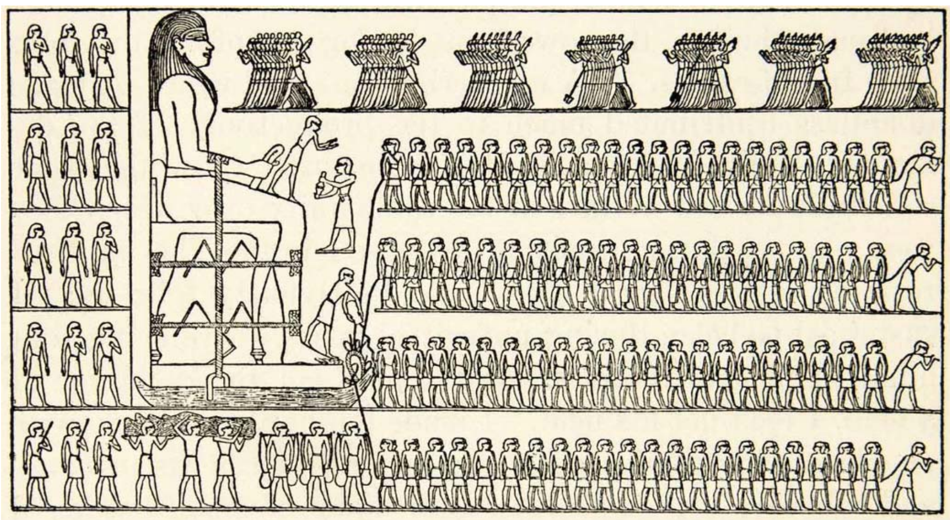

Figure 1: A Colossus of Alabaster Transported on a Sledge – El Bersheh.

The skills we needed were learned early at places like El Bersheh, Egypt (Figure 1). They are still in use today. In most of the cases, only a single movement was contemplated because the large structures created at one location were designed to be placed permanently at another location. Some of the structures we have moved are well known while others remain obscure. A few examples such as Marble Arch UK (1851) moved from a palace entry to a park, and Abu Simbel Egypt (1968), moved to avoid being submerged in a lake, were subdivided into pieces to be reassembled elsewhere later. Most of the other examples were moved only one time, but in dramatic fashion. Metropolitan rearrangements of entire buildings by sliding the whole structure horizontally, have much of the same techniques between the 1907 relocation of Villa Haux at Ebingen Germany (Figure 2), compared with repositioning the airport terminals at Newark USA (2001) and the Fu Gang building at Wuzhou China (2004).

For some of the one-time moves, the question of possible additional big moves in the future remains open. Natural changes of topography forced the 1999 movement of two lighthouses. One in Sussex UK was pulled back from the white cliffs and one in North Carolina USA was threatened by the shifting ocean sands of Cape Hatteras. Because natural changes affecting location cannot be arrested easily, nobody knows if another one-time move will be needed in the future. This can be contrasted with an evolving emergency situation such as our problems in the Ukraine where the Chernobyl containment housing (Figure 3), currently under construction, will be moved into a permanent protective position. It is designed to stay in place even if the site deteriorates.

Figure 2: Relocation of Villa Haux at Ebingen.

Figure 3: Chernobyl new safe containment.

Beyond the category of one-time moves, large structures have been designed for repetitive motion. One of the best examples is the crawler transporter at Cape Canaveral USA which has been employed for transporting large rockets and space vehicles from the vertical assembly building to the launch pad. This machine was developed directly from the track systems of large earthmoving excavators and the pace of movement is extremely slow for safety reasons. For the design of retractable roof systems, an increase in speed is desirable as a general characteristic. The rapid advent of stormy weather often mandates a need for swift adjustment in the same way an umbrella quickly provides cover. Putting a roof covering into accelerated motion is a suitable application for a wire rope reeving.

2 Examples of moving roof systems from 1960 to the present

The Pittsburgh USA Civic Light Opera was organized in 1946, aiming to present "Broadway"-style stage performances outdoors during summertime using the football stadium of the University of Pittsburgh to provide seating for large audiences. The shows at Pitt Stadium were successful but they were cancelled on more than one occasion by bad weather. A wealthy merchant named Edgar Kauffman who was a patron of the arts proposed a remedy. He urged construction of a new facility near the city centre to be equipped with a movable roof allowing the shows to be held regardless of the weather.

Pittsburgh Civic Arena was designed 1960 by Harold Helvenston (Figure 4). He proposed an unusual dome with a circular track around the circumference and a pivot point high in the air centred over the seating. The roof had eight structural steel segments covered with stainless steel sheets, six of which were movable. The diameter was 415 feet (126 m). The segments rested on 42 trucks mounted on 78 wheels, 30 of which were driven by geared motors with 480-volt AC motor drives. Advertisements claimed the roof could be fully opened in 2-1/2 minutes. The seating capacity, at first slightly more than 10,000, was gradually increased to over 17,000 at maximum.

The Civic Arena was the first structure of its kind in the world (Figure 5). It proved to be an immediate success from the time of opening in 1961. Soon it was converted into a multi-use facility for sports events, musical extravaganzas, religious conferences, rock concerts, political rallies, etc. It was given a nickname "The Igloo" when it became the home of a champion hockey team, The Penguins. During its 50-year lifespan, over 7000 events were held inside it. Unfortunately, the roof opening mechanism was rack-and-pinion style which proved very difficult to keep in good working order. Despite repairs, the problems continued. The occasions when it was opened became fewer and fewer. Ultimately the roof was permanently closed in 1994. The popularity of the hockey team led to construction of a modern fixed roof indoor stadium nearby which opened in 2010 with a significantly greater seating capacity. When the hockey team changed venues to the new facility, it was decided to demolish the Arena in 2012.

Figure 4: Harold Helvenston.

Figure 5: Pittsburgh Civic Arena.

The publicity associated with the success of the Civic Arena stimulated other cities to become aware of the possibilities for public entertainment provided by integrating movement into a large structure.The next significant realisation was also in North America but the primary cause leading to the concept was a severe rainstorm at the Grey Cup Canadian football championship of 1982. As a response to the demands of spectators, a study was made leading to construction of the Skydome at Toronto CANADA (1989) with a moving roof and seating for approximately 50,000 fans. This opened a new horizon for enclosed stadiums.

Some of the more recent large structures in the category include:

- Veltins Arena – Gelsenkirchen GERMANY(2000) with a moving roof and *also* a moving field
- Big eye – Oita JAPAN (2001); moving roof
- University of Phoenix USA (2005); moving roof and moving field (Figure 6).

