SUPERSPAN

The design of Cowboys Stadium, in Dallas, was meant to provide the winning combination of a larger, more technologically and environmentally advanced sports venue than the team's previous home that would retain the distinctive "hole-in-the-roof" design of that facility. But the new stadium, which features the largest single-span roof structure in the world, also adds a mechanized twist to the story: the opening in the new stadium's roof can be closed.

By R. John Aniol, P.E., S.E., Joseph Dowd, P.E., and David Platten, P.E., M.ASCE

THE DALLAS COWBOYS, long known for their innovative style, are now playing in a technologically and environmentally advanced stadium that makes engineering innovation part of their legacy. Cowboys Stadium replaces this National Football League (NFL) franchise's former home, Texas Stadium, which was constructed for the Cowboys in 1971 at a cost of $35 million and featured the famous "hole-in-the-roof" design. Cowboy fans liked to say that the rectangular opening in the roof was created so that God could watch the team play. With a seating capacity of roughly 65,000, however, Texas Stadium no longer met the Cowboys' game plan. Instead, the team's owner and general manager—Jerry Jones and the Jones family—along with the project's architecture firm, Dallas-based HKS, Inc., wanted to construct a monumental and technologically advanced facility that would retain such characteristic elements of Texas Stadium as the domed open roof and arched roof trusses while establishing a new generation of multipurpose facilities.

"The challenge was to make the game day experience more compelling" than what a fan would have at home, even if watching the

BLAKE MARVIN/HKS, INC.

The exterior of Cowboys Stadium features a fritted glass curtain wall 86 ft in height that slopes outward at an angle of 14 degrees from the vertical and is supported by a canted steel tube structure that weighs 1.3 million lb.

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game on a high-definition television set with a big screen, notes Bryan Trubey, an HKS design principal. "Leveraging the Cowboys brand and creating a truly different fan experience became the key."

The result is the $1.15-billion Cowboys Stadium, which opened last June and seats 80,000 (expandable to 100,000) in a 3 million sq ft, world-class venue with a retractable roof. Cowboys Stadium forms part of an entertainment district in Arlington, Texas—midway between Dallas and Fort Worth—that includes Rangers Ballpark, the home of the Texas Rangers Major League Baseball franchise, and the Six Flags Over Texas amusement park. The new facility has more than twice the floor area of Texas Stadium, which is located approximately 18 mi away in Irving, Texas, and is scheduled for demolition early this year.

To help pay for the new stadium, the City of Arlington, through a voter-approved increase in the city's sales tax, provided $325 million in bonds, and the NFL, in accordance with its stadium financing policy, provided the Cowboys organization with $150 million.

HKS and the Dallas and Austin, Texas, offices of Walter P Moore, the principal structural engineering firm for the project, were selected in 2005 to design the stadium on the basis of their prior collaborations on national and local sports facilities, including Rangers Ballpark and the American Airlines Center, in Dallas. Working together closely, the two firms designed a stadium that not only exemplifies engineering and architectural excellence but also establishes several world records for various innovative features:

- The single-span roof structure, which is supported by a pair of soaring arch box trusses that span 1,225 ft between abutments, is the world's longest. At 660,800 sq ft, the stadium's roof is also one of the largest domed structures in the world, and the two translucent panels that make up the retractable section slide lengthwise across the top of the dome, opening or closing in a mere 12 minutes.
- The operable glass doors located at the end zone plazas are the world's largest: 180 ft wide and 120 ft high. They consist of five movable panels and can be opened or closed in six minutes.
- The high-definition video screen system above midfield is the world's largest. This 25,000 sq ft unit measures 71.5 ft in height and 160 ft in width and is suspended 90 ft in the air directly above the 50-yard line.

The stadium's luxury suites are in close proximity to the playing field. The sideline suites are located 18 in. below the level of the field, for example, and in some places are just 20 ft behind the sideline bench, while other suites are located within 20 rows of the field. The stadium's more than 350 luxury suites are located on five separate levels in eight different settings, establishing a new standard in sports venue design.

Cowboys Stadium features the world's longest single-span roof structure, which is supported by a pair of soaring arch box trusses that span 1,225 ft between abutments. Each arch truss took approximately five months to erect.

