Investigation of the October 23, 1997 Collapse of the 1889' High TV Antenna Tower in Raymond, Mississippi

Office of Engineering
Directorate of Construction
Occupational Safety and Health administration
U.S. Department of Labor

April 1998

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DESCRIPTION OF THE INCIDENT:

On October23, 1997, an incident occurred in Raymond, Mississippi at about 9:30 A.M. when a 1889' high TV antenna tower collapsed killing three workers who were replacing the diagonal members of the tower. There were no other reported injuries to other workers at the site. At the time of the incident the workers were at an elevation of about 1480' above the base of the tower.

The tower owned and maintained by WLBT-TV3 of Jackson, MS was originally designed and furnished by Dresser Crane, Hoist and Tower Division, Columbus, Ohio. The tower was designed as per the code EIA-222-A of 1966. The design wind pressure of the tower was taken as 33.33 psf on the legs. It was constructed in 1967. The tower, an equilateral triangle in plan with each face equal to 10', was fabricated in 64 sections, the top most section was numbered # 1 and the bottom most section was numbered #64. All sections were 30' high except for section # 17, 2 and 1. See Fig. I for a typical elevation of a section. Each section was divided in three panels of equal height. In addition to the horizontal members, each face of the panel consisted of two diagonals and a secondary horizontal member also known as redundant member located at the intersection of the two diagonals. The tower legs consisted of solid round members of D88 95 ksi high strength steel, with diameters ranging from 2 *7/8"* to 5 1/2". The diagonals were round bars with diameter varying from 3/4" to 1 1/4", of 50 ksi high strength steel. The main horizontal members at the intersection of the diagonals and the legs consisted of two angles placed back to back. At locations of the guy wire ropes, channels were used instead of angles.

There were eight levels of guy wires at elevations of 218.75', 438.75', 668.75', 908.75', 1158.75', 1418.75', 1638.75' and 1888.75', as per the original contract drawing, see Fig.2. The diameter of the guy wire ropes at the elevations mentioned above were 1 3/8", 1 ½", 1 7/16", 1 ½", 1 3/4", 1 9/16", 1 13/16" and 1 9/16" respectively. The guys were numbered 1 thru 8 with the top most guy as # 8.

In early 1997, WLBT-TV3 contracted with Shoolbred Engineers, Inc., Structural Consultants, of Charleston, SC to:

- Visually inspect the tower, anchors and guy wires
- Determine the guy wire tensions
- Measure alignment of the tower
- Analyze the tower as per new applicable code TIA/EIA-222-F
- Recommend changes, if any

On February 2, 1997, Shoolbred Engineers completed a report where among other things, the following structural modifications were recommended:

1. Replacing new diagonals in four panels. The existing 3/4"diagonal rods in the lower and middle panels of Section 14 were to be replaced by I “diameter round bars. The 1" diameter diagonals of the upper panel of Section 35 and lower panel of Section 32 were to be replaced by 1 $^{1}/_{8}$" round bars.

2. Main horizontal members at elevations 910′-920′, 920′-930′, 930′-940′ and 1400′-1410′ were to be replaced by bigger size angles.

3. The guys at level four and six were also to be replaced by bigger wire ropes.

In addition to the above, the report recommended to adjust guy tensions and to correct the vertical alignment of the tower.

The owner, WLBT-TV3 awarded a contract to LeBlanc & Royale Telecom Inc of Oakville, Ontario, Canada for structural modifications including the preparation of shop drawings, fabrication and erection of new diagonals, horizontal members and guy wire ropes.

The construction crew arrived at the site on October 20, 1997 and rigging was completed the following day. On October 22, 1997, workers proceeded up the tower by the elevator carrying newly fabricated diagonals to replace the existing diagonals in the middle panel of Section 14. Reportedly, they unbolted one diagonal in the N-W face of the middle panel and attempted to position the new diagonal in its place but found that the new diagonal was longer by fraction of an inch and could not be placed. The workers, however, managed to connect the new diagonal by applying some force. They removed another diagonal on the same face of the middle panel and were faced with similar difficulty in positioning the new diagonal due to its longer length. It was reported that at that time the workers decided to quit and proceed to the ground level. The old diagonal was neither restored to its original location nor replaced by a new diagonal or any other equivalent member. The tower was reported to be without a diagonal in the middle panel of Section 14 for the night of October 22, 1997.

The next morning, on the instructions of the job superintendent, the workers proceeded to Section 14 by the elevator and placed back the old diagonal which was taken out the day before on the N-W face of the middle panel of Section 14. Having restored the old diagonal in its original position, the workers reportedly proceeded to the lower panel of the Section 14. On the N-W face of the lower panel of Section 14, they removed a diagonal and were believed to be attempting to place a new diagonal when the collapse of the tower occurred.

OBSERVATION OF THE COLLAPSED STRUCTURE:

Observation of the collapsed tower indicated that Sections 3 thru 5 remained interconnected with each other and remained intact. Sections 6 thru 9 and Sections 12 thru 14 were observed in two piles with members twisted and intermingled. Sections 10 and 11 were intact and remained connected to each other. Sections 15 thru 36, Sections 37 thru 54 and Sections 55 thru 64 remained intact and could be inspected with ease. See Fig.3 for the location of the collapsed sections as per the field survey conducted by a Consulting Engineers at the request of the WLBT. See Figs. 4, 5, and 6 for the collapsed and twisted tower sections.

Section 14 was closely examined to determine the integrity of the members in all three panels and to establish whether or not any member was removed prior to the collapse of the tower. The members were marked by one of the engineers representing one of the interested parties in the incident. We have followed the same markings for our reference as well. The N-W face, W-E face and the E-N face were identified as “a”, “b” and ‘c” faces respectively. For the “a” face (ie. N-W face), the main horizontal members were marked as 14.0a, 14.2a and 14.4a. The redundant and diagonal members were similarly marked in a logical sequence. See Fig. 7 for elevations of three faces of section 14.

A close examination of the “a” face of Section 14 revealed the following:

1. Diagonal member 14.5a1 was not connected at either end. The gusset plates at either end were intact with the tower legs with no signs of deformations in the bolt holes, see Fig. 8, 9 and 10. Connecting bolts were missing. This member was later examined by the laboratory and will be discussed later in the report.

2. Redundant member 14.5a was disengaged from both legs. The gusset plate at the west end was intact, its connecting bolt was missing and there were little signs of deformations in the bolt hole. The north gusset plate fractured and the bolt remained attached to its mating gusset plate at the tower’s north leg, see Fig. 11, 12 and 13. This member was also examined by the laboratory.

3. The connections of the two diagonals in the middle panel, e.g., 14.3a1 and 14.3a2 to the north leg were made by two new bolts.

4. One of the two bolts at the connection of the diagonal 14.3a2 to the west leg was new.

5. With the exception of the gusset plate connecting the redundant member, 14.5a to the west leg, all other gusset plates of the face “a” welded to the west leg failed by pulling off the leg and creating a complete separation.

The examination of the “b” face revealed the following:

1. Two gusset plates connecting the redundant members 14.1b and 14.3b pulled off the west legs creating complete separation. The gusset plate connecting the main horizontal member 14.2b and diagonals pulled off the west leg for about 50% of its height.

2. A snatch block was observed attached to the west leg at its intersection of the main horizontal member 14.4b location.

The examination of the “c” face revealed the following:

1. The gusset plate connecting the main horizontal members 14.0c and 14.4c pulled off the north leg for a height of about 50%.

2. The gusset plates connecting the redundant members 14.3c and 14.5c to the north leg fractured.

Critical to this investigation were the indications from the field observations that at least one diagonal (14.5a1) and one redundant member (14.5a) in the lower panel of Section 14 in the N-W face were removed or disconnected before the incident occurred. As this was of primary importance for any future analysis of the collapsed tower, the Salt Lake Technical Center of the Occupational Safety and Health Administration was contacted to examine the members and their connections to establish whether or not the diagonal and/or the horizontal members were removed prior to the collapse. The two members were shipped to the Salt Lake Laboratory where they were examined by scanning electron microscope. The mating surfaces which were still attached to the tower remnants were also examined at the site of the incident. See Appendix B for the full report of the laboratory. The Salt Lake Technical Center concluded that the diagonal 14.5a1 was removed before the incident and the redundant member 14.5a was not. The failure of the redundant member 14.5a occurred as a result of the collapse.

STRUCTURAL ANALYSIS AND DISCUSSION:

The tower structure between guy wire No. 6 and No.7 was analyzed for the conditions existing at the time of the incident to determine whether or not the removal of a diagonal member would significantly influence the structural integrity of the tower. In addition, the analysis would determine the internal member stresses of several members at and near the tower Section 14. In this analysis, the entire tower was not analyzed as it was determined to be adequate for the loads upon it in accordance with the applicable codes. The calculations by Dresser Crane, Hoist and Tower Division of 1968 were reviewed and found to be satisfactory. Further, the review by Shoolbred Engineers indicated that the tower design is adequate for low speed wind. The present analysis was limited to determine the value and magnitude of the impact of removal of a diagonal on the structural integrity of the tower. Therefore, only a segment of the tower, 220' high between guy #6 and #7 was analyzed. It is believed that analyzing the full height of the tower would not alter the conclusions of the report.

A three-dimensional computer model, representing tower Section 9 through Section 16 was developed for the analysis. The model consisted of 276 joints and 666 member elements see Fig 14 to 18. Physical dimensions of the sections and the member sizes of the structure were taken from the tower's original erection drawings of 1966. No deviations were assumed from the original drawings. Further, the analysis was performed based on the premise that the tower structure was plumb and square. Laboratory testing to determine the physical properties of the steel was not conducted. The analysis was based on the yield strengths of 95,000 psi for tower leg members and 50,000 psi for all the other members as stated in the "Design Investigation" report prepared by Dresser Crane, Hoist & Tower Division in 1968. The modulus of elasticity was assumed to be 29,000 ksi.

The structure was modeled as pinned supports at the lower guy locations. However, at the upper guy locations all lateral translations were assumed to be restrained expect in the vertical direction. Connections of the diagonal and horizontal redundant members to the tower legs were assumed to be pinned and the main horizontal members to the tower legs were assumed to be rigidly connected. Dead load of the tower and all attachments including top antennas, radio antennas, cables, etc., above guy wire No. 7 were taken from the computations of Shoolbred Engineers, Inc. and applied as concentrated loads at the top joints. The tension forces of the guy wires were also taken from the Shoolbred Engineers. The dead weights of the tower of Section 9 thru 16 were considered by the computer program as uniformly applied loads for all the members.

As the exact location and orientation of the antennas and other attachments to the tower were not known, the dead load of the members were doubled to account for the appurtenances on the segment of the tower. It was considered to be in close proximity of the dead load of antennas, platform, cables, wave guides etc. The eccentricity of the antennas and other attachments were ignored. The forces in the guy wires at the top and bottom supports were considered equal and the flexural moments at the guy supports were not considered because of the minimal wind load applied. The diagonals of the tower are slender members essentially capable of resisting tension loads only. Their compressive force capability is marginal. However, in the analysis of the segment of the tower, the diagonals did experience compressive forces in excess of their capacities and no iterative analysis was done to reduce the forces to zero, as the purpose of the analysis was limited to examine the change in the behavior of the tower segment due to the removal of certain members. All the above factors leading to the approximation of the solution are not considered to change the conclusion of this report.

The "Upper Air Weather Data" of the Jackson International Airport were obtained from the National Weather Service (See Appendix C for Weather data). It is indicated that at the vicinity of the elevation of the tower Section 14 (Approximately 1500 Ft. from the ground surface), the wind speed a day earlier was about 20 mph in the morning decreasing to 11 mph later in the day. The wind was generally from the North and the North-East direction. In the morning of October 23, 1997 (the day of the accident) the wind was coming from the south with a speed of approximately 15 mph and later, the wind increased to about 30 mph coming from the South-East direction. The "upper Air Weather Data" is only recorded twice daily as per the National Climatic Center. The analyses are, however, based on 20 mph wind speed.

Of significance to this report was the impact on the load carrying capacity of the tower leg of the removal of the diagonal bracing and/or horizontal redundant members especially at the middle and lower panels of the tower Section 14 location. Manual computations to determine the critical load of these members were performed in accordance with the Load Resistance Factor Design (LRFD) of the American Institute of Steel Construction (AISC). In such computation, the load and resistance factors were considered as 1.0.