Figure 6: University of Phoenix Stadium – moving roof and moving field.

3 The Singapore Sport Hub

3.1 Description

The newest one is the Singapore Sport Hub (Figure 7), which includes a moving roof and moving tiers of seating to accommodate various configurations specifically arranged for different kinds of events.

This paper focuses on the moving roof.

Figure 7: The Singapore Sport Hub.

The challenging application consisted of designing, producing, installing and testing the mechanisms that support and drive each panel of the roof.

The main parameters of this application are as follows (Figure 8):

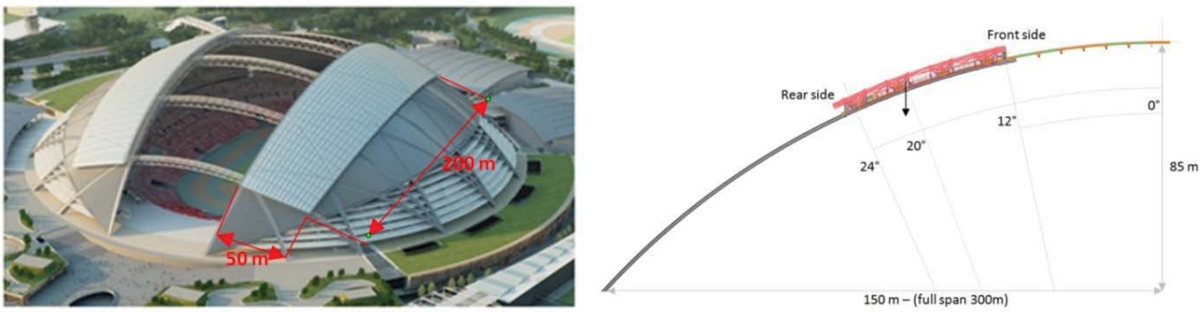

Figure 8: Singapore Sport Hub – main dimensions.

The surface of each roof panel is of 10,000 m² (200 m × 50 m), and the weight of one panel is 1,250 tonnes.

When the roof is closed the centre of gravity of each panel is located at an inclination of 8°. When the roof is open this inclination enlarges to 20°.

The travelling time for closing or opening the roof is restricted to 20 minutes maximum, thus the travelling speed is 2.5 m/min (0.042 m/s).

The maximum overall required driving force for closing (which includes friction, inertia and wind) is about 450 tonnes when the roof panel leaves its open position.

Each roof panel is supported on five runway trusses (RWT1 to RWT5) (Figure 9).

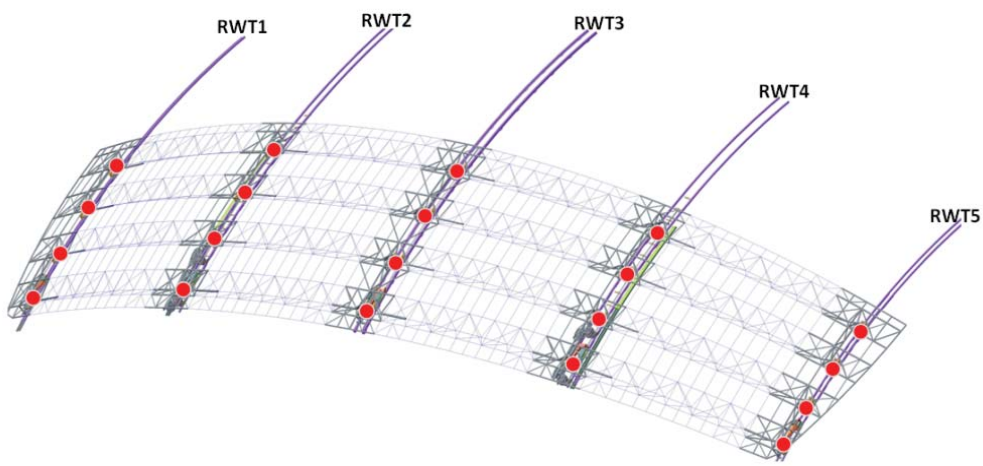

Figure 9: Five runway trusses support the bogies under each panel.

Four bogies are installed on each runway truss. The forces applied on these bogies which take into account gravity and wind, vary from 130 tonnes to 320 tonnes.

The span of the central arch which supports the RWT3 is 300 m and the height is 85 m. Because of these dimensions the supporting structure is extremely flexible.

Thus the connection between the bogies (which follow the track) and the structure of the moving roof must comply with significant lateral displacements which range from 0.15 to 0.5 m.

3.2 Supporting the moving roof

Each panel is supported by a total of 20 bogies. A storm brake trailer which is equipped either with 2 brakes (RWT1 and RWT5) or with 4 brakes (RWT2, RWT3, RWT4) is connected to the rear bogies (Figure 10).

The lateral forces are transferred only by the bogies of the RWT3 (Figure 11). On the other runway trusses the lateral displacements are handled by sliding bearings.