The exterior of the building features a 380,000 sq ft fritted glass curtain wall 86 ft in height that slopes outward at an angle of 14 degrees from the vertical. The curtain wall is composed of more than 5,000 glass panel units, some as much as 8.3 ft in width and 5.3 ft in height. Framed by aluminum mullions that, if laid end to end, would extend more than 23 mi, the glazed panels feature a fritting that varies from 90 percent at the bottom of the curtain wall to 30 percent at the top, creating a color scheme that changes from blue to light gray during the day. At night the wall is illuminated by external lights.

The curtain wall is supported by a canted steel tube structure that weighs 1.3 million lb. The glass panels are attached to the vertical, rectangular steel tubes with U-shaped clips; the tubes vary in cross section from 8 by 4 in. to 20 by 12 in. and are spaced approximately 8 ft apart along the perimeter of the building.

Natural light illuminates the seating bowl via a lens more than 900 ft wide and up to 33 ft high that is created by the clerestory glass wall between the upper seating bowl and the roof soffit. A metal-clad, tapered roof edge developed for both form and function conceals the 5 ft wide by 4 ft deep rain gutter that extends along the roof's perimeter.

The versatile roof structure both shelters spectators from inclement weather and supports the show rigging, lighting, and cameras that will enable the venue to host more than just sporting events. The playing field also features a "roll-up" surface that utilizes a technologically advanced synthetic turf, making it the first stadium in the country that can be used interchangeably for NFL football, college and high school football, and soccer.

Located 50 ft below the street level, the playing field was constructed within a 1.5 million cu yd excavation that features a 200,000 sq ft permanent retention wall along the perimeter consisting of two waterproofing layers, an 8 in. thick shotcrete wall, and a 14 in. thick reinforced-concrete facing wall that is tied back to the earth by more than 8,000 soil nails. These threaded steel bars are 1.25 in. in diameter and 50 ft long; the total length of the nails is 75 mi. Before the excavation work could begin, 1.5 million gal of water were pumped from the site to lower the water table more than 20 ft; a permanent dewatering system of four sumps and a drainage network collects and controls any groundwater that seeps beneath the playing field and behind the permanent retention system.

The nine-level seating bowl is roughly rectangular and was constructed from more than 200,000 cu yd of concrete and 21,000 tons of reinforcing steel. It consists of cast-in-place concrete moment-resisting frames, pan joist floor framing

