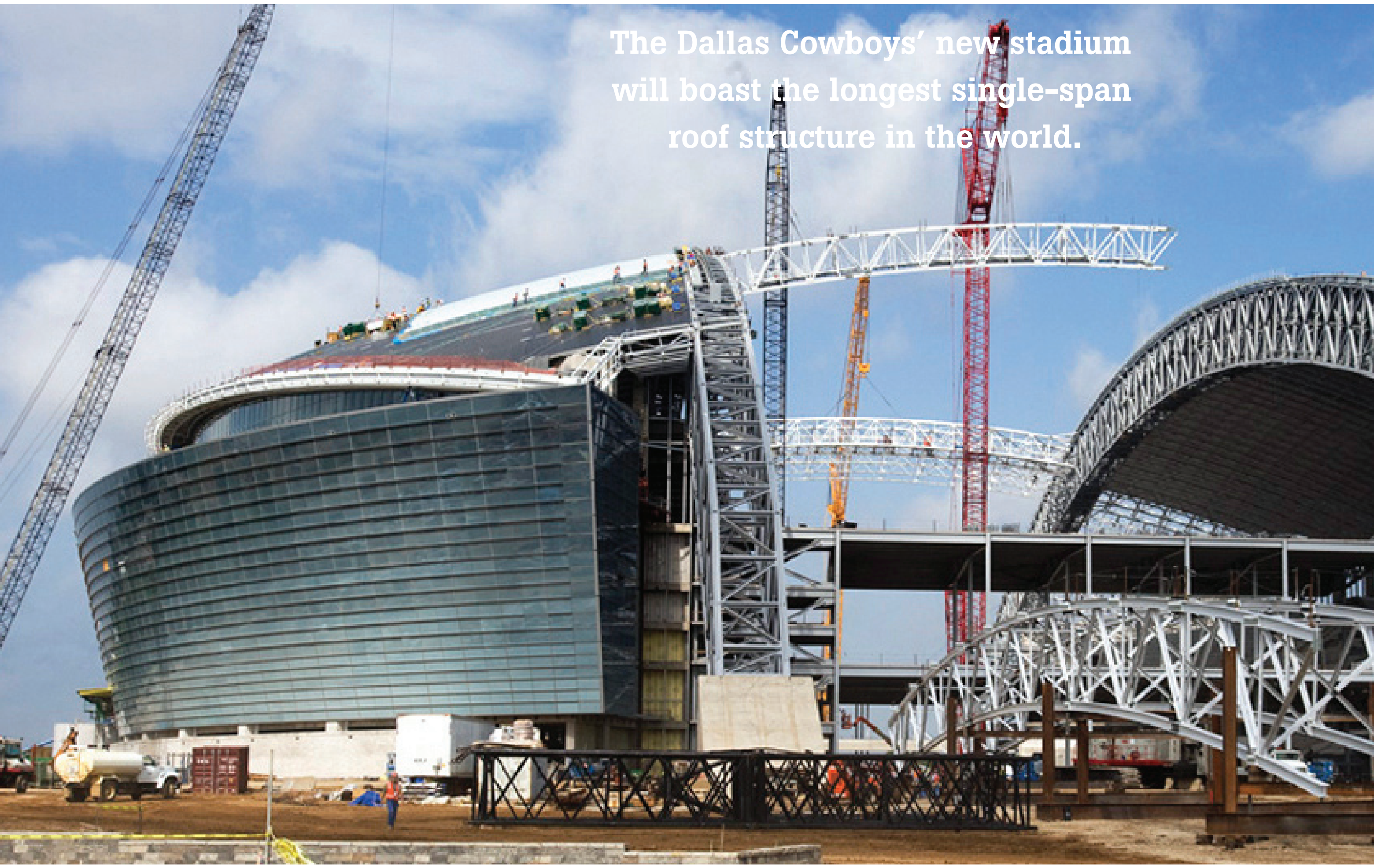
GOING LONG

BY R. JOHN ANIOL, P.E., S.E., JOSEPH DOWD, P.E., AND DAVID PLATTEN, P.E.