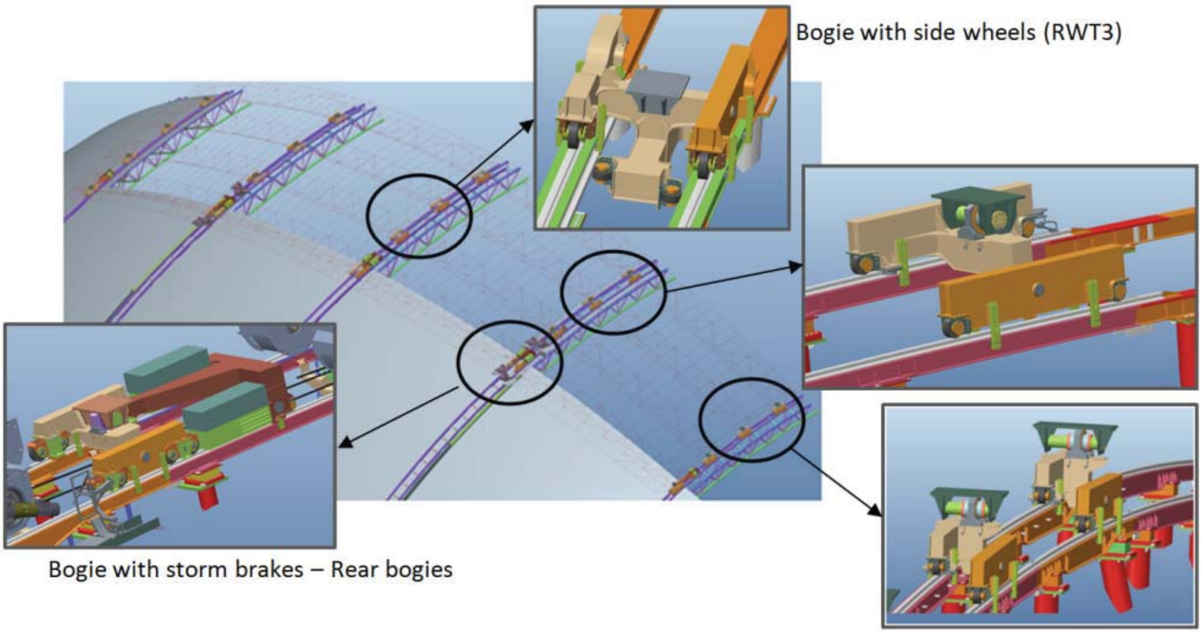

Figure 10: Supporting and guiding bogies.

Figure 11: Bogie for RWT3 – on site and during production.

Because of the flexibility, except on RWT3 (Figure 11), the connection between the bogie and the structure of the moving roof is performed by means of a specifically designed sliding bearing (Figure 12). This kind of special bearing was tested on a special test stand (Figure 13).

The stroke of a bearing is of 0.5 m, and during the testing each of two samples moved 15 km under loads up to 370 tonnes.

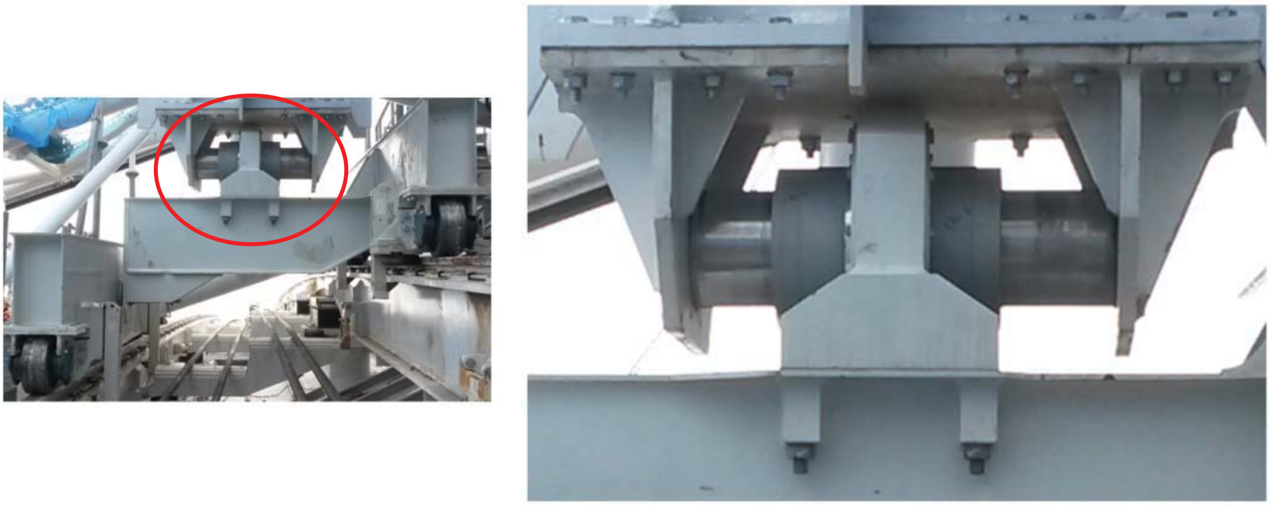

Figure 12: Sliding bearing.

Figure 13: Sliding bearing – test stand.

3.3 Driving the roof

Two systems were available for driving the roof, either the rack and pinion system (Figure 15) or a wire rope system.

If the inclination of the track is too small to ensure that the structure will move back under the gravity forces in the worst case when strong winds are present, either the rack and pinion system must be used, or else the wire rope system can be implemented only in the form of a pre-tensioned closed loop (Figure14).

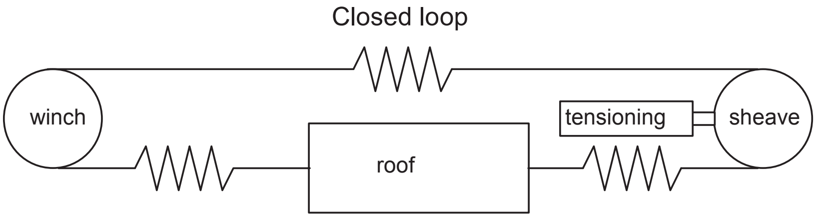

Figure 14: Pre-tensioned closed loop.

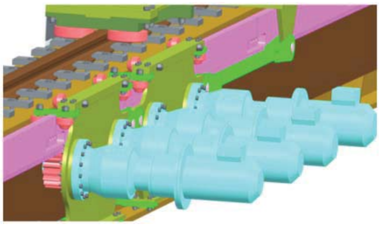

Figure 15: Rack and Pinion system.

With an open loop system, the movement would not be steady (Figure 16).

The rope behaves like a spring and thus the resisting forces (friction, inertia, wind,..) will create a stick/slip phenomenon. The line pull in the rope will increase in order to overcome the resisting forces. The increase of the tension will result in an elongation of the wire rope. As soon as the driving force overcomes the resisting forces, the friction and inertia will either reduce or disappear. Then the roof will jump forward with a velocity higher than the rotation speed of the drum, so as a consequence the rope will get shorter and the line pull will be reduced. The roof panel will stop until the wire rope elongates again because the drum is still running.

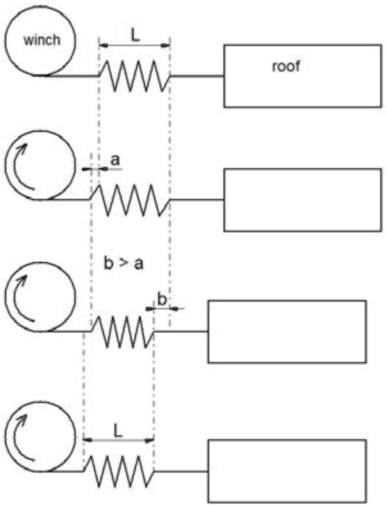

Figure 16: Open Loop System – Stick/Slip Phenomenon.

