Application of MSC/NASTRAN to Design and Analysis of SPACESHIP EARTH

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SPACESHIP EARTH is the central pavilion of Disney's latest showcase, Epcot Center, at Walt Disney World in Orlando, Florida. It is the home of a ride and show depicting the history of communications. The structure is a complete geodesic sphere, 160 feet in diameter, elevated 14 feet above the ground, and supported by six legs.

For orientation purposes we can divide the structure into two parts: the utility structure and the sphere (See Figure 1). The utility structure consists of the six support legs; a platform, hexagonal in plan, formed by six vertical planar trusses connecting the tops of the legs; the ride and show helix supported on the platform; and the ride entrance. The sphere consists of an inner structural spherical framework carrying closure panels and covered with a weatherproofing neoprene sheet; an aesthetically pleasing outer sphere, formed by panels, and supported by the structural sphere; and a transition structure between the sphere and the hexagonal trusses which serves to support the sphere. The focus here is on the design and analysis of the structural sphere and the transition structure.

STRUCTURAL SPHERE

The structural sphere is formed by 1363 struts, connected at 497 hubs in a triangular pattern. The struts are of eight different lengths ranging from 12 to 16 feet. The struts are fabricated from A572 Grade 50 steel wide flange sections of three sizes: W10X22, W10X33 and W10X45. The W10X45 sections are located in two tiers directly above the supports hubs for the sphere, followed by two tiers of the W10X33 sections. The top of the sphere and that portion of the sphere located below the support hubs are framed with W10X22 sections. The struts are bolted together at hubs consisting of two dished circular plates. The triangular space between struts is spanned by closure panels. These panels are supported on the struts and their connections to the struts are so designed that the panels do not participate in the gross structural action of the sphere. The cosmetic panels of the outer sphere are supported on aluminum standoffs at each hub.

The sphere is supported by the hexagonal trusses through 30 quadrupods. The quadrupods are pyramidal structures, each formed by four 8 inch diameter steel pipes. The apex of the quadrupod is connected through a support hub to the sphere. Two of the quadrupod legs are bolted to panel points of the top chord while the other two legs are bolted to panel points of the bottom chord of the hexagonal trusses. Thus the vertical load from the sphere is carried by the hexagonal trusses, while the horizontal load and kick loads in the quadrupods are resisted by the concrete decks at the levels of the top and bottom chords of the trusses. There are 14 different quadrupod types. Due to the geodesic geometry the elevation of the support hubs undulates. A schematic plan view of the system of quadrupods forming the transition structure is shown in Figure 2. A quadrupod in elevation is shown in Figure 3.

The support hubs which join the quadrupods to the structural sphere are complex weldments of steel plate. They consist of a spider of six plates welded to a circular, dished outer plate, a series of plates parallel to the outer plate for field welding to struts, and web plates for connecting to quadrupod pipes. A support hub is shown in Figure 4.

LOADS

The structural sphere is designed to resist dead load and wind loads. The Orlando area is seismically inactive and the live loads on the sphere were considered insignificant. The live loads applied to the ride and show structure, however, were considered since the platform, which supports the ride and show structure, is connected to the structural sphere via quadrupods. The dead load of the ride and support structure was not considered since this structure would be completed before erection of the sphere could begin.

The dead load consists of the sphere struts and hubs, the closure panels and the cosmetic panels.

The distribution of wind pressures over the surface of the sphere was determined from a 1/192 scale model tested in the Wright Brothers Memorial Wind Tunnel at the Massachusetts Institute of Technology. The model included not only the sphere of SPACESHIP EARTH but also the surrounding buildings and a part of the monorail. Because of the asymmetries introduced by the surrounding structures the wind was blown over the model from 24 directions evenly spaced around the compass. Pressures were measured at 285 taps on the model of the sphere.

The sphere is designed for a wind speed of 125 mph. This design wind speed is based on weather data collected at the Orlando airport and engineering judgement. The wind pressures were considered a static load.

SELECTION OF STRUCTURAL ANALYSIS COMPUTER PROGRAM

In the selection of the structural analysis program for use in the design and analysis of SPACESHIP EARTH, the following analysis requirements and design procedures were considered.

- The program should be capable of performing a static analysis of a three dimensional framework.

