Erecting and launching five huge truss structures one after the other enabled the use of a single set of falsework.

A Roof That's Ready for Takeoff

BY CURTIS L. MAYES, P.E.

THE FLORIDA MARLINS Major League Baseball team, with the help of Populous Architects, chose to build its world-class retractable roof ballpark using some interesting and rather contemporary architectural shapes. The new 37,000-seat stadium is a departure from the classic ballpark architecture that several of the more recently built ballparks have incorporated.

The massive 6,814-ton moveable roof consists of three independent rolling segments. According to the Tekla BIM models, the two lower roof panels on the east and west sides weigh in at 1,602 tons each and are made up of three trusses per side. The six-truss upper-center panel weighs in at 3,610 tons. When the roof is closed, the east and west panels match with the profile of the fixed roof to fully enclose the stadium. Enclosure allows protection for the players and fans from the elements and allows the massive air-conditioning systems to cool the space. When it is time for the field's natural grass to soak up some of that natural Florida sunshine and/or rain, all the panels retract to hover above and to the west of the first base line stands.

The roof trusses do not run perpendicular to the tracks, as one would expect, but are curiously skewed $6\frac{3}{7}$° out of square. Why the skew? The stadium architecture has a direct correlation to the street system, specifically the roof tracks run parallel to streets on the north and south sides of the site. However, the field geometry and the seating bowl orientation related to creating the best views of Downtown Miami and the home run

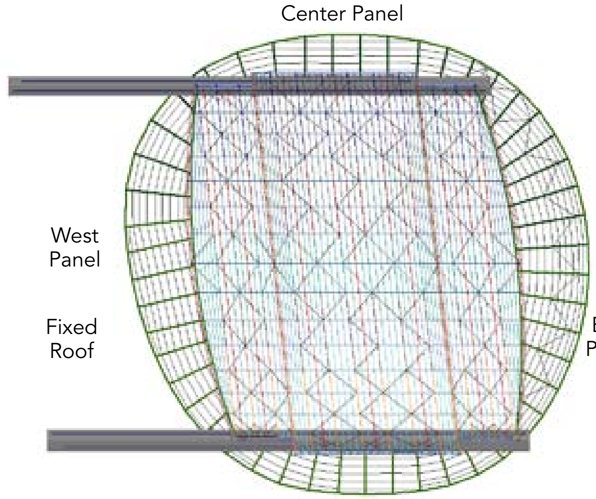
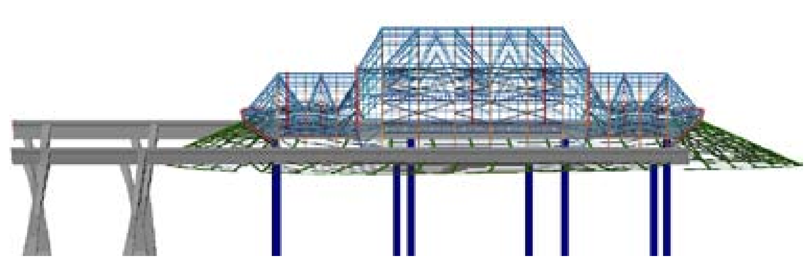
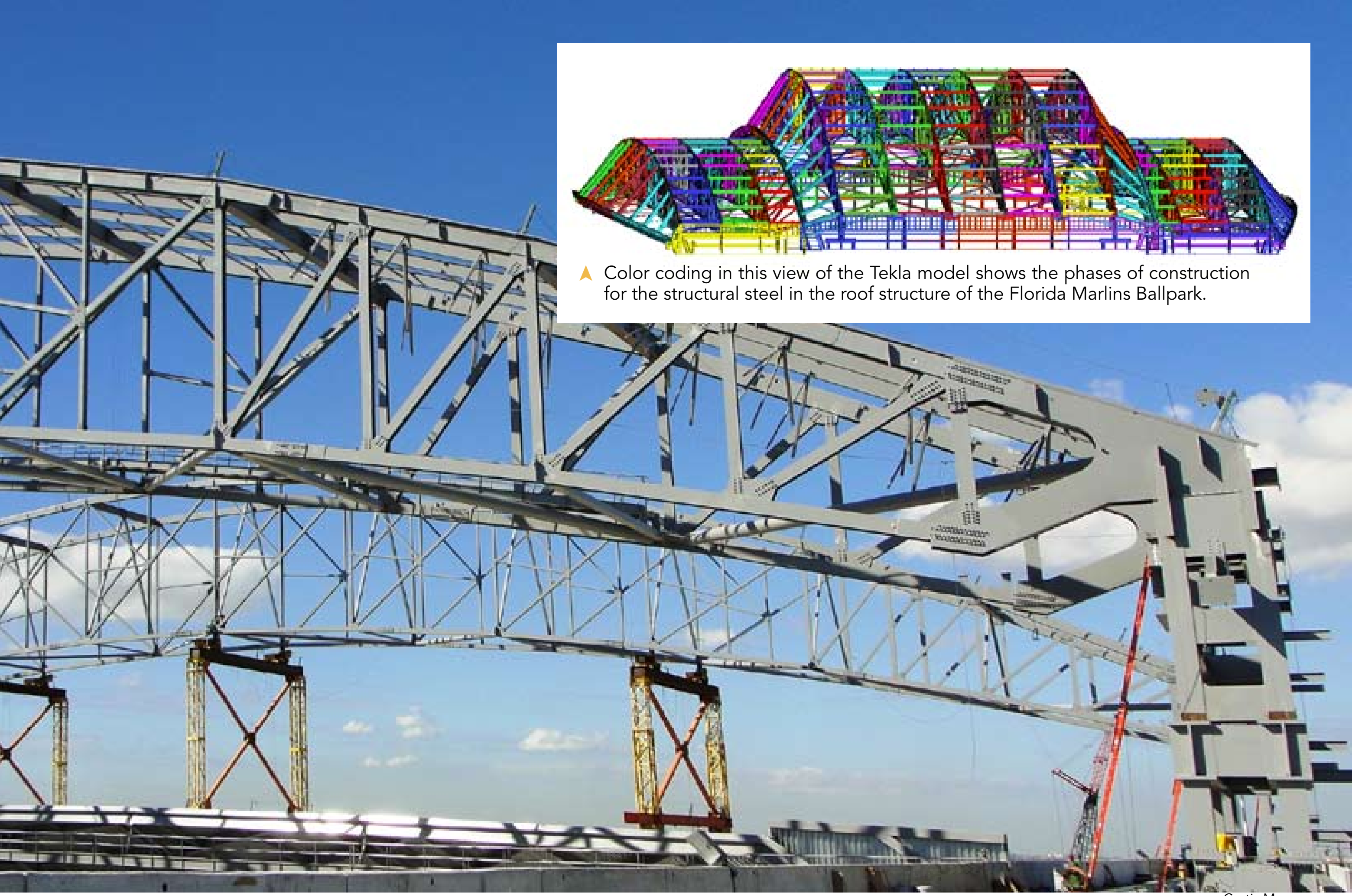