The tower structure between guy wire #6 and #7 was first analyzed based upon its original configuration, ie, with all the members intact, see Figs. 14 to 18. Loads imposed on the structure included the tower dead weights and all other loads from the structure above guy level No.7. Zero wind and 20mph wind loads were both considered by superimposing them to the above dead loads. Under these loading conditions, the analysis results indicated that the combined stresses of the vertical leg members were all well within the allowable value providing an adequate factor of safety.

The tower structure was then analyzed for the configuration with one diagonal member (Member identified as 14.5a1) deleted from the original structure, see Figs. 19 to 21. Under this condition, the analysis indicated that the deformation characteristics of the west leg at the Section 14 lower panel was significantly affected by the deletion of the diagonal member. See Fig.22 and 23 for a comparison of the deflected shapes of the west tower leg of the original tower structure and the structure with the diagonal removed. From the deflected shape it is estimated that the unbraced length of the west leg at the lower panel was approximately of 8.2 ft. Due to the increased unbraced length of the leg member, the analysis indicated that the interaction value of the combined axial compression and flexural stresses was determined to be approaching 1.0 based on the AISC equation H1-1a.

The structure was then further analyzed for the configuration when the other diagonal member 14.5a2 of the same face became ineffective due to its limited capacity to resist compressive load, see Fig. 24 to 26. Under this condition, the analyses indicated that the unbraced length of the west leg at the lower panel increased to approximately 9.48 ft see Fig. 23. The interaction value of axial compressive and flexural stresses was determined to be exceeding 1.0. The collapse of the tower structure would therefore be imminent. Please note that the load and resistance factors were taken as 1.0

The following is a comparison of the axial loads and bending moments of the west leg of tower Section 14 for the above analyses:

	Lower panel		Middle panel		Upper Panel	
Member #	13	14	15	16	17	18
Axial Load, (kips)	102.2	102.	101.4	101.1	100.7	100.4
My (#"), Start	-27.	516	127	443	137	469
My (#"), End	-516	1,042	-443	1028	-469	107.9

Axial Loads and Bending Moments of the onglnal structure at Section 14 west leg, *w/* no wind.

TABLE 1

	Lower panel		Middle panel		Upper Panel	
member #	13	14	15	16	17	18
Axial Loads (kips)	102.7	102.4	102.3	102	102	101.7
My (#"). Start	-209	562	42	493	55	530
My (#") End	-562	1,,054	-493	1,048	-530	1,076

Axial Loads and Bending Moments of the onglnal structure at Section 14 west leg, w/20mph Wind.

TABLE 2

	Lower panel		Middle panel		Upper Panel	
Member #	13	14	15	16	17	18
Axial Load, (kips)	104.	103.7	101.9	101.6	101.5	101.3
My (#"), Start	2,066	-54	-775	572	136	520
My (#"), End	54	2,268	-572	1,134	-520	1,156

Axial Loads and Bendmg Moments at Sect.14 West leg at the removal of 14.5a1 .w/20mph wind

TABLE 3

	Lower panel		Middle panel		Upper Panel	
Member #	13	14	15	16	17	18
Axial Loads (kips)	104.6	104.3	102.3	102.1	102.	101.7
My, (#") Start	-4,094	437	3,835	-440	250	500
My, (#") End	1.7	-3,354	440	870	-500	1,122

Axial Loads and BendIng Moments of Sect.14 w. leg at the removal of 14.5a1& 14.5a2, w/20mph wInd.

TABLE 4

The above analyses indicated that the removal of a diagonal member significantly altered the behavior of the tower structure and substantially reduced its load carrying capacity.

During our interview with the Shoolbred Engineers, Structural Consultant for the WLBT-Station, it was indicated that the standard practice of the tower industry was to position a come-along cable along the diagonal member scheduled for removal before it was actually disconnected. If the diagonal was designed to take compressive load as well, a special frame was bolted to the tower face before any member was removed.

CONCLUSIONS

Based on the above evaluation and discussions, the following conclusions are drawn:

1. The collapse of the tower occurred because a diagonal member of the tower was removed before the incident which overstressed the tower members. The overstressing resulted in the buckling of the tower legs and the collapse of the tower.

2. The tower legs were constructed with high strength steel of 95,000 psi and their bending stiffness were relatively low. All diagonal members were therefore critical to the structural integrity of the tower and the removal of a diagonal member could substantially decrease the load carrying capacity of the tower legs.

3. The tower contractor did not follow the general industry practice to install a temporary special frame or a come-along cable before disconnecting any member. If a come-along or a special frame was used, this incident would have been avoided.

4. The structural consultant did not caution the contractor in its report about the sensitivity of the tower in regard to the diagonal removals. The structural consultant considered the use of a come-along or a special frame before removing any member of the tower as a standard practice of the contractor. The documents prepared by the tower contractor did not specifically mention that the come-along or special frame must be used by the workers before attempting to remove any members.

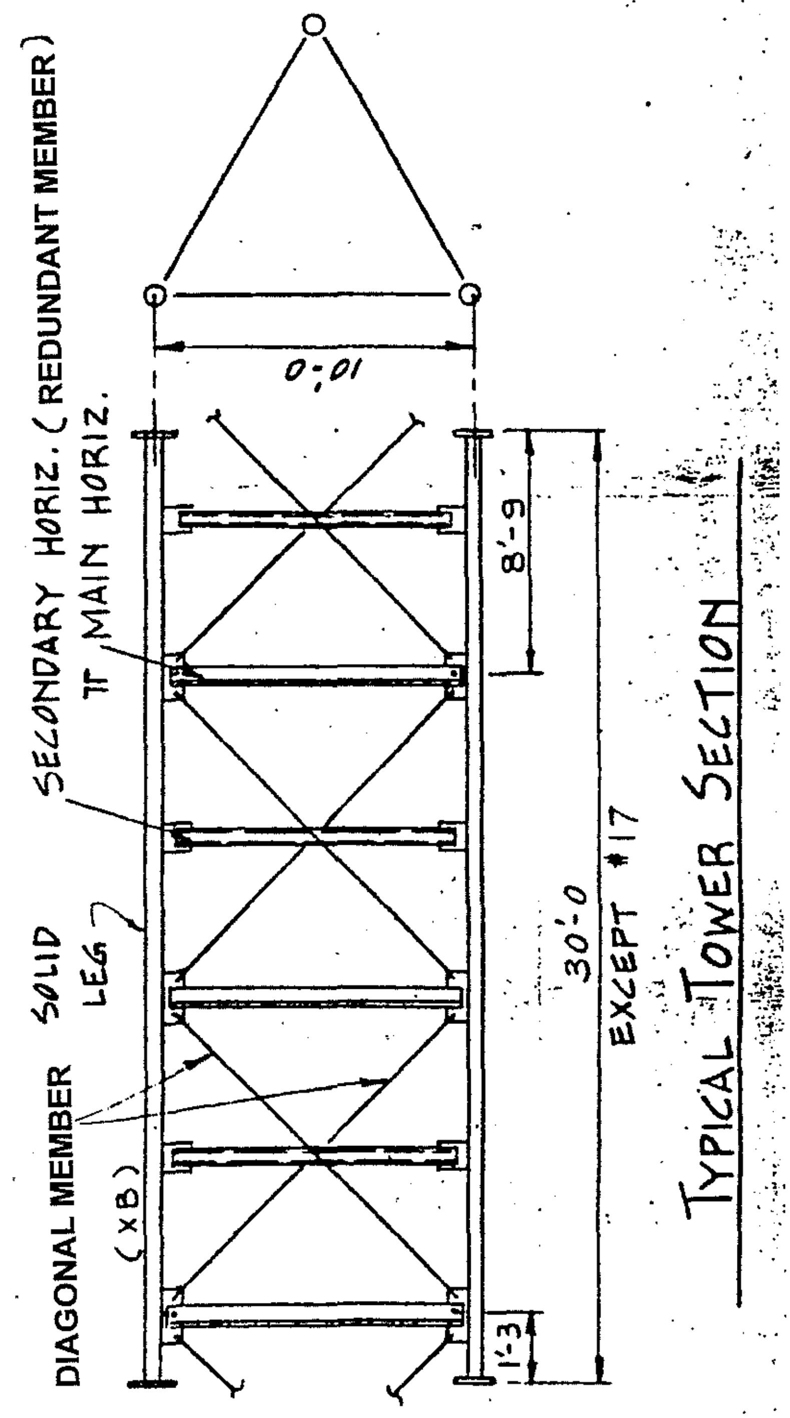
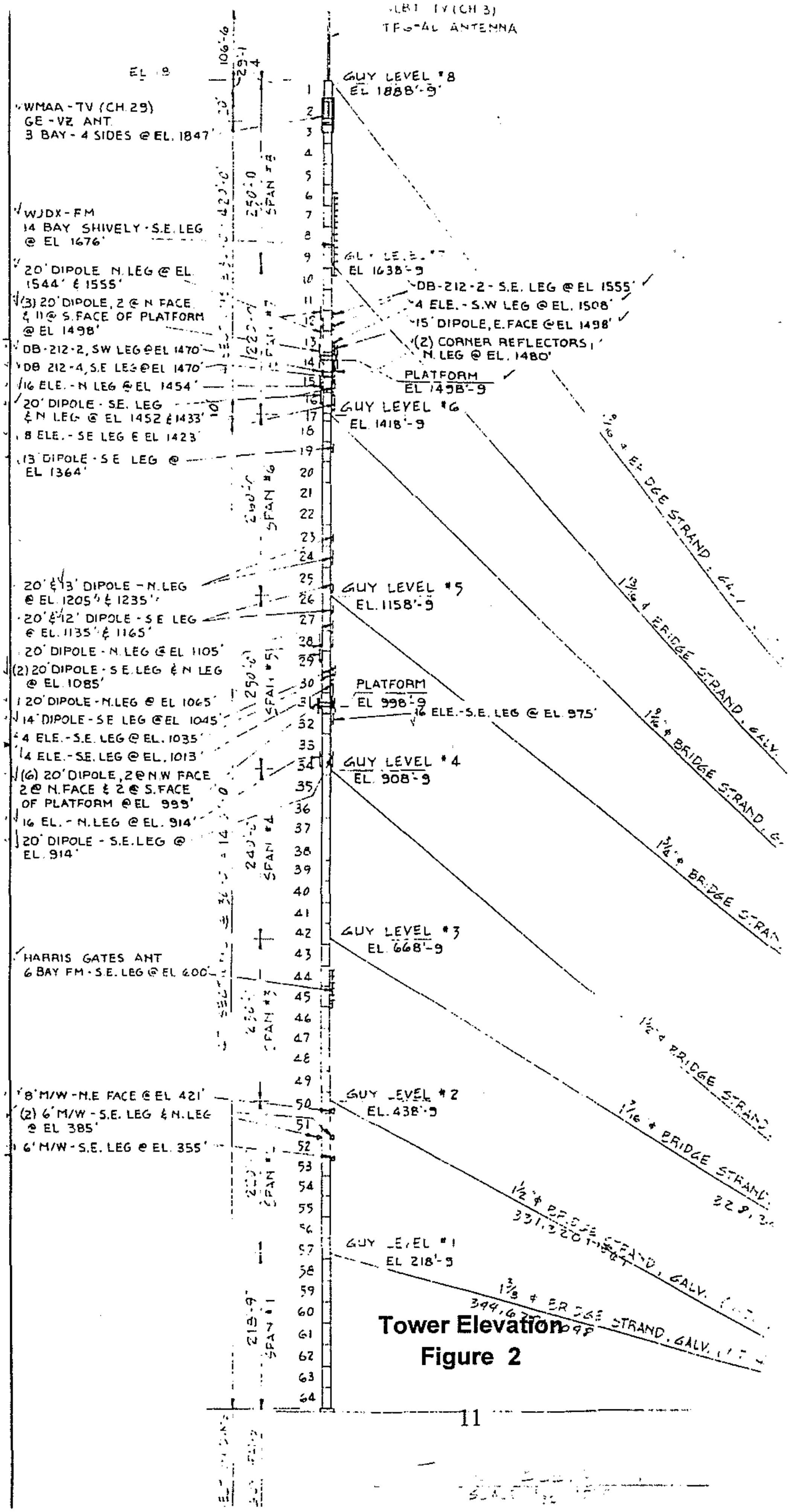
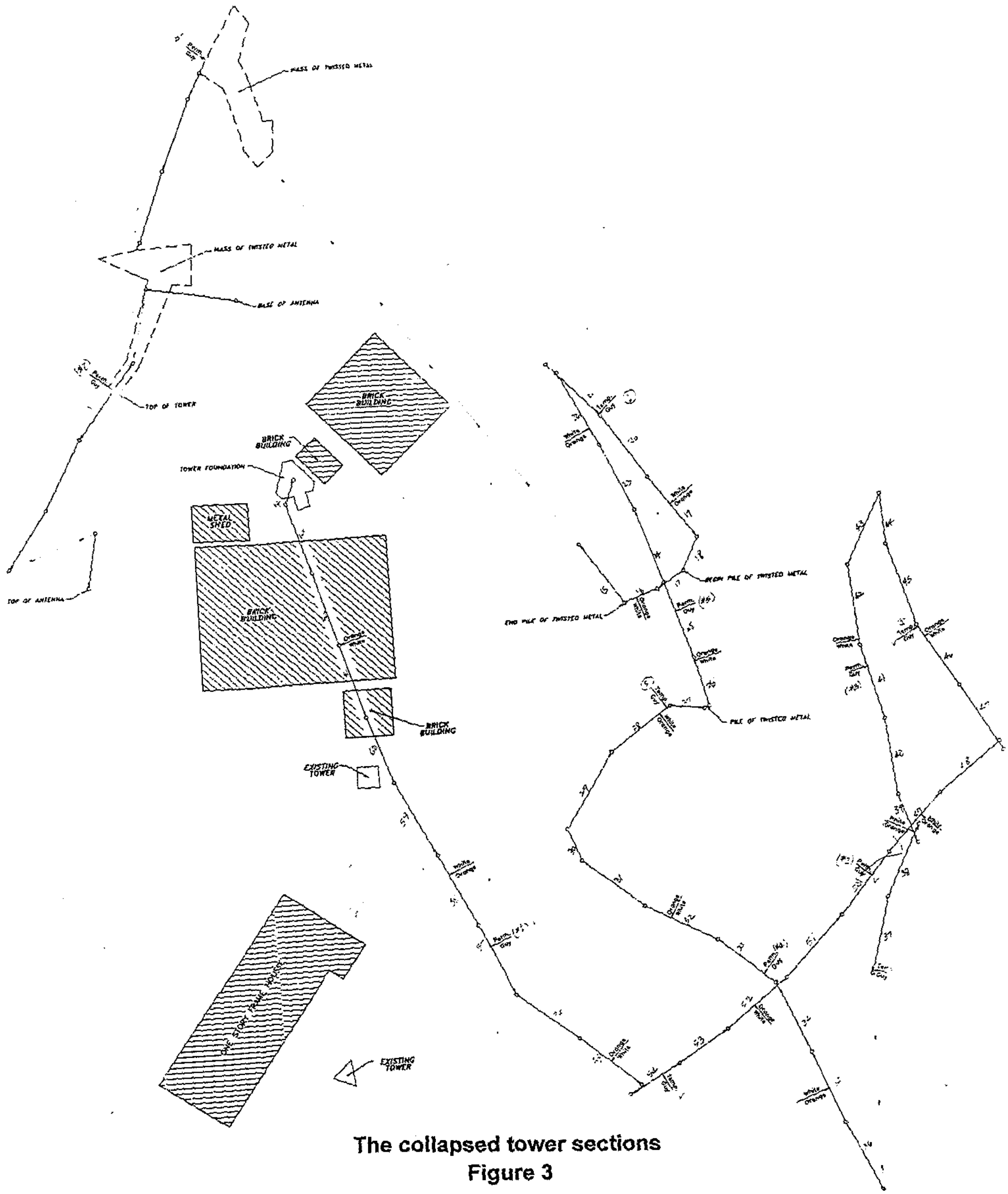

