Wide-Open **Spaces**

Brian H. Caudle, P.E

Photo by Mark Green

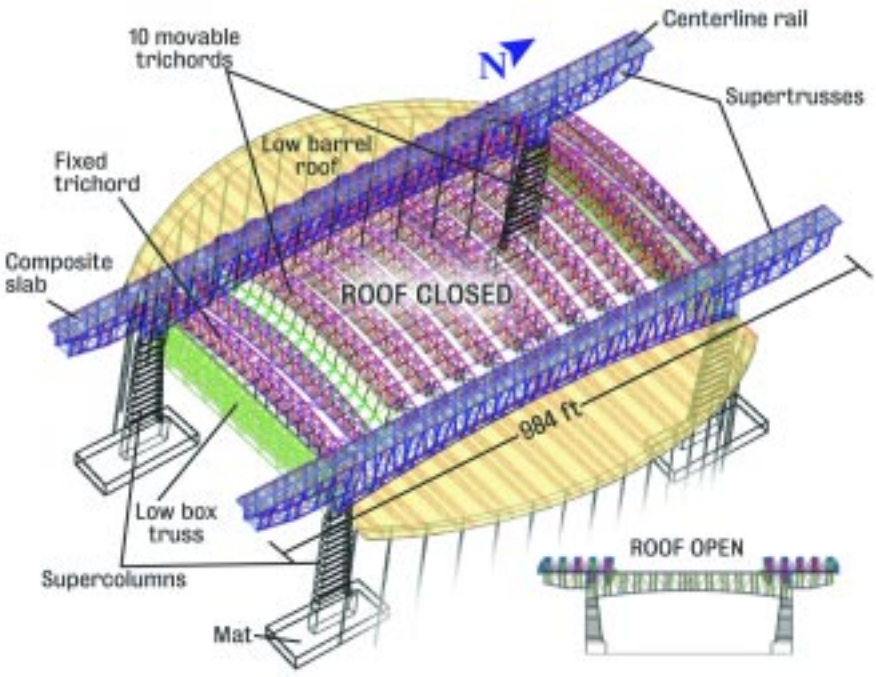
Houston's Reliant Stadium features the largest retractable roof in the U.S., made possible by innovative engineering and high-strength steel.

A new age in multipurpose venues began when Reliant Stadium opened in Houston, TX last August. Reliant Stadium is home to two major tenants: the Houston Texans and the Houston Livestock Show and Rodeo. These two tenants have vastly different requirements. The Houston Texans are the newest team in the National Football League and prefer to play their games on natural grass turf in an open-air setting. However, the Houston Livestock Show and Rodeo fill the seats from late February to mid-March and need a weather-tight arena-like setting for the rodeo and its concert events. The solution to satisfy these diverse needs was to build the NFL's first retractable roof stadium.

This modern venue is located less than 200 yards from another milestone structure, the Astrodome. The Astrodome opened in 1965 as the first enclosed football or baseball stadium and was called the "Eighth Wonder of the World." The curved steel lamella dome supports a 640' roof span, which more than doubled any previous roof span. After years of hosting thousands of his-

torical sporting and entertainment events the venerable old stadium is ready to share the lime light with another trend-setting showplace, Reliant Stadium.

Signaling a new standard for stadiums throughout the world, Reliant Stadium opened to rave reviews from players, fans and the media. Reliant Stadium is the NFL's largest stadium, covering over 12 acres and comprising 1.9 million sq. ft. With 12,000 tons of cooling capacity, it is the largest indoor air-conditioned space in Texas and, other than multi-terminal airports, Reliant Stadium is the state's largest public assembly space. It is also the first NFL stadium with an operable roof, and at 4.25 acres, it is the largest such roof in the United States. The translucent fabric roof creates an instant architectural landmark and a positive new image for the City of Houston.



Schematic drawing of Reliant Stadium roof structure. The roof system was extensively tested to withstand wind uplift, unbalanced loading, lightning strikes and corrosion damage. It is the first roof of its kind to be constructed in the United States.The tri-chord-truss-framed roof splits and glides toward end zones on supertrusses.