Fig. A: Plan view of the roof and supporting track structure.

Fig. B: Elevation view of the roof and supporting track structure (low roof support and stadium not shown).





Color coding in this view of the Tekla model shows the phases of construction for the structural steel in the roof structure of the Florida Marlins Ballpark.

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First of the three panels for the upper roof section, with the second visible in the background as it nears completion.

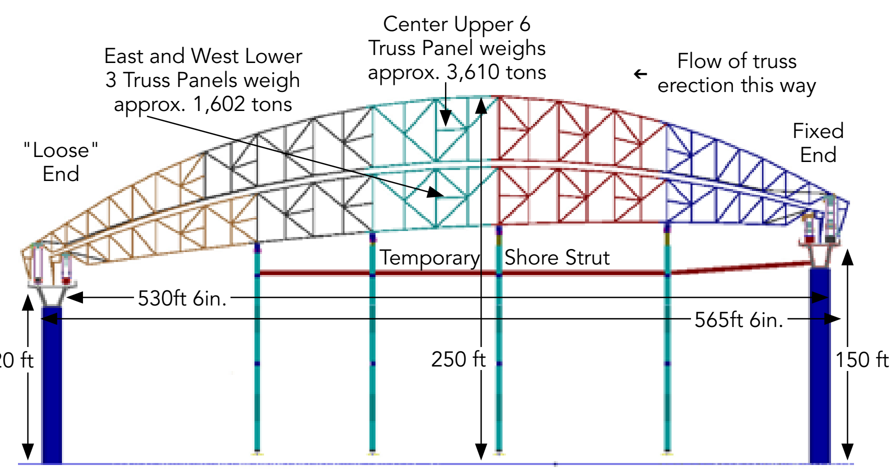

Fig. C: View of roof trusses profiles, shoring system and supporting track structure.

fence dimension. While seemly arbitrary, the combination of factors resulted in the alignment. Designing the roof panels to sit askew to the roof track was done to create a more dynamic appearance and to enhance the amount of sunshine available to grow the playing field. It also aligns the trusses parallel to the third base line.

