ASTRODOME
AN ENGINEERING MARVEL OF THE 1960's
By

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Abstract:

Originally called the Harris County Domed Stadium, the Astrodome was completed in 1964. Conceived as the home of the Houston Colts and the Houston Oilers, it was termed by many as the Eighth Wonder of the World. It was the first time that a stadium was built for both baseball and football that was totally enclosed and fully air-conditioned. The building covers 9.14 acres of land. Circular in shape, the outer diameter of the Astrodome is 710 feet, and the clear span of the dome roof is 642 feet.

This paper provides an overview of the different structural challenges that faced the design team in the nineteen sixties. Some of the issues that had to be dealt with included the design and construction of the dome structure and the assessment of the wind forces on the dome roof, allowance for forces caused by thermal expansion and contraction of the dome structure on the supporting columns, bracing for lateral loads at the seating area, bracing of the 33 feet tall perimeter concrete retaining walls for lateral earth forces and the foundation design at depths far below the water table elevation.

This facility served the Houston professional baseball and football teams very well until recently. The Astros now play at the Minute Maid Park and the new Houston football team, the Houston Texans, play at the Reliant Stadium. As a result, Preservation Texas has named this building as one of the thirteen most endangered in the State.

Introduction:

Figure 1

In the 1960's, many businessmen pondered over the possibility of bringing and national baseball team to Houston, Texas. However, the challenges in Houston appeared to be insurmountable, not from the point of view of patronage and fan support for the game, but from the vagries of weather coupled with heat, humidity and mosquitoes that certainly does not make either playing or watching such ballgames an enjoyable experience. However, one business man dared to dream about a fully air-conditioned stadium that had never been done before. This man was Roy M. Hofheinz (1912-1982), a Houston politician and entrepreneur (Figure 1). He had the distinction of being the Harris County judge from 1936 to 1944, and then mayor of Houston from 1953 to 1955. After serving as the Harris County judge, he became known as Judge Roy Hofheinz for the rest of his life.

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Judge Roy Hofheinz and his business partner, Robert (Bob) E. Smith created the Houston Sports Association with the goal to get a major league franchise in Houston. In order to build the world's first air-conditioned stadium, Houston Sports Association needed the Harris County voters to approve a public bond issue planned for February 1961. This was a daunting task considering that Judge Roy Hofheinz and Bob Smith needed the support of African American voters. They decided to elicit help from Mr. Quentin R. Mease, a World War II Air Force veteran and one of Houston's most respected and influential African Americans. Mr. Mease and the other African American leaders agreed to campaign for the bond issue on the condition that the new stadium be opened as an integrated facility. This had become an important issue since it was only in 1960 that various lunch counters in Houston had become integrated. Judge Roy Hofheinz and Bob Smith both agreed to Quentin Mease's condition, and the bond issue of $42,000,000 was passed to pay for the project.

Once the commitment was made for the new air-conditioned stadium, the Houston Sports Association got its major league franchise, the Houston Colt 45's that played in a temporary stadium adjacent to the Astrodome.

Project Name and Design Team:

This new stadium, owned by Harris County was called the "Harris County Domed Stadium" during its design and construction phase. The design team that is credited for this facility is:

Architect:	Lloyd & Morgan and Wilson Morris Crain and Anderson
Consultants:	Praeger • Kavanagh • Waterbury, Engineers, Architects, Consultants
Structural Engineer:	Walter P. Moore and Associates, Inc.
Mechanical/Electrical/Plumbing Engineer:	I.A. Naman & Associates / Dale Cooper and Associates
Consulting Engineers:	J.G. Turney / Lockwood, Andrews & Newnam, Inc. / Bolt, Bernaek & Newman

The General Contractor for the stadium was H.A. Lot

Basic Information on the Domed Stadium:

The stadium is architecturally a domed circular concrete and steel framed building with an adequate playing field for both football and baseball. The building covers 9.14 acres (398,138 square feet) of land. The diameter of the domed roof is 642 feet, and the outer diameter of the stadium itself is 710 feet. The playfield diameter is 516 feet. Vertically, the stadium has nine levels. Level one is the field level and contains principally the exhibition spaces and mechanical and electrical rooms. Level two is devoted to mechanical equipment, dressing rooms, locker rooms, concession areas, offices for athletic teams and moveable stands. Level three has the administrative offices, local team offices as well as storage areas, mechanical areas and ticket booths. Level 4 functions as the main seating level with concessions spread around in various location. Level 5 has box seats, press and television spaces and concessions. Level 6 has luxury box suites. Level 7 has box and grandstand seats which is the second largest seating area. Level 8 has the low roof area in the original design which was converted to more seating area in the expansion project in 1989. Level 9 has the skybox seating level 107 feet above the playfield level.

