# Pivot Points

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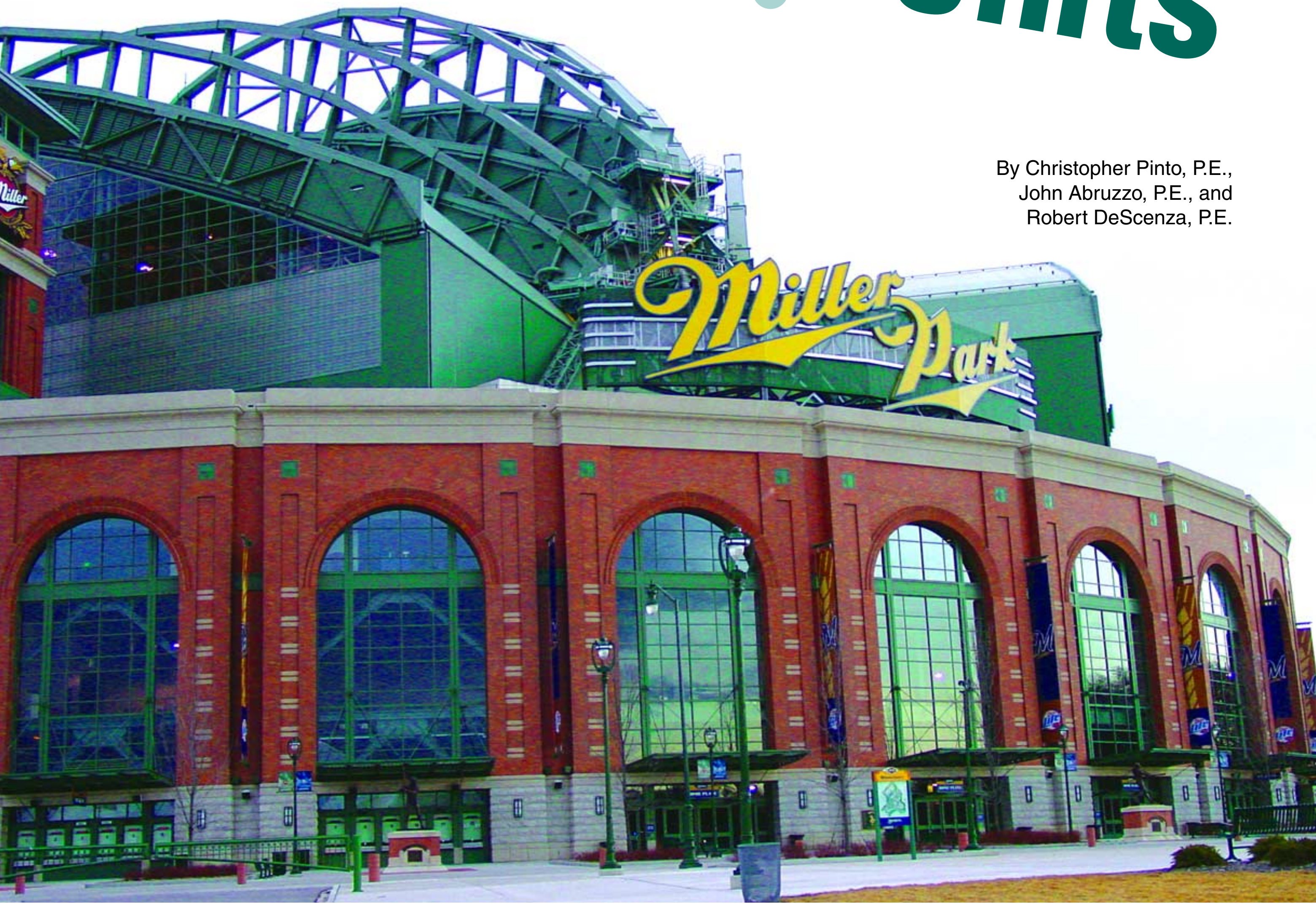



New pivot bearings for Miller Park's moveable roof hit a home run with the park's owners and the team's fans.

