Retractable Roof Design and Construction

WALTER P MOORE
Presentation overview

- Site/Structural Layout
- Mechanization
- Wind environment
- Roof positions
- Wind tunnel analysis
- Construction
Let’s start with a very brief history of baseball stadia.

Huntington Avenue Grounds
(Boston Americans/Red Sox 1901-1911)
Fenway Park was built in 1912 and is still in use today.
The Eighth Wonder of the World started a new trend in stadium design in 1965.
In 1992, Camden Yards ushered in the “retro-ballpark” era.
The Marlins Owner wanted something new to reflect south Florida.
The Marlins Owner wanted something new to reflect south Florida.
Populous got to flex their muscles for the design of this ballpark.
At the beginning of the project, some parameters were already defined.
The “simplest” solution is to use a single panel.
Keeping the structure shallow with two panels requires either a bi-parting roof...
Or it requires a two-level track where one panel dives under the other.
A 3-panel roof needs more height but minimizes the stacking area needed.
Site limits and cost dictated stacking on one side, a level track and three panels.
Minimizing the overall track height is limited by seating/sight requirements.
The 1st rule of a roof for baseball is don’t let a ball hit the structure in the field of play.
We can rule out an arch structure due to thrusts and height required.

What gaps are required?

548’ c-c

\[
\frac{\text{Span}}{12} = 45' \text{ depth}
\]
WPM chose planar trusses with varying depths for the primary roof trusses.
Orthogonal trusses cause problems with the roof opening and layout of the field.
The roof opening and layout of the field dictated skewed trusses.
Horizontal bracing is provided in the plane of the bottom chord to simplify erection of the roof.
Vertical bracing in the secondary direction spreads load and braces the top chords.
Now, let’s see about moving that roof.
Normally, reducing costs for long-span roofs dictates minimizing piece count.

Rule #1: Don’t design to least weight

Rule #2: Make it easy to erect

Rule #3: Minimize number of pieces

Rule #4: Detail field connections for speed
Balancing structural efficiency with mechanization costs is critical.
So the rules change for the structural design of retractable roofs.

Rule #1: Design to mechanization capacities

Rule #2: Refer to Rule #1

Rule #3: Don’t design to least weight

Rule #4: Make it easy to erect
From our experience, these are aspects of the most economical roof system.

- A “simple” (determinate) structure
- All loads taken by single rail
- A traction drive system
- A system which drives majority of wheels
One of the biggest challenges is how to deal with tolerances and thrusts.
Using pinned supports, loading our shape will always generate thrusts.
One solution is to “let go” at one end of the roof in the longitudinal direction.
A 4-bar linkage achieves the release while maintaining stability.
The 4-bar linkage is stable up to a 1:10 inclination.
<table>
<thead>
<tr>
<th>Panel</th>
<th>Total Movement [in]</th>
<th>4-bar Height Required [in]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower</td>
<td>20</td>
<td>200</td>
</tr>
<tr>
<td>Upper</td>
<td>30</td>
<td>300</td>
</tr>
</tbody>
</table>
At the north end, a moment frame provides the entire stability for the roof.
With moving structures, there are more operating conditions to consider.

• Three operating conditions
  – Moving
  – Parked
  – Tied down
Operating wind loads are based on probabilities.
The roof will be watertight for most thunderstorms encountered.
The roof will be watertight for most thunderstorms encountered.
The 800-lb gorilla in the room is the wind load in the Miami environment.
Miami’s design velocity pressure is 2.6 times that for the majority of the U.S.
First, we considered what position the roof should be in to survive hurricanes.
Second, we tried to determine exactly what the code wind loads were.

2007 Florida Building Code

SECTION 1620 HIGH-VELOCITY HURRICANE ZONES — WIND LOADS

1620.1 Buildings and structures, and every portion thereof, shall be designed and constructed to meet the requirements of Section 6 of ASCE 7, as more specifically defined in this section, based on a 50-year mean recurrence interval.

1620.2 Wind velocity (3-second gust) used in structural calculations shall be 140 miles per hour (63 m/s) in Broward County and 146 miles per hour (65 m/s) in Miami-Dade County.

1620.3 All buildings and structures shall be considered to be in Exposure Category C as defined in Section 6.5.6.3 of ASCE 7.
Code wind pressures are based on shape and pressurization/leakage.

6.5.12.2 Main Wind-Force Resisting Systems.

6.5.12.2.1 Rigid Buildings of All Heights. Design wind pressures for the MWFRS of buildings of all heights shall be determined by the following equation:

\[ p = q GC_p - q (GC_{pi}) \text{ (lb/ft}^2\text{) (N/m}^2\text{)} \]  

(6-17)
Our shape is very complicated, so we need to figure out which $C_p$ chart fits us.
Using just a single chart from the code will woefully underestimate wind loads.
Our roof seals are not hurricane-proof and they can allow dominant openings.
Initial CFDs indicated a gapped roof was promising.

Video courtesy of RWDI
Aeroelastic model testing late in design confirmed the stability of the roof.
Long-span design is tough. Moving the roof significantly increases the challenges.

- Limits of mechanization
- Inertial loading
- Relative movements
- Wind loads multiply
- Several expansion joints
- Stiffness of supporting structure
Loading on individual retractable panels adds conditions not usually considered.
Moving down the track, wheels shed and attract load – but how much?
Minimizing stiffness of the roof structure is desirable, but not totally possible.

± 500k
Transporters take the loads from the roof trusses and deliver them to the track.

- Upper panel – 24 transporters – 12 each side
- East & west panel – 10 transporters – 5 each side

Image courtesy of Uni-Systems
Nominal motors at most transporters drive the roof.

Images courtesy of Uni-Systems
This is the load transfer mechanism during operation.

Image courtesy of Uni-Systems
The rail to track connection is critical.

Images courtesy of Uni-Systems
The attachments increase at the hurricane tie down locations.

Image courtesy of Uni-Systems
Rail clamps engage as soon as the roof stops.

Images courtesy of Uni-Systems
Rail clips provide uplift resistance for thunderstorms.

Image courtesy of Uni-Systems
Rail clips provide uplift resistance for thunderstorms.
Manually deployed tie downs provide lateral resistance for hurricane winds.

Image courtesy of Uni-Systems
Manually deployed tie downs provide lateral resistance for hurricane winds.
Similar tie downs provide longitudinal resistance.
Similar tie downs provide longitudinal resistance.
Construction of the roof spanned two hurricane seasons and fortunately went very smoothly.