SECONDARY HORIZ. (REDUNDANT MEMBER)
MAIN HORIZ.
SOLID LEG
DIAGONAL MEMBER (XB)
10'-0
8'-9
30'-0
EXCEPT #17
1'-3
TYPICAL TOWER SECTION

Figure 1



Tower Elevation
Figure 2

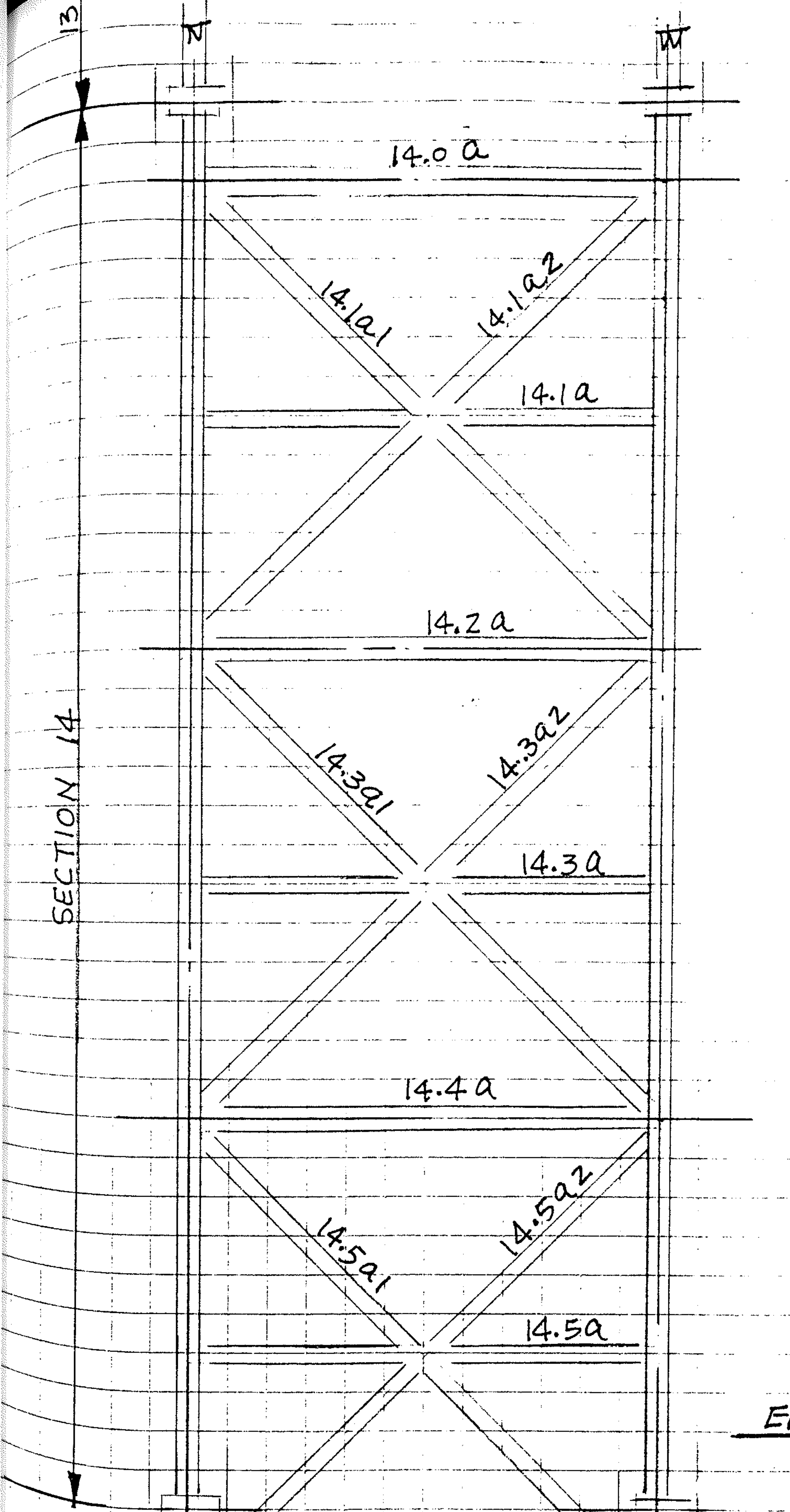


The collapsed tower sections
Figure 3

Figure 4

Figure 5

Figure 6


13
N
W
14.0 a
14.1a1
14.1a2
14.1a
14.2 a
14.3a1
14.3a2
14.3a
14.4a
14.5a1
14.5a2
14.5a
SECTION 14
ELEVATION
FACE (a)

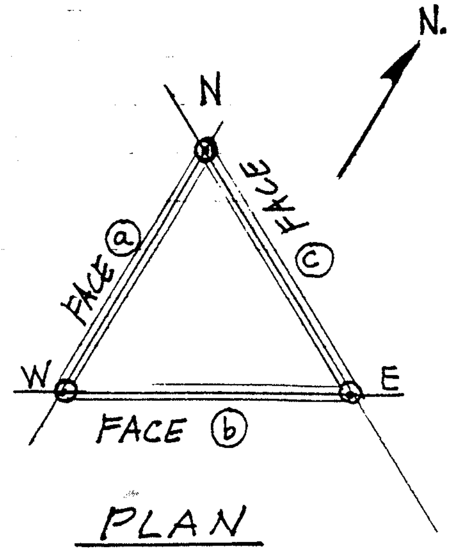

N.
N
W
E
FACE ⓐ
FACE ⓑ
FACE ⓒ
PLAN

Figure 7

North Leg at
14.4, 14.5c2,
and 14.5a1
intersection

Diagonal
14.5a1

Figure 8

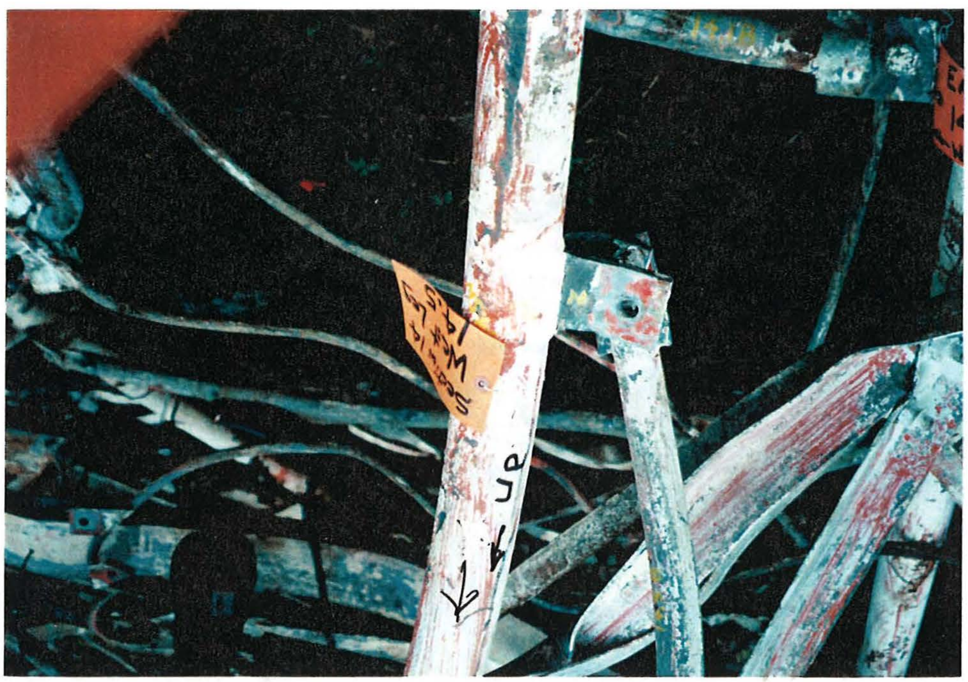
North leg at
14.4a, 14.5a1
and 14.3a2
interesting pt.

Gusset plate
of 14.5a1 at
north leg,
bolt missing,
hole intact

Figure 9

Gusset plate of diagonal 14.5a1 at the West leg.
Connecting bolt missing, member intact.

Figure 10



Gusset plate of redundant member 14.5a at the west leg.

Figure 11

Redundant member 14.5a west end and its gusset plate to the west leg.

Figure 12

Redundant member 14.5a to the north leg connection.

