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Structural Fatigue in the 34-Meter HA-Dec Antennas

R. A. Van Hek and B. P. Saldua
Ground Antenna and Facilities Engineering Section

Structural modifications to the 34-m hour-angle-declination antennas, coupled with the use of the antennas beyond their intended lifespans, have led to structural fatigue, as evidenced by damage to the declination drive gear and cracks on the structural members and gussets. An analysis and simulation were made of the main antenna structural members. The analysis showed that the total stress to the antenna structure substantially exceeds the maximum levels recommended by the American Institute of Steel Construction (AISC). Although each of the separate static conditions of stress is only 50 percent of the total stress and does not reach the AISC reduced yield limit, fatigue can and did occur, causing the material to crack in the weakest places.

I. Introduction

Three 26-m hour-angle-declination (HA-dec) antennas, designed for a lifespan of 20 years, were built in the early 1960s for the National Aeronautics and Space Administration's (NASA's) Deep Space Network. After 16 years of operation, the antennas were upgraded to support near-term and planned flight-project missions to outer planets. The upgrade increased the diameter of the antennas from 26 m to 34 m, improved surface dish tolerances, and added X-band receiving capability. The antenna modification was called the 26-Meter Antenna S-X Conversion Project [1].

The design required a structural weight increase of about 50 percent in both the HA and dec structures to achieve the desired improvements. In addition, counterweight was added to balance the rotating structures. The total added counterweight on the dec wheel amounted to 200 percent of the initial weight. The HA wheel also had a substantial weight increase. Because of these weight ad-

ditions to the original design and the tracking mode of the reflector, many stress-reversal conditions occurred in the structure. These stress reversals eventually caused "fatigue" in some areas. These fatigue conditions are discussed in this article.

II. Structural Modifications to the Original Design

Prior to the 34-m conversion, other modifications were made to the antennas that required increases in counterweight on both wheels. An S-band improvement in the mid-1960s consisted of the following changes:

- (1) The prime focus feed was changed to a Cassegrainian feed system.
- (2) A feedcone and subreflector were added to the reflector and apex.
- (3) A dewar hoist was added.

- (4) Surface panels were replaced with stiffer panels.
- (5) Counterweight was added to rebalance the structure.

The S-X Conversion Project, which was initiated in 1978, consisted of the following changes:

- (1) The outer ribs in the reflector were replaced with longer and stiffer ribs to increase the diameter to 34 m.
- (2) The inner structure was reinforced to increase stiffness.
- (3) The quadripod structure was replaced with a truss-type apex and legs to accommodate a more accurate subreflector.
- (4) The surface panels were replaced with S-X compatible panels.
- (5) The subreflector was replaced with a three-axis dual-function tilttable subreflector positioner.
- (6) The existing feedcone was replaced with a dual-frequency cone with dichroic plate and ellipsoid reflector.
- (7) Stiffening members were added to the hour-angle and declination wheel structures as well as to the pedestal frame.
- (8) Counterweight was added to both the hour-angle and the declination wheels.
- (9) The existing hydraulic drive was replaced with a new electric drive system, including drive skids.
- (10) Cable trays were added and new cables were provided to the feedcone and to the subreflector.

Before the S-X conversion modifications were made, an extensive optimization design was made of the structure with the aid of JPL Iterative Design of Antenna Structures (IDEAS) [2]. An extensive study was also performed on the bolted connections. All joints were checked for stiffness and acceptable stress levels. One major result of the study was the decision to stiffen all the bolted connections by welding all the structural joints, changing the original pin-jointed space frame to a rigid frame. Because of this structural joint stiffening, some members are now subject to end moments in addition to the axial forces; these stiffer joints reduce the structural deflections. Subsequently, the antenna movements cause stress reversals as well as reversal of moments in the connections.

The structural stiffness of the various subassemblies could not be maintained with the individual member stiffening due to the added weight. Additional accuracy was obtained by the conversion to a Cassegrainian system and by setting the panels at a specific antenna position.

Although extensive stiffening took place, the addition of all the counterweight caused large deflections in the declination wheel, although this did not affect the pointing accuracy.

After the S-X conversion was completed, regular antenna maintenance was increased, including the periodic inspections.

III. Antenna Structural Problems

The antenna structural problems all originated from the additional counterweights on the antenna, beyond the design-calculated amounts, that were required to balance the antenna structure. These additional weights resulted in increased forces acting on the antenna structure during operation and have led to the problems described below.

