

Collaborate and Conquer

BY MARK C. WAGGONER, P.E., AND DAVID P. WRIGHT

A team effort by a structural engineer and a steel fabricator resulted in a dynamic roof structure for the Arizona Cardinals.

FROM THE INCEPTION OF CARDINALS STADIUM IN FALL OF 2000, ENGINEERS AT WALTER P. MOORE HAVE COLLABORATED WITH SCHUFF STEEL COMPANY TO DEVELOP AND DELIVER A WORLD-CLASS ROOF STRUCTURE.

This unique relationship enabled a design process that was driven by the long history of the stadium's development, close attention to the fabrication details of the steel, and a bold early decision by Schuff to build a major portion of the roof on the stadium floor and raise it into place through a single "superlift." Such attention to the processes involved in steel fabrication and erection during design resulted in an economical roof structure that was successfully built and stands ready for a long life of service to Cardinals' fans.

Roof Structural System

The stadium design developed by architect Peter Eisenman called for the roof form to present a relatively low-profile surface rising above the undulating metal panel façade of the bowl structure. However, the depth of the roof structure could also not impede the sightlines of the fans in the upper seating areas. Provision for a stiff line of support to guide the operable roof structure was also a key functional requirement.

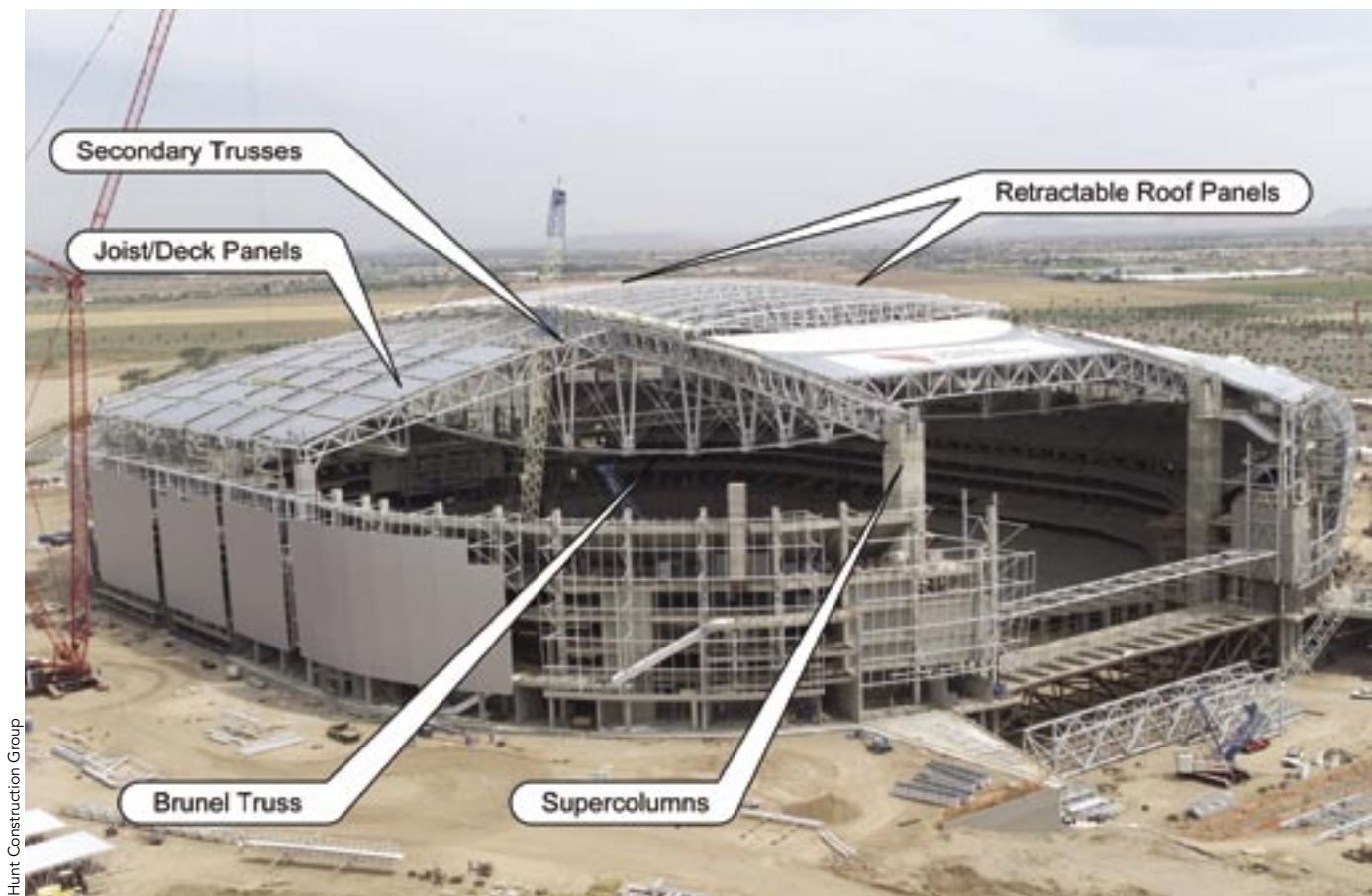
Each of these program demands were addressed through the use of two primary roof elements, dubbed "Brunel Trusses," that span 700 ft parallel to the field sidelines and rest on four concrete supercolumns at the corners of the bowl structure. The Brunel Trusses derive their name out of deference to the similarity of their lenticular form to the Royal Albert Bridge, completed in 1859 by the famous British engineer I.K. Brunel. With their 87 ft structural depth split between a shallow rise semi-domed surface above the roof eave and a catenary element slung below the roof eave, the Brunel Trusses fit well with the architectural program. In addition, they provide a natural line of support for the operable roof and form the backbone of the roof steel erection concept.



