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# Retractable Roof Olympic Stadium Montreal

Toiture rétractable du Stade Olympique de Montréal

Einziehbares Dach des Olympiastadions Montreal

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**SUMMARY**
The 20 000 $m^2$ retractable roof of the Montreal Olympic Stadium consists of a Kevlar fabric suspended from a 168 m high inclined tower. 46 winches and other mechanisms are used to lift the roof to the top of the tower. The engineering and construction of this unusual structure have recessitated a number of innovative technical solutions.

**RÉSUMÉ**
Le toit rétractable du Stade Olympique de Montréal est constitué d'une toile de Kevlar de 20 000 $m^2$ suspendu à un mât incliné d'une hauteur de 168 m. Quarante-six treuils et autres mécanismes permettent de le remonter dans un espace réservé à la partie supérieure du mât. La conception et la réalisation d'un tel ouvrage ont fait appel à des solutions techniques innovatrices à plusieurs égards.

**ZUSAMMENFASSUNG**
Das einziehbare Dach des Olympiastadions in Montreal besteht aus einem Kevlargewebe von 20 000 $m^2$, das an einem 168 m hohen Turm befestigt ist. 46 Winden und andere mechanische Einrichtungen ermöglichen das Heben und Einziehen des Dachs in einen dafür vorgesehenen Raum im oberen Teil des Turmes. Ein derartiges Bauwerk konnte nur mit neuartigen technischen Mitten konzipiert und ausgeführt werden.

## 1. INTRODUCTION

The 20 000 $m^2$ fabric roof of the Montreal Olympic Stadium closes an elliptical opening of 220 X 140 m in the existing concrete roof covering the grandstands. It is suspended from a 168 m high inclined tower with an average angle of 30 deg. from the vertical. Even though the initial concept of architect R.Taillibert was followed, the original design was considerably reworked especially regarding the snow load and all the lifting mechanisms. Indeed, strong concerns about the feasibility and reliability of the snow melting system considered in the earlier design required an increase of the nominal snow load from the initial 0.45 kN/$m^2$ to 1.65 kN/$m^2$. The consequences of this change include a complete redesign of the suspension system and the hardware pieces, an optimized geometry, a strengthening of the fabric joints and major modifications to the mechanisms retracting the roof. (See fig.1)

Special attention was given throughout the design to reconcile such diverging objectives as having a flexible and easily foldable structure during retraction and obtaining a very stiff and stable roof supporting heavy loads in the closed position. An effort was also made to isolate the mechanisms from the structural parts carrying heavy wind and snow loads.

Fig.1 Overall View of the Stadium

## 2. ROOF AS A STATIC STRUCTURE

### 2.1 General description

The roof is roughly ellipsoïdal in shape and is suspended by 26 points, looking like Chinese hats distributed over the entire roof surface. On the periphery of the ellipsoïd, the fabric is attached to circular edge cables which join together at anchoring plates called boomerangs.

A normal surface reaction at each suspension point is achieved by a suspension cable connecting the suspension point to the top of the tower and one or two liaison cables linking two suspension points or a boomerang.

## 2.2 Membrane Material

The original membrane material is a PVC coated Kevlar 49 fabric with a Panama weaving. The breaking strength is 600 kN/m in the warp and 550 kN/m in the fill. The strain at 20% of breaking load under biaxial tension is about 1.4%. The compensation factors are 1.5 and 3.5‰ in the warp and the fill respectively which characterize an extremely stiff behaviour.

In order to improve the durability of the material, both faces were coated with a film of polyurethane. The final total thickness is about 2.5 mm and the mass per unit area close to 2.9 kg/m$^2$. Over 400 fabric samples are exposed on the concrete roof and will periodically be submitted to cyclic folding to monitor the actual aging of the fabric with time.

## 2.3 Suspension Point

The top of the Chinese hats (See fig. 2) consists of a cast steel piece to which are attached suspension and liaison cables. Forty small steel cables, called "suspenders", spread out from the bottom part of this piece. The lower end of every suspender is attached to a cast steel clamp that holds the Kevlar fabric.

These clamps are made out of two halves bolted together and shaped to squeeze a pocket of Kevlar fabric where an aluminium cylinder is inserted. The suspenders are covered with a translucent polyester PVC coated fabric for water tightness and skylight effect at each of the 26 suspension points (See fig. 2).