As shown in Figure C, the roof trusses are arch shaped. A classic arch structure is quite efficient, but it requires a support at each end that can resist the internal thrust of the arch. Because the supports for the roof of this structure are elevated, it would have required massive buttresses and associated foundations to resist the horizontal arch thrust loads all along the roof track rail support structure. Structural engineer for the roof, Walter P Moore (WPM), and the specialty engineer for the roof transport system, UNI-Systems, devised an ingenious method allowing the trusses to flex like a beam in spite of their arched shape, while also allowing for the movement of the roof structure

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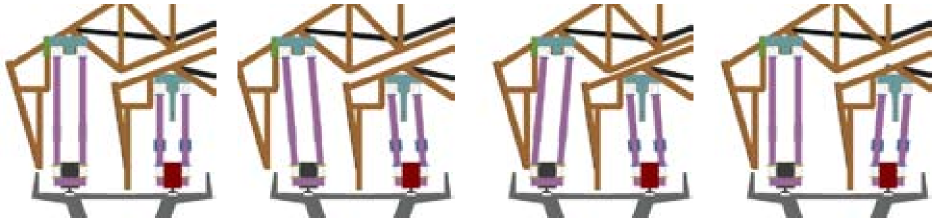

Fig. D: "Four-bar links" showing range of movement allowed at south end of structure.

under the thermal and hurricane wind forces. A cluster of structural members and heavy-duty hinges were designed and assembled to comprise what is known as a "four bar link" positioned on top of each of the south transporters. Each of the roof trusses connect to the top of these parallel rotating links, which allow for movement of up to 2 ft, 7½ in. in either direction. (See Figure D.)

Taking Advantage of the Roll

Original structural drawings from WPM suggested a preliminary erection scheme using four temporary shoring towers supporting each truss span. This shoring plan was adopted resulting in trusses being field assembled in five segments on the ground and set in place across the shoring towers. The complex asymmetrical geometry of the roof, coupled with the four bar link support system, required the fabrication and erection of the roof to a precisely cambered shape in all three dimensions. Cambers of individual work points in the structure were set to accommodate deflections of as much as 18 in. downward, up to 9 in. to the south (as the four bar links swivel south) as well as up to 6 in. to the east or west (depending on the panel). Position and alignment of the trusses during construction was carefully controlled using a sophisticated 3D alignment control plan that began as an integral part of the structural steel detailing process. Structal's in-house Tekla modelers worked meticulously with LPR preconstruction engineers to incorporate alignment control "holes" in the structural steel truss members. These holes were created for the sole purpose of receiving total station surveying prisms that were fastened in place as required for survey and alignment purposes. Once detailing was complete, a comprehensive spreadsheet was developed containing all of the theoretical surveying prism XYZ coordinate locations. That data was then merged with the WPM-provided deflection data spreadsheet to generate all the theoretical survey information for various stages of construction throughout the project.

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The four-bar link on the south end of the lower roof section, showing three of the four pivot points.

The temporary shoring system was designed not only to support the weight of the trusses but also to resist potential hurricane force winds that might be imposed at any construction stage during the 2010 hurricane season. Due to the extreme height of the shores—in the 250-ft range—they required stabilizing, which is usually provided by guy cables for such temporary structures. In this case, LPR utilized a few of its pre-fabricated shoring towers, turned horizontal and used as struts, to stabilize the vertical shoring components. The temporary shore struts took full advantage of the permanent wind resisting capability of the high track on the north side. These horizontal shoring struts also were used as convenient and safe walkways between the shores for worker access. (See Figure C, previous page.)

The basic design wind speed for hurricanes in Miami is a whopping 146 mph, as compared to the most typical design speed of 90 mph across the nation. This resulted in temporary construction design wind pressures theoretically as much as 263% higher than required in most U.S. regions. LPR contracted with KL&A engineers to perform a detailed engineering analysis and design of the roof shoring system and associated temporary foundations.

Designing the shoring system to perform in hurricane conditions was no simple task. LPR intended to use its shoring system that was already designed and fabricated for loads in the order of magnitude for the project, but the 146 mph basic wind speed resulted in tremendous horizontal loading on both the skeletal roof structure as well as directly on the shoring itself. KL&A ultimately ran all the calculations and detailed the shoring system using the SDS/2 3D BIM modeling system. As it turned out, the shores that were "in stock" were not quite up to the task of standing up to the hurricane wind forces. A significant amount of reinforcing was added to the "stock" shores to bring the system up to capacity for the specialized task.

The engineer of record responsible for the entire project is Bliss & Nyitray, Inc., who took care of the structural design from the foundations up through the stadium, including the massive elevated concrete trapezoidal box girders that support the rails for the roof (see Figure C, previous page). The structural design of the moving roof itself was contracted to WPM and UNI-Systems. On this project, the general contractor, Hunt/Moss and the owner allowed LPR to speak freely with Walter P Moore and UNI-Systems as long as any significant discussions that could change scope of work were followed up in writing via request for information (RFI).