The playfield has an elevation of 33 feet which is 207 feet below the level of the dome framing. The dome has a rise of 93 feet. Generally, the level around the perimeter of the stadium (parking area) is at an elevation of 57 feet. The playfield level is thus 24 feet below the grade level. A ramp to the field level is provided in centerfield.

For baseball, the distance from home plate along the foul lines is 340 feet, and to dead center, the distance is 405 feet. For football, the field is regulation size, and the areas normally black for baseball are covered for football. As designed originally before the 1989 expansion, the seating for various events was:

Baseball:	45,772
Football:	52,382
Boxing:	66,000
Conventions:	55,000

Even though this paper focuses on some structural challenges, it will be interesting to note that the stadium is cooled and heated using equipment with approximately 6,000 tons of cooling capacity and circulating approximately 2,000,000 cubic feet of air per minute. Fresh air intake is approximately 200,000 cubic feet per minute. Smoke and hot air are both expelled at the top of the dome.

Material Quantities:

Information obtained from the general contract for construction indicated the following quantities used in construction:

- Earthwork, including excavation and backfill: 250,000 cubic yards
- Cast-in-place concrete: 40,000 cubic yards
- Reinforcing steel bars: 2,500 tons
- Structural steel
  - a. General stadium framing: 6,000 tons
  - b. Dome structure: 3,000 tons
- Pre-stressing tendons: 25,000 lineal feet

Structural Cost:

In terms of the 1960's dollars, the structural cost of the stadium was as follows:

- Stadium: $9,300,000
- Dome: $1,500,000

Structural Challenges:

1. Dome Structure: This is the most spectacular element of the stadium, and has been a big attraction for the past 40 years. So much depended on the selection of the framing and covering of the dome roof structure. First and foremost were the cost, and then the aesthetics. How this will affect the air-conditioning and air flow was also a major consideration. There was also a keen desire to successfully grow grass in the stadium as well. No prototype was available to draw on for guidance and to learn from past experiences. Decision was then made by Harris County in consultation with the architects involved, that competitive design proposals be received from interested firms that had experience and expertise in long span roof structures provided the designs conformed the their specifications.

   The minimum design criteria for the dome as given in the specifications were as follows:

   - Live Load: 15 PSF
   - Sonic Boom Loading: 2 PSF
   - Wind Load: 40 PSF or load from wind tunnel test using sustained wind velocity of 135 mph with gusts of 165 mph.
   - Dead Load:
     a. Self weight of structure
     b. 3 inch thick Tectum deck on bulb tees with plastic skylights

The specifications also required that a 1/8 scale model test be performed in a wind tunnel to verify wind forces on the dome structure. The wind tunnel test was conducted by McDonnell Aircraft Corporation in St. Louis, Missouri (Figures 2, 3 and 4). Results of the tests were independently evaluated by Herbert Beckman, Aerodynamicist, Dr. Ing, Professor of Mechanical Engineering, Rice University, Houston, Texas. In his report dated 9/29/61, Dr. Beckman wrote: "During the tests, the model is subjected to a steady air stream while hurricane winds consist of small grain turbulence with a gust diameter of usually not more than 100 or 200 feet. These gusts will result in only partial loading of the building, and as a consequence, are less effective than a steady wind would

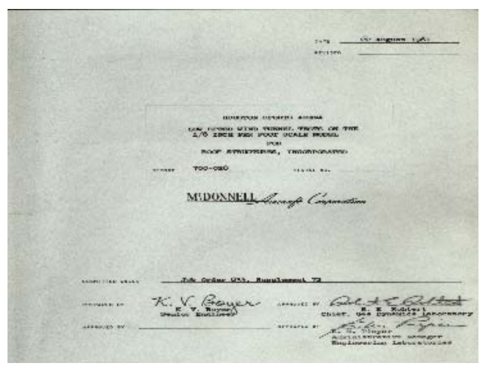
McDONNELL Aircraft Corporation
K. V. Boyer

Figure 2

Figure 3

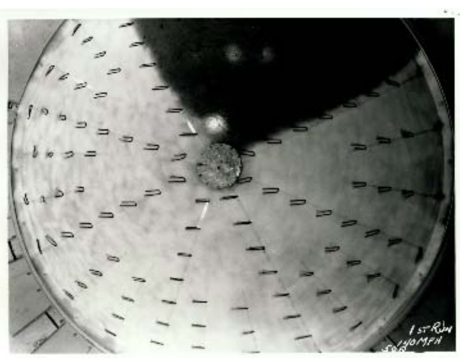

Figure 4

be. The wind tunnel data can be considered to give "conservative" loads compared with corresponding flow conditions in hurricanes."