A. Gear-Mesh Separations

One of the most serious problems with the antenna is the excessive declination-axis bullgear-to-pinion separation that occurs as the antenna is moved from the east to the west horizon. The gear mesh separates when the reflector points to the horizon because the counterweight bends the rim and gear downward, causing a large deflection of the declination wheel. This reduced gear-mesh engagement has twice sheared off the pinion teeth at the DSS 12 antenna and three times at the DSS 42 and 61 antennas (Figs. 1 and 2). The gear-mesh separation increases during high winds, so the antennas are currently stowed before the wind reaches 45 mph.

B. Hour-Angle Bearing Deterioration

There are two bearings on the hour-angle shaft, the upper and the lower bearings. The lower bearing was designed with plenty of safety margin (of 2.5:1 in fact), while the upper bearing had a design safety margin of only 1.12:1. Because the antenna needed more counterweight than the design indicated, the actual safety margin was reduced to 0.98, and this margin decreased even further to 0.95 in winds of 30 mph. There has been excessive wear and denting in the bearing race for all three antennas. Fortunately, the slow speed of the antenna (approximately two revolutions per day) has made this bearing damage tolerable. However, analysis and observation indicates that the risk of bearing failure is increasing with use.

C. Structural Failures

Until March 1989, no major problems were found on the HA-dec antenna structures except for small weld cracks and occasional sheared and loose bolts, mostly in the secondary members and their connections. In April 1989, additional cracked welds were discovered in more significant areas (e.g., see Fig. 3), but action was postponed until after the planned annual inspection in July 1989. A close watch was kept to see if the cracks were getting worse, and this continued until the annual inspection.

On the day of the annual inspection, May 25, 1989, a major failure was discovered at DSS 12; it must have occurred between April and May 25. The failure occurred in a gusset plate near the declination bearing. There are four such plates, and a crack developed in three of the four plates. The gusset plates connect primary members from the wheel rim to the bearings; these members support the weight of the counterweight and the dec house when the antenna is looking east or west (Figs. 4 and 5). The longest crack was 4 in. long (Figs. 6 and 7), while the two other cracks were only 0.5 in. long. All the cracks looked recent. (Note that the cracks were very similar to the gusset plate crack that caused the NRAO 300-ft antenna to collapse.)

Immediate action was taken to repair the gussets and reinforce the structural connections (Fig. 8). All minor repairs were also made at this time.

IV. Analysis and Results

An analysis of the declination-wheel structural failures was made by the Ground Antenna and Facilities Engineering Section's Structural Group. The IDEAS finite-element model of the HA-dec antenna that was used in the original S-X conversion design was resurrected to find the maximum member forces for a 1.0-*g* loading in the X, Y, and Z axes. To determine whether the critical stress level was reached, member forces from the computer output were postprocessed in an HP 41C programmable calculator to obtain maximum and minimum forces in the structure for any combination of declination and hour angle. For an hour-angle/declination-angle axes-combination configuration, the angle between the gravity vector and the principal axes of the structural model becomes a function of the declination, hour, and latitude angles [3].

Specifications and loading conditions for A-7 steel with an ultimate yield strength of 33,000 psi were used (Fig. 10). Three loading conditions were applied to simu-

late three different positions of the antenna (Fig. 9). The loading conditions that were simulated are the following:

- (1) The reflector points at zenith and the declination wheel is vertical. Gravity loads in the Z direction.
- (2) The reflector points at the east or west horizon and the declination wheel is horizontal. Gravity loads in the X direction.
- (3) The reflector points at the south horizon and the declination wheel is vertical. Gravity loads in the Y direction.

The worst stresses occurred in loading condition (2) because a reversal of loads at the east or west position caused a reversal of stress in the members and their connections, which are the gusset plates. Thus the gusset plates are subject to stress reversals from (1) combined compressive stress plus bending stress due to eccentricity and (2) combined tensile stress plus bending due to eccentricity.

In addition, even if the critical stress levels were never reached, repeated loading and unloading might eventually result in failure. This phenomenon is known as "fatigue." In condition (2), where the loading is reversed from tension to compression and back again with an additional eccentricity in the connection causing a bending stress, fatigue is likely to occur. In fact the cracks in the plates occurred adjacent to the welding, where the parent material was weakened by weld undercuts.

The American Institute of Steel Construction [4] provides fatigue design parameters for most connections. The DSN HA-dec antenna structure falls under Category 1, which applies for a minimum of 20,000 cycles. This is equivalent to two applications per day for 25 years. (The DSN HA-dec antennas are now 27 years old.) The plate or gusset connection conforms to loading Condition 1 of Category E, where the allowable range of stress is 19,250 psi. The actual total stress from cyclic conditions, tension, compression, and bending amounts to 27,206 psi, substantially exceeding the range limit of 19,250 psi. Although each of the separate static conditions of stress is only 50 percent of the total stress and does not reach the reduced yield limit, fatigue can and did occur, causing the material to crack in the weakest places.