Compared to the rack and pinion system, the pre-tensioned closed loop of wire rope leads to a significant increase of the forces in the fixed structure that supports the moving roof.

For the Singapore stadium, on the one hand the rack and pinion system was not compatible with the flexibility of the structures, and on the other hand, the inclination of the track (8° minimum) was hopefully adequate to avoid installing a closed loop system.

Consequently, we decided to use an open loop wire rope system. The rope had to be fixed onto a roof panel at one end, and attached onto the drum of a winch at the other end.

There were several options for the location of the winches.

Option 1 (Figure 17a) - The winches are located in a winch room on the ground level (inside the concrete structure of the building). A sheave installed on the edge of the fixed roof structure diverts the wire rope toward the winch. The main inconveniences of this option are: the load transferred to the fixed structure by the sheave; the space required for the winch room; and, the exposure of the wire rope to possible terrorist action.

Option 2 (Figure 17b) - Consists of transferring the winch room to the top of the concrete structure of the building. This is positive regarding the terrorist actions, but there was no space available for the winch rooms.

Option 3 (Figure 17c) - Consists of removing the sheave and installing the winch on the opposite side. The ropes for two of the panels would then cross the pitch inside the runway truss, creating a negative visual impact.

Figure 17-a: Winch rooms on the ground level

Figure 17-b: Winch rooms on the top of the concrete structure

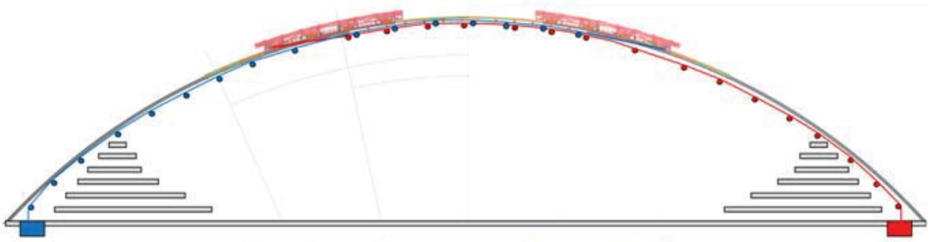

Figure 17-c: Winch room on the opposite side

Figure 17: Position of the winch rooms.

With all of these three options there is always a significant length of rope between the roof panels and the winch, whatever is the position of the roof. Due to the spring-like behaviour of the wire ropes, this gives the system the ability to dampen some accidental dynamic effects; for example, if a roof panel gets stuck and leads to creation of slack in the rope, and then gets released.

Option 4 (Figure 18a) - Consists of installing the winches inside the moving roof. Thus the space previously required for the winch rooms becomes cleared, and this is really good from the architects' point of view. The moving roof will have to be equipped with a system of electrical connections for communication with the control room which remains located inside the arena.

The winches are installed on the front side of the moving roof. This keeps a significant free length of rope even in closed position, and the winches have better access for maintenance. There are two disadvantages; the winches are visible by the spectators on the tiers, and it is more likely parts might fall down into the pitch.

Option 5 (Figure 18b) – This one was selected. The winches are located on the rear side of the panel. With this arrangement the two main disadvantages identified for the option 4 are solved, but yet the problem of the significant free length of rope remains.

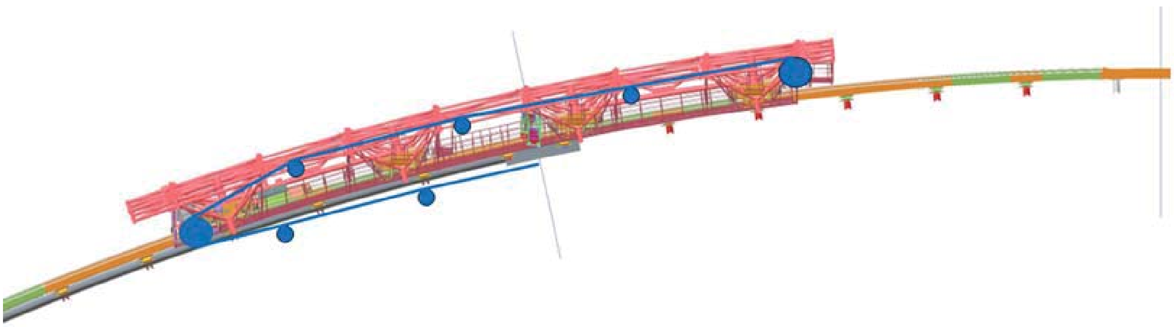

Figure 18-a: Winch on the front side of the moving roof

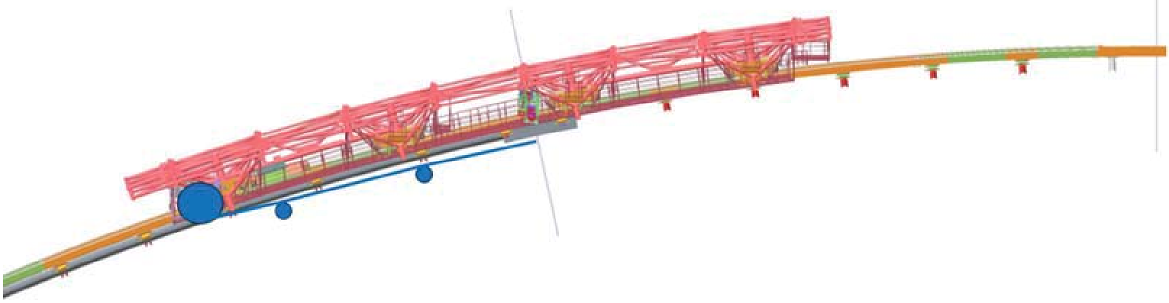

Figure 18-b: Winch on the rear side of the moving roof

Figure 18: Winches installed on the moving roof.

The other basic question regarding the architecture of the driving system was to decide whether to install one driving line per runway truss or two driving lines as a whole.

With one driving line per runway truss (Figure 19a) at least two wire ropes are required for some lines, thus the problem of the distribution of the load in accidental failure situations remains critical. Furthermore the installation of a platform for the winch on RWT1 would have been difficult because of the transversal inclination.

We finally selected the option with two driving lines, on runway trusses RWT2 and RWT4, with four wire ropes and winches per line (Figure 19b).