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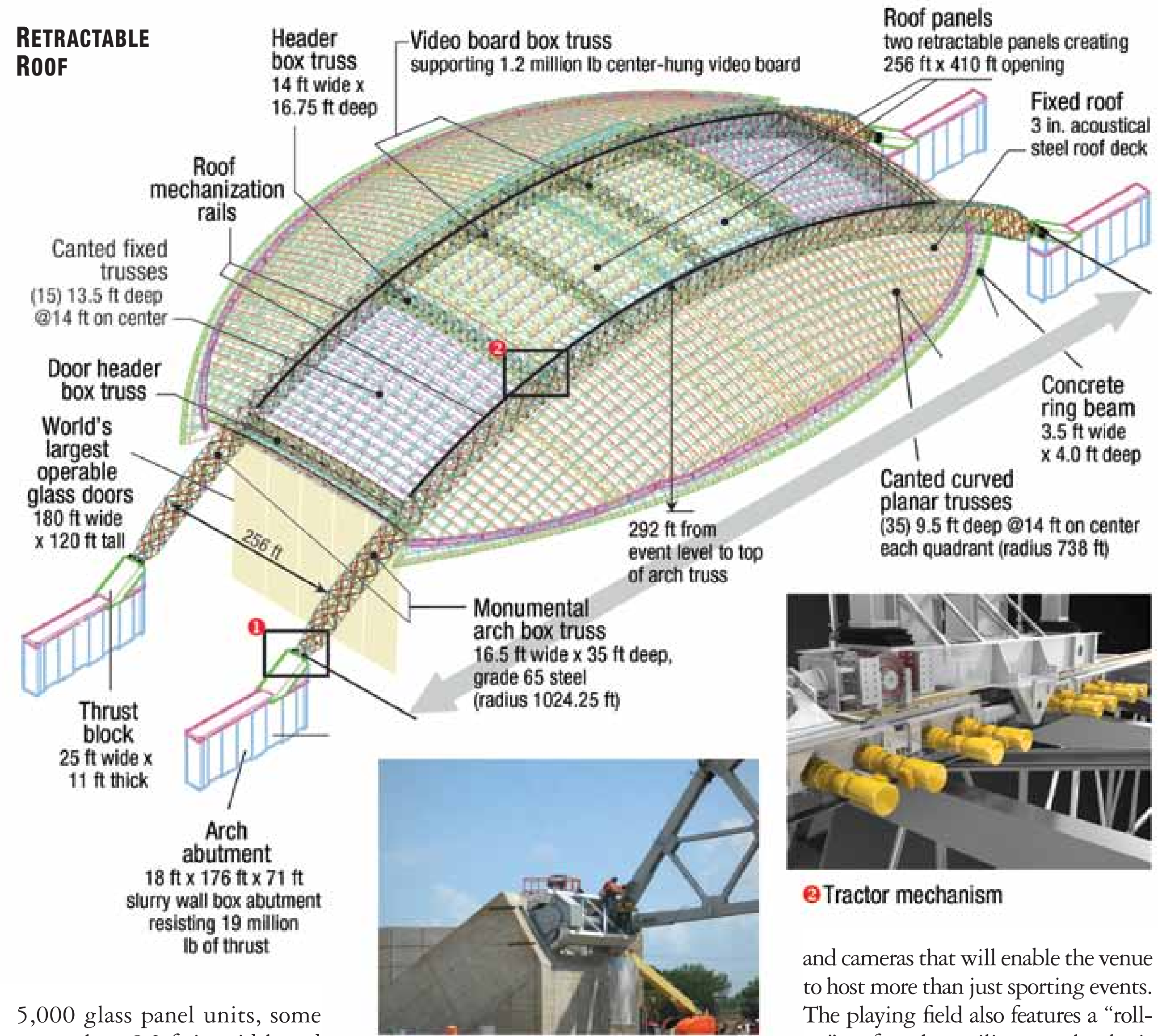

❶ Arch truss bearing pin assembly

❷ Tractor mechanism

WALTER P MOORE

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THE NINE-LEVEL SEATING BOWL IS ROUGHLY RECTANGULAR AND WAS CONSTRUCTED FROM MORE THAN 200,000 CU YD OF CONCRETE AND 21,000 TONS OF REINFORCING STEEL.

involving cast-in-place concrete reinforced with mild steel, and seating units of precast and prestressed concrete. The column bay sizes in the concourse areas range from 36 to 48 ft by 26 to 38 ft. To achieve these floor spans, the design features a pan-formed floor system with a 29 in. total depth, a 5 in. thick slab, and girders with depths of as much as 48 in. at select locations. Cantilevered concrete raker beams 36 in. wide by 48 in. deep help to create a column-free seating bowl; the cast-in-place concrete raker frames are aligned between the walls of every third suite and are spaced at distances of 36 to 48 ft, which helped to create the maximum suite widths and minimal column projection into the suites.

Because only a small portion of the seating extends beyond the end zones, the structural framing at those locations, which consists of concrete topping on composite steel floor decks, composite steel beams, and steel-braced frames, gives fans open vistas into and out of the seating bowl. To accommodate thermal shrinkage and lateral frame movements, a series of eight expansion joints, each 4 in. wide, were placed symmetrically around the seating bowl.

The seating bowl is supported by more than 700 straight concrete piers 24 to 90 in. in diameter that were drilled into the underlying layers of sand, shale, and sandstone to depths ranging from 20 to 80 ft. Vertical circulation within the enclosed, climate-controlled seating bowl is achieved via high-speed escalators and by elevators, stairs, and two 18 ft wide ramps of cast-in-place concrete.