Reactions on the dome support columns using the wind tunnel test results were very close to the reactions computed manually by Mr. Louis O. Bass of Roof Structure, Inc. Credit for the design work on the dome roof structural goes to Dr. G.R. Kiewitt and Mr. Louis O. Bass of Roof Structures, Inc.

The dome roof pressure contours obtained from the wind tunnel tests, and the simplified pressures used for the design of the dome roof are given in Figure 5.

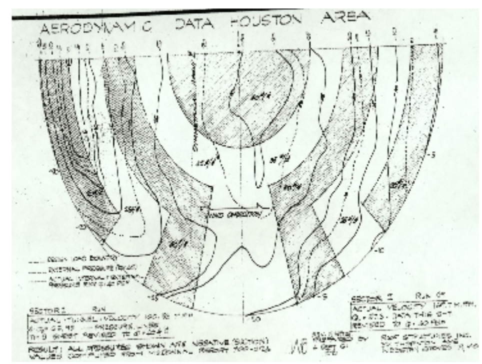

Figure 5

The lamella dome structure has a diamond shaped pattern on the spherical surface. The arch ribs or ring members are steel trusses having an overall depth of 5'-6". The top and bottom chord sizes vary from WF 16 x 58 to WF 16 x 78. The web members are two angles 3-1/2" x 3-1/2" x ¼". The short lamellas between ring members are also steel trusses 5'-6" deep. The top and bottom chords of these trusses vary from WF 14 x 30 to WF 14 x 53. In these trusses also, the web members are two angles 3-1/2" x 3-1/2" x ¼". The lamella dome framing is supported on a tension ring which is also a truss 5'-6" deep. The top chord of this highly stressed member is WF 14 x 370, and the bottom chord is WF 14 x 314. Once again, two angles, 3-1/2" x 3-1/2" x ¼" were used as web members in the tension ring also. All structural steel used in the lamella dome structure was ASTM A36 steel. Connections between the various elements of the lamella framing were made using ASTM A325 bolts. All welding was done using AWS E7018 electrodes. Continuity in the top and bottom chord members of the tension ring was provided by using full penetration butt weld splices (Figure 6).

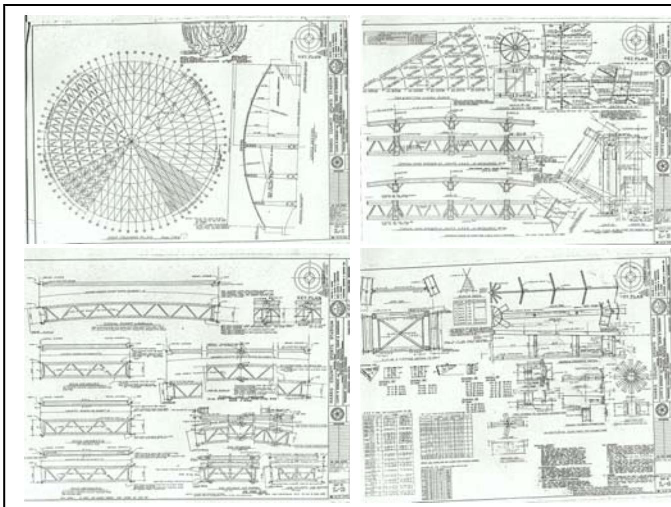
Figure 6

The erection of the dome framing required the fabrication and erection of 37 steel tower (Figure 7). The erector placed the dome framing in pie sectors in opposing pairs, there being twelve sectors of thirty degrees each (Figure 8). The erection of the steel presented some problems since it was a criteria that at a temperature of 60 degrees Fahrenheit, and with the dead loads applied, the tension ring should stay vertical. Jacks were placed at the top of the

Figure 7

erection towers to make the adjustments as the erection progressed. After the alignment was confirmed and all connections were made, the plan was made to remove the jacks in the early days of 1964.