Figure 13

MN/ELEM

STRUCTURE DATA

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NM = 666
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NL = 4
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ZMAX= 8.7

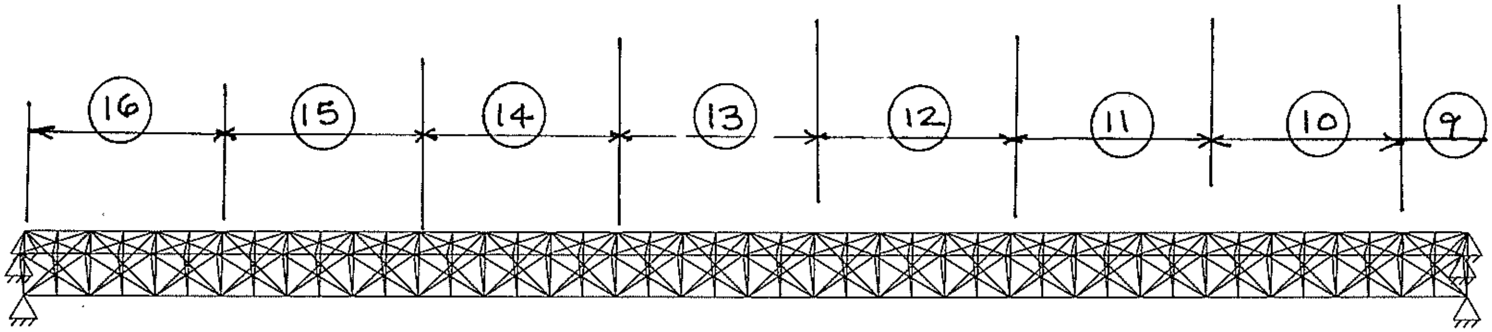

Figure 14

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UNIT FT POU

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DATE: APR 6, 1998

TITLE: - TV TOWER IN JACKSON MS. (TOWER1A)

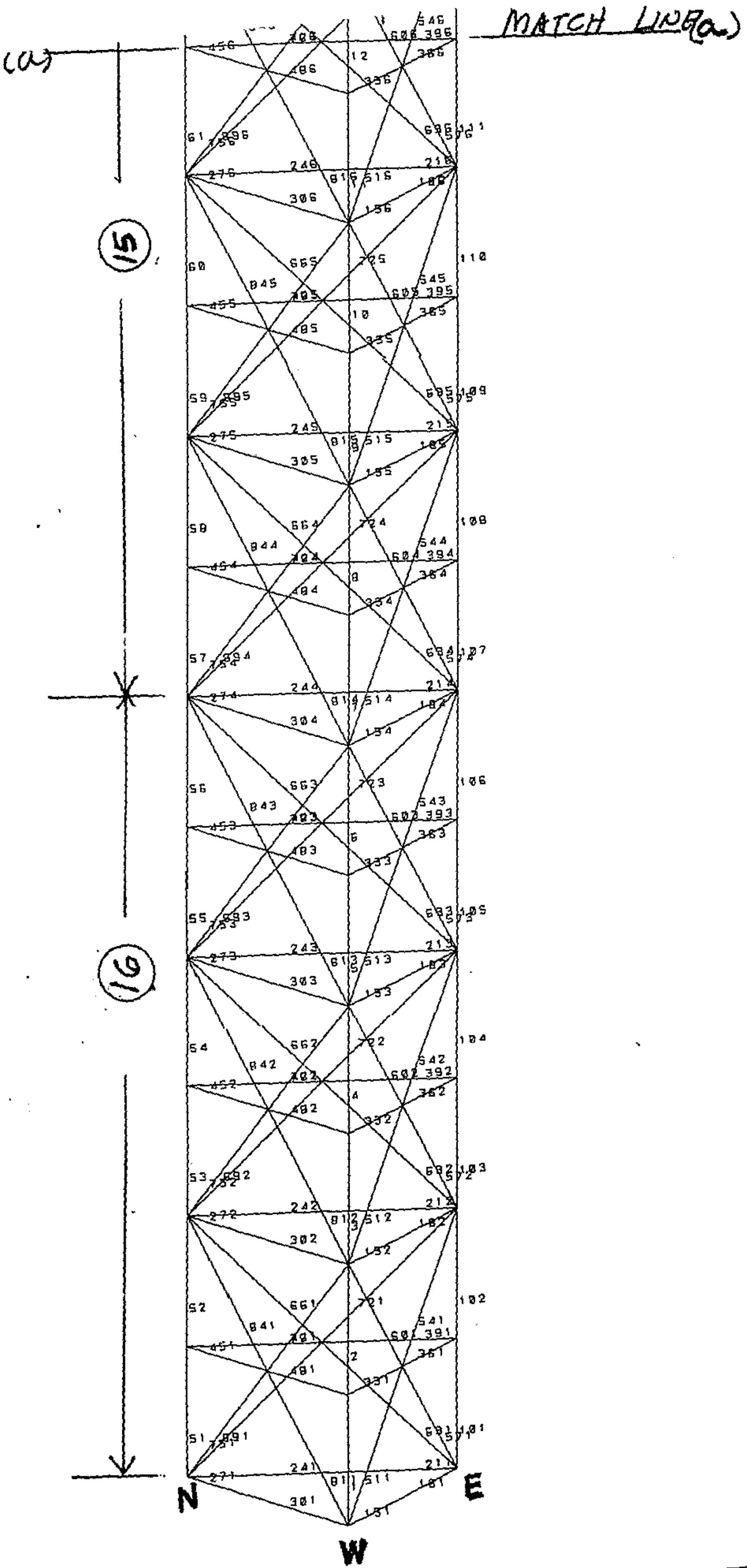

Figure 15

UNIT INC POU

DATE: FEB 4, 1998

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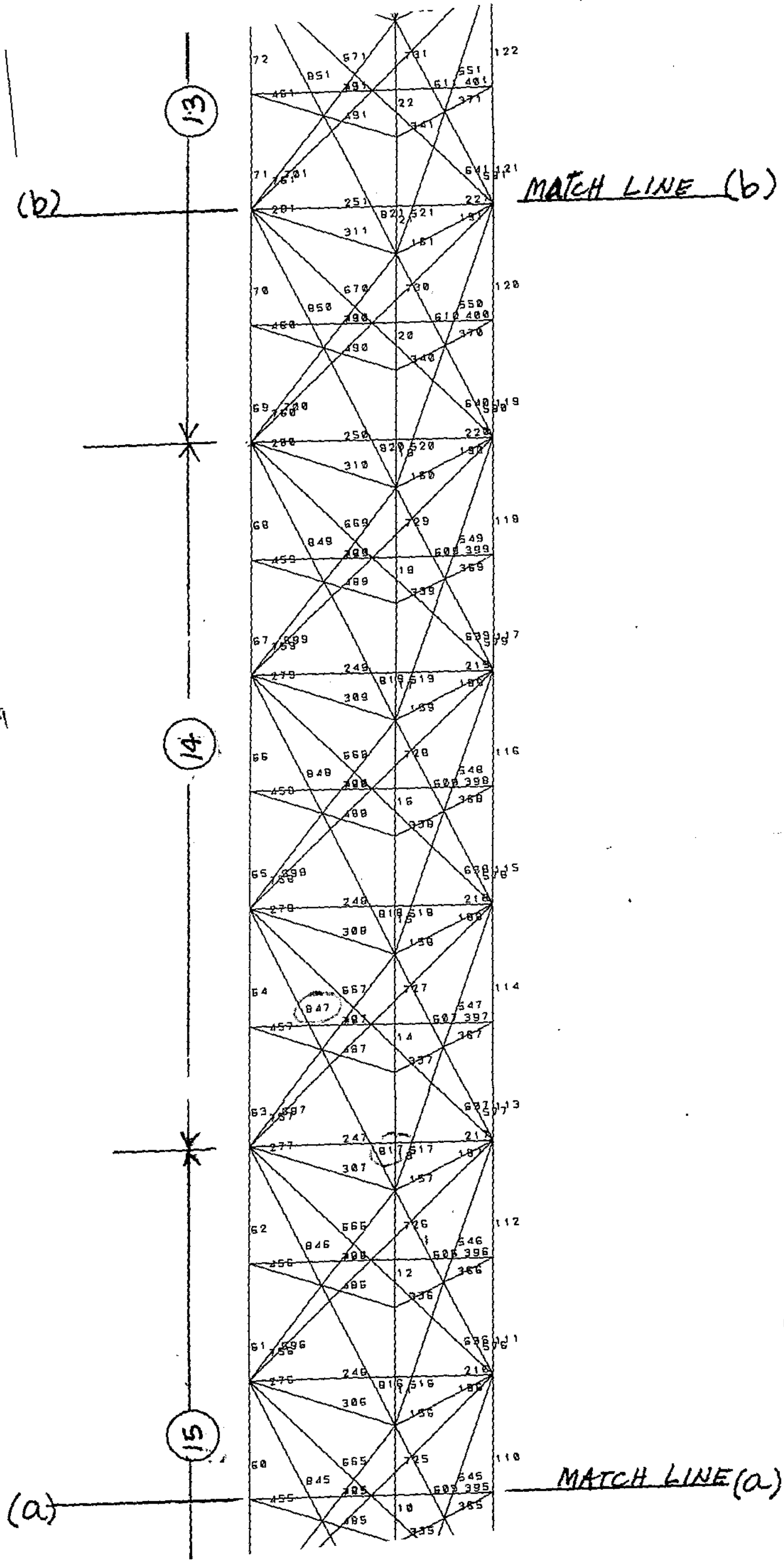

