Denver Broncos Pin Their Future on Steel

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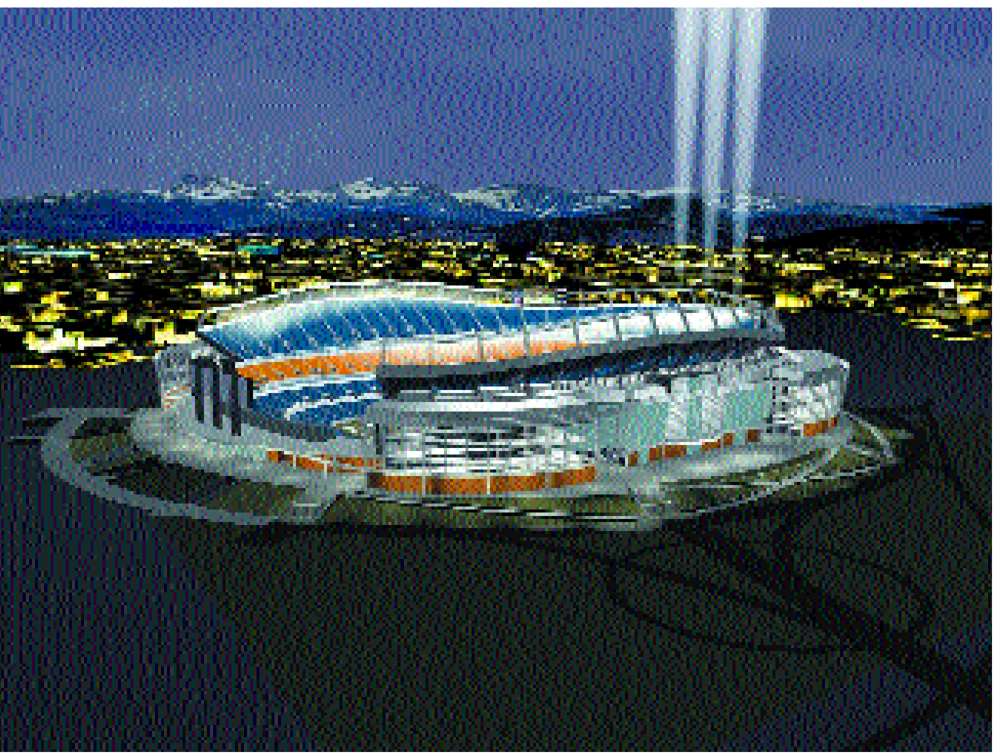
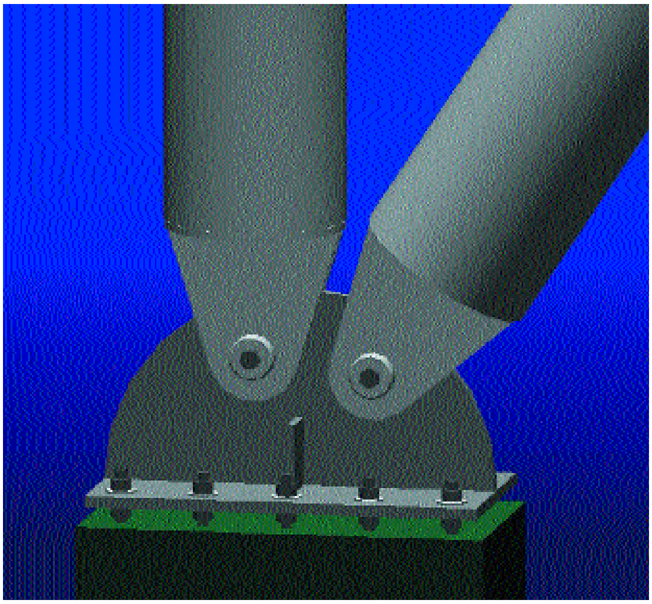


In November 1998, in the afterglow of back-to-back NFL World Championships won by their beloved Broncos, taxpayers in Denver and six surrounding counties voted to replace the famous Mile High Stadium. Slated to open in time for the 2001 NFL season, the new $364 million, 76,125 seat stadium is a design/build project headed by HNTB Design/Build Inc. and Turner Construction Company.

Designed by HNTB Sports Architects, in association with Fentress Bradburn Architects Ltd. and Bertram A. Bruton and Associates, and with structural engineering by Walter P. Moore, the new stadium exhibits a sleek modern facility, full of weeping curves, exposed HSS structural steel and metal-panel cladding around the rim of the upper deck. The facade of the building is wrapped in a sinuous latticework of aluminum, glass and metal panel curtain wall.