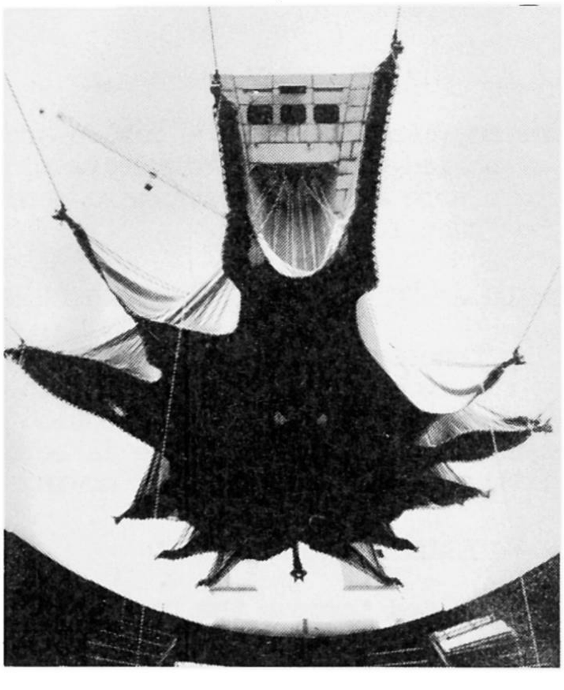

Fig.2 Hats during Erection

## 2.4 Boomerang and Anchorage

The boomerangs are cast steel pieces having in general a saddle for the continuous edge cable, connectors for the hauling and the liaison cable and a large cylindrical hole which receives a pin up to 300 mm in diameter to make the anchorage. The inside of the hole is covered with a reinforced teflon in order to create a good hinge around the axis of the pin.

The anchoring structure attached to the concrete has some funnel shaped plates and the boomerang itself carries some rollers to guide it into its anchorage (See fig. 3).

2.5 Edge

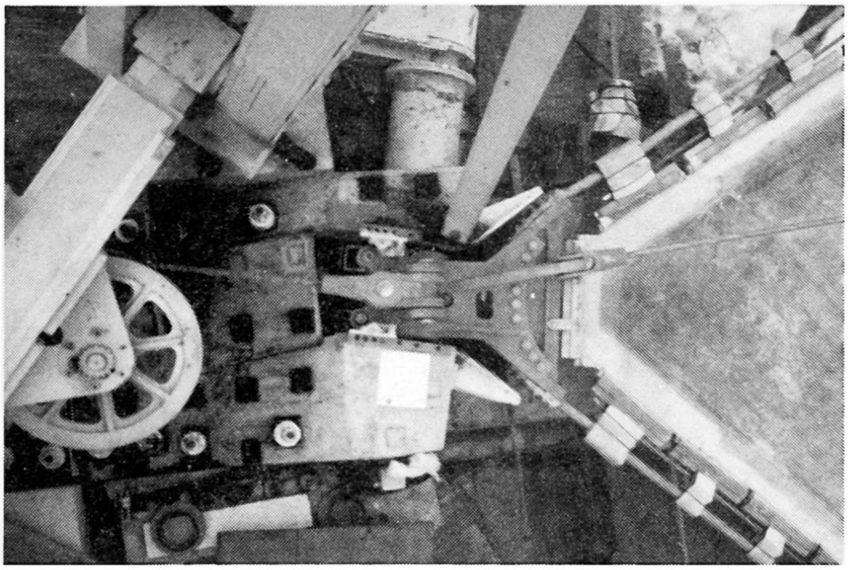

Fig.3 Boomerang and Anchorage

The attachment of the fabric on the edge cable consists of a series of cast steel fabric clamps similar in principle to the ones used for the hats. In order to preserve the flexibility of the edge, only one of four fabric clamps is rigidly attached to the cables. The three others have U shaped connectors which allow a free bending of the cable during the retraction. These connectors can only transfer radial forces.

The tangential forces which appear under wind or snow load are carried by a small "tangential cable" attached to all the fabric clamps which runs parallel to the edge cable (See fig. 3).

2.6 Suspension and liaison cable

All the suspension, liaison and edge cables are lock coil ropes with two or three layers of shaped wires. The diameters range from 37 to 95 mm. Special design parameters were adopted to optimize bending flexibility while maintaining a modulus higher than 160 000 MPa.

2.7 Prestressing Jacks and Top Anchorages of suspension cables

The prestressing tension in the membrane is applied through 12 centerhole jacks located at the top anchorage of the suspension cables. Extending the piston by 0.7 to 1.0 m is enough to increase the tension in the fabric from about 3 kN/m to 10 kN/m. When the hydraulic pressure is released, the piston sits directly on the cylinder body via a large ring gear moving on the piston.

2.8 Shape Finding and Cutting Pattern

The shape was optimized through the use of mathematical models to achieve a state of uniform biaxial stress in the fabric under prestressing. The cutting pattern was prepared to fit this state. The end product is an anticlastic shape built from 76 main strips cut in 3.1 m wide rolls. Around the hats, the assembly of the main strips leaves circular holes 12.5 m in diameter. A conical shape with a circular generating line joins the periphery of this opening to the fabric clamps at bottom of the suspenders.

Due to the extreme stiffness of the material, a high precision of less than ±2 mm was required in the cutting of the strips. For the cutting patterns, a compensation factor was applied in either main directions of fibers according to the results of the biaxial tests (see 2.2). Along the edges, the fabric was "decompensated" up to 7.5‰ to fit the stiff edge as well as to avoid any circonferential tension in the fabric close to the edge.