Daryl Fields/HKS

THERE'S A JOKE THAT'S POPULAR AMONG DALLAS COWBOYS FANS: WHY IS THERE A HOLE IN THE ROOF OF TEXAS STADIUM? SO GOD CAN WATCH HIS FAVORITE TEAM PLAY.

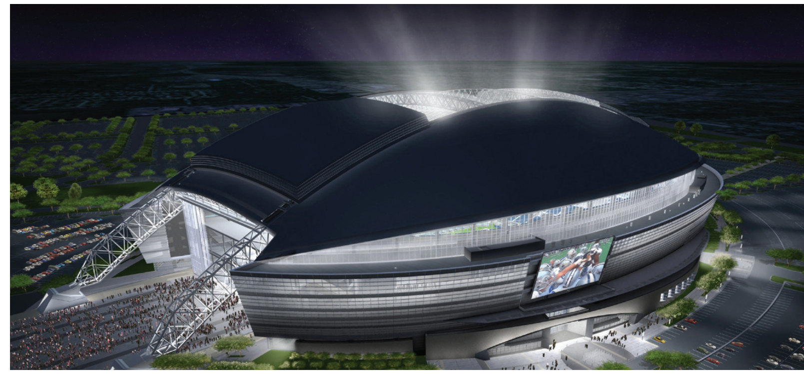
Despite the well-known "hole in the roof," the Cowboys' home since 1971 no longer exemplifies the team's winning tradition. Hence the Cowboys' move to a new stadium, one that does reflect the organization's commitment to success but doesn't compromise Texas Stadium's characteristic design elements or the Cowboys brand. When it opens in June 2009 in Arlington, Texas, the new $1.1-billion, 3-million-sq.-ft Cowboys Stadium will take its place among the world's premier sports venues, establishing several world records:

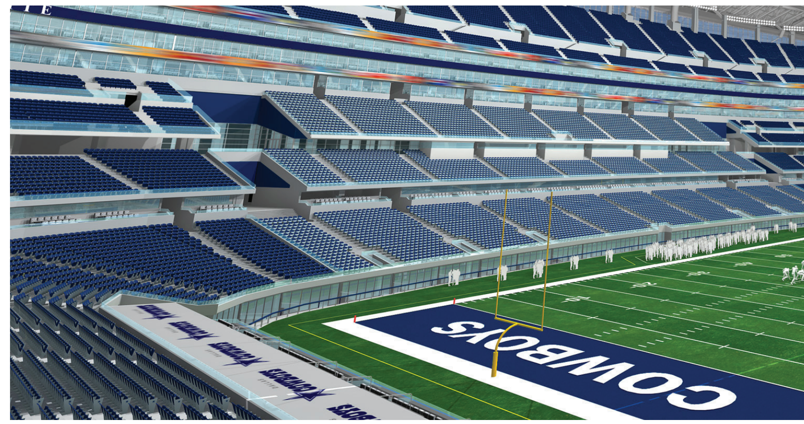
- The world's longest single-span roof structure. This will be supported by soaring twin arch box trusses that span 1,225 ft between abutments. At 660,800 sq. ft, the stadium's roof will be one of the largest domed structures in the world. The "hole" will remain but can now be closed when necessary, as the new stadium's roof is retractable. Formed by two bi-parting mechanized panels, each measuring 63,000 sq. ft, it can open or close in 12 minutes.
- The world's largest (at 25,000 sq. ft) center-hung high-definition video display board. Suspended 90 ft directly over the 50-yard line, the structure measures 72 ft high and 186 ft wide.
- The world's largest operable glass doors—each measuring 180 ft wide by 120 ft high—located at each end of the stadium.