The distribution of the load among the wire ropes of the same driving line is of a great importance. The control command system takes this function into account for the normal configurations of operation. The system must also be able to survive accidental situations. The most critical accidental situation could take place during the roll back of the roof at the beginning of the opening motion. If one of the winches stops while the others keep moving, the corresponding wire rope will very soon support the full load alone. The elongation of any wire rope is directly proportional to its length. A short length has only a small elongation. If the unsafe situation identified above happens, it will be “absorbed” in a very short time. The shorter the free length of wire rope is, the quicker the rope will get loosened. This emphasizes why the free length is significant.

The management of the line pull in the wire ropes is consequently a safety function. It has been implemented in order to fulfil the requirements of the Safety Integrity Level SIL 3. The lack of tension and the over tension in a wire rope are checked with the highest priority.

Due to the risk of windstorms, “storm brakes” which clamp the roof panel on the track have been installed (Figure 20). Because of the above statement these brakes are also used as emergency brakes. They are not only used as parking brake. They additionally have the same function as the track rope brake on an aerial ropeway. Thus in case of lack of tension or over tension in any rope, as well as in case of over-speed of any panel, the roof will be stopped by the closing of the “storm brakes”.

As already explained any situation with sagging ropes is not acceptable because it could lead to a “free fall” of the roof panels which then creates huge dynamic effects when the roof is stopped by the wire ropes. When the storm brakes are closed the wire ropes can get loosened (perhaps by failure of a component, or a mistake during maintenance) without causing any noticeable effect on the roof. So in order to avoid creating a dangerous situation during the opening of these storm brakes, they must be open only if the wire ropes are properly tightened. The line pull in the wire ropes are checked and if necessary adjusted to a preset threshold before the opening of the brakes. This threshold which depends on the position of the roof is calculated by the PLC system on the basis of the information provided by the linear encoders (Figure 21).

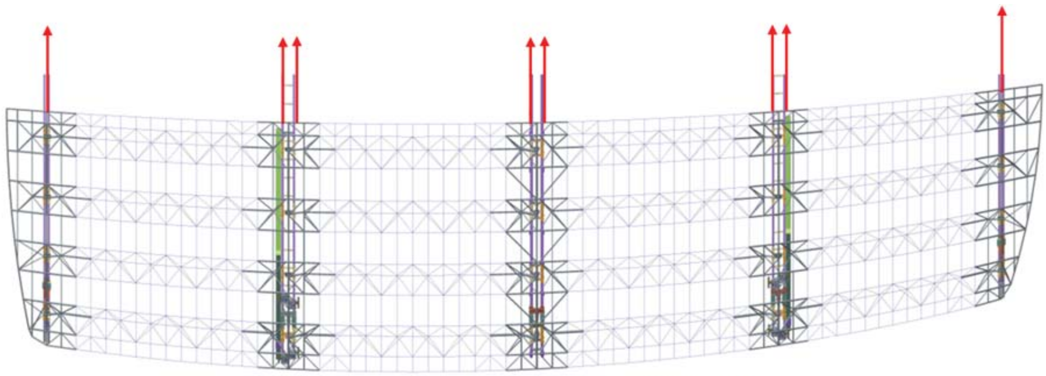

Figure 19-a: Arrangement with five driving lines

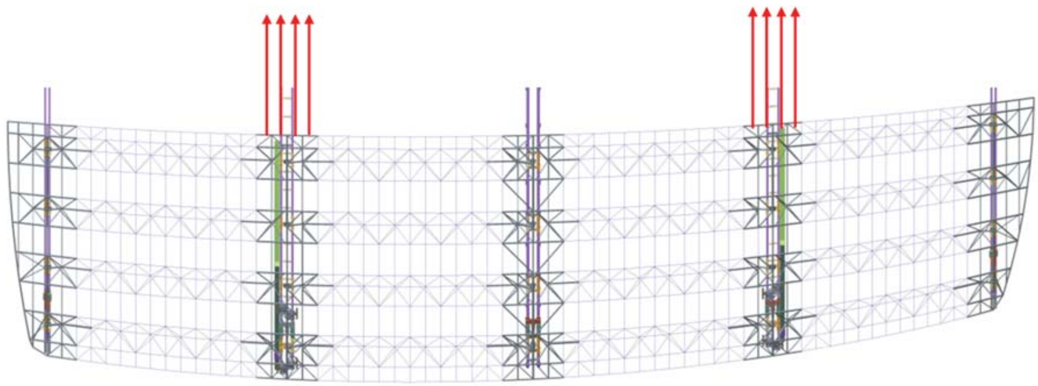

Figure 19-b: Arrangement with two driving lines

Figure 19: Number and position of the driving lines.

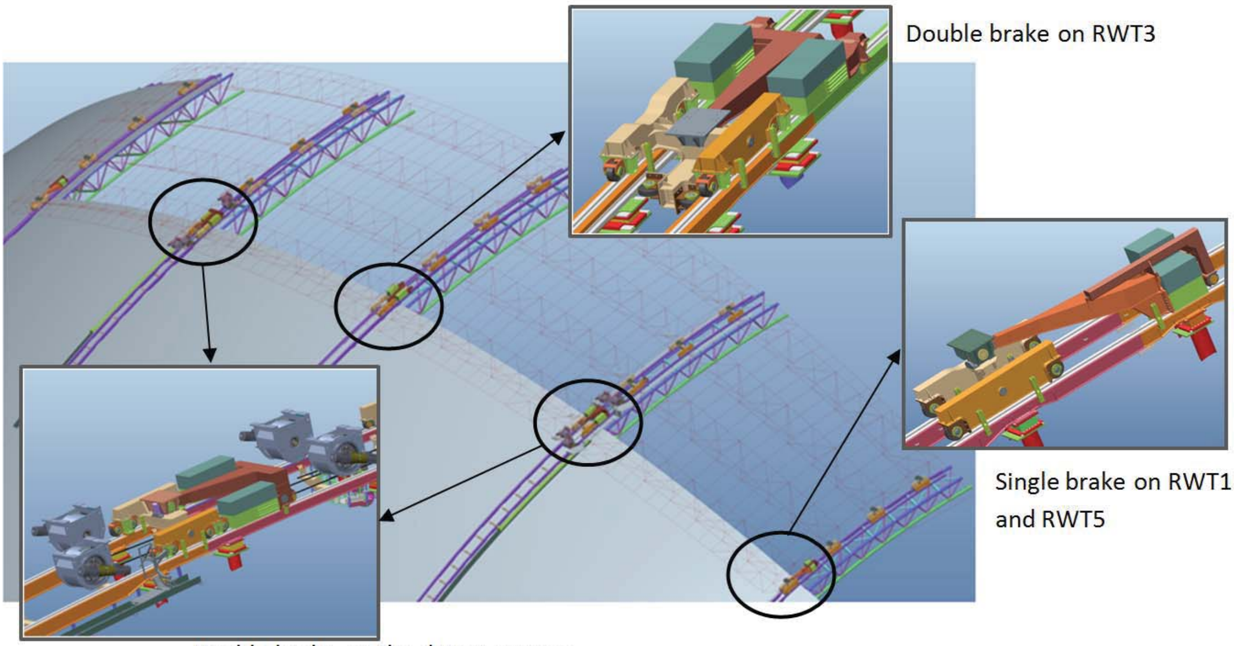

Figure 20: Emergency brakes.