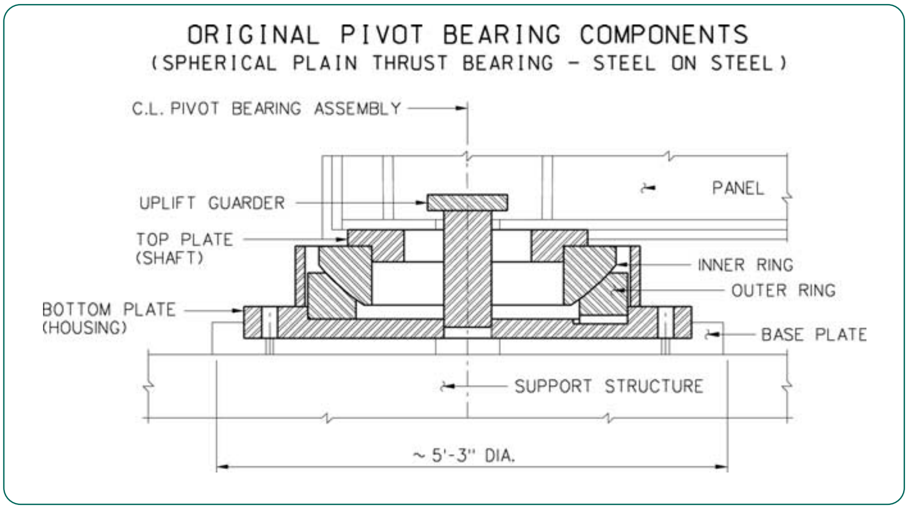
Miller Park, home of the Milwaukee Brewers professional baseball team, opened to the public for the 2001 baseball season. But the showpiece of the 42,500-seat stadium, its domed retractable roof, presented water-leakage and noise problems during the first two summers of its operation. Careful testing and computer modeling helped a project team design an effective solution to replace the roof's pivot bearings in time for the 2003 baseball season.

## Signature Ceiling

The stadium roof originally had been designed to fully open or close within 10 minutes. Unlike the retractable roofs of most stadiums, the moveable sections of the roof pivot about a series of points centered behind home plate, and then they stack over the stands along the first and third base lines.

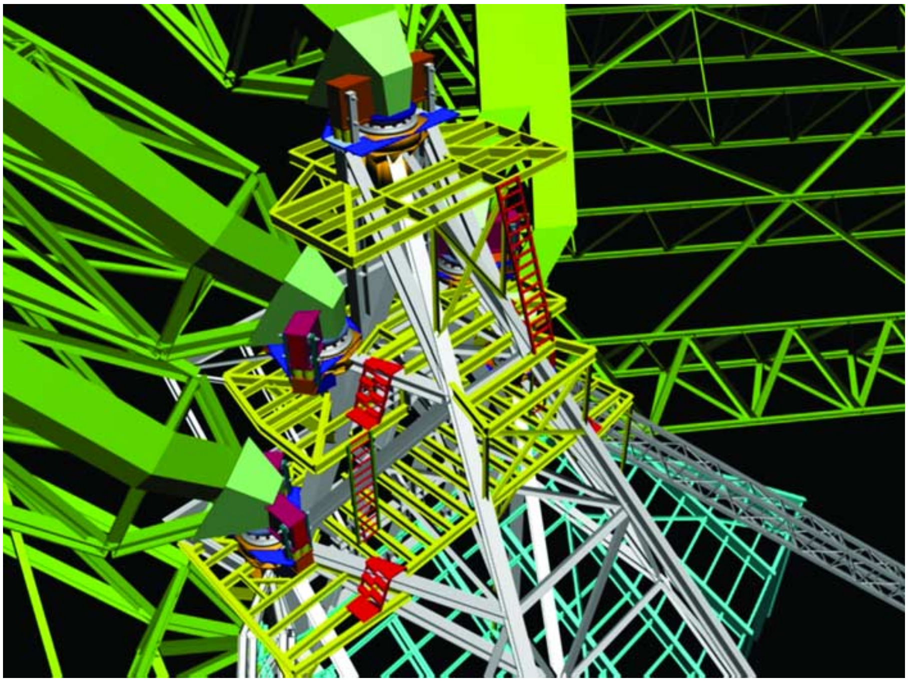
The roof consists of five moveable panels (panels 3L, 2L, 1L, 2R and 3R) and two fixed panels (panels 4L and 4R). The two fixed panels, which are trapezoidal in plan, arch over the stands along the first and third baselines. The fixed panels are supported along three sides, with each panel spanning approximately 555′ on the interior edge of the stadium. The five moveable panels are all triangularly shaped in plan and arched in elevation. The moveable panels each span approximately 600′ over the field, and are approximately 140′ wide at the outfield end. A concrete circular track beam along the outfield wall of the stadium supports two bogie carts per panel, one on each side of the outfield end of the panel. The bogie carts provide the motive power to open and close the roof. A steel frame supports the "pivot end" of the moveable panels. The pivot support structure consists of a planar frame in a "Christmas tree" shape with a three-dimensional-truss rear-brace structure to provide out-of-plane force resistance. The pivot bearings themselves were steel-on-steel spherical thrust bearings.