757 787
758 788
759 789

Figure 16

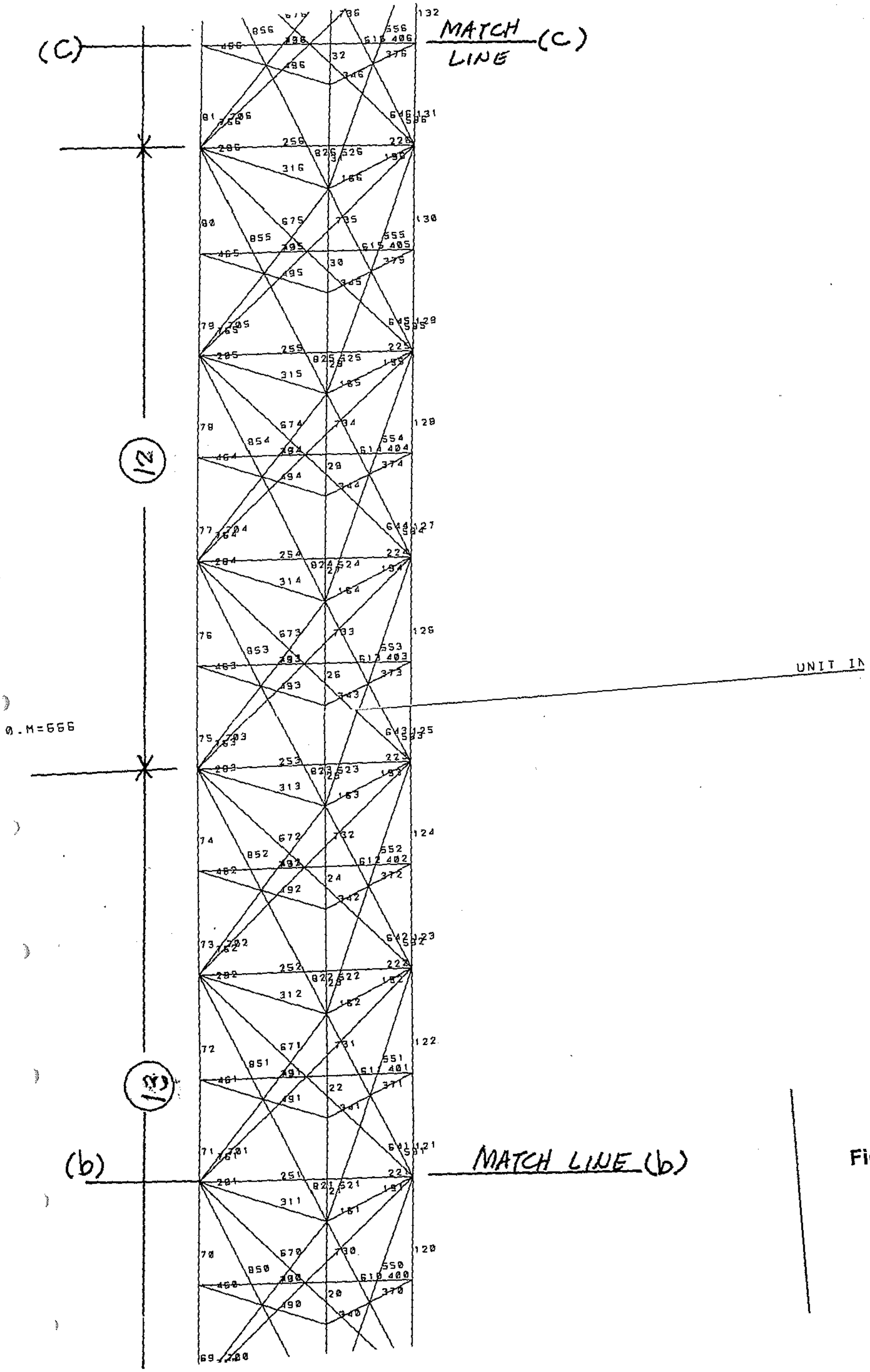

Figure 17

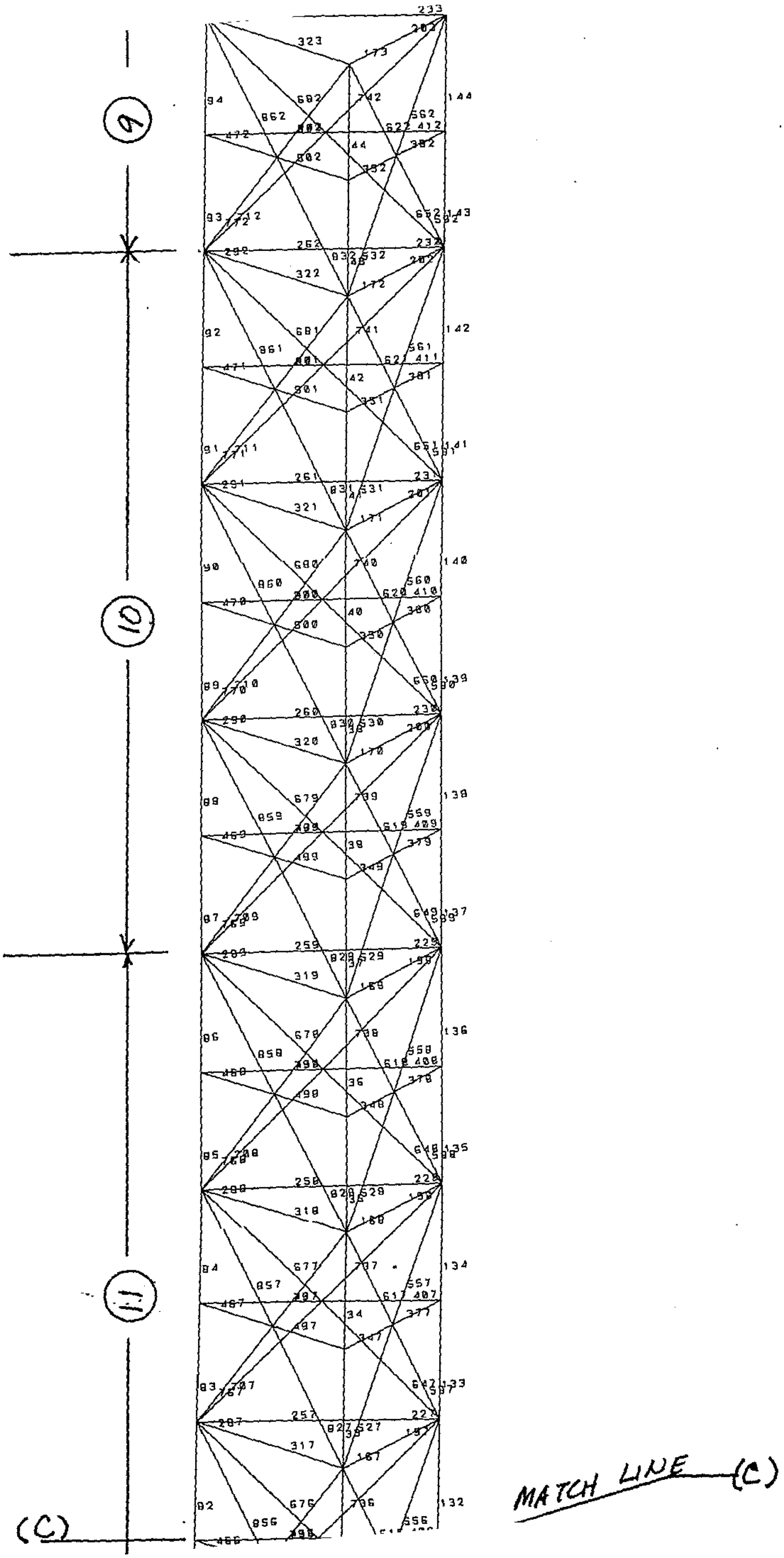

Figure 18

MN/ELEM

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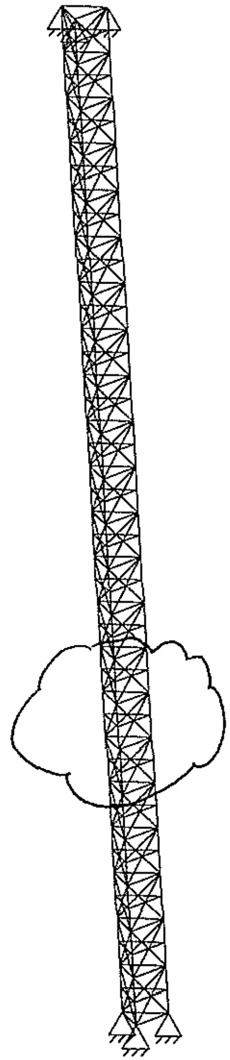

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UNIT FT POU

S T A A D P O S T - P L O T (REV: 22.3)

DATE: APR 9, 1998

TITLE: - TV TOWER IN JACKSON MS. (TVTOWERS)

Figure 19

User ID: US dept. of Labor/OSHA

MN/ELEM

STRUCTURE DATA

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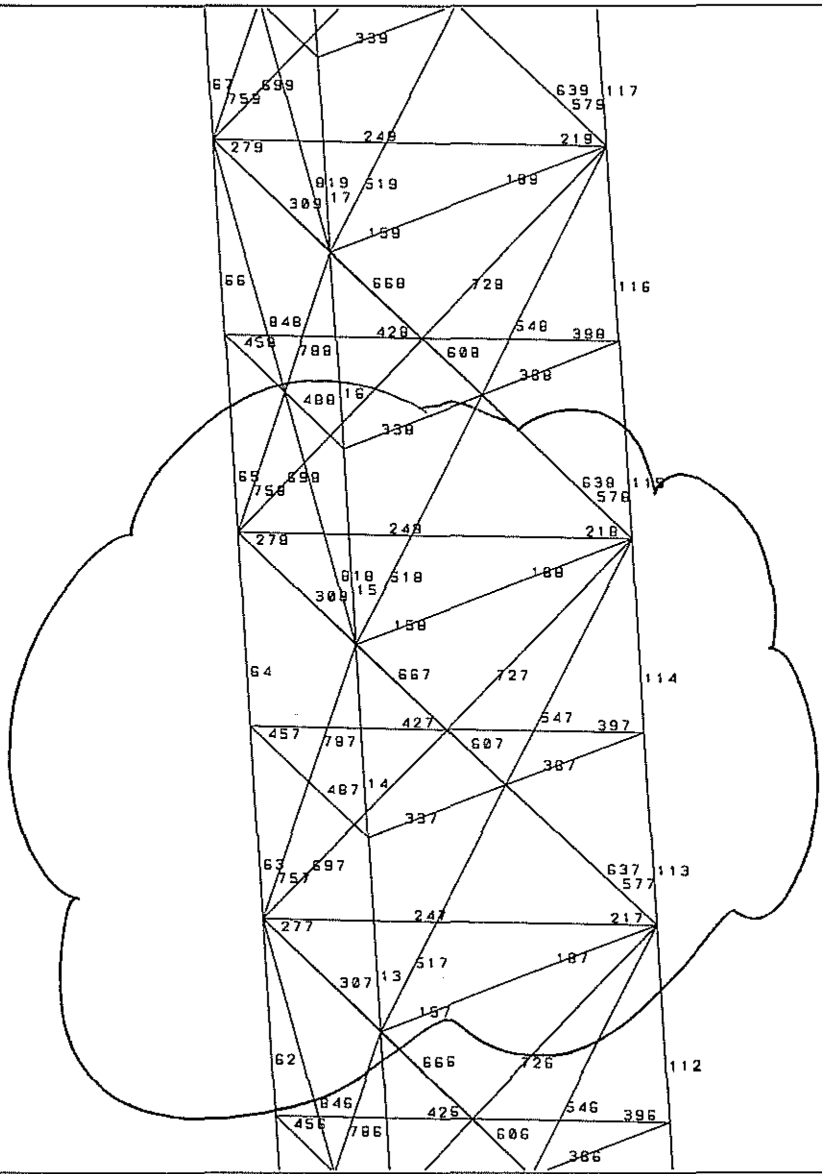

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UNIT FT POU

S T A A D P O S T - P L O T (REV: 22.3)

DATE: APR 9, 1998

TITLE: - TV TOWER IN JACKSON MS. (TVTOWERS)