- Previous experience with the design of geodesic domes for the United States pavilion at the 1967 World's Fair in Montreal and a temporary cover at the construction site of a nuclear power plant suggested that overall stability would not drive the design of the structural sphere. However, such a stability analysis could not be completely ruled out. Hence, the capability to perform a linear buckling analysis of the sphere was considered to be desirable.

- The design and analysis of SPACESHIP EARTH would be performed by two branches of Simpson Gumpertz & Heger Inc. The sphere and transition structure would be designed at the Cambridge office and the utility structure at the San Francisco office. Since a strong interaction between the sphere and the utility structure was envisioned, the possibility of using one analysis model for both design efforts was considered. Hence, substructuring capability was also considered desirable.

- SPACESHIP EARTH is designed according to the AISC Specifications for the Design, Fabrication and Erection of Structural Steel for Buildings. It was envisioned that the evaluation of members for stresses and stability would be performed by a separate program. Hence, the ease with which member loads could be output in a form suitable for post processing was of great importance.

- From the outset, the design team was concerned with the geometric complexity of the transition structure which bridges geodesic and hexagonal geometries. The team envisioned that plots of portions of the sphere and transition structure, derived from the structural model, could help the design process and the preparation of contract plans. Thus, a versatile structural plotter was also of great importance.
- Previous experience with the program was important.

MSC/NASTRAN was selected for the design and analysis of the structural sphere for the following reasons.

- Members of the design team had extensive experience in the application of MSC/NASTRAN to complex structures.
- Of the structural analysis programs that members of the design team were experienced with, only MSC/NASTRAN had the buckling analysis capability.
- The structural plotter of MSC/NASTRAN was considered superior.

STRUCTURAL MODEL

The basic geodesic sphere has a six cycle symmetry. However, the cyclic symmetry is destroyed by the penetrations for the legs, the ride tube and elevator. Consequently, the structural sphere has reflective symmetry about a vertical plane which contains the center line of the ride tube. The structural model of the sphere, therefore, included one half of all the members of the sphere, the transition structure, and the hexagonal trusses. These members were modeled as beams with all six degrees of freedom. The model included 1067 CBARs connected at 405 GRIDs. The geometry of the sphere was specified in a spherical coordinate system and each hexagonal truss was specified in a separate cartesian coordinate system. Displacements were computed in the same coordinate system that was used to specify the geometry. The model was supported at points representing the tops of the support legs.

Card images for specifying dead and wind loads on the model were computed by a program specifically written for this structure. The input to the loads program consisted of the GRID, CBAR and PBAR cards from the MSC/NASTRAN input file, current estimates for the unit weights of the closure panels and the cosmetic panels, the location of the pressure taps on the model of the sphere, and a tape containing the wind pressures measured on the model sphere in the wind tunnel. The dead loads part of the program output a file containing PLOADI cards for the weight of the struts, FORCE cards for the weight of the cosmetic panels and hubs and PLOADI cards defining a triangular distribution of load on the struts due to the weight of the closure panels. The wind loads part of the program integrated tap pressures over the tributary area of a hub to compute a load at the hub normal to the surface of the sphere. The progam also broke down this load into its symmetric and antisymmetric components and output a file of corresponding FORCEI cards.

At first, the wind loads program output PLOADI cards representing triangular distributions of load over the span of a strut. However, the resulting number of PLOADI cards (675 members, 2 cards for each member, 4 wind directions each with symmetric components and 2 wind directions with antisymmetric components) exceeded the capability of MSC/NASTRAN on a CDC Cyber 175. This was not a serious setback because bending, caused by loads on the span of a strut, turned out to be critical only for a handful of struts, which were easily evaluated by hand calculation. Consequently, wind loads were applied at the hubs as concentrated loads via FORCEI cards as described above.

The wind loads program also output the lift and drag coefficients of the sphere for each wind direction.

ANALYSIS METHOD

Very early in the design cycle it became apparent that two separate structural models, one for the sphere and the other for the utility structure were more convenient and the interaction between the two models could be adequately accounted for by including the hexagonal trusses and the loads on them in both models. The structural model of the sphere was analyzed for 8 separate load conditions, one dead load, one live load and 6 wind load conditions. These load conditions were superposed in 5 combinations. Buckling analyses were not performed because a hand calculation estimated the factor of safety against buckling to be about five.