The management of the skew of the panel influences the distribution of the load between the two driving lines. The position of the roof is measured on each runway truss by the mean of an absolute linear encoder (Figure 21). The accuracy of the measurement is better than +/- 1 mm. The relative position between the two driving lines is managed on the basis of this measurement by the mean of the adjustment of winch velocity. There are two reading heads in redundancy for safety purposes.

Figure 21: Linear encoder – position measurement.

There are four winches on each driving line. There are two motors (functional redundancy) on each winch. For each winch one of these two motors is the master and the other is the follower. The velocity of the follower is adjusted in order to equally share the torque between the two motors. Among these four masters, one is the master of the line. The velocity of the three followers is adjusted in order to get the same line pull in the four wire ropes. The line pull information is provided by a load cell that is installed at the rope anchoring point on the fixed structure (Figure 28). Among the two masters of the driving lines, one is the main master. The velocity of the follower is adjusted in order to comply with the skew requirements. The relative position between the two panels of the moving roof is also checked. In case of discrepancy of more than 1 m, the two panels are stopped.

For the non driven runway truss, the measurement of the position is required in order to check that the bogies have not become stuck. The structure of the moving roof is so flexible that a dangerous deformation of the structure will not lead to a measurable increase of the line pull. Thus the position measurements performed on the non driven trusses are implemented to check the deformation of the moving roof.

The natural deflection of the roof panel generated by the variation of inclination between the open and the closed position is bigger than the admissible deformation regarding the safety of the structure (Figure 22). Thus, comparing the position between the bogies of the driven and of the non driven trusses was not sufficient for checking the deformation of the moving roof structure. The control command system recorded the base reference profile during the commissioning testing and then the check of the proper position of each runway truss is performed on the basis of this learnt curve.

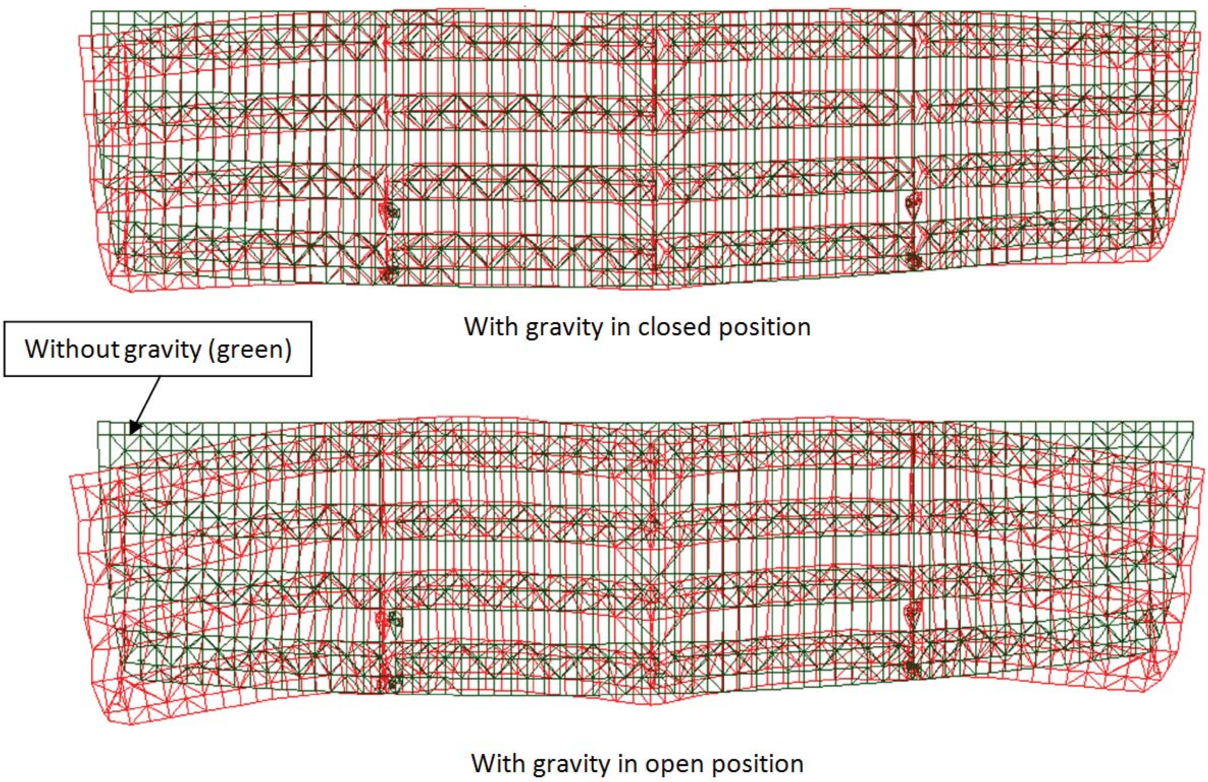

Figure 22: Variation of the natural deformation of the moving roof.

3.4 Drive unit – Wire rope system

There are four winches per driving line (Figures 23 and 24).

Each winch is fitted with a 50 mm high performance wire rope (8 strands, plastic infill, compacted outer and inner strands).