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Two "Brunel trusses" span 700 feet along the sidelines and rest on four supercolumns.

The remainder of the fixed roof consists of conventional fully welded one-way secondary trusses spanning between Brunel Trusses and from Brunel Truss to the concrete bowl at the perimeter. Each secondary truss is tied hard to the concrete bowl structure to form a discrete lateral load path. Secondary trusses are infilled by 8-ft-deep joist girders likewise supporting 24-inch joist panels and 1½-inch metal deck. The joist girders are connected at top and bottom chords to provide torsional stability bracing to the secondary trusses. No horizontal diagonal bracing is used in the roof as each roof element is fully stable through discrete and torsional bracing systems. Localized metal deck diaphragm action is only necessary to transfer the relatively minor drag wind loads imparted upon the roof surface.

The 240 ft by 360 ft roof opening is intended to provide an open-air feel to the stadium during Phoenix's pleasant fall climate. Grass is grown through a movable field (see sidebar). Such shorter spans allowed the creation of two shallow operable panels that bipart along the path of the top chord of the Brunel Trusses, creating the first operable roof in the U.S. to move along a significant incline.

Brunel Truss

The Brunel Truss, in fact, does not function like a truss at all, but rather as the superposition of an arch and a catenary tension element. An important result of this behavior is that the majority of shear in the system is carried through the sloping component of axial load in the top and bottom chords. This allows the primary connections to be simple end plates at the top chord compression elements and axial splices at the bottom chord tension elements. The complex chord-diagonal gusset plate connections of more conventional truss forms are avoided entirely.

The top chord of the Brunel Truss is formed from a 15-ft-square shop-welded laced box section to provide in-plane and out-of-plane stability. Chords are W14 of A913 Gr. 65 and lacing is of simple double angles. The sloping top chord boxes are separated from the underslung twin W14 bottom chord through a pair of 24 in. by 24 in. HSS box shapes. Resolution of the confluence of tension, compression, and bearing forces at the ends of the Brunel Truss is handled through a carefully shaped assembly of plate girders, which also served as the attachment point for roof lift strands.

A unique challenge arose from the need to reuse roughly 4,000 tons of W14 material originally intended for a scrapped version of the stadium at another site. Working from an inventory of material sizes and lengths developed by Schuff, Walter P. Moore engineers had to find a place for each piece of existing steel in the new roof structure design. In the end, nearly all of the existing steel was utilized with a minimal premium on the tonnage of the structure.

Only light x-bracing made of rod material is required in the Brunel Truss webs to resist unbalanced roof loads. Early on, Schuff field personnel determined that it was impractical to impart the level of prestress required to prevent sag in the Brunel Truss diagonal rods using traditional in-line turnbuckles or sleeve nuts. Walter P. Moore engineers devised a method by which the rods pairs on opposite faces of the Brunel Truss were drawn inwards towards one another using a single central connecting rod. This method allowed the necessary 110 kips in each rod to be generated from a single induction of 15 kips into the draw-in rod.

Operable Roof Panels

Moving the operable roof along an incline forced a departure from the traction drive systems used successfully on past oper-



Brunel truss box sections in transport.

Schuff Steel Company

able roofs with flat tracks. Mechanization designer Uni-Systems devised a system driven by a pair of cable drums that were mounted to and moved with the two-wheeled carrier assemblies that ride on rails affixed to the Brunel Truss and support the roof panels. One end of the cable attaches to a point on the Brunel Truss at the peak of the roof, while the other end of the cable is driven by the cable drum. To open the roof, the cable drum simply unwinds, using the weight of the roof to move the structure downhill. The roof is then closed by winding the cable back onto the drum.

The structure of the operable roof panels consists of a series of 15 ft maximum depth lenticular trusses spaced roughly 25 ft apart. PTFE-coated glass fabric is tensioned between each truss to form the roof surface. A vierendeel-lenticular sys-

tem was developed for the operable trusses that allowed very simple welded connections of HSS verticals to the rolled HSS chords. Coupled with horizontal bridging between trusses, the operable panel structural system presents a regular orthogonal grid of framework that avoids the cluttered appearance of most long-span systems with diagonal webs.

Detailing and Fabrication

Detailing of the roof structure was performed by BDS Steel Detailers through an extensive X-Steel model. Information was fed from the design team to Schuff and BDS through electronic data interchange methods ranging from basic geometry information to text files defining repetitive connection designs that were directly processed into the model using custom macros

developed by BDS. Due to the deflection of the Brunel Trusses before and after the roof lift, different pieces of the roof had to be detailed to different geometry.