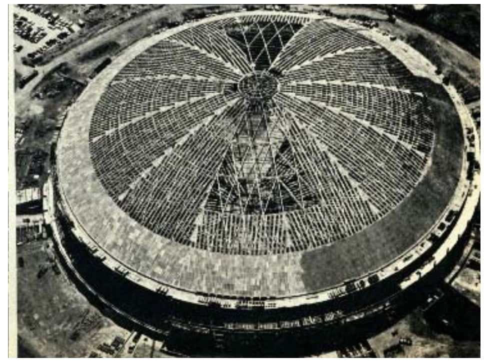
Figure 8

Jacks were gradually retracted over all the towers, and at each lowering, tension ring alignment and supporting column plumbness was checked. However, the results of the plumbness of the columns varied daily. This obviously was of great concern to not only the engineers with Roof Structures, Inc., and Walter P. Moore, but it also made the County Commissioners very nervous. However, after checking and rechecking the monitoring data carefully, and ensuring that there was nothing amiss with the design of the supporting columns, the decision was made to retract the jacks all the way and to set the frame free.

The monitoring work, however, continued in order to verify whether the degree to which the columns were out of plumb stayed constant from day to day. Unfortunately, this number did not stay constant, but varied daily. Several days elapsed before Kenneth Zimmerman (principal author of this paper) figured out that the variation is due to the temperature effects. The columns needed to be checked at the same time on successive days to ensure that there were no variations in temperature. Calculations had been done earlier in the design phase for temperature effects. As such, Kenneth Zimmerman made the comment, “The old girl was behaving just as was predicted!”

2. Dome Deflections:

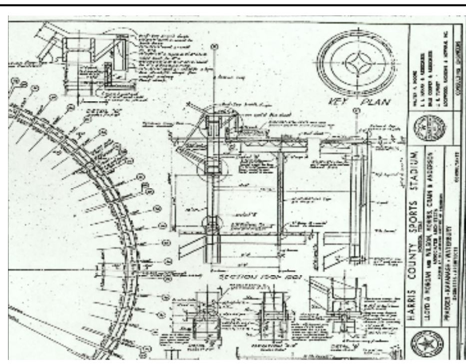
Figure 9

There was a great amount of interest in the deflections of the dome under various load conditions. The dead load deflection was calculated to be 1.88”. When the jacks were released, and the dome was free from all erection towers, the deflection measured was within 0.25”of what was predicted. The live load deflection was predicted to be 0.94”. Considering that the dome was going to be air-conditioned, a temperature differential of 70 degrees Fahrenheit was used above or below the base temperature of 60 degrees Fahrenheit for temperature stresses and movements, which was determined to be plus or minus 1.80”. For the design wind load, the horizontal movement was 5.5”. This posed a challenge to both the architects and engineers on the design of the expansion joint at the edge of the dome. The joint needed to be designed for a total movement of 11”. The design team came up with a very elegant solution which is virtually maintenance free to a large extent. This is illustrated in Figure 9. The solution consisted of a screen attached to the tension ring that extended beyond a concrete curb on the edge of the stadium roof just below the dome. The screen and the curb lap sufficiently that would not allow the rain to blow in the interior, and the curb height was designed to not allow rain water from spilling down the roof edge.

3. Columns Supporting Dome:

The dome structure is supported on steel columns WF 12 x 65 located at every 5 degrees around the perimeter of the dome. These columns had to be designed to permit the movement of the dome structure towards or away from the centroid, but not to allow movement from the tangential shear forces resulting from the lateral wind loading. This was accomplished by using a "knuckled" column design conceived by Kenneth Zimmerman shown in Figure 9. The knuckled columns have 4 inch diameter high strength steel pins at each end of the column. The lower bearing of the pin is welded to its plate support, and the top side is free to rotate in a close-fitted plate with milled surface. Anchorage is provided at the top against uplift with U-bolts.

4. Lateral Wind Loads

The lateral wind loads were resisted by X-braced bents extending the stadium to the foundation. However, in certain areas, it was not feasible to provide X-braced system, so moment frames were used instead. Since there are several expansion joints around the perimeter of the dome structure, each isolated sector had to have its own system of lateral load resistance frames.

5. People Generated Sway Loads:

The rhythmic movement of people in some events was known to cause sway loads in arenas and stadiums. The code required that the stadium be designed for 12 pounds per lineal feet of seating normal to the seats and 24 pounds per lineal foot of seating parallel to the seating. These sway loads were considered additive to the wind lateral forces, and the same system of X-braced frames and rigid frames were used for such forces as well.