While the main longitudinal steel trusses for the panel are only 12′ deep, an additional tall arch projects above the roof on one side of panels 3L, 3R, 2L and 2R, and on both sides of panel 1L. This arch, called the box chord, reaches a maximum height of 100′ above the roof surface at the center of the span. Cables below the span provide additional depth for the longitudinal trusses on the opposite side of the box chord of panels 3L, 3R, 2L and 2R. With the box chord reaching above the roof on one side and the cable spanning below the roof on the other side, a profile through the roof looks like a "Z" shape that is arched along the length as well as tapered.




*Above:* Roof panels did not rotate properly on the original pivot bearing design, requiring that the bearings be replaced.

*Below:* The pivot bearings (blue) for the moveable roof panels (green) were located on a "Christmas tree"-like structure (white/gray) at varying elevations. New framing (yellow) was installed to facilitate the installation of new bearings and future maintenance.



## Roof Ruckus

The roof of Miller Park presented a series of problems to the Southeast Wisconsin Professional Baseball Park District, which owns and operates the facility. The seals between roof panels leaked during heavy rains and high winds, dousing the fans and field with water. During the stadium's inaugural season, noises audible above the background ball game began emanating from the pivot bearings of the moveable panels while the panels were in motion. The owner retained LZA Technology (LZA), a Division of the Thornton-Tomasetti Group, and Hardesty & Hanover, LLP (H&H) to investigate the cause and implications of the noise.

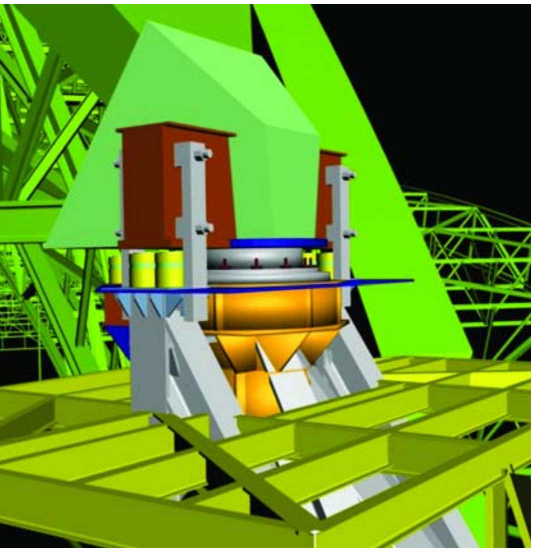
By investigating the roof movement, it was determined that pivot bearings were not rotating completely on their intended-bearing surface. The bearing started to partially rotate on the surface between the housing and the upper bearing ring. The noises were produced by a "stick-slip" operation of the bearing. LZA's review of the roof structure demonstrated that in the event of a lock-up of the bearing, the driving force at the bogie end of the panels was sufficient to cause significant overstresses within the roof panel. LZA and H&H implemented a monitoring program for the 2002 baseball season to determine if there was any further degradation of the bearings, and to provide a warning system to stop the motion of the roof in the event of a bearing failure. At the end of the 2002 season, the volume of the noise emanating from the bearings continued to increase. In addition, perceptible vibrations were felt by observers standing on the roof support structure. As a result, the owner chose to replace each of the five pivot bearings by the start of the 2003 baseball season, and directed LZA and H&H to perform the engineering for the project. The district also contracted H/C Construction, a joint venture between Hunt Construction and Clark Construction, to perform the duties as construction manager for the project.