V. Conclusions

Estimates were made of the cost and feasibility of extending the lifespans of the HA-dec antennas for another

15 years and increasing their reliability. The result indicated great cost (on the order of \$5M) and a long downtime (6 to 8 months). Even after these improvements, the DSN would still be left with an antenna network limited in use to X/S-band only.

The TDA Office instead recommended that the three HA-dec antennas be replaced with 34-m az-el antennas similar to those in the existing DSN az-el antenna network. These antennas would be equipped with a center-fed beam-waveguide feed system with the capacity for multi-frequency transmitting plus improved performance. These plans have been approved and the antennas are currently

in the final design stages. Implementation will start in FY90, and the three antennas will be operational in mid 1993, 1994, and 1995. Until the new network is operational, increased maintenance and observation will be required to keep the 34-m HA-dec antennas operational.

It is planned to continue to inspect the antennas periodically and make repairs if required. The antennas will not be subjected to any further increase in loads because of additional microwave system modifications during their currently estimated future lifespan, which is planned to be complete when the 34-m beam-waveguide replacement antennas become operational.

References

- [1] *26-Meter Antenna S-X Conversion Project*, JPL Publication 82-26, Jet Propulsion Laboratory, Pasadena, California, March 15, 1982.
- [2] R. Levy, "Optimization of Antenna Structure Design," *Proceedings of the Eighth Conference on Electronics Computation (ASCE)*, Houston, Texas, pp. 114-129, February 1983.
- [3] M. S. Katow and R. Levy, "Computation of Gravity RMS for HA-dec Antennas," *TDA Progress Report 42-27*, vol. March-April 1975, Jet Propulsion Laboratory, Pasadena, California, pp. 139-147, July 15, 1975.
- [4] *Manual of Steel Construction*, Eighth Edition, American Institute of Steel Construction, Inc., Chicago, Illinois, pp. 5-86-5-91, 1980.

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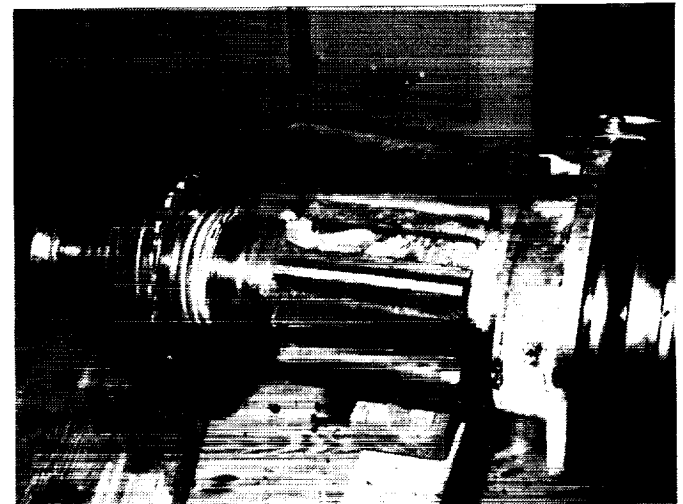
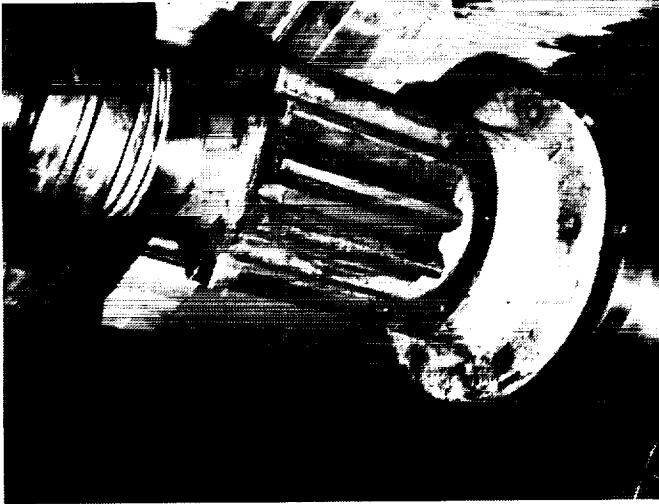


Fig. 1. Broken pinion teeth of declination wheel drives, DSSs 42 and 61.