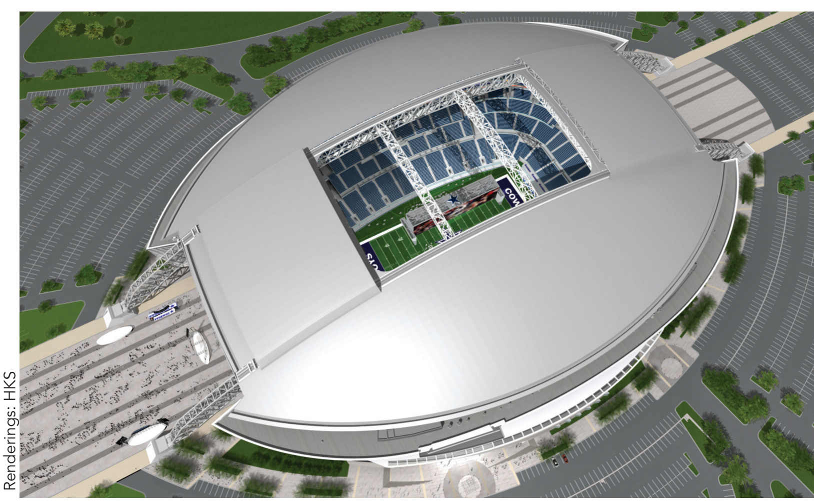
Monumental Arch Trusses Go the Extra Yard(s)

The record-setting arch box trusses have a radius of 1,025-ft. The apex of the arches occurs 292 ft above the field below, providing enough clearance for the Statue of Liberty below. Each 17-ft-wide by 35-ft-deep arch truss weighs 6.5 million lbs, the equivalent of 20 Boeing 777s. The four truss chords of each box truss are comprised of ASTM A913 Grade 65 steel, with sizes

A crane hoists a segment of one of the six box trusses into position between the soaring twin arch trusses.







Renderings: HKS

ranging from W14×311 to W14×730, made by ArcelorMittal in Luxembourg.

The project's structural engineers were able to realize an approximate 25% increase in yield strength and subsequent steel tonnage savings by minimizing the arch truss chord slenderness ratios ($33 < KL/r < 40$). (For more detailed information on the use of ASTM A913 steel, refer to "High-Strength Steel in the Long-Span Retractable Roof of Reliant Stadium" by L. Griffis et al, from the 2003 NASCC *Proceedings*, available at **www.asic.org**.) According to the project's steel contractor, W&W Steel, the cost of ASTM A913 group 4 and 5 shapes is virtually the same as ASTM A992. This saved the owner approximately $3 to $4 million.

The arch trusses feature a Quadrangular Warren web configuration, creating a Scottish argyle (diamond or checkerboard) pattern of web members along each vertical side, one of the world's most ancient three-dimensional spacing patterns. A Warren configuration was also used for the top and bottom chord horizontal bracing (lacing between each chord). After analyzing numerous web configurations, the engineers determined that employing the Quadrangular Warren configuration (repeating-X) along each vertical side would not only reduce the stress on the heavy chord members, but also enable them to stay within the W14×730 shape limit, thereby eliminating the need for costly built-up shapes or the use of more than four truss chords.

Each of the four 64,000-lb cast solid-steel arch-pin bearing assemblies support a 19-million-lb thrust reaction. The design-build arch pin bearing assembly, consisting of ASTM A148 Grade 50 and made by Uni-Systems, was cast in a custom sand mold and sits atop a 25-ft by 11-ft solid concrete thrust block column that launches out of the ground at a 32° angle from the horizontal to receive the ends of each arch. The real enormity of the system lies hidden below ground, as the thrust block column is anchored to a slurry wall box abutment that transfers the thrust into the surrounding soil.

The fixed side roof and fixed roof over the end zone seating areas are held aloft with planar trusses oriented to remain perpendicular to the roof's curving surface. This cant's variation matches the radial

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Ironworkers tighten bolts in one of the slip-critical end plate splice connections that link the 56-ft long segments of the arch truss chords.

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A 64,000-lb cast steel pin assembly touches down on one of four massive concrete abutments that transfer 19 million lb of thrust from an arch truss into the ground.

configuration of the arch truss, creating an elegant, sweeping structural system that emphasizes both rhythm and repetition.