6. Codes Used in Design:

It will be interesting to note that all the concrete elements were designed using the working stress method in accordance to ACI 318-56. Ultimate strength design was given a consideration but not used due to lack of complete code coverage at that time. Maximum concrete strength of 3,000 PSI was used in the project. Extensive use was made of light weight concrete for all elements above ground. The slab on grade and basement walls were cast in normal weight concrete. The structural steel design was in accordance with AISC 1959, Fifth Edition. Grade of steel used for both the bowl structure and dome structure conformed to ASTM A36.

7. Foundation Design:

The foundation design for the dome structure turned out to be astonishingly simple. The design was based on the geotechnical recommendations by National Soils Services, Inc. of Houston. Because of the sandy characteristics of the underlying strata, the differential settlements were negligible. Interestingly, 50% of the footings were founded on predominately pure sand located approximately five feet below the play field level. It was only in the ten foot deep combined footings at the expansion joints where some wet conditions were encountered. This was remarkable given the fact that the original water table was at an elevation of 44 feet, the playfield elevation was at 33 feet, and the bottom of the deepest excavation was at an elevation of 25 feet. The water table was lowered by the use of well point system designed by Lockwood, Andrews & Newnam, Inc. ahead of the general construction work.

8. Perimeter Retaining Walls:

For about 60% of the perimeter, the retaining wall extends from the first level to the fourth level for a height of thirty-three feet. The other 40% of the perimeter wall extended from the first to the third level for a height of twenty-five feet. Three concepts were developed to design the walls:

a. Counterfort system
b. Wall braced to interior column footings by diagonal struts, and horizontal struts between footings
c. Tie-backs using pre-stressing strands to dead-man anchors around the perimeter of the dome structure.

Cost comparison of the three different schemes indicated that the system using tie-backs and dead-man anchors was the most economical.

In order to reduce the lateral earth pressure against the retaining walls, a drained sand backfill was used. The geotechnical engineer computed the lateral equivalent fluid pressure to be 30 PCF.

All walls were designed to span horizontally, with tie-backs placed at 2.5 degrees around the perimeter. Two levels of tie-backs were provided such that the positive wall moments and the negative wall moments were approximately equal. The lower tie-back was placed close to the footing, and the second tie back was placed close to the mid-height of the wall.

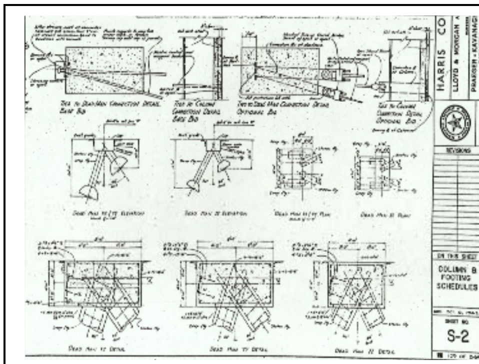

Figure 10

Strands used were 0.25” in diameter. The distance from the wall to the dead-man anchors was approximately 80 feet. The system used is shown in Figure 10. Since the strands needed to be buried in the soil, there was a serious concern about the possibility of corrosion over the years, and the resulting loss in cross section of the strands. As such, a decision was made to use the cathodic protection system to protect the strands from the corrosive effects of the soil. This cathodic protection is still operational as of this date.

Conclusion:

At the time the domed stadium was completed, the United States had entered into the space age with the NASA facility located in Houston. The prefix "Astro" had started becoming very popular that become synonymous with gigantic. Judge Roy Hofheinz renamed the Houston Colt 45's to be the Astros, and the Harris County Domed Stadium became known as the Astrodome. The dream that Judge Roy Hofheinz had become a reality, and he branded the Astrodome as the "Eighth Wonder of the World"! (Figure11).

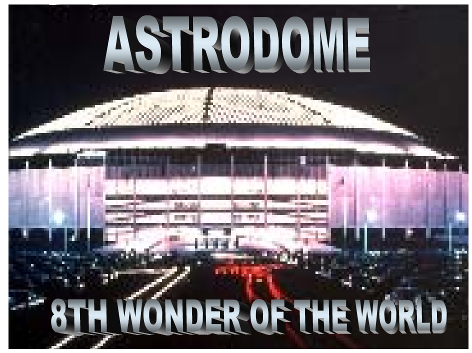

Figure 11

Acknowledgements:

Several of the photographs used in this paper are from the archives of Houston Sports Arena and Houston Chronicle.