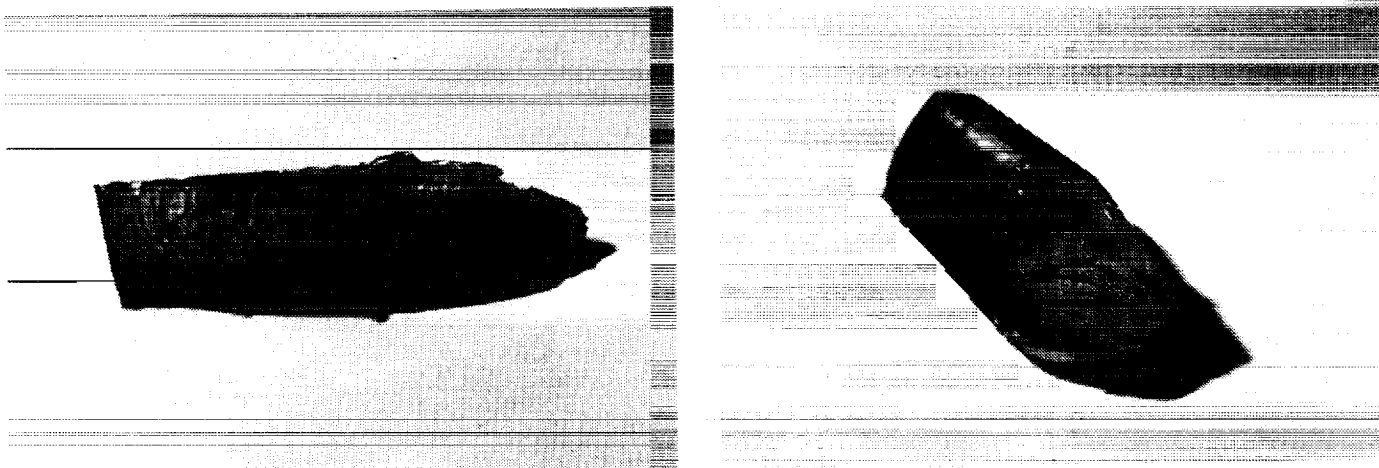


Fig. 2. Pieces of broken pinion teeth from the declination wheel drive, DSS 42.