The new stadium is also unique in that the seating treads and risers consist of 3/16" thick bent steel plate. Two factors led the designers to choose bent steel plates in lieu of the usual L-shaped precast concrete sections. First, the entire east sideline of the existing Mile High Stadium uses steel treads and risers in order to save weight in the world's largest movable-seating structure. The eastern section (all three tiers of seating) can retract 145' to make room for a left field during baseball season. Secondly, in the geometrical layout of the new stadium each column grid line skews relative to the adjacent column grid lines. In most modern stadiums, the sideline and end zone seating sections are linear, with either a 90-degree segmented curve through the corner, or a linear corner turned on a 45-degree chamfer. HNTB and Walter P. Moore defined the grid system of the new stadium as a doubly symmetric 48-sided polygon based on broad-radius arcs at the sidelines and end zones with tighter arcs through the corners. The continually curving seating rows created by this grid system provide better sightlines and field proximity for stadium patrons and generate the appearance of a smoothly curved seating bowl. As a result of this design feature, each successive row of seats is slightly longer than the previous row throughout the stadium. This would have substantially increased the number of different precast riser members required and decreased the economic viability of precast. Therefore, steel risers became an excellent and affordable alternative.

With over 12 acres of exposed steel plate in three seating bowls, maintenance of the structure was a major factor in design. The solution



View of typical pinned connection for HSS columns at upper bowl (rendering generated from 3D CAD model).

View of same typical pinned connection, as built (existing Mile High Stadium is in the background).

leaves the top surface of the plates unpainted. Extensive testing and metallurgical analysis of the existing stadium indicated that the steel treads were killed A36 material. Also, due to Denver's naturally dry climate, the only corrosion problems in the treads at the old stadium exist at locations where water became trapped on top of the plate by poor drainage or badly adhered traffic coating.

Based on this information, the riser plates of the new stadium consist of killed A36 steel, and each tread was detailed with a 1/2" per tread drainage slope. Defining the slope per tread instead of per foot helped in keeping these consistent and made the detailer's job a little easier. Furthermore, all proposed traffic coatings are being tested in the field. To provide a watertight system, penetrations through the riser plates were minimized, all welds are continuous and a secondary subroof is provided between the riser plates and any finished interior spaces below.

Butt-welds join the treads in single row sections at the change in alignment at each grid line. During fabrication, each section is bent to form a 2" return at the top of the riser section with a second bend creating the heel of the tread. The front of each tread bears directly on the 2" return of the section below, and a 3/16" continuous fillet weld seals the sections together. An automated welding machine that runs around the nosing of each tread makes fillet welds, allowing for a total weld length of over 17 miles.

A subframing system of rolled wideflange sections supports the riser plates. Vertical L3×3 stubs on stringers spaced at distances of up to 16' support each tread. The stringers span along the slope of the bowl between girders, which in turn span between rakers on the column grid lines. Precast concrete makes up the rakers at the lower bowl, while the middle and upper bowl rakers are steel. Stringer sizes vary from W14×22 to W30×124, and girder sizes vary from W24×55 to W36×280.

Due to the combination of long spans and high live load to dead load ratio, vibration was a significant concern in the design of the seating framing. Each subframing member throughout the entire stadium was analyzed for dynamic response to two excitation modes. The first mode simulated fans rhythmically jumping in the stands and was represented by a 30-psf live load under harmonic excitation with a frequency of 3 Hz and a dynamic load factor of 25%. The second mode simulated fans stamping their feet by increasing the frequency to 5½ Hz and decreasing the dynamic load factor to 5%.

Rather than setting a minimum fundamental frequency of vibration for all members to satisfy, each member, analyzed individually, allowed consideration of the individual loads and stiffness. Limitation of the effective peak acceleration was chosen as the design criteria. The effective peak accelerations in the stringers were limited to 5% of the gravitational acceleration (5% g) for both jumping and stamping. The effective peak accelerations in the girders were limited to 7% g for jumping. The effective peak acceleration in the girders due to stamping was not limited due to the large tributary area for the girders. Research has shown that large groups of people cannot maintain unison with higher frequency activities such as stamping.