For each load case analyzed, MSC/NASTRAN output the member loads on a file for post processing. The post processing program was written to evaluate stresses and stability of the struts for compliance with AISC Specifications for Design, Fabrication and Erection of Structural Steel for Buildings. The input to this program, besides the file of member loads, included the GRID, CBAR, and PBAR cards from the MSC/NASTRAN input file, the number and size of bolts at each end of the strut and the yield strength of the steel. The output for each end of each strut consisted of the stress interaction number, the contribution to the stress interaction number from the axial load and the bending moments about two axes, and the shear on each bolt. Members whose interaction numbers exceeded a set value were flagged.

CONTRACT DRAWINGS

The structural model together with the MSC/NASTRAN plotting capability proved to be effective in reducing the cost of preparing contract drawings. The plans showing the 14 different quadrupods in plan view and elevation were prepared with the aid of plots derived from the structural model. Two plots were made of each quadrupod, a plan view and an elevation view perpendicular to the hexagonal truss. These plots were made to the desired scale and included the four members of the quadrupod, the six struts of the sphere framing into the support hub and a few members of the hexagonal truss. The draftsman traced these plots onto the drawings to establish the centerlines of the members and then completed the views in the standard way. An elevation view of a quadrupod taken from the contract plans is shown in Figure 3. This approach saved the draftsman the job of computing, from a complex geometry, the required dimensions and angles. Linear dimensions and angles needed to adequately describe the quadrupods and their connection to the hexagonal trusses, and also the support hubs, discussed below, were computed by a program which used MSC/NASTRAN GRID and CBAR cards as input.

A similar approach was taken in the preparation of drawings for the 14 different support hubs. Again two plots were made of the four members of a quadrupod and the six members of the sphere framing into each support hub: a view normal to the surface of the sphere and an elevation view in a plane containing the center of the sphere. Two views for one support hub, taken from the drawings, are shown in Figure 4.

Plots derived from the structural model were helpful in preparing drawings for the special framing of the sphere near the penetrations for support legs, ride entrance and elevator.

The schematic key plan of the system of quadrupods, shown in Figure 2, was also traced from a plot. Plots of the complete sphere were used by the architects as key plans for the location of the gutter and service ladders.

CLOSURE

MSC/NASTRAN was of immense help in the design, analysis and preparation of contract plans for SPACESHIP EARTH. The MSC/NASTRAN input file for the structural model served as partial input to several preprocessors and postprocessors, which greatly simplified the analysis of this unusual structure.

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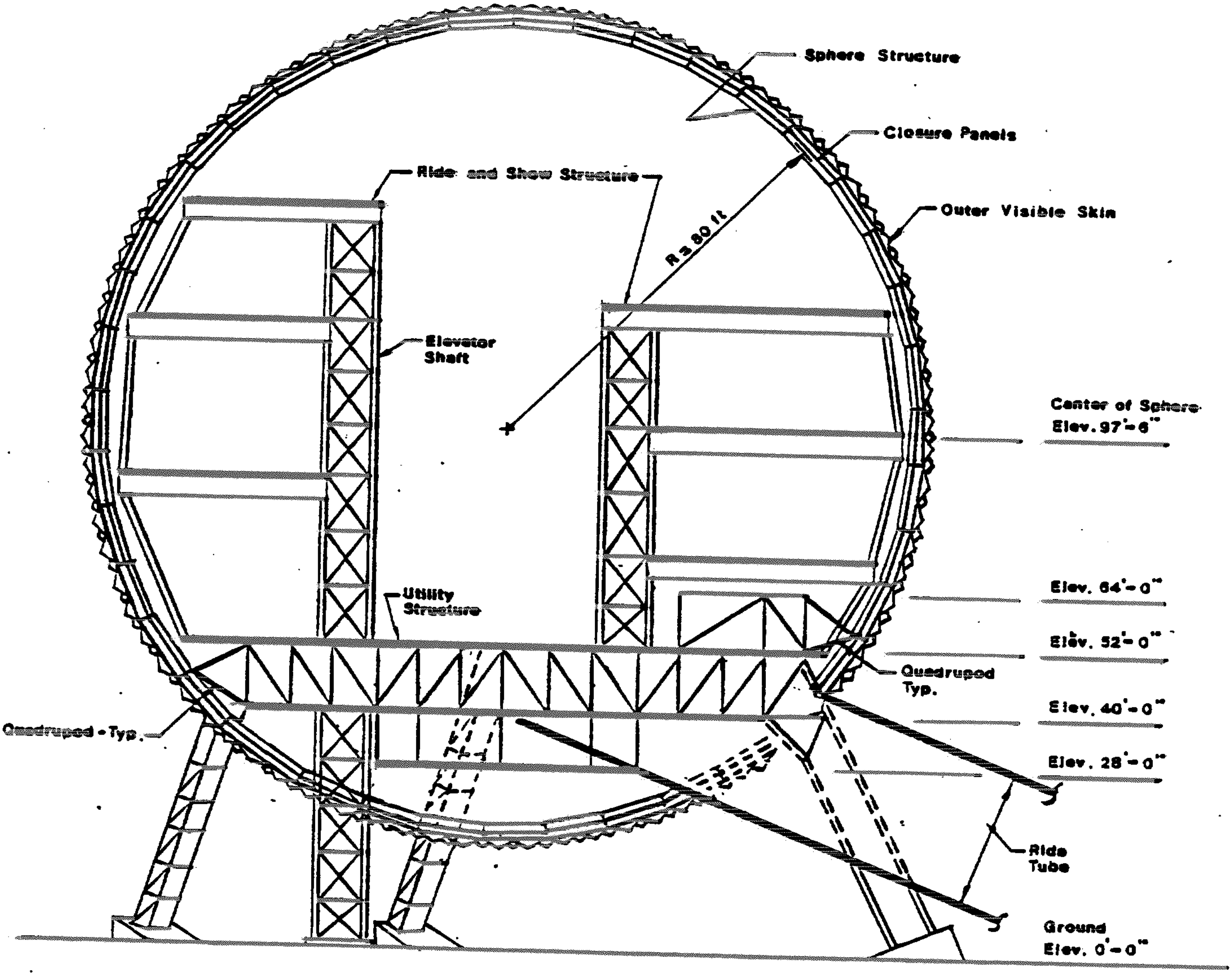