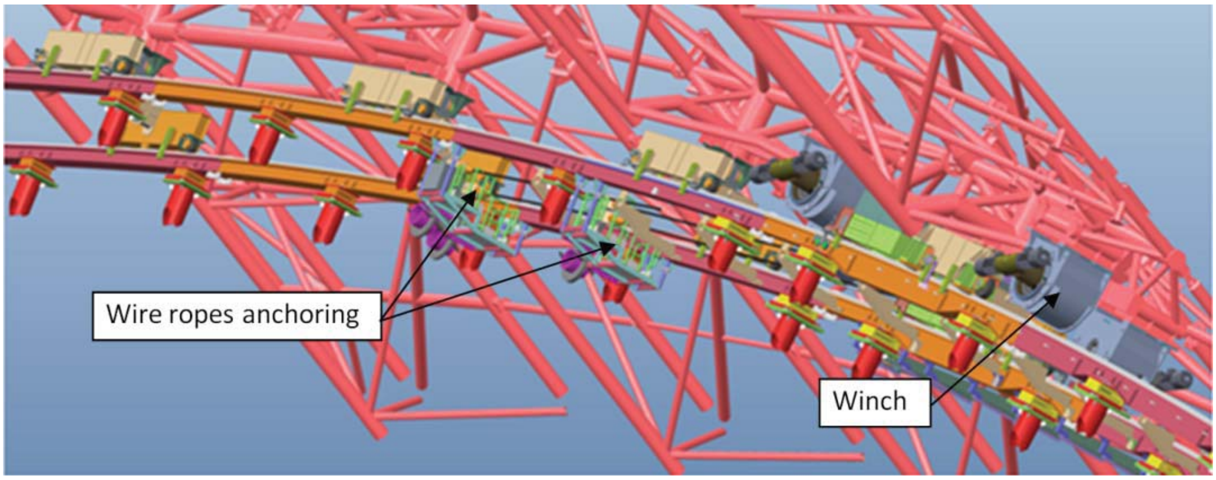

Figure 23: Drive unit – wire rope system.

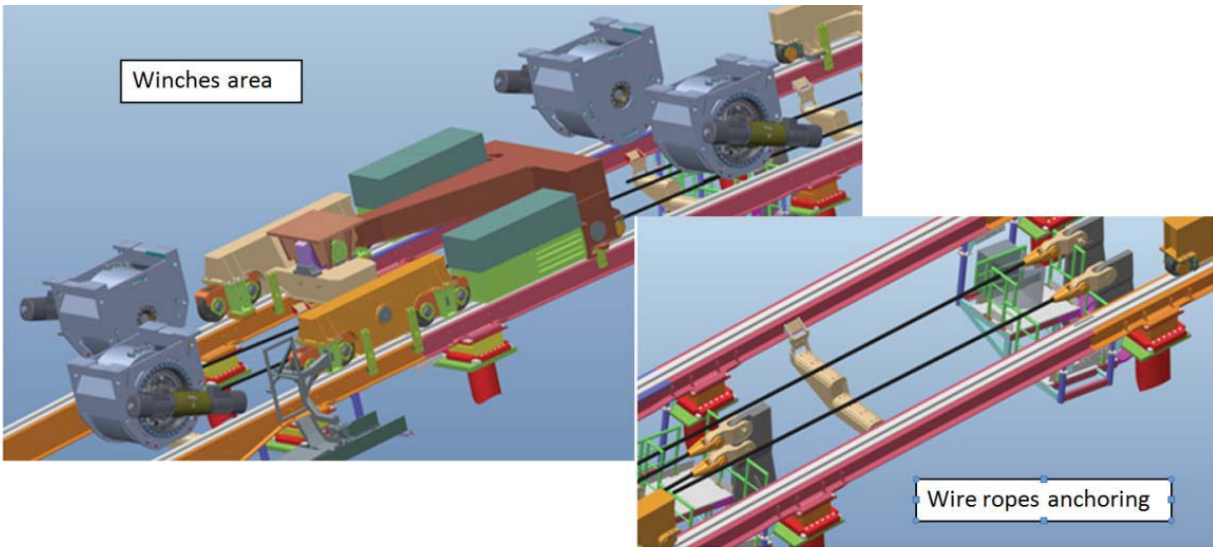

Figure 24: Drive unit – wire rope system.

The area is really congested (Figure 26). There is almost no space available between the rear winches, the rear bogie with its storm brakes trailer, the front winches and the next bogie (Figure 24).

So the winches had to be as small as possible. The diameter of the drum was optimized in order to comply with a service life of 60 years, and with the available space. The width of the drum had to be minimized. When the roof is in open position (Figure 25a) the required dead wraps must be present. When the roof is in closed position (Figure 25b) the rope must not jump outside the drum.

Thanks to a network of catwalks, all these items are accessible for maintenance and inspection (Figure 26).

Figure 25a: Open position – Dead wraps on the drum.

Figure 25b: Closed position – The drum is full.

Figure 26: Drive unit – Catwalk for access and maintenance.

During its path toward the anchoring points (Figure 27), the wire rope is supported by fixed nylon saddles. The angle of deflection of the rope above these saddles is lower than 1.5°.

Figure 27: Path of the wire ropes toward the anchoring points.

The wire rope is anchored onto the fixed structure via a spelter socket. A load cell monitored the line pull in each wire rope (Figure 28).

Figure 28: Wire ropes anchoring.

The significant flexibility of the supporting structure leads to important relative motions between the elements. The wire rope system is thus more convenient than the rack and pinion for this application. However a very deep analysis had to be performed in order to avoid any clash between the wire rope and either the frame of the side roller, or the uplift claw of the bogie, or the bearing of the track beam (Figure 29).