RETRACTABLE ROOF— A STEEL AND FABRIC KITE

Design of the distinctive retractable roof was the most challenging aspect of the project for Walter P. Moore, the structural engineer for Reliant Stadium. Imagine constructing a giant lightweight kite, one football field wide and three football fields long—and then try to control that kite in hurricane force winds! The operable portion of the roof consists of two enormous but elegant fabric-clad panels that ride along two parallel supertrusses. The two bi-parting panels abut over midfield and dock over each end zone. Each 385′-by-250′ panel is framed with five tri-chord trusses spanning across the width of the playing field. The 24% translucent Teflon-coated fiberglass fabric is tensioned between the trichord trusses.

Walter P. Moore worked closely with Uni-Systems, the mechanization engineers, to create the computer-controlled moving roof. Each tri-chord truss is supported on a carrier beam with two 36″-diameter steel wheels riding on a single steel rail. A computerized system of 40 5-horsepower, 460-volt, three-phase motors power the 40 steel wheels that can open or close the roof panels in less than 10 minutes. The 6″-tall, 175-lb. crane rail rests on a concrete slab at the top chord of the supertrusses. The operation of the roof is

A 400-ton crane and a 650-ton crane perform a tandem lift of a fabricated side section of the east supertruss. The scoreboard box truss (still supported on erection towers) can be seen framing into the left side of the concrete supercolumn.

Photo by Wes Thompson

so quiet that fans hardly notice it is moving overhead.

To accommodate the vertical tolerances of the 1,000′-long rail, an innovative two-wheel transporter system was designed. A "plug 'n play" electrical system allowed the tri-chord roof trusses to be quickly erected at the north end of the stadium and immediately moved south along the rail with a minimum of field electrical connections. Erecting the tri-chord trusses in one location then moving them on the rail allowed reuse of the erection towers and saved time by not having to move the cranes, further speeding construction.

Inside of each carrier beam are hydraulic scissor clamps that can be tightened around the rail as soon as the roof panels stop moving. This first-of-its-kind computerized clamping system keeps the steel and fabric panels from "flying away" during high winds

FOUR BAR LINKAGE

One of the design and engineering innovations developed for the Reliant Stadium roof was a unique stress-relief four-bar linkage detail. The design of a long-span roof system to accommodate potential restraint forces caused by temperature, creep, shrinkage, foundation settlement and construction tolerances is always a significant challenge. This is particularly true for a roof that moves on a parallel rail system.

The roof structure rides on rails along the supertruss that can vary significantly in the distance between them, caused by supertruss movement under lateral load, temperature, and construction tolerance. When all expected tolerances and deflections were added up, it was determined that one end of the truss had to be able to move laterally plus or minus 21" inches relative to its supporting rail position. This lateral motion had to be accommodated in a relatively short vertical distance of 16′. At the east end of the retractable roof tri-chord trusses, a four-bar linkage was integrated into the truss to form its connection to the transport carrier beams riding along the rail. This linkage allows free lateral movement of the east end of the roof trusses while keeping the transporter carrier wheels vertical. This concept allows only modest lateral thrust loads and reduces potential wear on the wheels and rail. This linkage system provided an economical, easily constructed solution to a very challenging design problem. (Read more about stress relief in long-span roof systems in the article "Stress Relief" in November 2002 issue of *Modern Steel Construction* at **www.modernsteel.com**.)

THE SUPERTRUSS

An elaborate, but efficient, steel structural system supports this enormous roof. Two massive supertrusses clear span 620′ between concrete supercolumns along either field sideline. The bottom chord of each supertruss is gently arched to accommodate for sight lines of the seating bowl, creating a truss with minimum depth of 50′ at mid-span and a maximum depth of 72′ at the supercolumns. In order to find an economical design for a truss with the mid-span depth shallower than the depth at the supports, the structural engineer tied the truss rigidly to the supercolumn, thereby achieving a rigid frame action between the truss and its supporting columns.

The maximum factored moment at the top of each supercolumn is 800,000 kip-feet. The transfer of load from the supertruss to the supercolumn was accomplished through six large built-up steel columns supported on base plates large enough to distribute the compressive loads and to accommodate the required number of 2½"-diameter, 20′-long, ASTM A354, Grade BD anchor rods. The lateral shear was transferred through steel "drag" plates with 2½"-diameter ASTM A354, Grade BD anchor rods.