To support the stadium's domed roof, which is composed of 14,100 tons of structural steel, the design team developed a pair of monumental arch box trusses that feature a 1,225 ft span and a 1,025 ft radius of curvature. Located on the northern and southern sides of the building, the arches reach their apex 292 ft above the 50-yard line, high enough to erect the Statue of Liberty beneath the stadium roof. Each arch truss is 17 ft wide by 35 ft deep and weighs 3,200 tons. The four truss chords of each arch box truss are composed of grade 65 steel as specified by ASTM International's standard A913, and their sizes range from W 14 × 311 to W 14 × 730. The steel fabricator—W&W/AFCO Steel, of Oklahoma City, Oklahoma—purchased the high-strength steel from Luxembourg-based Arcelor Mittal, which rolled the steel in its mill and shipped it to Houston. From there it was transported to W&W/AFCO Steel's facility, where it was fabricated, preassembled, disassembled, and then trucked to Cowboys Stadium for field assembly.

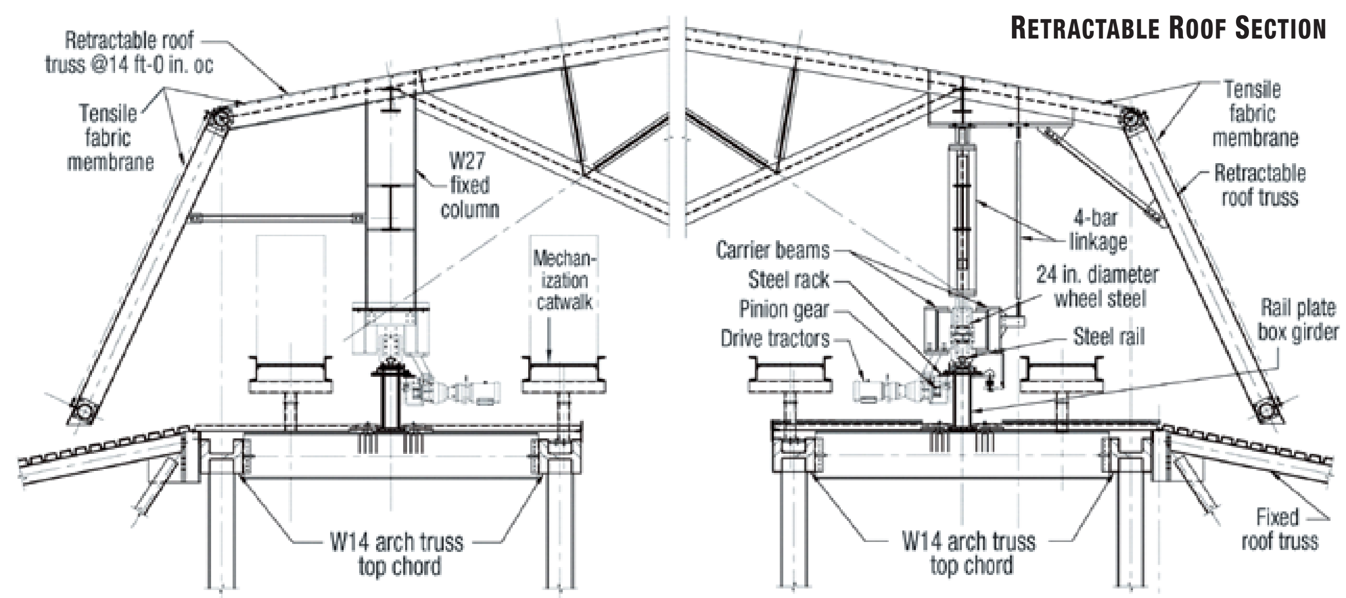
The Walter P Moore structural team for the roof conducted extensive research into long-span bridges around the world to better understand key architectural and structural economies.

The stadium's retractable roof section is composed of twin mechanized translucent panels that slide lengthwise across the top of the dome. Suspended from the roof's arch trusses 90 ft above the field is the world's largest high-definition video screen system.