## Requirement Roster

The performance requirements for the bearing replacement project provided a series of daunting challenges for the design team. Provisions for the bearing replacement were not built into the original stadium design, and access to the pivot

*Above:* The original bearings were approximately 5' in diameter. Note the jacking bracket (left in photo) attached to the base of the roof-panel frame.

*Below:* A rendering of the new bearing, in place. The jacking brackets (shown in brown) remain in place in the final configuration.



bearings was achieved by a series of narrow catwalks on the inside of the pivot frame, which were not suitable for supporting heavy construction loads. The original bearings were welded in place, requiring a series of machining operations in order to remove the bearing. Also, any steel components added during the project were to remain after the bearing-replacement project was completed to provide the ability for future repairs or replacements.

Construction work had to maintain the condition of the field, as well as provide roofers access to the gaps between the panels to repair the leaking roof seals. Since the design phase of the project began in early September, construction would need to be performed during the cold Milwaukee winter.

One of the prime considerations for the jacking system was to provide a system with built-in redundancy. LZA developed a scheme to lift each roof panel at the pivot bearing with hydraulic jacks at three discrete locations. They selected jacks with the capacity to support the weight of the roof on the bearing if only two jacking locations were engaged. In addition, it was decided that there should be two jacks at each support point, and that each jack should have the capacity to support the entire load imposed at that point without any contribution from the other jack. This system would provide redundancy in the lift points for safety, and in the event of a single-jack failure, allow the jacking process to continue without interruption. Since pivot reactions varied between 750 tons and 1,100 tons, jacks with a 350-ton capacity were selected for the project.

The existing bearings, each approximately 5' in diameter, were supported on stiffened pedestals atop the pivot frame called "pivot-frame heads." Each pivot-frame head was sized to be only slightly larger than the existing bearing, making direct use of the pivot frame to support a system of jacks an impossibility. Therefore, jacking brackets had to be constructed on both the pivot-frame heads and the roof panels themselves to provide support points for the jacks. To maintain reasonable stresses within the brackets (which would need to be cantilevered from the structure) and still permit sufficient access to remove and replace the bearings, the initial design concepts placed the jacks approximately 2.5′ from the edge of the pivot-frame head. The jack supports attached to the fixed structure were called "strong arms," and the jacks supports attached to the roof panels were called "jacking brackets."

The geometry that related the pivot frame and the roof panels was complex, and LZA began the design process by assembling a three-dimensional graphical model of the pivot frame and roof panels to describe the area. One of the first uses of this model was to determine the best position of the roof panels for the jacking operations and the optimal orientation for the strong-arms and jacking brackets. The field at Miller Park is a live-grass field, and groundskeepers preferred that the roof remain open during the construction operations. Since work needed to be performed on all of the seals that prevent water infiltration between the roof panels, the roofers required that the roof not be placed in the full open position, but did not necessarily require all of the roof panels to be closed. To accommodate all of the parties involved, it was determined that the roof could be parked and lifted in a 20′ (6.1 m) offset position, so that there was 20′ (6.1 m) of available roof space at the bogie end of each of the panels to allow the roofers to work, and still allow light to reach most of the field. However, it also was determined that, since panel 1L was the only symmetric panel, and the heaviest one, it would be more appropriate to lift this panel while it was in the full closed position in the center of the stadium.

Placing the roof in this position presented two challenges to the design team. First, the bogies were intended to move between two points where they could be locked down. Placing the roof in the 20′ (6.1 m) offset position meant that new locking points and a new locking mechanism would need to be created for each of the panels. Ideally, these locking points would also become permanent additions to the stadium. Secondly, the condition of leaving panel 1L in the center for an extended period of time was not originally investigated for wind loads. Therefore, the design team recommended that the original wind- and snow-load consultant, RWDI Consulting Engineers, be contracted to perform additional studies to determine the loads on panel 1L for a 50-year windstorm while isolated in the center of the stadium.