For further economy, the concrete rail slab atop the supertrusses was made composite with the truss top chord. The composite steel/concrete supertrusses on Reliant Stadium are believed to be the largest ever used in a building structure.

To speed construction, the supertrusses were erected in large, prefabricated pieces, starting at each column and working toward the center. The final pieces were custom-fabricated to fit perfectly. In total, there are more than 1.5 linear miles of primary long-span trusses in the roof of Reliant Stadium.

HIGH STRENGTH STEEL

Throughout the roof, ASTM A913 Grade 65 steel was used to reduce tonnage, contributing greatly to the economy of the Reliant Stadium structural system. ASTM A913 Grade 450 was selectively used in the long-span trusses to reduce steel weight and cost.

As with all compression members, truss members in Grade 65 steel rely on maintaining short unbraced lengths for economy. Several strategies can be employed in large trusses to keep unbraced lengths in an economical range for Grade 65 steel usage. The primary strategy used on Reliant Stadium was the use of built-up laced compression members in the supertrusses. In total, roughly 2950 tons of A913 Grade 65 steel was used in Reliant Stadium, which resulted in an overall savings of approximately 740 tons.

The full economic benefit of using Grade 65 is difficult to quantify, but fabrication, handling, and erection savings due to reduced weight did magnify the pure material tonnage savings. In addition, the lighter steel weight led to savings in the supercolumns and foundations. The light steel weight was crucial in fitting the supertruss base plates in the very limited bearing area available on top of the supercolumns. The lighter steel weight made possible by using Grade 65 steel also helped to control differential settlement between the supercolumns and the bowl concourses.

EXCEEDING GOALS

The owners had multiple goals in designing and building Reliant Stadium, each of which was successfully achieved:

The erection towers have been removed from beneath the west supertruss. The lacing of the truss chords and vertical web members are visible in this picture. The first fabric panels have been installed on the left end of the main truss span.

- The specific needs of two tenants were met. The Livestock Show & Rodeo has a roof to avoid concert rain-outs. The Houston Texans have their open-air venue with a portable grass playing field.
- The roof will support 170,000 lb. of audio equipment, video equipment or other rigging loads for the rodeo and other major events, comparable to any modern arena.
- Superior amenities are offered to the spectator—maximized sight lines, wide concourses, themed entertainment areas, 8,200 club seats and 177 luxury suites.
- The Houston Texans sold all 60,000 of their season tickets, with a waiting list established. The club is expected to generate about $200 million in revenue this season.
- The project was completed within budget and on time—in a short 30 months.

Reliant Stadium's unique retractable roof and its incomparable fan amenities promise not only to bring NFL football back to Houston in great style, but also to create a new home for the largest rodeo event in the world – all in an open-air or fully enclosed, air-conditioned environment. The total stadium structure utilized over 17,000 tons of structural steel. Its structural design incorporated several unique features to make it functional and affordable. The stadium was built within budget and in less than 30 months, proving that Houston will have accomplished its goal of setting the standard in stadiums once again. ★

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LEAD STRUCTURAL ENGINEER
Walter P. Moore and Associates, Inc., Houston

ARCHITECTS
Houston Stadium Consultants (HSC), a joint venture of Hermes Architects, Houston
and Lockwood Andrews Newnam, Houston

ARCHITECTURAL STADIUM CONSULTANT
Sports Design Architect: HOK Sport+ Venue+Event, Kansas City, MO

CONTRACTOR
Manhattan/Beers, a joint venture of Manhattan Construction Co., Houston, and Beers Skanska, Inc., Atlanta

ROOF MECHANIZATION CONSULTANT
Uni-Systems, Inc., Minneapolis

STEEL FABRICATOR
Hirschfeld Steel Co., San Angelo, TX (AISC member)

STEEL ERECTOR
Derr Steel Construction Co., Euless, TX (AISC, SEAA member)

STEEL DETAILER
Dowco Consultants, Toronto (NISD member)

ENGINEERING SOFTWARE
SAP 2000, AutoCAD

DETAILING SOFTWARE
Xsteel (initial model imported from Walter P. Moore SAP model)

BENDING SERVICES
Bendco, Inc., Pasadena, TX