BLAKE MARVIN/HKS, INC., *TOP;* WALTER P MOORE, *OPPOSITE*

The arch trusses feature a quadrangular Warren web configuration of repeating X-shaped diagonals, creating a pattern of web members along each vertical side that resembles the Scottish argyle design, one of the world's oldest three-dimensional spacing patterns. A Warren configuration was used for the top and bottom chord horizontal bracing. After analyzing numerous web configurations, the engineers determined that the quadrangular Warren configuration on each vertical side would not only reduce the stress on the heavy chord members but also make it possible to stay within the W 14 × 730 shape limit, dispense with costly built-up shapes, and use no more than four box truss chords. The structural engineers also minimized the arch truss chord slenderness ratios for the

RETRACTABLE ROOF SECTION



THE VARIATION IN THE INCLINATION OF THE FIXED TRUSS MATCHES THE RADIAL CONFIGURATION OF THE ARCH TRUSS, CREATING AN ELEGANT, SWEEPING STRUCTURAL SYSTEM THAT EMPHASIZES BOTH RHYTHM AND REPETITION.

compression members and thereby achieved a 25 percent increase in yield strength while reducing the required steel tonnage and cutting steel costs by at least $3 million.

Each of the four arch truss pin bearing assemblies is of solid cast steel, weighs 64,000 lb, and supports a 19 million lb thrust reaction. Designed and constructed by Minneapolis-based Uni-Systems, LLC, the assemblies are of grade 50 steel as specified by ASTM International's standard A148 and are anchored atop concrete thrust block columns that measure 25 by 11 ft and launch out of the ground at an angle of 32 degrees from the horizontal to receive the ends of each arch. Belowground the thrust block columns are anchored to a slurry wall box abutment that transfers the thrust into the surrounding soil. Designed by Walter P Moore in collaboration with Clyde N. Baker, S.E, P.E., a senior principal of AECOM who is based in Vernon Hills, Illinois, the concrete slurry wall box abutment comprises a series of subterranean trenches containing 36 in. of concrete. The rectangular box is 18 ft wide, 176 ft long, and 71 ft deep.

The fixed roof framing is formed by perforated acoustical steel roof deck elements 3 in. thick that span up to 14 ft to planar steel trusses that are oriented in such a way as to remain perpendicular to the roof's curving surface. The variation in the inclination of the fixed truss matches the radial configuration of the arch truss, creating an elegant, sweeping structural system that emphasizes both rhythm and repetition.

Emulating the soaring box truss span design of Texas Stadium was one goal in designing the new facility, and retaining the "hole in the roof" was of paramount importance to the owner. Another key design goal, however, was to create a fully enclosed building that would lend itself to a variety of events. The design team accommodated these seemingly mutually exclusive requirements with the retractable roof.

Engineering ingenuity was the crucial ingredient in achieving the Cowboys Stadium roof. Walter P Moore's structural engineers applied lessons the firm had learned in designing and building other facilities with retractable roofs. The innovations that emerged in designing the Cowboys Stadium roof are sure to be applied to future retractable roofs with long spans.

The massive operable glass doors at the end zone plazas are each 180 ft in width by 120 ft in height. They comprise five movable, overlapping panels flanked by stationary side panels.

The end zone door panels weigh 115,000 lb apiece and move on steel wheels powered by traction drive motors. The wheels roll along steel rails that are embedded in the concrete floor structure.

BLAKE MARVIN/HKS, INC., BOTH

The mechanization system for Cowboys Stadium was designed by Uni-Systems in close collaboration with Walter P Moore. It represents the first application in North America of a rack-and-pinion system for a retractable roof, and with a maximum slope of 23 degrees it is also the largest and steepest such roof application in the world. There are 32 motors per roof quadrant, and each of these 128 motors powers a pinion gear that eases the operable panels down 328 ft of toothed steel rack that is attached to the arch trusses. As the moving roof panels progress downhill, the slope becomes more dramatic. Twelve minutes later, when the two massive panels are parked in the open position, the rack-and-pinion drive system maintains the roof panels at the maximum slope of 23 degrees. Lowering the panels is difficult enough, but the drive system also had to be designed to push the retractable panels back into the closed position, conquering this steep slope in the uphill direction.