Figure 20

Figure 21

STRUCTURE DATA

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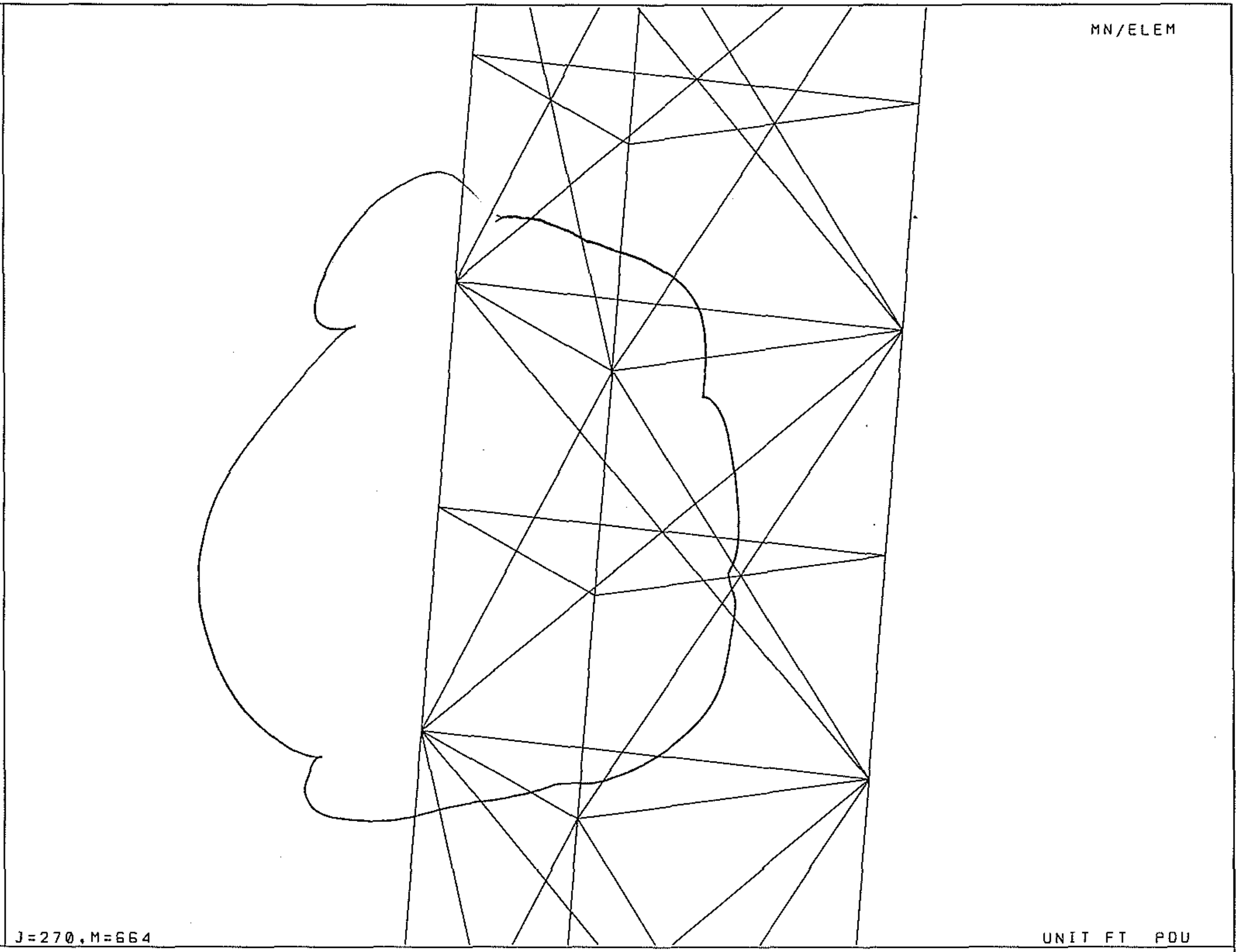
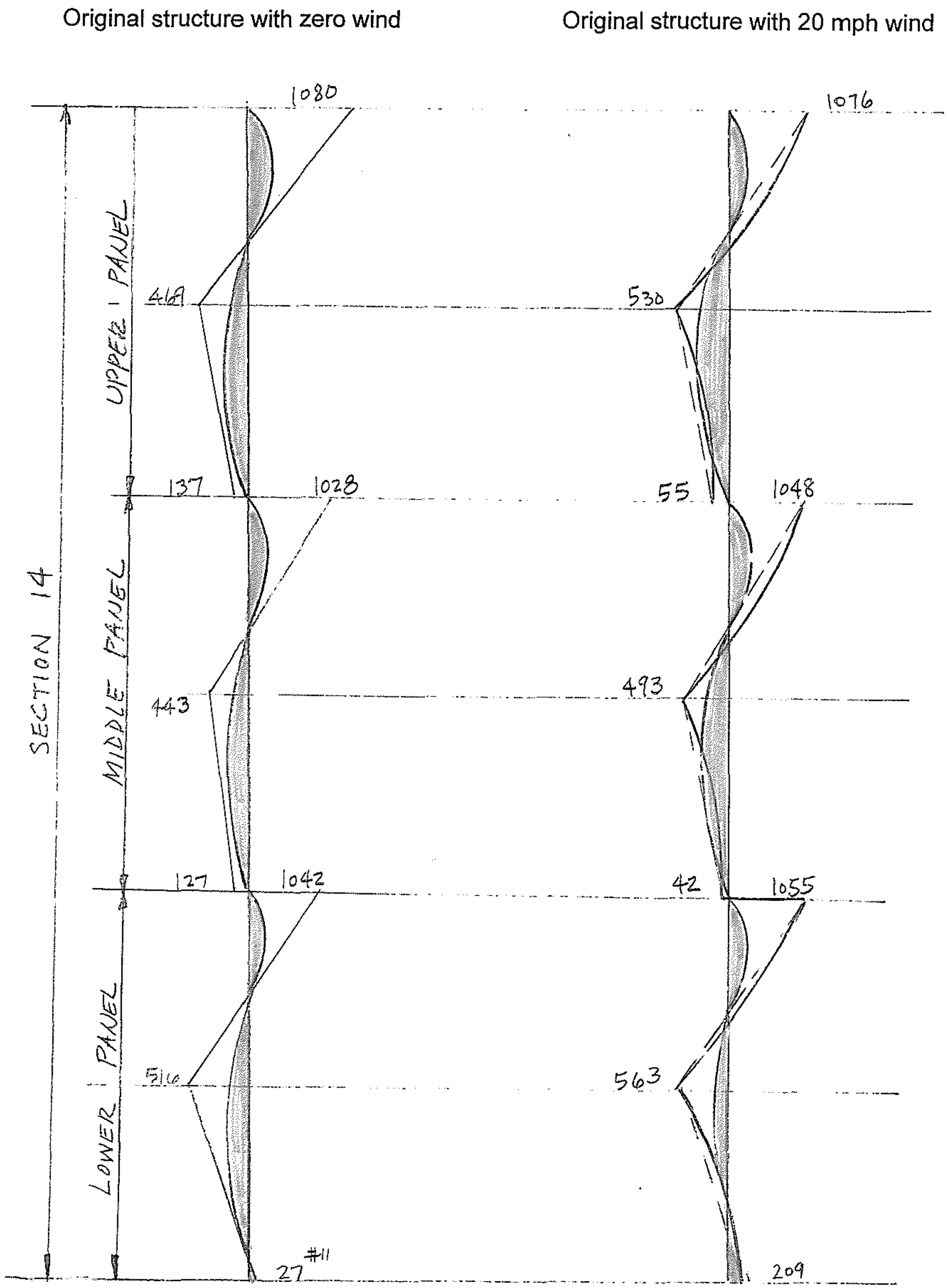


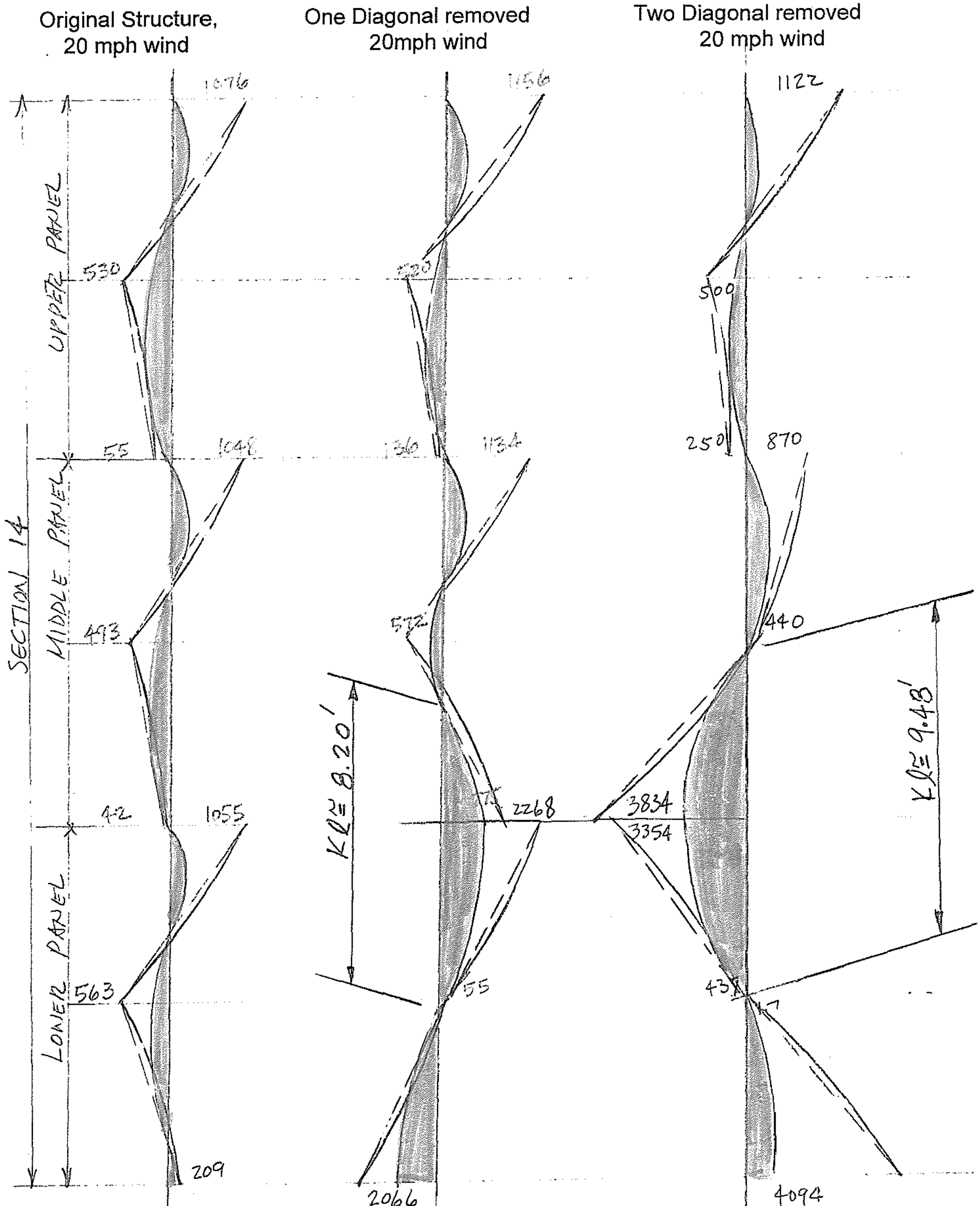
S T A A D P O S T - P L O T (REV: 22.3)

DATE: APR 9, 1998

TITLE: - TV TOWER IN JACKSON MS. (TVTOWER5)



Bending Moment (MY), and The Deflected Shape (Section 14, West Leg) **Figure 22**



Bending Moment (MY), and The Deflected Shape
(Section 14, West Leg)

Figure 23

MN/ELEM

STRUCTURE DATA

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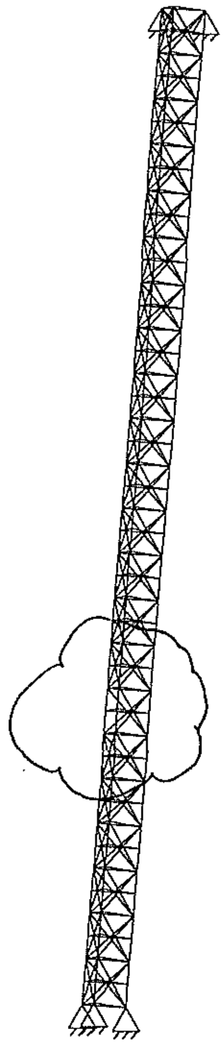

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UNIT INC POU

S T A A D P O S T - P L O T (REV: 22.3)

DATE: APR 9, 1998

TITLE: - TV TOWER IN JACKSON MS. (TVTOWER7)

Figure 24

STRUCTURE DATA

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NRJ = 6
NL = 4
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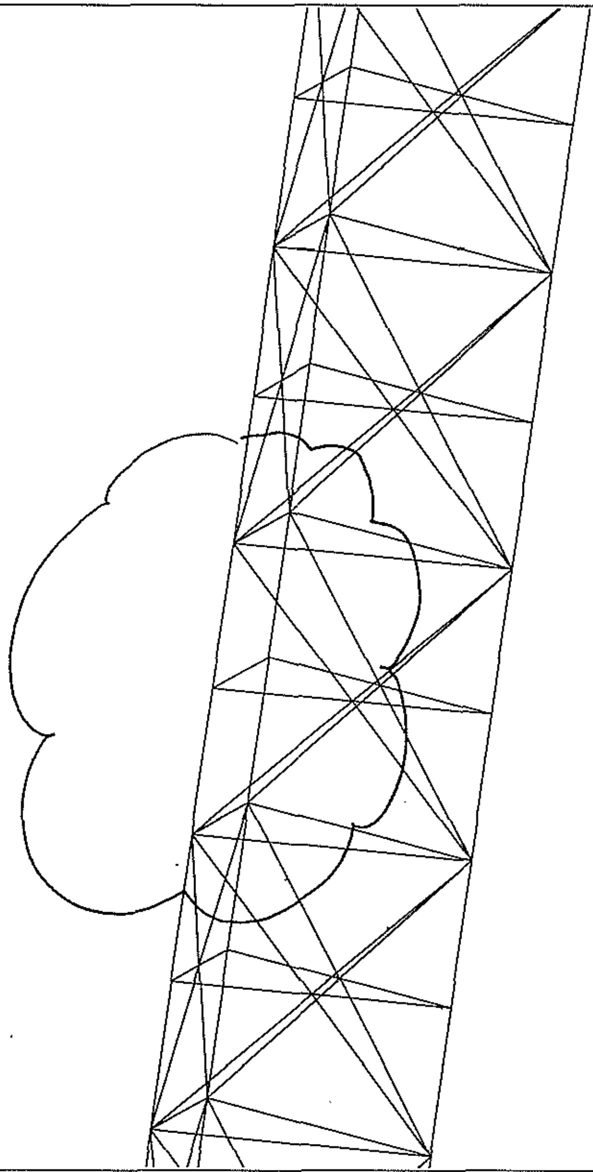
YMAX = 2640.0
ZMAX = 103.9



S T A A D P O S T - P L O T (REV: 22.3)