A Really, Really Big-Screen TV

In addition to supporting the stadium's roof, the arch trusses permanently hold aloft the world's largest center-hung, high-definition video board—weighing 1.2 million lbs—plus an additional 200,000-lb show-rigging allowance that can be placed in dozens of configurations.

The 72-ft-tall center-hung video board, with over 25,000 sq. ft of video displays, looms over the football field in an enormous I-shaped plan that extends from nearly one 20-yard line to the other. The structural design team created a 72-ft-tall steel structure that contains a ten-level network of catwalks and is clad on all four sides with video displays. Behind this dynamic cladding lie full-height trusses that carry the total gravity load to the video board's support cables.

ASTM A586 structural spiral strand steel cables (3-in.-diameter) grip each end of the video board structure's I-shaped plan and extend vertically upward toward the opening in the roof. The cables are tethered to 14-ft-wide by 17-ft-deep steel box trusses that span the 256-ft opening between the twin arch trusses.

Detailing and Fabrication Execution

The project team held a series of collaborative coordination meetings during the design development and construction document phase to discuss design, fabrication and erection issues including roof geometry, connection design, erection sequencing, thermal movements, tolerances, and fit-up. The arch was fabricated in 56-ft segments, which enabled the basic geometry of each segment to be the same, reducing detailing and fabrication costs. To facilitate fabrication and erection preferences, W&W Steel proposed an alternate arch truss connection that consisted of a gusset plate shop groove welded to the toe of the chord flange and field bolted to the W14 diagonal and vertical members. An end-plate bearing chord splice connection was specified, resulting in significant connection tonnage savings. Regardless, each arch required 46,500 ASTM A490 bolts for assembly.

Roof and Video Board Erection

To facilitate more efficient construction, Manhattan Construction and Derr Steel proposed an alternate roof erection sequence to what was originally shown on the contract documents. The revised sequence consisted of erecting each arch on six temporary shoring towers, beginning at one abutment then progressing to the 50-yard line, where two bracing trusses were installed before moving to the other abutment where the sequence was repeated. Erection of a 56-ft keystone segment at the 50-yard line completed each arch. Upon completion of the south arch, shoring towers were moved to the north arch and the entire sequence proceeded again. Each arch truss took approximately five months to erect; the fixed roof and roof deck installation followed. The center fixed roof, six box trusses, and retractable roof will complete the roof erection for a total of 17 months.

Barnhart Crane and Rigging Co. will use several strand jacks to lift the completed video board steel structure from the playing field level to its final position, 90 ft above, then the high-definition video display panels will be installed on the completed structure.

Post-Game Recap

When Cowboys Stadium opens in 2009, innovation will truly score big in this world record-setting, monumental structure. The stadium's sleek and brilliant form, efficient function, robust structure, and fleet movement will team together to evoke the definitive Dallas Cowboys' image. With the roof ready to roll, the team and its spectators will experience games and events in an environment that champions originality and creativity. MSC

R. John Aniol is a Walter P Moore principal and served as Cowboys Stadium's structural project manager. Joseph Dowd is a senior associate with the firm and served as the structural project engineer for the roof. David Platten, a senior principal with Walter P Moore, served as the structural principal-in-charge. All three work in the firm's Dallas office.

Owner
City of Arlington, Texas

Developer
Blue Star Development/Dallas Cowboys

Architect
HKS, Inc., Dallas

Lead Structural Engineer
Walter P Moore, Dallas and Austin

Associate Structural Engineer
Campbell and Associates, Inc., Dallas

Roof Steel Fabricator
W & W Steel, LLC., Oklahoma City (AISC Member)

Roof Steel Erector
Derr Steel Erection Company, Euless, Texas (AISC Member)

Roof Steel Connection Engineer
W & W Steel
Computerized Structural Design, S.C., Milwaukee