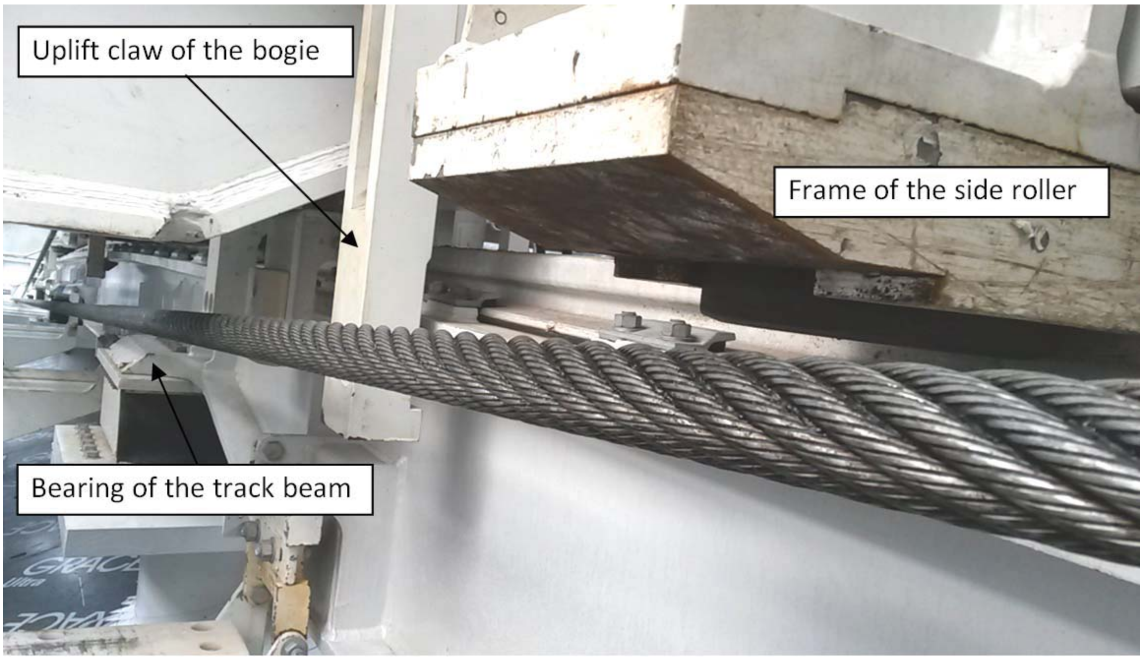

Figure 29: Potential interferences with the wire rope.

The PLC of the control command system was designed in order to equally share the load among the wire ropes of the same driving line. The PLC however can't manage some transitory phases such as the deceleration via the mechanical brakes for example.

When the roof panel is decelerated via the Variable Speed Drive of the control command system, there is no impact onto the line pulls (Figure 30a). The line pull in each wire rope remains at the same level as just before the closing of the brakes which takes place when the velocity becomes null. The slight difference between the four wire ropes results from the accuracy of the master follower relationship between the four VSD's. As soon as the roof moves, the PLC system works in order to maintain the proper distribution of the load (Figure 30b). When the mechanical brakes of the electrical motors are activated the behaviour is totally different (Figure 30c). This behaviour mainly results from the reaction times of the brakes, which furthermore are not identical, and from the torque capacity of each brake. There are two electrical motors on each winch for a matter of functional redundancy, thus a winch can be operated with only one motor and thus only one brake whereas the other winches are operated with two motors and thus two brakes. The winch with the lower braking capacity will take longer to stop. If this occurs during a lowering motion of the roof, the winches that will be stopped first will finally support more load. For the example in Figure 30, we can assume that the rope with the lower line pull (c) was driven by a winch with only one motor, and that the discrepancy among the others comes from the reaction times.

We can notice that the process of the resetting of the line pull in the rope before the opening of the storm brakes, which was implemented in order to avoid any risk of “free fall” of the roof (see above), is also able to compensate this phenomenon (the storm brakes are forcibly closed before each start of motion).

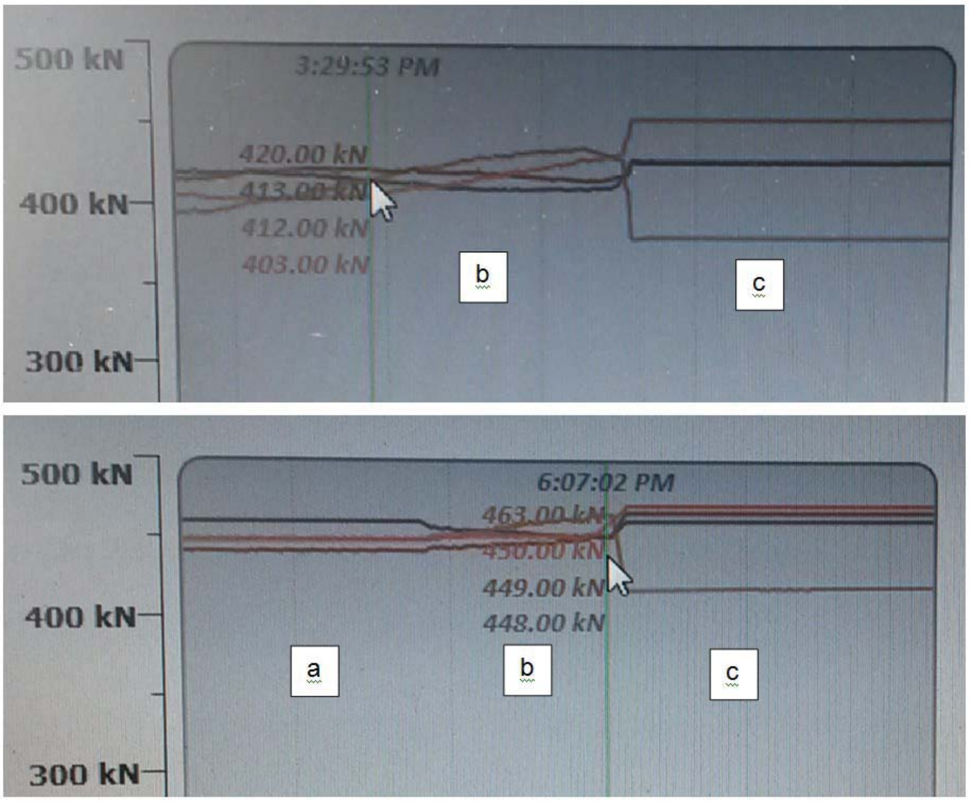

Figure 30: Load cells readout – different phases of the motion.

4 Conclusion

The challenge of moving large structural roof panels back and forth in the air above crowds of people presented mechanical and hazard confrontations of the highest complexity at Singapore. The chosen architecture for the Singapore Sport Hub was very pleasing in the eyes of the architects, but it was far from being the easiest to work with for the engineers. In many ways it was the same old story of “form vs. function” dating back to the era of the Roman architect M.V. Pollio during the reign of Augustus.

Because of the importance of the project, Availability was the master word. Because of the presence of humans, Safety was also of the highest importance. We had to deal with these two constraints which are basically contradictory, with almost no tolerances.

The wire rope operational solution was very convenient for dealing with all the specific parameters of the project. Keeping the working condition of the ropes in an acceptable state was a big dilemma that has been overcome with the help of the latest development of the safety PLC systems

5 Acknowledgments

The authors would like to thank DSPL who kindly gave authorisation for the publication of this paper.

- Dragages Singapore Pte Ltd (DSPL) is the main contractor.
- ARUP is the architect and general designer of the stadium.
- The design and calculation of the structural elements have been carried out by ARUP.
- The design and calculation of the elements of mechanism have been performed by DEP Engineering.
- The specific elements of mechanism have been produced on the behalf of MHE-Demag, who was the sub-contractor for the mechanism of the moving roof.