The system's efficiency is demonstrated by the modest power requirements used to move the 3.5 million lb of panel weight back up the slope: Each of the 128 motors has a capacity of 7.5 hp, making the total horsepower required to close the roof roughly equivalent to just three Ford Mustang GT automobile engines. Each retractable roof truss is supported by a fixed column on one arch truss and by a thrust-releasing four-bar linkage on the other arch truss. This configuration enables the retractable roof to "breathe" laterally while preventing the buildup of excessive lateral force.

The two translucent retractable roof panels are each 290 by 220 ft and feature 13 ft deep steel trusses spaced 14 ft apart. The panels travel along the arches and, as mentioned above, meet above the 50-yard line. To make them translucent, the panels are clad in a polytetrafluoroethylene-coated fiberglass tensile membrane. They also feature one of the world's first applications of a photocatalytic titanium dioxide coating that in using sunlight to break down dirt makes the roof essentially self-cleaning.

In addition to supporting the stadium's roof, the arch trusses permanently hold aloft the world's largest high-definition video board, which weighs 1.2 million lb. Support must also be provided for 200,000 lb of show rigging, which can be configured in dozens of ways. Designed and manufactured by Mitsubishi Electric Power Products, Inc., of Warrendale, Pennsylvania, the $40-million video board features two 160 ft wide by 71.5 ft high light-emitting diode (LED) display panels facing the sidelines and two 29 ft high by 51 ft wide LED panels facing the end zones. Each sideline LED panel alone has a display area equivalent to more than 1,000 big-screen television sets.

To support the LED display panels, Walter P Moore designed a 71.5 ft tall steel structure having 10 levels of internal catwalks. With the video displays on its four sides, the structure was erected on the ground and then hoisted into position by four strand jack assemblies, each with a capacity of 450 tons. Shortly after the system was installed at the proper height for football games, however, the owner decided to retrofit the video board so that it could be lowered and raised to meet the needs of other events.

To effect this change, Uni-Systems worked with the project's design team to replace the support cables, which originally had linked the board to a series of full-height trusses that are located behind the video display cladding and carry the board's gravity loads. A series of eight spirally wound structural cables that had gripped each end of the board structure and had extended vertically toward the opening in the roof were replaced with 16 steel wire rope gravity cables, each

WHEN OPEN, THE PANELS "PARK" BEHIND A FIXED PANEL ON EACH SIDE OF THE OPENING.

1.5 in. in diameter, that were fed through a series of steel sheaves 48 in. in diameter to gain mechanical efficiency. Eight other sway cables also were replaced with eight wire ropes having the same specifications as the 16 new gravity cables. The sheave configurations also are similar. Each of these 24 new mechanization cables is attached to a cable drum whose rotation controls the movement of the board.

The weight of the cable drums, sheaves, and other mechanization equipment added nearly 500,000 lb of load to the roof structure. This additional load was located strategically within the roof structure, and new load paths were integrated into the design of the existing trusses. The cable drums, for example, were located in the arch trusses, and the cables pay out horizontally beneath the box trusses that span between the two arches. The cables continue horizontally until they reach a point at the center of the field, and from there they take a vertical direction via the sheaves and continue down to the video board.

While the placement of additional load and the adaptation of load paths for the existing loads were achieved in the design, the installation of the new equipment produced its own set of challenges. Perhaps the most significant hurdle involved the replacement of the cables while the video board was suspended 90 ft in the air. To accomplish this, temporary steel rods 2.5 in. in diameter were installed between the video board structure and a hydraulic lifting system mounted in the box truss above. The rods were tensioned until the load of the video board was transferred from the old cables to the temporary rods. The old cables were then replaced with the mechanization cables. Finally, the cable drum mechanization system slowly tensioned the new cables to relieve the load in the temporary steel rods and transfer it to the new mechanization system.

Although the 90 ft height of the video board exceeds the NFL's requirement that such a board be at least 85 ft above the field, the board was struck by a punted ball during a preseason game. The Cowboys organization has no plans to raise the board for football games, but an advertising sign that had been located on the underside of the board was moved to the upper part of the structure.

BLAKE MARVIN/HKS, INC.

Cantilevered concrete raker beams 36 in. wide by 48 in. deep help to create a column-free seating bowl; the cast-in-place concrete raker frames are spaced at distances of 36 to 48 ft.