## 2.9 Loading and Analysis

The final maximum uniform snow and wind loads are 1.65 kN/m$^2$ and 0.70 kN/m$^2$ respectively, based on codes and wind tunnel tests. In cooperation with Prof. Linkwist of Stuttgart University, a number of static F.E. analysis were performed to determine the stresses and deformation over the entire roof surface under various combinations of wind and snow.

## 2.10 Membrane assembly

The assembly joints between kevlar strips are either sewn (15 stitches) or High Frequency (H.F.) welded and sewn (26 stitches) to meet strength requirements of up to 100% of the base material. Unique H.F. welding machines and 15 needle long arm sewing machines were specially designed and built for the execution of these joints which required hundreds of mechanical tests to perfect. The accuracy of the assembly is better than $\pm 2$ mm per joint. All joints are coated with polyurethane for water proofing and U.V. protection. After completion of the work in the assembly plant, the 65 ton membrane was transported in a single piece to the stadium for the attachment of the hardware.

# 3. MECHANISMS

## 3.1 Lifting Sequences

The roof is operated by 26 hoisting cables in series with suspension cables in addition to 17 hauling cables attached to the boomerangs. Each cable is connected to a winch.

When the roof opens, the prestressing tension is first decreased by lowering the 12 hydraulic cylinders. The hauling winches are then activated to separate the boomerangs from their anchoring pins; an electrically driven mechanism pulls out the pin. Immediately after, the boomerangs are lifted using sheave elevators as described in 3.5.

Then, the hoisting winches slowly lift the fabric into a specially designed space in the mast called the "niche". Simultaneously, the hauling winches keep an antagonist tension. In addition a circular cable called a "lasso" connects all boomerangs, giving a better control on their position (See fig. 4).

All the sequences are automatically controled by computer in order to closely follow the predetermined intermediate positions. The lowering sequence is exactly the reverse of the lifting one.

Fig.4 Roof during Retraction

In the final stage, an additional cable pulls the boomerang closest to the tower to the inside of the niche and at the same time, the lasso is tightened to bring the membrane into its final parking position. Wind tunnel tests show that the stability of the membrane during the lifting is satisfactory for wind speeds up to 25 km/h.

### 3.2 Hoisting system

The hoisting and the suspension cables are rolled up from their anchoring position at the top of the tower to the hoisting winches located at the base of the tower. The hoisting cables are round strand rope with diameter and length up to 57 mm and 294 m respectively. To avoid rubbing against the many guiding rollers, the connection piece between the hoisting and the suspension cable is equipped with wheels rolling on parallel tracks

### 3.3 Hauling system

From the boomerang, each hauling cable is guided to its winch through by two sheaves. The first one, close to the anchorage, is hinged around one axis to accommodate the variation of inclination of the cable when the boomerang moves up. The second one is fixed and guarantees a proper fleet angle on the drum of the winch. The hauling cables are similar to the hoisting cables but with a diameter up to 70 mm. All hauling winches are hydraulic and behave like counterweight of variable mass.

### 3.4 Lasso

Two lasso winches are located at the bottom of the niche. Each is able to store 400 m of cable and has a 700 kN pulling capacity. The lasso is a single cable 850 m long, 57 mm in diameter.

The lasso is going out of the niche through the first winch. It is then deviated by one vertical and one horizontal sheave over to the boomerang closest to the tower and then thru a "lasso saddle" hanging from all the other boomerangs. It circles around the stadium and goes back to the second winch in a symmetric way. A typical lasso saddle includes a sheave and two arms hinged in the plane of the sheave. In the parking position, all saddles are touching each other.

### 3.5 Other mechanisms

Apart from the prestressing jacks and the driving mechanisms of the pins at the boomerangs, an additional mechanism was needed to prevent the contact between the edge cable and the fixed roof during the retraction. For that purpose, the first deviation sheave of the hauling cable is installed on a movable support sliding on tracks 3 to 4 m high bolted on a frame. This support is electrically driven with 4 screws.

## 4. CONTROL SYSTEM

Up to 46 winches have to be synchronized during retraction. Every cable is equipped with a measuring device of the winded or unwinded length and with a number of limit switches for safety.

All winches have their own Local Programmable Computer which manage some basic logic. Three larger Local Programmable Computers and two micro computer dispatch the instructions and coordinate the complete operation. They also allow the communication with the operators and display system status, informations and faults. Some changes to the calculated sequences can be undertaken by the system itself to keep the actual sequence within fixed boundaries.

## 5. CONCLUSION

The Montreal Olympic Stadium Retractable Roof has been finally completed after three years of engineering, manufacturing and construction efforts. Dealing with unusually large dimensions and an extremely complex geometry has required innovative solutions out of standard guidelines. The end product is a prototype of an hybrid structure being at the same time a large span suspended roof and a huge machine.