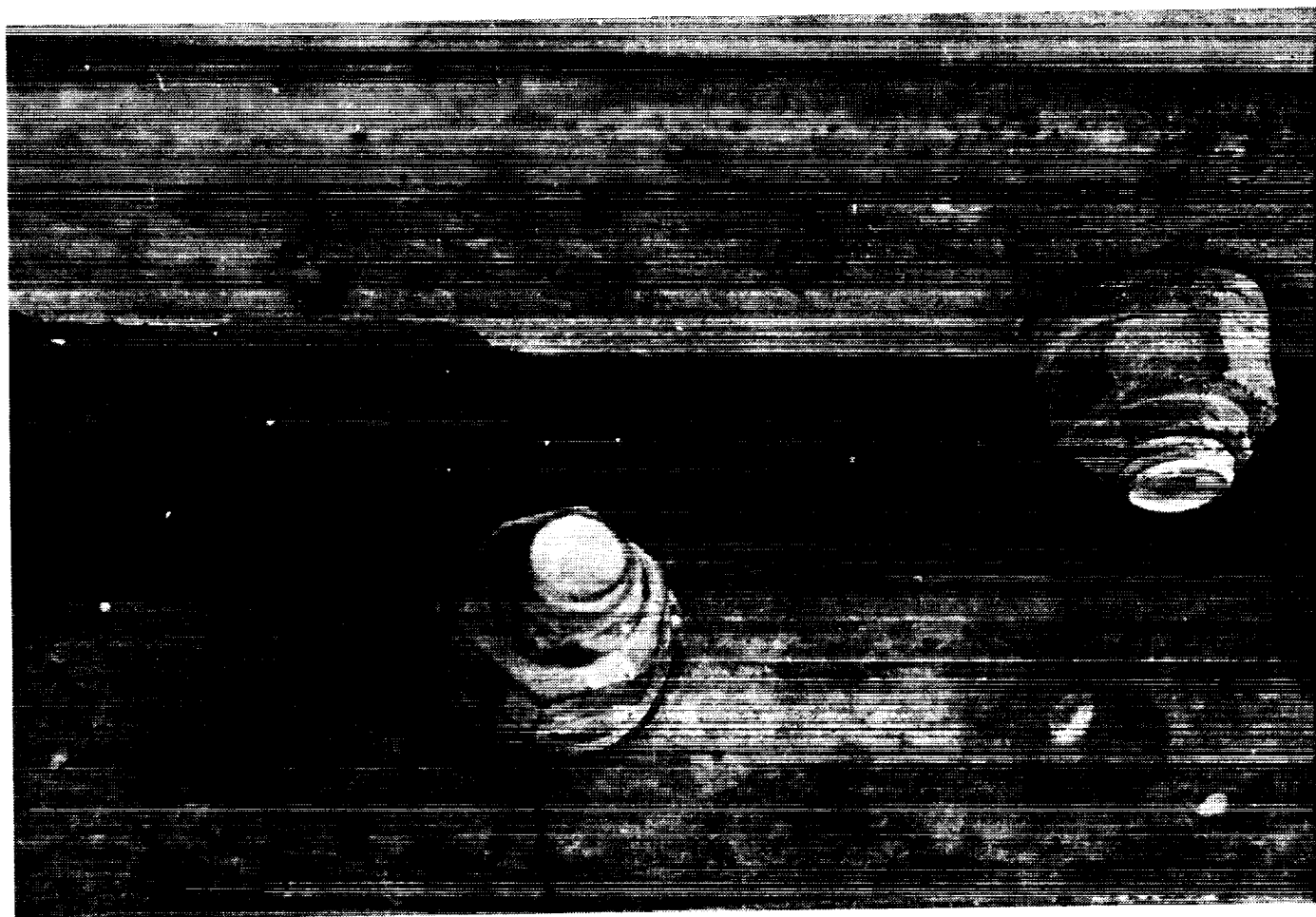


Fig. 3. Typical crack in the polar wheel structural member, DSS 12.

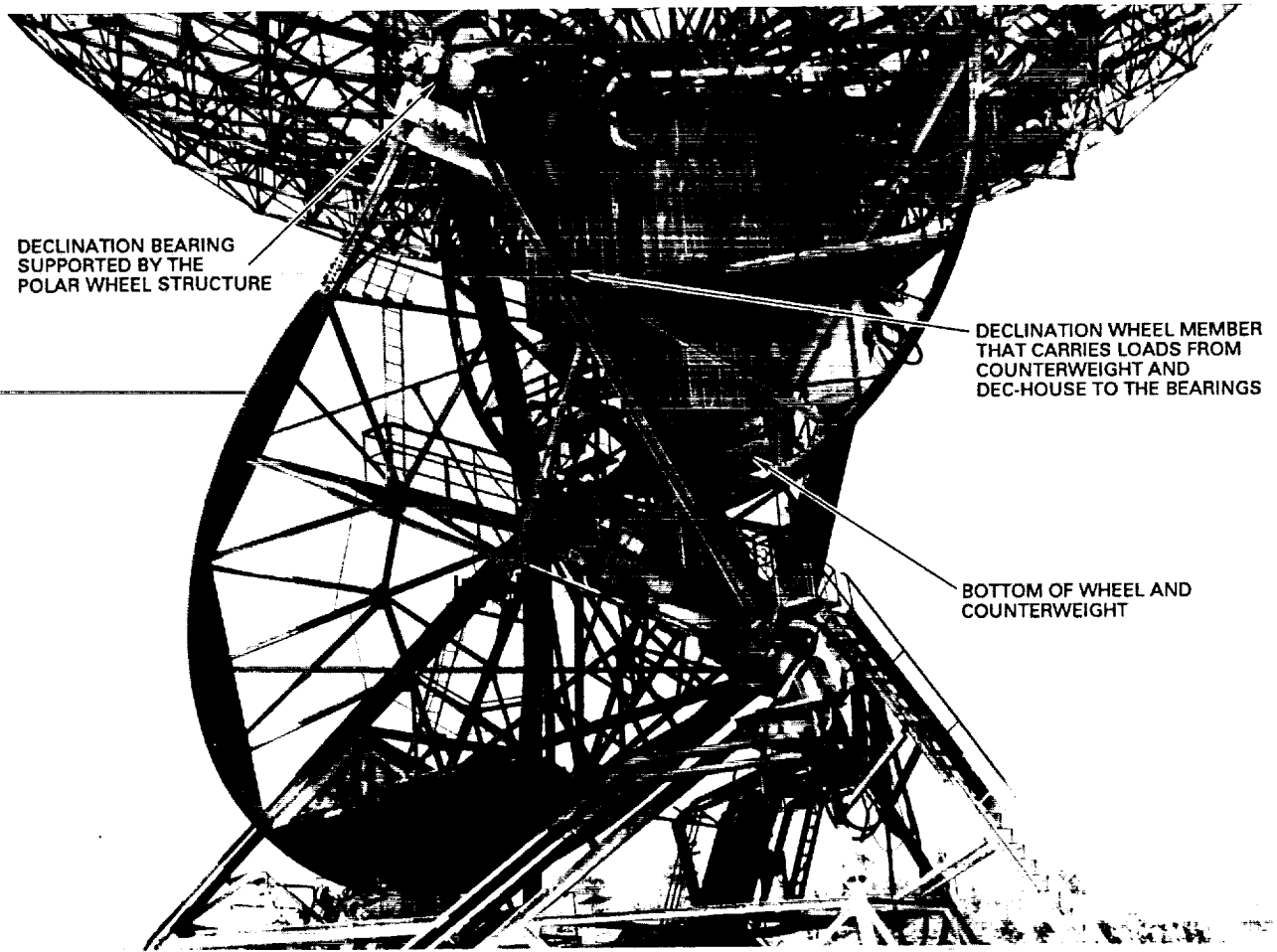


Fig. 4. The 34-m HA-dec structural support structure, DSS 12.