Fabrication of the Brunel Trusses centered around progressive pre-assembly of the entire truss on its side in Schuff's Phoenix shop. Entire sections of the truss were fabricated and assembled as a unit in the shop, with each connection point carefully matched and drilled through extensive shop fixturing. This approach proved tremendously successful as there was virtually no need for modifications once pieces were assembled in the field.

The major fabrication components consisted of the 15-ft square Brunel Truss top chord box sections that ranged in length from 40 ft to 70 ft. Due to the proximity of the Schuff shop to the stadium site, these

Inside Out: A Movable Field

Cardinals Stadium is designed to be a multi-purpose venue. The key element that allows the stadium to quickly trans-

form from a world-class NFL facility to a world-class convention floor is the operable field structure. The 234 ft by 403 ft by

39 in. tall field travels on 13 steel rail lines leading out of the south end of the stadium over a distance of 740 ft in 65 min. Twin W18 composite steel beams form the structural grid, spanning between wheel boxes that are spaced along the rail lines. The steel frame is topped by a 5 in. composite slab, a drainage mat, and 12 in. of soil capped by the playing turf. Field tray guidance is provided by sets of horizontal rollers along the central rail line, while flangeless steel wheels are allowed to slip slightly atop the other rail lines to allow for thermal movements. Design of the steel framing system was controlled by the stiffness required to provide a suitable playing surface for football, which was verified through extensive testing of mock-ups.

Designer

Uni-Systems, LLC

Structural Consultants

Walter P. Moore; Thomas Murray and Mehdi Setareh, Virginia Tech

Steel Frame Fabricator/Erector

Schuff Steel Company (AISC member)



Operable field under construction in outboard position.

Hunt Construction Group



Superlift assembly prior to lift.

units were fabricated and transported as fully welded assemblies. Following preliminary fit-up in the full truss pre-assembly fixturing, each box was turned four times to complete all welding in the flat position. The entire box unit was then sand-blasted, painted, and loaded onto specially designed transporters for a short drive to the site.

The Superlift

At the stadium jobsite both Brunel Trusses, the fixed trusses that span between them, and the operable roof panels were assembled on the ground, roughly 120 ft below their final position. Stability of the system both during and after the lifting process was provided by a giant temporary X-brace that was created at the midspan of the roof to function as a torsional brace. A temporary laced box strut connected the bottom chords, while special temporary connections were made to allow four of the operable roof trusses to serve as a strut connecting the top chords. Temporary two inch diameter strand cables formed the cross bracing.

Because the erection intent was known at the outset of the project, Walter P. Moore was able to explicitly include the effects of the superlift in the design of the roof through the use of nonlinear staged construction analysis in the SAP2000 model. The temporary conditions during the roof lift and subsequent erection steps were also considered early in the process. Such measures included a separate wind tunnel test of just the roof lift assembly by consultant RWDI.

The roof was lifted by two strand jacks installed atop each of the four supercol-

umns by lifting specialist Mammoet. Each strand jack carried 56 strands. Strands are lifted through an upper collar of wedge grips that is raised several inches at a time through hydraulics. At the top of the stroke a lower collar holds the strands while the upper collar resets. At its peak, the strand jack system would lift the roof at 20 ft per hour.

What is believed to be the largest roof lift ever was successfully completed over five days in late February 2005. Movement and strain behavior of the roof were monitored throughout the lift using an extensive array of wireless monitoring equipment installed by consultant WJE. The actual behavior of the roof was found to be very close to predictions. Interestingly, the 10,843 kip weight estimate of the lift assembly was verified to be 10,850 kips through load cells in the strand jacks.

Ready to Roll

Following the superlift, the remainder of the roof was erected by Schuff using more conventional crane techniques. The roof surface was created through joist girder/joist/deck panels that were assembled on the ground and lifted as units. Other erection challenges included a complex wall that spanned over the south end of the stadium to allow the field to pass underneath.

Once the roof was substantially complete, the roof rails underwent a final alignment process to set the exacting straightness necessary to allow trouble-free operation of the roof panels. Final commissioning of the roof mechanization followed, and the roof now stands ready for its debut. The success of the Cardinals Stadium roof stands as a

testament to the collaborative spirit that drove every step of its creation.

For more detailed information on the Cardinals Stadium roof fabrication and erection, see "Planning for a Complex Project: A New Home for the Arizona Cardinals" by David P. Wright and Chris Fischer in the 2006 NASCC Proceedings. The proceedings are available online to AISC members and ePubs subscribers at www.aisc.org/ePubs. **MSC**

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Arizona Cardinals Football Club

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HOK Sport + Venue + Event, Kansas City, Mo.

Structural Engineers

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TLCP Structural, Inc., Phoenix (bowl)

Construction Manager

Hunt Construction Group, Phoenix

Fabricator/Erector

Schuff Steel Company, Phoenix
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Detailer

BDS, Auckland, New Zealand

Mechanization Consultant

Uni-Systems Inc., Minneapolis

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Engineering Software

SAP2000 Nonlinear Advanced

Detailing Software

Tekla XSteel