The three-dimensional graphical model also was used to determine the plan and elevation limits for working platforms suitable for the project. The existing catwalks used to service the pivots were only on the inside of the stadium. They were approximately 3′ wide, and in some cases did not allow enough headroom to do more than crawl underneath the roof. The new platforms were designed to provide access at a level that permitted workers to walk underneath the panels, and to provide a work area of approximately an 8′ radius around each of the bearings. Cantilevered brackets were supported off of the pivot frame to create these platforms, and the graphical model demonstrated that the platforms could be constructed so the panels would not impact the platforms while they were in motion.

## Getting Our Bearings

The roof panels were designed to operate on pivot bearings that allowed rotation about all three axes of motion. The original bearings were spherical steel-on-steel thrust bearings. Due to the methodology used to erect the roof, none of the panels were set so that the bearings were installed in a level position. Instead, each bearing sat at varying angles, depending on the tilt of the panel and the tilt of the pivot-frame heads. After careful consideration of several options, H&H suggested the use of a different bearing design than the initial installation. The new design used a spherical roller bearing to accommodate the loads and rotations required for each roof panel. In order to maximize the life of the new bearings, H&H also devised a system of tapered shim plates to be installed above and below the new bearing so that the bearing could be installed within 0.1 degrees of level.

Once the panel was supported on the three jack-support points, the pivot end of the panel would temporarily not have the ability to rotate freely about the three axes of motion. Also, the plan locations of the jacks required to minimize the impact on the existing structure and allow for the removal and installation of the bearings imposed a moment about each of the plan axes, on both the roof panels and the pivot frame, during jacking operations. The roof panels were reinforced as required to resist the jacking moments imposed while lifting the dead load of the panel, and to resist the fixed-end reactions imposed by snow and wind loads which might have occurred once the panel was lifted.

A series of finite-element models were analyzed to determine the stresses within the roof panels and pivot structure during jacking operations. The preliminary models concerning the roof behavior were constructed out of beam elements within MSC.Nastran for Windows 2001. While this was an appropriate model to determine the effects of jacking over most of the roof span, the beam elements ignored the complexity of the pivot end of the model. At the pivot end, the top and bottom chords of both longitudinal trusses frame into a common work point. To make the construction of this node a possibility, a "tub" was fabricated, consisting of a trapezoidal box with internal stiffeners, welded together with full-penetration welds. The analytical node point was housed in an internal stiffened box that was 2′-by-2′ in plan. These stiffeners served to carry the vertical weight of the panel to the bearing. Jacking brackets were to be welded to this tub, and all of the stresses at the pivot end of the panel were focused through it as well. LZA created a finite-element model of the tub including all of the internal plates, and linked this model to the beam-element model of the remainder of the roof panel. Stresses in these plates and members were analyzed for different jacking scenarios.

A similar set of models was created for the fixed structure. The steel frame that supports each of the panels rises far above the stands, but distributes lateral forces through the stadium framing to the foundation. Therefore, it was necessary to construct a finite-element model of the entire portion of the stadium behind home plate. While the basic model consisted entirely of beam elements, it was also necessary to analyze all of the localized stresses within the pivot-frame heads created by jacking. The pivot-frame heads consisted of a complicated set of horizontal and vertical plates required to connect all of the bracing of the pivot frame together. The strong arms were intended to connect to the top plate of the pivot-frame head and to a second horizontal plate located between 16″ and 21″ below the top plate (depending on the roof panel).

The pivot bearings also served to resist the lateral loads imposed by the roof due to wind. It was necessary to construct an alternate way of transmitting these loads back to the pivot frame, while allowing the vertical movement of the panels during the jacking process. To accommodate these demands, a set of long, thick plates were bolted to each of the jacking brackets. These plates, dubbed "keeper plates," extended from the jacking brackets down to below the top plates of the strong arms. To ensure that each keeper plate was engaged, and to add bracing to the top flange of the strong-arms, a steel plate "ring beam" connected all of the strong-arms together at the top of the pivot-frame head. The keeper plates fit through sleeve openings in the ring-beam plate. The keeper plates were analyzed for wind-load combinations to ensure that they could transmit lateral wind-load forces from the panel to the pivot frame.