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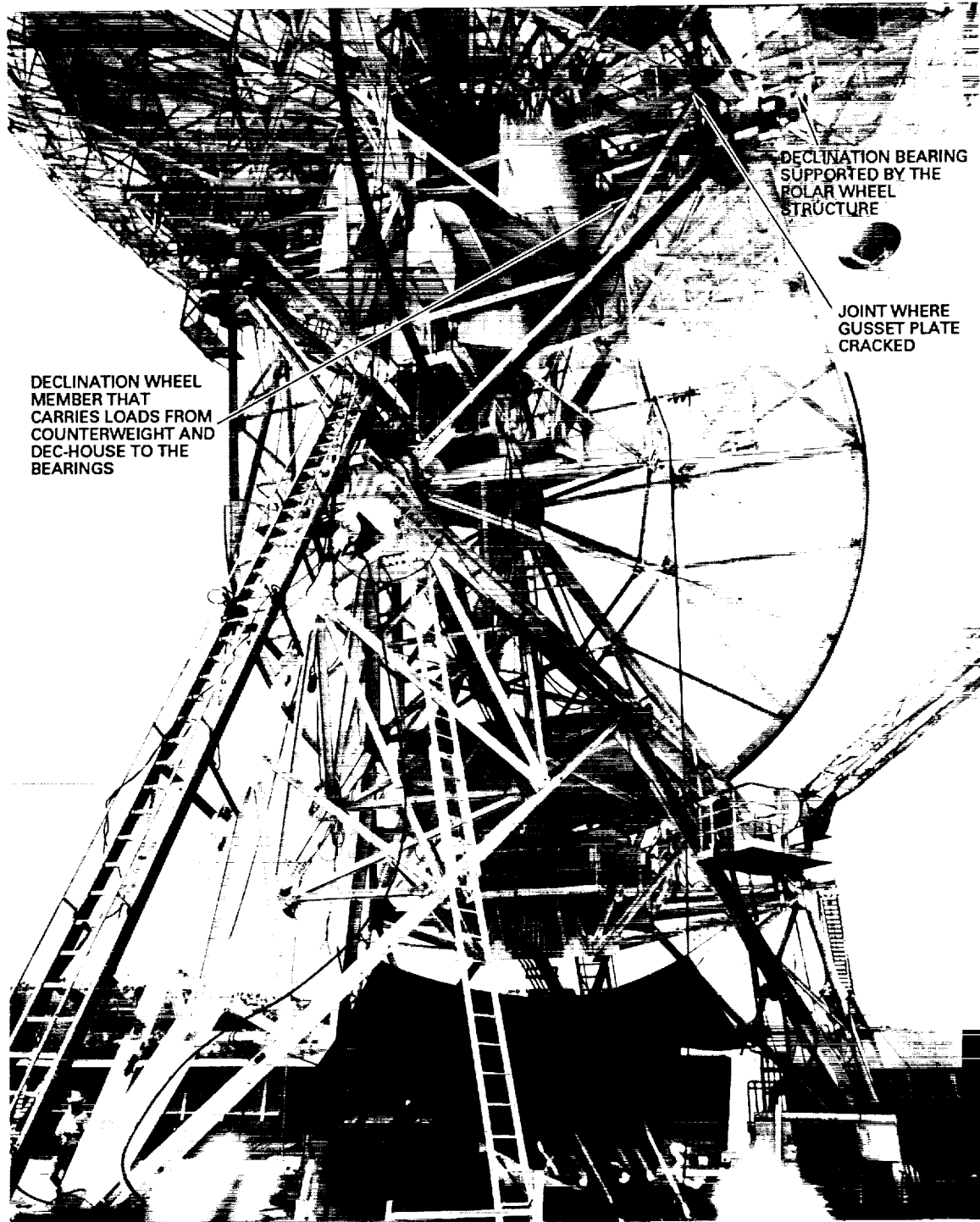


Fig. 5. Hour-angle and declination wheel support structure, DSS 12.