The post-tensioned cast-in-place concourse framing is separated into eight midrise buildings to relieve

View of club (middle) and lower bowl framing and both levels of suites at north endzone.

thermal, creep, and shrinkage stresses, and to isolate lateral wind and earthquake loads. To accommodate differential thermal movements between the riser plates and the subframing below, the connections between the treads and the stringers consisted of either fixed or slip-capable details. The slip connections allowed differential movements around the bowl between the treads and the stringers underneath. Rigid fixed connections were used in the two center bays of each of the building sections, with the slip connections in the remaining bays (those bays within two grid lines of a building expansion joint). Longitudinal bracing between the bowl framing and the concourse frame was also located in the center bays of each building section.

The raker frames at the middle bowl extend from the upper suite level down to the club level, with a cantilever extending out over the lower suites. These frames consist of W33 raker beams with W14 columns at the fulcrum of the cantilever. A heavy W24 shape serves as a strut from the club level out to the end of the W33. The W24 extends beyond the W33 to support the spandrel member at the front fascia of the bowl, which contain the only structural precast members in the middle and upper bowls. Since the raker frames effectively tie together two levels of the cast-in-place concourse frame, they were included in the lateral analysis of the concourse framing. Slip-critical bolts field bolt all connections.

The raker frames in the upper bowl are one of the signature items of the new stadium. The raker beam consists of a tapered wide flange section built-up from 1”×26” A36 flange plates and ½” A36 web plates varying in height from 25” to 66”. The raker beam has a straight taper along its lower length, with a curved taper at its upper end. Since the height of the upper bowl varies around the stadium, the radius of the curve at each raker varies in order to maintain a constant work point at the lower end and a vertical depth of 72” at the upper end. At the four raker frames supporting the scoreboards and video boards in the northern corners of the stadium, the flanges become 2” thick in the upper portion of the raker beam to support the extra weight. The longer raker beams at the sidelines and end zone consist of a bolted field splice for ease of shipping and erection.

HSS 24×½ columns that lean toward and away from the field in the plane of the raker supported the upper raker beams. The connections at the ends of the HSS simplify function, erection and appearance. Rather than having a complex weldment between HSS at odd angles, the designers chose a true-pinned connection. Three feet from the end work point of each column, the HSS 24 section terminates into a 1” round cap plate. Two 1” clevis plates spaced 2” apart are welded to the cap plate, with a 4” diameter hole in each clevis plate at 18” from the end work point of the column. The clevis plates fit on each side of a 1½” thick half-round gusset plate. The gusset plates, 24” in radius, center on the end work points of the columns with a matching 4” diameter hole on a radius of 18”. A 4” diameter round stock pin fits through the holes in the gusset and clevis plates, with ¼” thick plate washers serving as spacers between the plies and six inch diameter, 1¼” thick cap plates on each end of the pin. The column load is transferred through bearing on the plates and shear in the pin. Six-inch diameter pins were used in the connections of some of the more heavily loaded columns.

The gusset plates at the upper end of the columns are field bolted to the underside of the built-up raker beam with slip critical bolts in oversized holes. The lower gusset plates bear on cast-in-place pedestals, which are 4’ tall extensions of the cast-in-place concourse frame. The pedestals increase concourse circulation space by raising the lower end workpoint of the columns above the headroom required for the patrons, and they also elevate the pin connections to eye level of the patrons on the upper concourse.

Two brace columns occur at the center raker frame of each building section, and extend from near the upper end of the raker beam to the outermost pedestal of the adjacent raker frames. These brace columns stabilize the upper bowl for lateral and erection loads. Walter P. Moore used three-dimensional CAD models to describe and define the complex geometry of the raker frames and the undulating shape of the rear of the upper bowl.