Uni-Systems also designed and constructed the massive operable glazed doors that are located at each end of the stadium. Each door consists of five overlapping 38 ft wide panels that weigh 115,000 lb apiece and move on pairs of 24 in. diameter steel wheels at the bottom of the panels that are powered by pairs of 10 hp traction drive motors. The wheels roll along three separate steel rails that are embedded in the concrete floor structure; the tops of the door panels glide along the door guide assembly, which is laterally supported by the roof's steel box truss. When open, the panels "park" behind a fixed panel on each side of the opening.

The structure of the stadium was developed via a three-dimensional computer analysis model of the roof and bowl that examined 30,000 frame elements, 15,000 nodes, and 4,000 area elements. The geometry of the analysis model was created in the AutoCAD three-dimensional modeling software system, developed by AutoDesk, Inc., of San Rafael, California. The centerline geometry defining the frame elements and nodes was then imported into the SAP2000 FEM analysis software, which is produced by Computers & Structures, Inc., of Berkeley, California. Certain features, such as the area elements, had to be built into the model after phasing the model from AutoCAD to SAP2000.

The area elements formed the skin of the model and were used primarily for applying load to the structure. This external shell had to be established early in the design phase of the project so that the model could be provided to the wind tunnel consultant—RWDI, of Guelph, Ontario—to assist in establishing the locations for the 1,000 pressure taps used in the 1:400 scale wind tunnel model. RWDI also created a map that linked each of the distinct names assigned to the individual area elements with the corresponding pressure tap from the wind tunnel model. This approach facilitated a straightforward technique of spreadsheet data manipulation that greatly simplified the application of the more than 150 wind load cases. The stadium is designed to resist a maximum wind speed of approximately 130 mph.

The design team's careful consideration of various challenging loads and other atypical conditions contributed to the large number of load combinations that the structure has been designed to accommodate. Perhaps the most obvious examples are associated with the retractable roof and the operable doors at the end zones. As these distinctive features move, they load the structure in a multiplicity of ways and induce deflections in the structure that had to be accommodated in the detailing. For instance, the arches deflect by more than 1 ft at the midspan. While such a deflection would seem unacceptable in many structures, the span length of the arch trusses is such that the total load deflection is only about $L/1{,}000$, a remarkable achievement.

Moreover, while the deflections in stadiums with fixed roofs are static once the dead load has been applied, this is

The use of alternative materials in the stadium's design reduced the amount of energy-consuming cement in some of the larger concrete elements by a total of more than 5 million lb.

DARYL SHIELDS/HKS, INC.

not the case with stadiums having retractable roofs. In the latter, the dead-load patterns change as the roof opens and closes, causing variations in the resulting stresses and deflections. What is more, the retractable roof panels have bumpers at both the uphill and downhill ends of travel that are incorporated into the arch truss. These bumpers are each designed to accommodate an emergency load of 463,000 lb of force if impacted by the retractable panel. Another consideration is that when the retractable roof panels are in motion they can be stopped instantaneously in the event of an emergency via a mechanical braking system that engages as quickly as the springs can uncoil, resulting in a unique load that must be transferred into the arch truss.

The design team's need to take all of these unique conditions into account made it necessary to consider more than 500 global load combinations.

The erection sequence also was studied via computer modeling so that the residual forces built into the structure during construction would be accurately addressed. This second-order staged construction analysis included all of the major steps of erection and captured the effects of the shoring towers for the main arch trusses, the temporary erection bracing, and the temporary erection slide bearings at the fixed truss seat connections to the ring beam.

Beginning in March 2005, the project team held a series of coordination meetings during the design development and construction document phases to discuss such design, fabrication, and erection issues as the roof geometry, connection designs, erection sequencing, thermal movements, tolerances, and fit-up. The arches, for instance, were fabricated in 56 ft segments, which allowed the basic geometry of each segment to be identical and thus reduced the cost of detailing and fabrication. Moreover, Walter P Moore collaborated with the contractor and the steel erector—Dallas-based Manhattan Construction Company and Derr Steel Erection Company, of Euless, Texas, respectively—to determine the most efficient methods for constructing the world's longest roof span. The erection sequence was established in the early stages of design and explicitly modeled in the engineer's analysis, which not only lowered costs but also shortened schedules.