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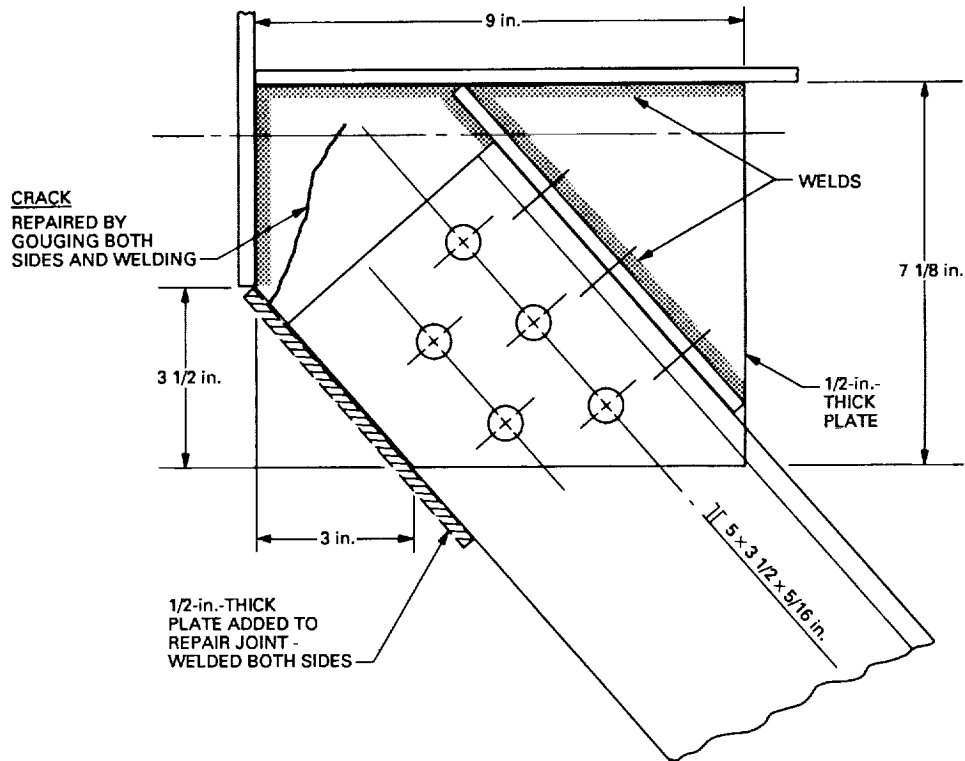


Fig. 6. Failed joint detail drawing, DSS 12.



Fig. 7. Cracked gusset, inboard side, DSS 12.

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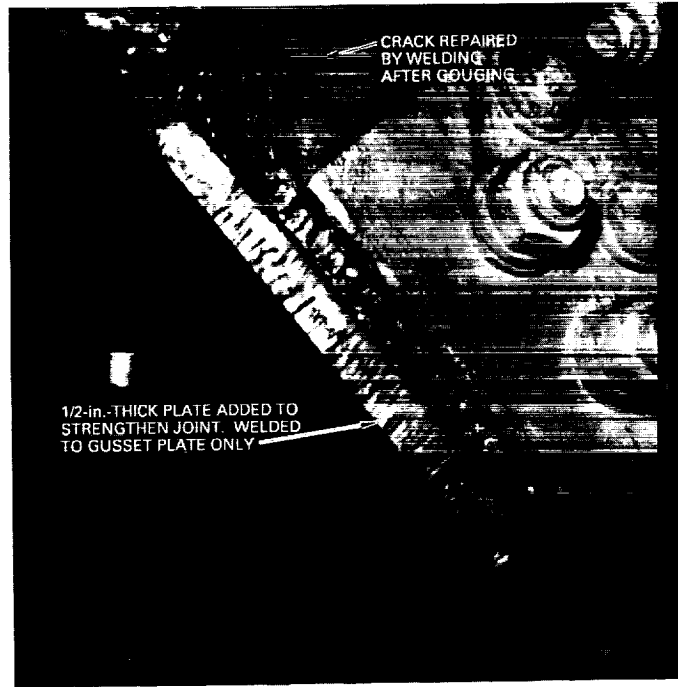


Fig. 8. Repair of failed joint, DSS 12.