FIGURE 1

NORTH-SOUTH SECTION THROUGH SPHERE

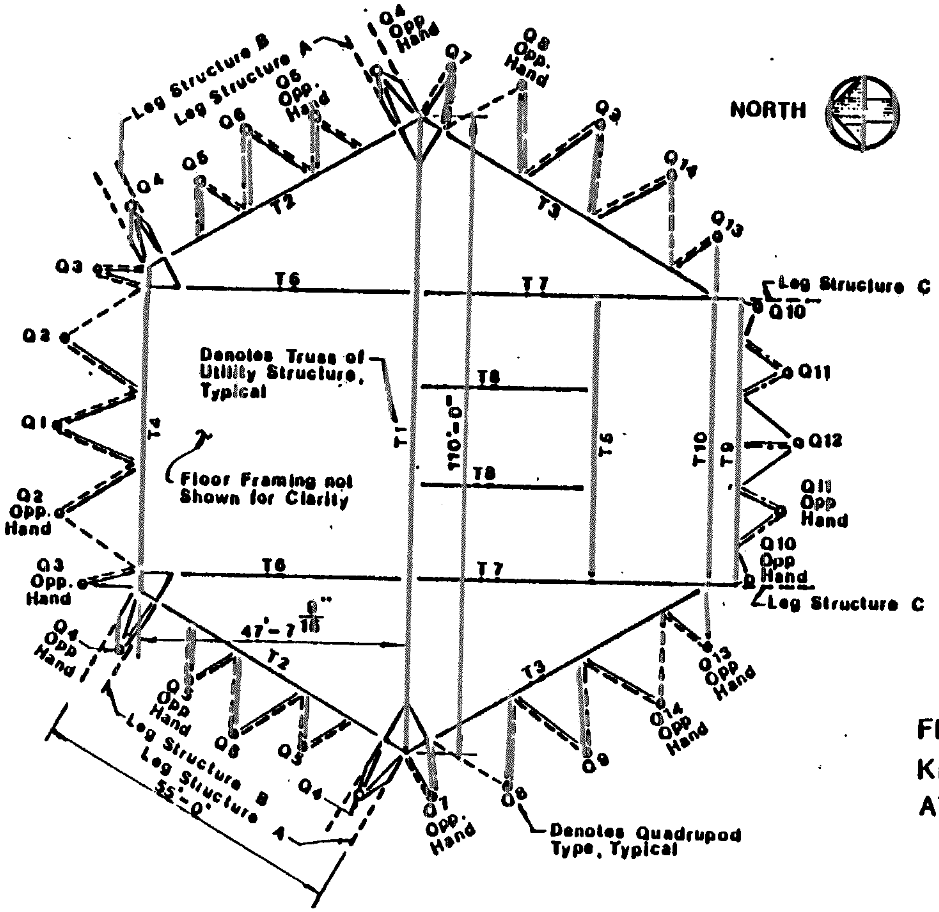


FIGURE 2
KEY PLAN FOR TRANSITION STRUCTURE
AT ELEVATION 52'-0"