DATE: APR 9, 1998

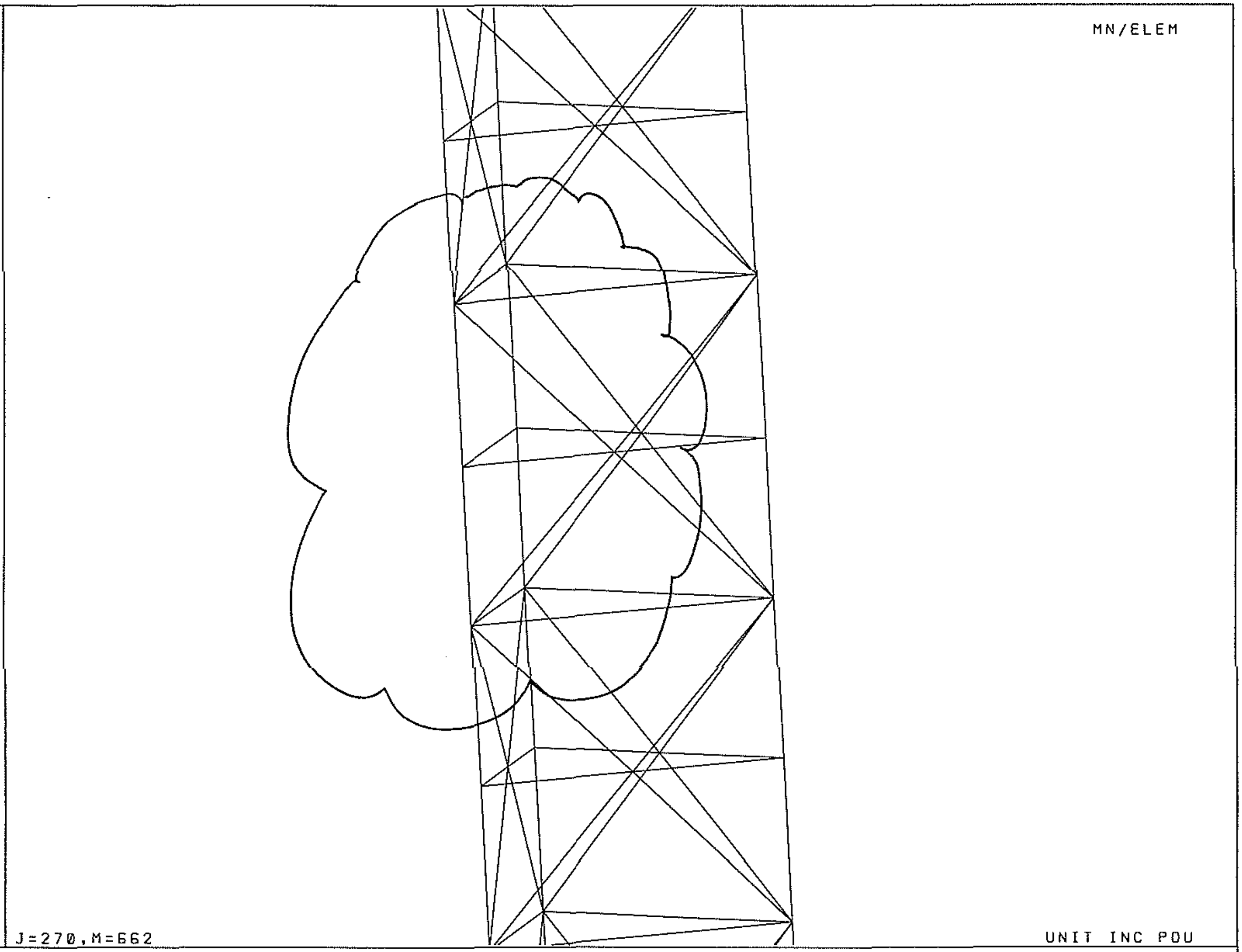
TITLE: - TV TOWER IN JACKSON MS. (TVTOWER7)

Figure 25

Figure 26

STRUCTURE DATA

TYPE = SPACE
NJ = 270
NM = 662
NE = 0
NS = 0
NRJ= 6
NL = 4
XMAX= 120.0
YMAX= 2640.0
ZMAX= 103.9



S T A A D P O S T - P L O T (REV: 22.3)

DATE: APR 9, 1998

TITLE: - TV TOWER IN JACKSON MS. (TVTOWER7)

Appendix B

Laboratory Report

Report of examination of sections of a transmission tower submitted by the Jackson, Mississippi Area Office

The following sections of the WLTB tower were sent to the Salt Lake Technical Center for evaluation. SLTC was instructed to forgo any destructive testing and restrict analysis to appropriate non-destructive methods. This limited the applicable methodology to observation.

1. Diagonal section 14.3A1 attached to Gusset 14.4A from the West leg
2. Gusset 14.4A from the West leg
3. West portion of cross brace 14.4A attached to Gusset 14.4A from the West leg
4. Diagonal section 14.5A2 attached to Gusset 14.4A from the West leg
5. Diagonal 14.5A1 not attached but with a bolt in a hole in one fish head end
6. North end of 14.5A redundant brace
7. West end of 14.5A redundant brace
8. A bolt and nut were collected at the site by Daniel T. Crane on 10 March 1998.

Figure 1 is a photo of the pieces as received at the Salt Lake Technical Center.

Figure 2 illustrates the original relative location of the pieces as reported by the area office to SLTC.

Gross description of submitted pieces (Refer to figure 2 for orientation):

1. 14.3A1
   a. The north connection at 14.2N missing. The fish head flange was fractured perpendicularly to the longitudinal axis of the member at a point between the end of the rod and the first (proximal) hole. The actual connected portion was not sent to SLTC. (Figure 3)

   b. The top connector at 14.3A redundant was missing. The connector failed at the weld. (Figure 4)

   c. The bottom connector at 14.3 redundant was present with no gross damage. The appearance of the hole was unremarkable.

   d. The west fish head at 14.4W connection gusset is intact with new hex-head bolts. The connection shows some obvious signs of strain.

2. Gusset 14.4A from the West leg (Figure 5)

   a. The fish head of 14.3A1 is attached with two new bolts.

   b. The cross brace at 14.4 is attached with one original bolt.

   c. The fish head of 14.5A2 is attached with two original bolts.

   d. The gusset failed along the weld on the west leg.

3. Cross brace 14.4A (Figure 6)

   a. The brace is constructed of angle steel and the submitted portion has 29 remaining inches connected with one bolt to the west leg 14.4A gusset at the west leg. This connection is somewhat loose, the nut having stripped partially off the shank of the bolt.

b. The cross brace fractured approximately 28 inches from the point of connection on the west leg.

4. Diagonal section 14.5A2

   a. The top connection (fish head) is connected to the West 14.4A gusset with two original bolts and shows some strain.

   b. The top connector at 14.5 redundant was present with no gross damage. The appearance of the hole was unremarkable. (Figure 7)

   c. The bottom connector at 14.5 redundant was present with no gross damage. The appearance of the hole was unremarkable.

   d. The fish head connector at 15.0A North leg was missing having failed in the rod proximal to the fish head flange. (Figure 8)

5. Diagonal 14.5A1

   a. This diagonal section did not appear to have been attached at the time of the accident (Figure 9)

   b. All bolt holes are unremarkable.

   c. One of the bolt holes had a bolt in it. The bolt was loosely done up with a spring-loaded lock-nut. It had been slightly wedged into the hole. (Figure 10)

6. North end of redundant brace 14.5A. (Figures 11 through 17)

   a. The end flange connector at 14.5A West is bent approximately 15 degrees, toward the tower structure. This end of the flange was deformed approximately 1/16" distal to the bulk of the member and centered consistent with gouging noted by the hole. Mushrooming consistent with impact noted on distal end of flange. The paint around the nut does not appear to be disturbed except at the gouge site. The pipe end at the flange connection point shows damage consistent with contact with the fixed flange on West leg at 14.5. The damage is consistent with the bolt being in the hole at the time of the tower collapse.

   b. The center end of redundant member parted in apparent ductile fracture distal to the center connecting assembly. The fracture was relatively symmetric indicating axial load at the failure point.

7. West end of 14.5A redundant brace.

   a. The center flange assembly was present on this piece showing ductile fracture at the end consistent with axial stress as noted in 6.b above.

   b. The North end of the redundant member showed ductile fracture in the flange with little bending. (Figure 18)

   c. The piece was bent in a "U" shape.

Examination of the 5/8"" x 1 3/4"" bolt and nut collected at the site was conducted by light and scanning electron microscopy (SEM). The gross appearance was that the head of the bolt sheared off at approximately the point of attachment. There was some deformation to indicate this. The fracture surface was obliterated by corrosion so that examination by SEM was uninformative. The importance of this piece was that it is an observed mode of failure in this accident for bolts to fail at the head with little deformation of the shank. This could be related to the mode of failure of the redundant flange connection at 14.5A West. (Figure 19)

At the site, near Jackson, Mississippi, the attachment points of these pieces were examined. Of particular note were the attachment points of the redundant member 14.5A.

1. The attachment point on the North leg still had the mating portion of the flange bolted to redundant member 14.5A. The fracture surface had the same appearance as that on the redundant member. It had the appearance of ductile fracture and approximately the same degree of corrosion. The attachment flange on 14.5A north leg was bent. (Figures 20, 21)

2. The attachment point on the west leg was slightly bent with damage on the top, outside edge consistent with damage on the 14.5A redundant west pipe. The hole in the flange was deformed axially. The damage is consistent with a bolt having been in this hole at the time of tower collapse. (Figures 22, 23, 24)

Conclusion:

All members except the 14.5A1 diagonal were attached at the time of the collapse. The diagonal member 14.3A1 failed at the North leg with the fish-head failing aby fracture. The cross-brace at 14.4 failed by fracture about 28 inches from its point of attachment to the West leg. The diagonal member 14.5A2 failed at the North leg. The redundant member 14.5A failed at the north connection flange by apparent ductile fracture, and on the west side of the middle connector by apparent ductile fracture. The 14.5A redundant member was connected to the West attachment lug at the time of the collapse. These determinations were made by the presence of catastrophic fracture, physical damage and hole distortion of the submitted pieces.