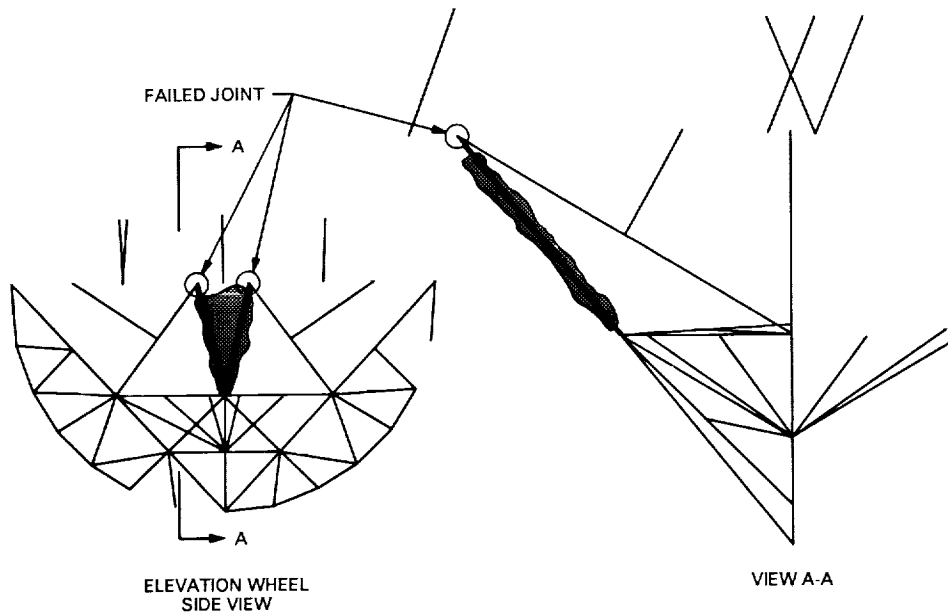


Fig. 9. Computer model of declination wheel.

SECTION B1 LOADING CONDITIONS; TYPE AND LOCATION OF MATERIAL

In the design of members and connections subject to repeated variation of live load stress, consideration shall be given to the number of stress cycles, the expected range of stress, and the type and location of member or detail.

Loading conditions shall be classified as in Table B1.

The type and location of material shall be categorized as in Table B2.

SECTION B2 ALLOWABLE STRESSES

The maximum stress shall not exceed the basic allowable stress provided in Sects. 1.5 and 1.6 of this Specification, and the maximum range of stress shall not exceed that given in Table B3.

| | | | | |
|---------------------------|---|-----------|---|------------|
| Fillet welded connections | Base metal at intermittent fillet welds. | T or Rev. | E | |
| | Base metal at junction of axially loaded members with fillet welded end connections. Welds shall be disposed about the axis of the member so as to balance weld stresses. | T or Rev. | E | 17,18,20 |
| | Weld metal of continuous or intermittent longitudinal or transverse fillet welds. | S | F | 5,17,18,21 |

* "T" signifies range in tensile stress only; "Rev." signifies a range involving reversal of tensile or compressive stress; "S" signifies range in shear including shear stress reversal.
 b These examples are provided as guidelines and are not intended to exclude other reasonably similar situations.

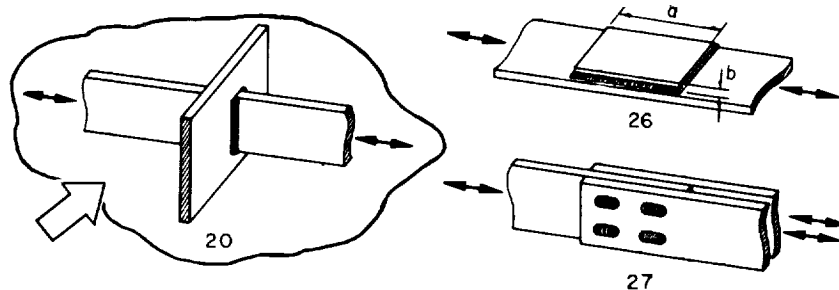


Fig. B1. Illustrative examples

TABLE B3
ALLOWABLE RANGE OF STRESS (F_{sr}), KSI

| Category (From Table B2) | Loading Condition 1 F_{sr1} | Loading Condition 2 F_{sr2} | Loading Condition 3 F_{sr3} | Loading Condition 4 F_{sr4} |
|--------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| A | 60 | 36 | 24 | 24 |
| B | 45 | 27.5 | 18 | 16 |
| C | 32 | 19 | 13 | 10 ^a |
| D | 27 | 16 | 10 | 7 |
| E | 21 | 12.5 | 8 | 5 |
| F | 15 | 12 | 9 | 8 |

^a Flexural stress range of 12 ksi permitted at toe of stiffener welds on webs or flanges.

NOTE
THIS TABLE IS FOR A-36 STEEL AND SHOULD BE REDUCED FOR A-7 STEEL BY 9 PERCENT TO PRODUCE A VALUE OF 19.25.

Fig. 10. Reference chart excerpted from [4]. (Reprinted by permission of the American Institute of Steel Construction, copyright 1980.)