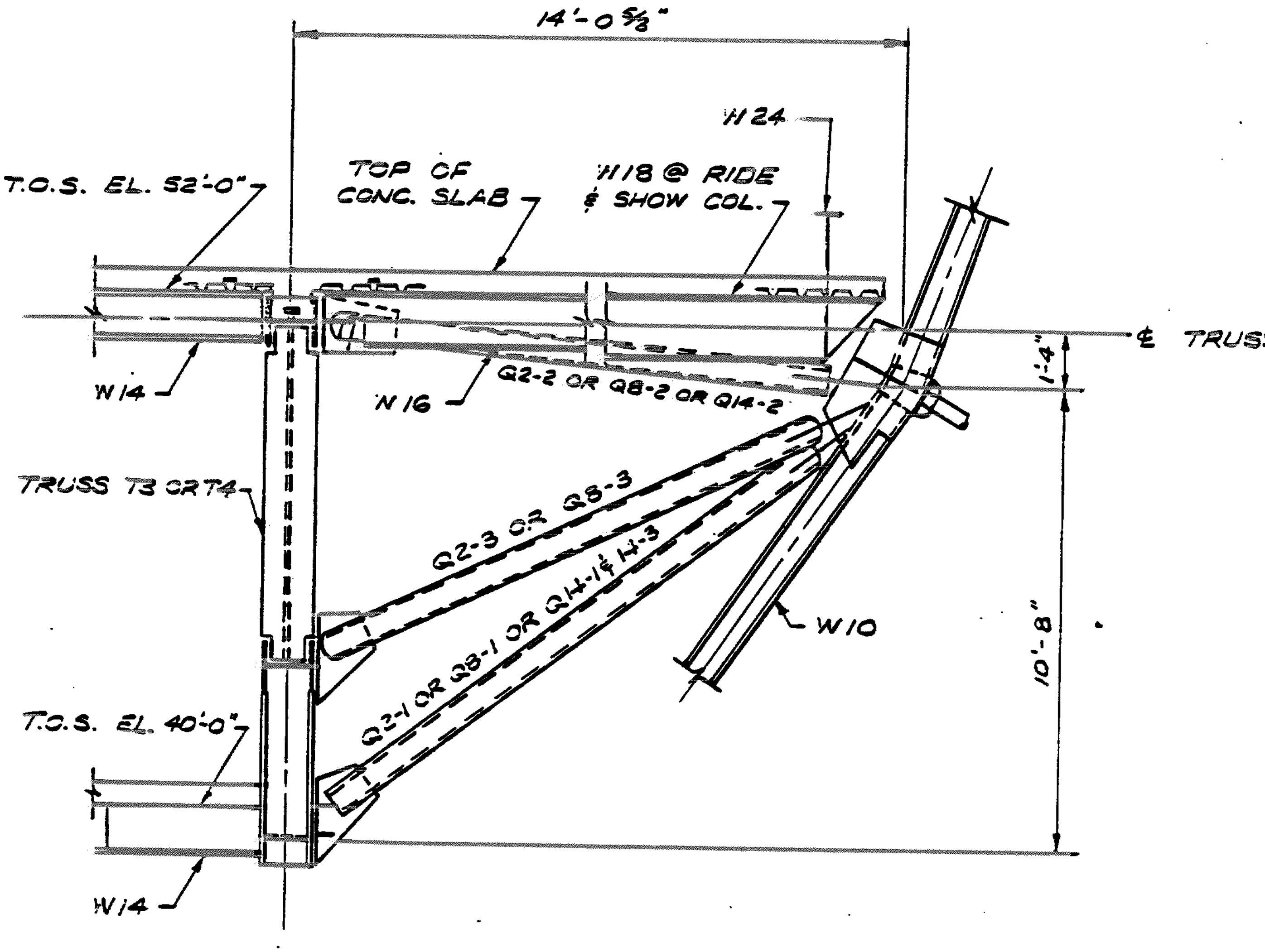
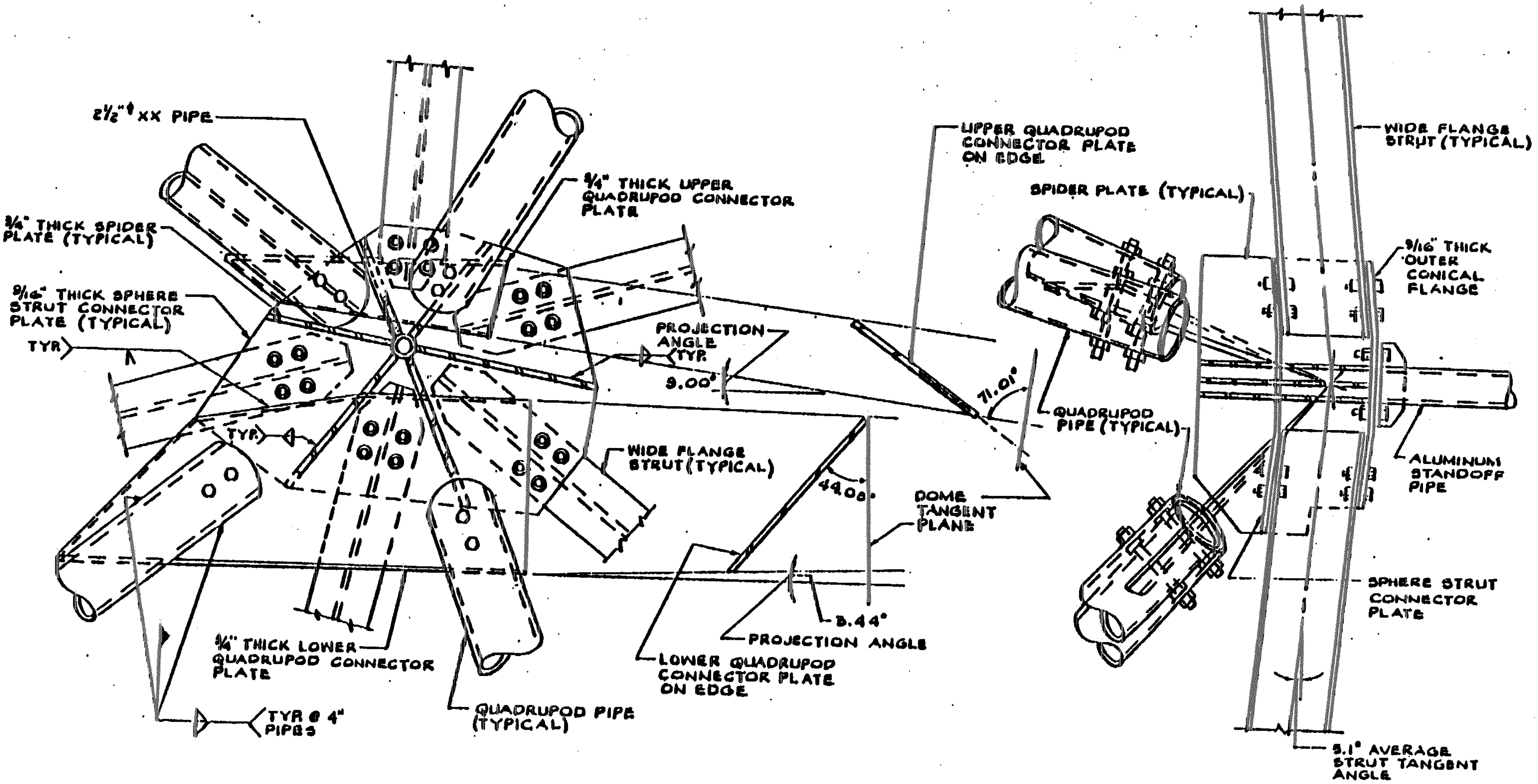


FIGURE 3
ELEVATION OF QUADRUPOD



PLAN

SUPPORT HUB Q11
RADIAL VIEW FROM CENTER OF SPHERE

SECTION

SUPPORT HUB Q11
TANGENTIAL VIEW

FIGURE 4
SUPPORT HUB