The sequence involved erecting each arch on six temporary shoring towers. Work began at one abutment and progressed to the 50-yard line, where two bracing trusses were installed. Work then moved to the other abutment, where the sequence was repeated. The southern arch was completed first, and the shoring towers were moved so that work could proceed on the northern arch. Each arch truss took approximately five months to erect, after which the fixed roof and the roof deck were installed. The center fixed roof, the box trusses, and the retractable roof were completed in a total of 17 months.

Cowboys Stadium is expected to generate a considerable amount of revenue for the local and state economy. It provides the north Texas region with its first enclosed venue capable of accommodating as many as 100,000 people, and it has already been chosen to host the 2011 Super Bowl, the regional economic effect of which could be as much as $1 billion. The stadium will also regularly host college football's Cotton Bowl and the championship game in the Big 12 Conference and will be the venue of the National Basketball Association's All-Star Game in 2010 and of the semifinals ("final four") in the National Collegiate Athletic Association's basketball championship in 2014. A 2004 financial study estimated that the facility would generate $7 billion to $16 billion for Arlington's economy over the next 30 years.

THE COWBOYS ORGANIZATION WANTED TO MAKE ITS NEW STADIUM A LEADING VENUE NOT JUST FOR ATHLETIC ACHIEVEMENT BUT ALSO FOR ENVIRONMENTAL STEWARDSHIP.

And the field won't be the only thing that's green. The Cowboys organization wanted to make its new stadium a leading venue not just for athletic achievement but also for environmental stewardship. Toward that goal, nearly 20 percent of the materials used to construct the stadium had undergone recycling. For the reinforcing and structural steel, the figure was 80 percent. At least 65 percent of the structural materials for the project were sourced regionally, and at least 90 percent of the construction waste was recycled. The translucent fabric in the retractable roof and other features of the building are intended to reduce electricity consumption by allowing natural light to reach the interior, the operable doors at the end zones will facilitate natural ventilation, and there are 30 acres of landscaping and grassy, permeable parking pavement surrounding the site. Moreover, the use of alternative materials enabled the design team to reduce the amount of energy-consuming cement in some of the larger concrete elements by a total of more than 5 million lb. This in turn reduced the embodied carbon dioxide in the concrete structure by an amount roughly equivalent to the emissions of 400 people driving to work over the course of a year.

With its sleek and polished form, efficient operation, and innovative engineering, Cowboys Stadium is one of the most technologically and environmentally advanced venues for sports in the country. **CE**

R. John Aniol, P.E., S.E., is a principal, Joseph Dowd, P.E., a senior associate, and David Platten, P.E., M.ASCE, a senior principal in the Dallas office of Walter P Moore. Aniol was the structural project manager, Dowd the structural project engineer of the roof, and Platten the structural principal in charge on the Cowboys Stadium project.

PROJECT CREDITS **Owner:** City of Arlington, Texas **Developer:** Blue Star Development/Dallas Cowboys Football Club, Irving, Texas **Architect:** HKS, Inc., Dallas **Lead structural engineer:** Walter P Moore, Dallas and Austin, Texas **Associate structural engineer:** Campbell & Associates, Inc., Dallas **Roof, wall, and video board mechanization consultant:** Uni-Systems, LLC, Minneapolis **Mechanical, electrical, and plumbing engineer:** ME Engineers, Inc., Wheat Ridge, Colorado **Wind tunnel consultant:** RWDI, Guelph, Ontario **Geotechnical consultant:** Landtec Engineers, Arlington, Texas, and Gregory Geotechnical, Stillwater, Oklahoma **General contractor:** Manhattan Construction Company, Dallas **Roof steel fabricator:** W&W/AFCO Steel, Oklahoma City, Oklahoma, and Prospect Steel Company, Little Rock, Arkansas **Roof steel erector:** Derr Steel Erection Company, Euless, Texas **Video board manufacturer:** Mitsubishi Electric Power Products, Inc., Warrendale, Pennsylvania **Fabric roof contractor:** Birdair, Inc., Amherst, New York