## Designing for Repairs

The original bearings were welded in place, but the new bearings were fastened to both the fixed and moveable structure via bolts, facilitating future replacement of the bearings. To make this fastening method possible, H&H designed the bearing housing to extend beyond the region required to transmit vertical load through the structure. The lower portion of the bearing housing was extended to the edges of the pivot-frame head, and the upper portion of the housing was extended beyond the edges of the tub. An additional external plate was welded to the edge of the bottom plate of the tub to provide locations to fasten the roof panel to the upper housing. This tub extension plate also served to brace the tension flange of the jacking brackets. The fasteners were a combination of bolts and threaded studs. Bolts were used wherever it was possible to access both ends of the fastener after installation. Tapped holes were used for all of the remaining fasteners.

## Raising the Roof

The jacks selected for this operation were limited to a fully retracted height of 15″, as this was the existing distance between the top of the pivot-frame head and the underside of the tub. To remove the bearing and prepare the surfaces for the new installation, it was necessary to lift the panel 8″. The jacks were limited to 4″ of stroke due to the height limitations. A fleeting maneuver had to be performed to lift the panel to the required height. This meant lifting the panel to the full extension of the jacks, and seating the panel on a temporary "fleeting stool" adjacent to each set of jacks. Once the panel was seated, the jacks were retracted and shimmed. The panel then was re-lifted to the required height.

LZA analyzed two separate methods to jack the roof. The first method involved lifting each roof panel with equal loads in all of the jacks. This required the simplest setup of the hydraulic jacking system, but also meant that the roof would rotate about each of the two horizontal axes (equal force in the jacks but not equal stroke). The other method would be to use different forces in each set of jacks, and to try to lift the roof with equal stroke at each jack or variable stroke to minimize the change in rotation. Studies determined that due to the stiffness of the roof panel and the positions of the jacks, it was not possible to lift the roof panels and maintain even displacement on all of the jacks—it was only possible to minimize that rotation. Because of this, and the requirement for a more complex hydraulic system, it was decided to maintain equal loads in each of the jacks during the lifting process and adjust the bearing installation with tapered bearing plates above and below the housing.

While preparation for the construction phase of the project was underway in December 2002, construction of the platforms, strong arms and jacking brackets did not begin until January 2003. In early February 2003, the first panel was ready to be lifted. The final sequence of operation for the bearing replacement consisted of jacking the panel and then machining out the welds connecting the original bearing to the structure. Once the bearing was removed, the surface profile of the structure was measured to determine the flatness of the upper surface of the pivot-frame head and the lower surface of the tub. One of the assumptions inherent in the housing design was that the bearing was to sit on a surface that was flat within a tolerance of 0.01″. Since the new bearing housing was to be considerably larger than the original, a machining operation was required to make the entire bearing surfaces flat.

Once the surfaces were machined, the new bearing was inserted into place on top of a pre-made tapered lower shim. The panel then was lowered onto the existing bearing to measure the required taper for a top shim plate. The top shim was not pre-tapered due to the design-team's concern that the taper of the shim could not be accurately determined analytically because of the number of measurement corrections required to account for the machining process. Once the taper of the top shim was determined, the panel was re-jacked, and the required fastener holes were drilled and tapped into the pivot-frame head. When the top shim was constructed, it was inserted into place, and measured to verify the accuracy of the construction. Then the structure was lifted one more time to drill and tap for the required fasteners connecting the bearing to the tub.

## Home Stretch

The final bearing was fastened to the structure on March 11, 2003, nine days earlier than the anticipated completion date. Opening and closing the roof panels proved the replacement of the bearings to be a success. The Miller Park retractable roof now operates with virtual silence and no noticeable vibrations, and Milwaukee Brewer's fans can enjoy their indoor/outdoor experience during ball games. ★

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### Software

MSC.visualNastran for Windows 2001, AutoCAD and 3D Studio Max

### Construction Manger

Clark Construction, Bethesda, MD
Hunt Building Corporation, El Paso, TX

### Steel Contractor

National Riggers and Erectors (AISC member), Plymouth, MI

### Machining Subcontractor

In-Place Machining, Milwaukee