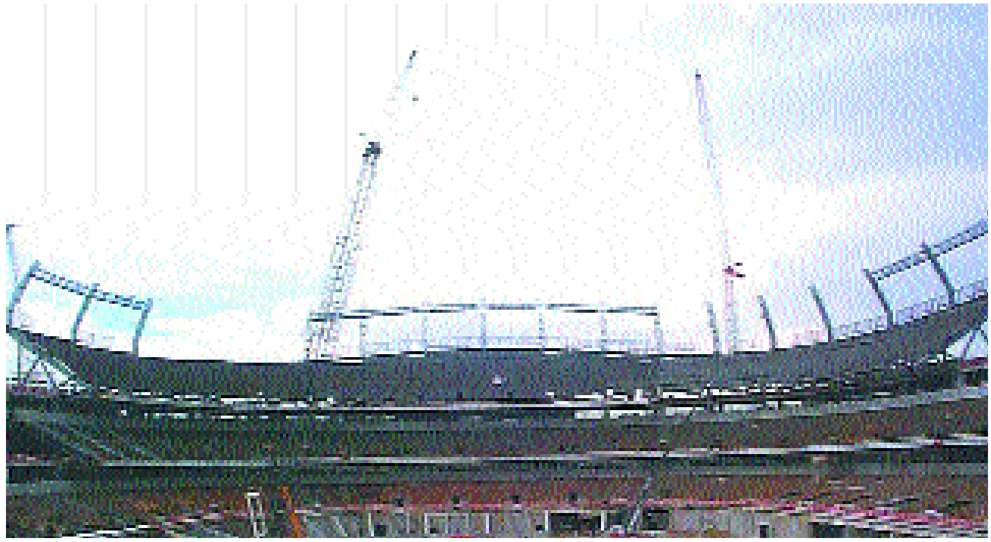
Tolerance in erection of the upper bowl raker frames is provided by the rotation of the pins and the oversized holes in the gusset plate connections.

A rigid welded connection detail would have locked in the raker frame geometry, without sufficient erection tolerance.

At the upper end of each raker beam is a pair of built-up wideflange "tusks" three feet apart. These tusks, typically 30" deep with ½" thick webs and ¾"×10 ½" flange plates, curve 40' upward and 18' inward over the upper bowl. A 5'-4" deep Vierendeel truss connects the tops of the tusks, with HSS 18 bottom chord, HSS 12¾ top chord, and HSS 8 5/8 verticals at 9'-2" maximum spacing. This truss supports the distributed sound system and banks of field lighting and the catwalk that services them. Walter P. Moore also employed three-dimensional CAD models in defining the geometry of the truss members, since the light truss varies in elevation and location similarly to the top of the upper bowl. Due to the slope of the tusks, the top chord of the light truss leans in closer to the field than the bottom chord, which further complicated the geometry.

Exposed structural steel exists as a common theme at all vomitories leading into the seating bowls. The stringer on both sides of each vomitory ramp and stair is exposed, and the ends of the riser plates are closed with a vertical bent plate. The vomitories within each bowl make sure that all stringers adjacent to vomitories are of a similar size (i.e. W21×6½" in lower and upper bowls, and W18×6" in middle bowl), and the horizontal return on the bent closure plate matches the flange width of the stringer underneath.

As part of the design/build process, the prime fabricator and erector, AISC-member Schuff Steel Company of Phoenix was brought into the team at an early stage to assist in the development, detailing, and constructibility of the project. Because of the design-build process, Schuff Steel's early participation, like numerous other subcontractors, increased the effectiveness of the design and added value to the project.



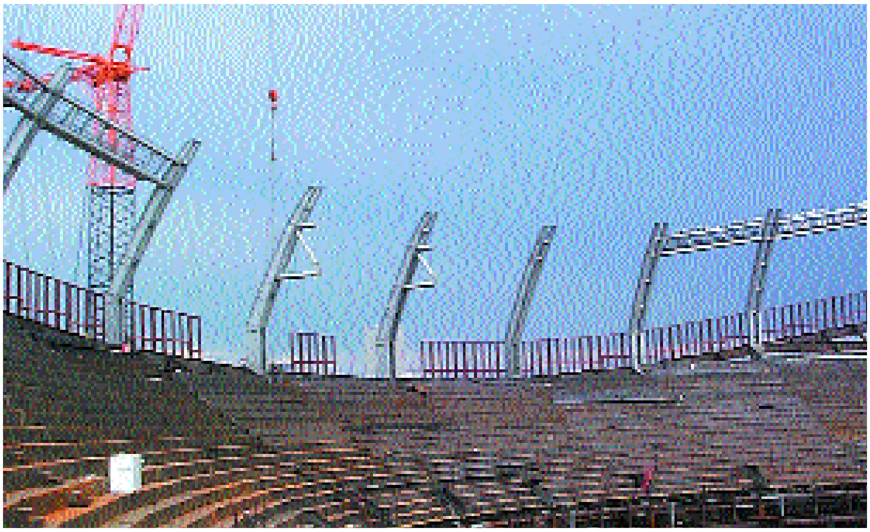
View of north (enclosed) endzone upper bowl, taken from south (open) endzone.