Early discussions resulted in the transmittal of WPM's SAP2000 structural roof models to LPR and KL&A. These models were used extensively in the subsequent analysis and design of the shoring system as well as the detailed erection procedure. LPR and the design engineers had many discussions concerning the expected behavior of the roof system resulting in an erection plan in full compliance with design expectations. After final agreement on the intended erection plan, WPM developed and shared an extensive collection of roof structure deflection data based on the various intended stages of construction.

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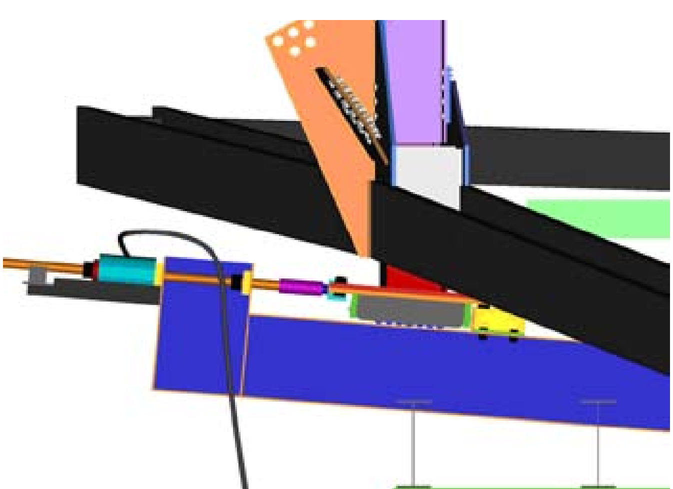
The method used to remove the roof panels from the shores was a first in the construction industry as far as we know. Because the trusses deflected not only downward, but also deflected significantly toward the south at the same time, LPR engineers conceived, designed and fabricated an innovative ramp and roller system for lowering the truss panels off of the shores. Ramps with an average slope of about 5° were built atop the shores under each temporary truss support point. Heavy-duty customized Hilman construction rollers were secured on each ramp, and the truss segments were then erected and secured on top of the blocked rollers, as shown in Figure E.

Once the entire skeletal roof panel was completed, rods were attached to the Hilman rollers and anchored at the top of the ramps. Hydraulic center-hole jacks were used to lower the rods in 5½-in. stages to eventually end up 92 in. down the ramps, where the rollers



Ironworkers Donny Star (left) and Josh Coble measure for placement of the stop nuts on one of the hydraulic jacks.

Although LPR was able to use its existing shores (yellow) as falsework, a significant amount of reinforcing was added in various areas for this specialized application. The orange steel was fabricated specifically for this project to enable the shoring system to resist hurricane-force winds.

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Fig. E: Ramp, roller, temporary block, rod and hydraulic jacking diagram.

lifted off of the ramps and the roof panel spanned on its own. Ramp slopes and skews were based on a combination of the WPM provided deflection data, coupled with LPR's retaining rod and hydraulic jacking system design calculations. The ramp lowering system provided the advantage of a very smooth and gradual transfer of the load from the shores to the trusses and a considerable reduction of the intermediate localized forces usually required to remove trusses from the shores, while also decreasing safety hazards associated with the entire process.

After all the calculations and planning were done and fabrication was under way, construction began. One of the most interesting days on the jobsite was when the first panel was "launched" off of the shores. LPR provided theoretical calculations for the loads in the rods that were used to lower the roof, as well as the theory indicating that the Hilman rollers would lift off of the ramps at 92 in. of horizontal travel. It worked.

The maximum recorded actual liftoff dimension for the entire project was 99 in. Sometimes a roller lifted off as soon as 71 in. down the ramp, indicating the structure was a little lighter than the design calculations assumed. There was an additional ramp in place in case of a minor miscalculation, but WPM provided very accurate predictions regarding the actual design behavior of the roof.

Mission Accomplished

The project came in on budget and ahead of schedule, thanks to the synergy of a great design and construction team. Each person on the team was instrumental to the successful construction of this monstrous moving 3D puzzle. Everyone did their part in providing innovation, determination, precision and especially cooperation, which enabled everyone else on the team to shine at what they do best. The ballpark is on track to host the Marlins' opening day game in April 2012. MSC

Owner
Miami-Dade County, Fla.

Architect
Populous, Kansas City, Mo.

Structural Engineer
Walter P Moore, Tampa, Fla.

Steel Detailer and Fabricator
Canam Steel Corporation, Structal Division, Point of Rocks, Md. (AISC Member)

Steel Erector
LPR Construction, Loveland, Colo. (AISC Member)

General Contractor
HuntMoss, A Joint Venture, Miami