General Contractor
Manhattan Construction Company, Dallas

Mechanization Consultant
Uni-Systems, LLC, Minneapolis

Video Board Structure Lifter
Barnhart Crane and Rigging Co., Memphis, Tenn. (TAUC Member)

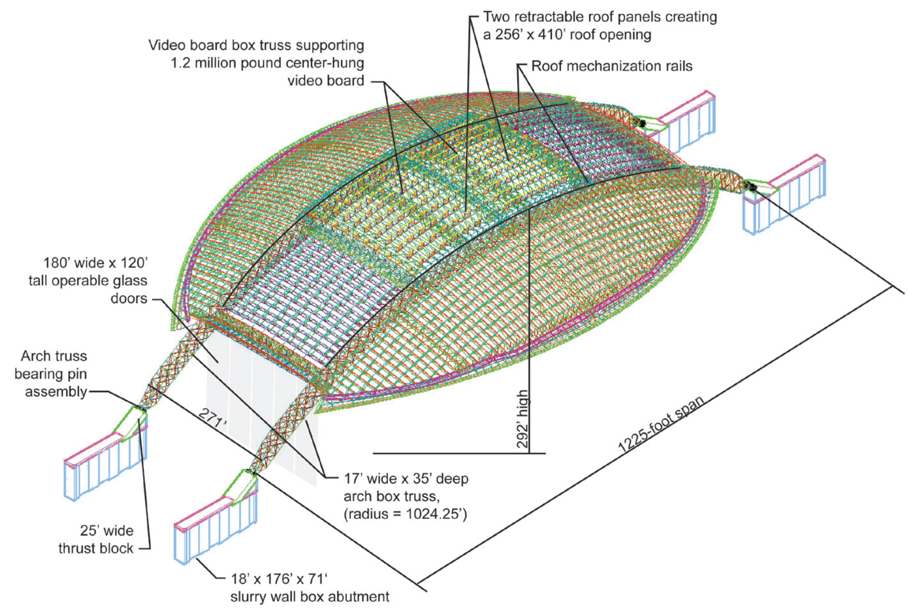
Software
SAP 2000
Tekla Structures and AutoCAD 3D

Rolling Roof Plays to Win

While it was important to bring the "hole" design from the old stadium to the new one, another key design goal was having a fully enclosed stadium roof to protect spectators from inclement weather and enable the structure, which can be configured to seat 100,000, to function as a multi-purpose venue capable of hosting NCAA Basketball Final Four Tournaments, the Cotton Bowl, concerts, and even the Super Bowl. The design team accommodated both of these seemingly mutually exclusive desires with a sleek, bi-parting, retractable roof, which can open or close in 12 minutes.

The two translucent retractable roof panels—using Birdair cladding—each measuring 290 ft by 220 ft, travel along the length of the arches to meet at the 50-yard line. The panels are clad with a Telflon PTFE-coated fiberglass tensile membrane (Sheerfill I–HT by Saint-Gobain Performance Plastics Corp.). The mechanization system, designed by Uni-Systems in close coordination with Walter P Moore, is the first application of a rack-and-pinion retractable roof in North America. Each of the roof's 128 motors (32 per roof quadrant) powers a pinion that eases the operable panels down 328 ft of toothed steel rack permanently attached to the arch trusses. As the moving roof progresses downhill, the slope becomes more dramatic as the arches maintain their constant radius curve.

When the two roof panels are parked in the open position to reveal the iconic roof opening, the rack-and-pinion drive system holds the roof panels at a slope of 23°. While this feat is impressive enough, the drive system must also power the retractable panels back into the closed position, conquering this 23° slope in the uphill direction. The efficiency of this system is demonstrated in the modest power requirements to move the panels' 3.5 million-lb weight back up the slope. Each of the 128 motors produces 7.5 horsepower, making the 960 horsepower required to close the roof roughly equivalent to only three Ford Mustang GT engines.



A computer analysis model with more than 30,000 frame elements helped structural engineers conquer the stadium's distinctive challenges.

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