Some of the modifications that were suggested by Schuff and incorporated into the design by Walter P. Moore include a combined bolted and sleeved connection between each light truss segment and the tusks and moving the connection between the tusks and the upper bowl rakers to the top of the raker beam. A collaboration of the designers and contractors also resulted in some minor material cost savings by specifying A36 material instead of grade 50 steel for some of the deeper (W27 and above) and heavier (over 100 pound footweight) sections in the seating subframing. Since the design of many of these members was controlled by vibration, the change in material strength did not affect member size.

Three NISD members, BDS Detailers (Brisbane and Melbourne, Australia), Coast Detailers (Topeka, KS) and Steel Draft (Woodland, CA) supplied the detailing for the project, with the Brisbane office of BDS detailing the bulk of the bowl framing (more than 3,000 sheets of shop drawings). In addition to the 2,000 tons (over a half million sq. ft.) of 3/16" steel plate, Schuff Steel was also responsible for the fabrication of more than 4,500 tons of seating subframing and raker frames, and 550 tons of tusks and light trusses. By the time the stadium opens for the 2001 football season, Schuff Steel will have supplied and erected approximately 12,000 tons of structural steel, including the circulation ramps, elevator core areas, concourse infill framing, scoreboards and curtain wall framing.

A variety of software was used to design this project. The stringers and girders of the stadium seating subframing was designed with an MS Visual Basic/MS Excel program written specifically for this project to accurately predict the dynamic response of the subframing members. RISA-3D was used to analyze the club level raker frames as well as to performed the preliminary analysis for the upper bowl rakers. SAP-2000 was used for the final analysis of the upper bowl raker frames, including the tusks, the lighting trusses and the scoreboards; it was also used for design of the building frames. RAM S-Beam was used to design the steel-framed infill floors of the concourses.

The project is financed primarily by the continuation of the 0.1% sales tax originally used to construct Coors Field for baseball's Colorado Rockies. The Denver Broncos Football Club is contributing 25% of the project's cost, and any proceeds from the possible sale of the naming rights will reduce the public's debt. In addition to the 76,125 seat capacity, the stadium also features approximately 8,500 club level seats adjacent to two 38,000 sq. ft. clubs, 106 suites, seven party suites, over 400 points of sale



View of the tusks and light truss at the northeastern corner of the upper bowl. The pipe Z-frames will support one of the two scoreboards that are hung from the tusks in the northern corners. Also apparent are the geometrical complications due to the "sombrero" shape of the rear wall of the upper bowl - notice the steps in the tread supports along the wall.

for concessions, thirteen elevators, more than eight escalators, two video boards (including one that measures 96' by 27'), 550 televisions and cupholders in every seat. The new stadium also has more appropriately apportioned men's and women's restroom fixtures than Mile High Stadium. The total square footage of the new stadium contains over 1.7-million sq. ft. – more than twice the size of the existing stadium. The seats are also wider (ranging from 19 to 21") and have more legroom (33" typical row spacing), and the main concourses are much wider (minimum width of 45' at the lower concourse and 30' at the upper concourse, versus eighteen and twelve feet at the existing stadium). The stadium, ADA compliant, has 730 pairs of ADA-accessible spaces and companion seats, compared to only 26 pairs at Mile High Stadium. With such fan-friendly and family-friendly amenities available in a new state-of-the-art facility, the Broncos will undoubtedly continue their thirty-year-long streak of home sellouts.

Dennis R. Tow, P.E., an Associate with Walter P. Moore and Associates, Inc., served as structural project engineer for the bowl framing of the new Denver NFL Stadium.

Michael S. Fletcher, P.E., S.E., a Vice President with Walter P. Moore, worked as the firm's structural principal-in-charge for the project.

Lanson B. Nichols, an Associate Vice President with HNTB, served as senior project manager for the new Denver NFL Stadium.

Pardon me, do you speak stadium-ese?

Vomitories also are loosely described as "portals" or "tunnels". They are the entrances into the seating bowls from the circulation concourses.

Rakers are the primary sloped framing members which occur at each gridline, where the bowl geometry changes direction.

Owner: City of Denver

Structural Engineer: Walter P. Moore

Steel Detailing: BDS Detailers, Coast Detailers and Steel Draft

Steel Erector and Fabricator: Schuff Steel

Software: MS Visual Basic/MS Excel, RISA-3D, SAP-2000, RAM S-Beam

Architects: HNTB Sports Architects in association with Fentress Bertram Architects Ltd. and Bertram A. Burton and Associates

Construction: HNTB Design/Build and Turner Construction