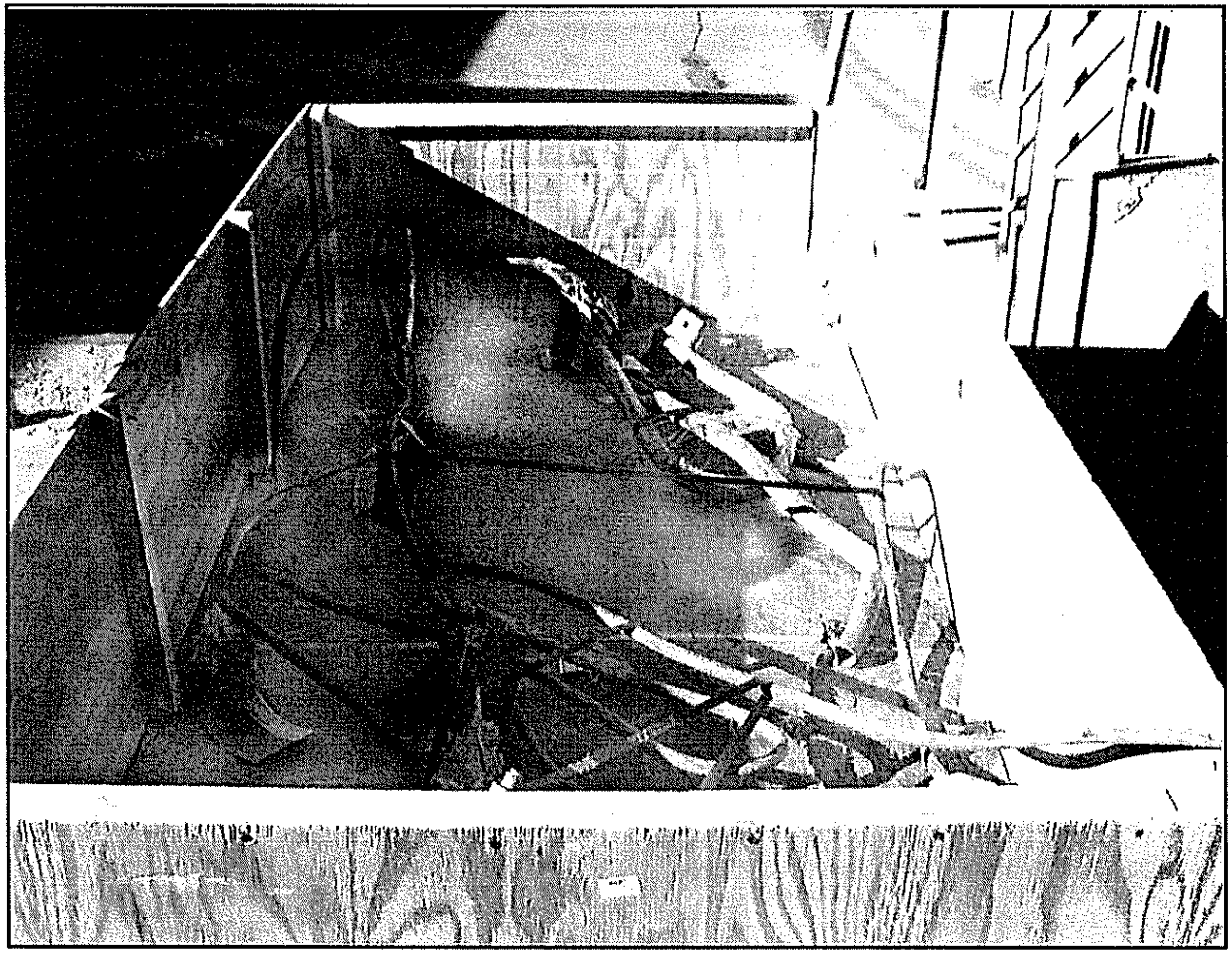


Figure 1: Tower pieces as received in box at Salt Lake Technical Center

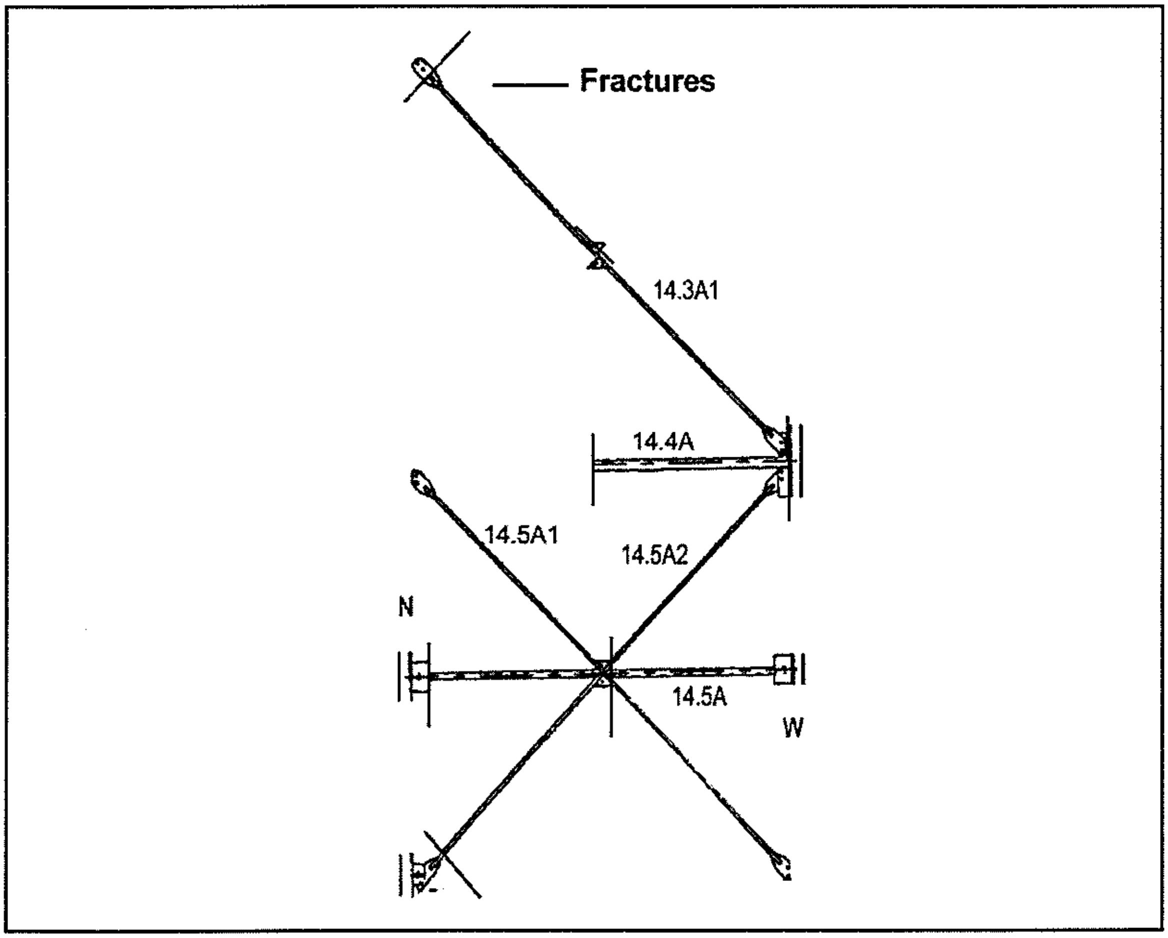


Figure 2: Relative position of submitted members in the tower before collapse. The points of fracture are noted by solid lines (Red in the original).

Figure 3: North connection at 14.3 of 14.3A1. This piece was attached at the time of failure as indicated by the fracture of the "fish head."

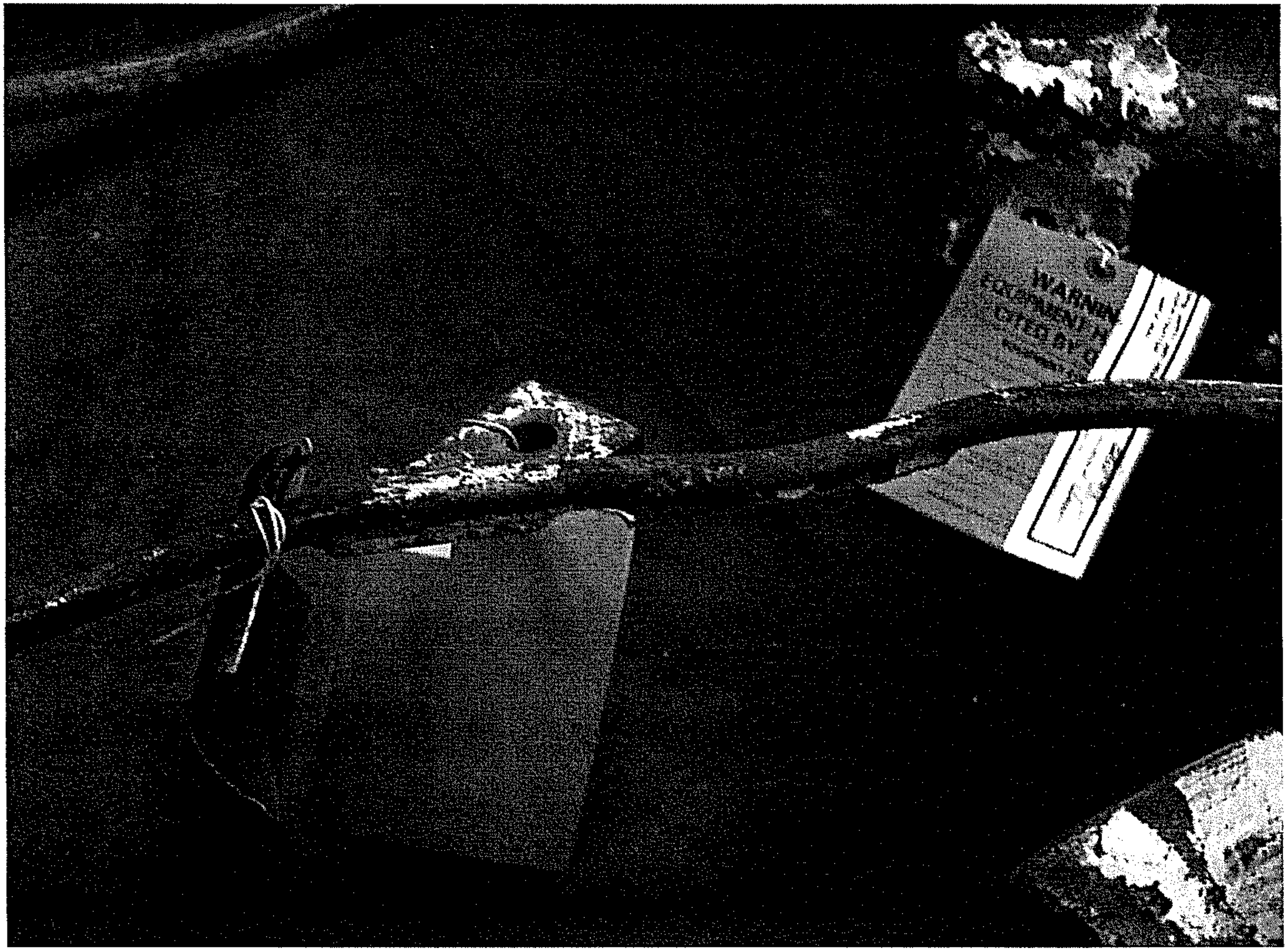


Figure 4: Center connection points of 14.3A1. The upper tab is missing having failed at the weld, while the lower tab remains. The hole is unremarkable.

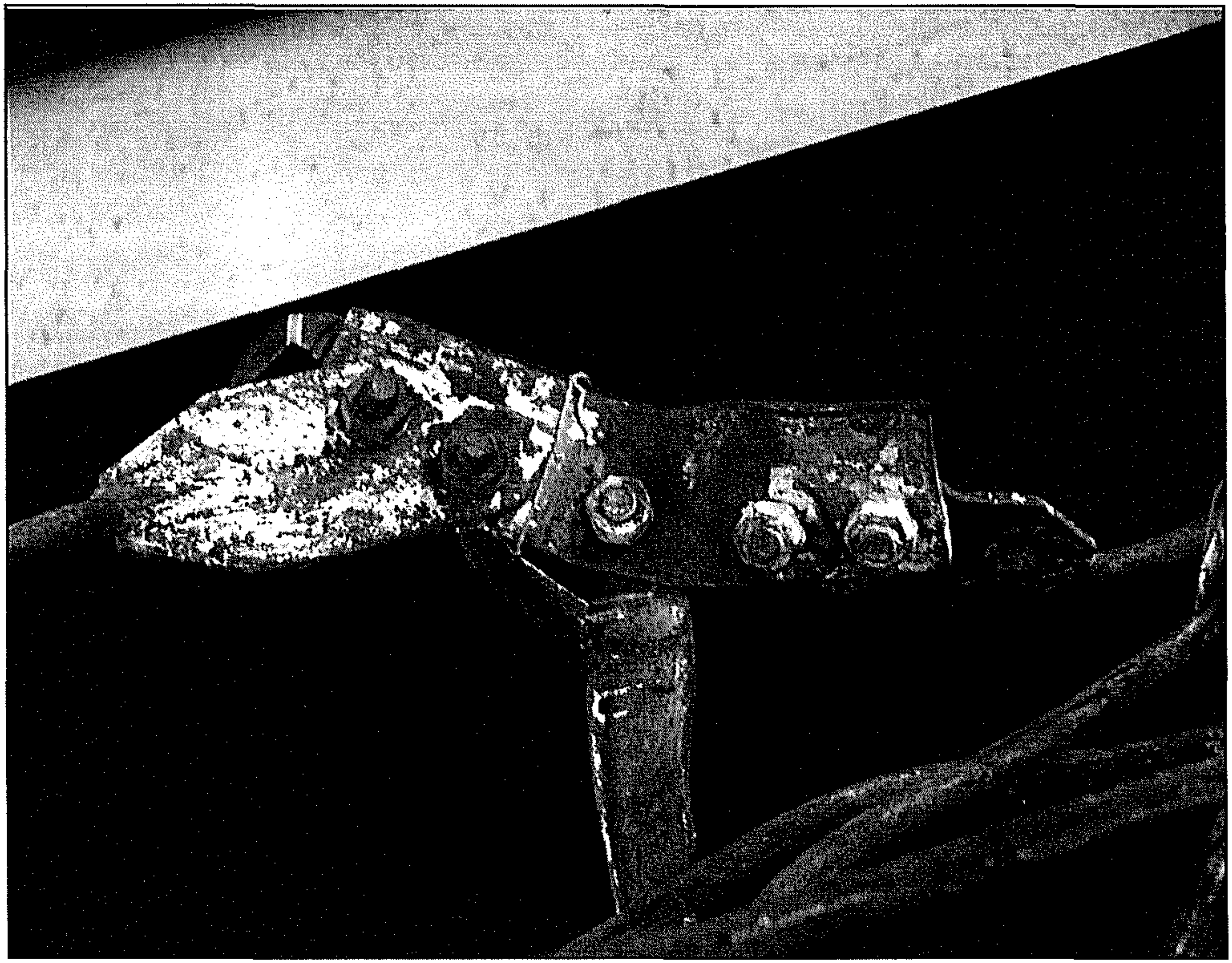


Figure 5: This is the separated main leg gusset from the West leg at 14.4. Shown are the connections for 14.3A1 diagonal, 14.4 horizontal brace and 14.5A2 diagonal. The fish head for 14.3A1 is attached with new bolts, while the remaining members are attached with original spring-loaded bolts.

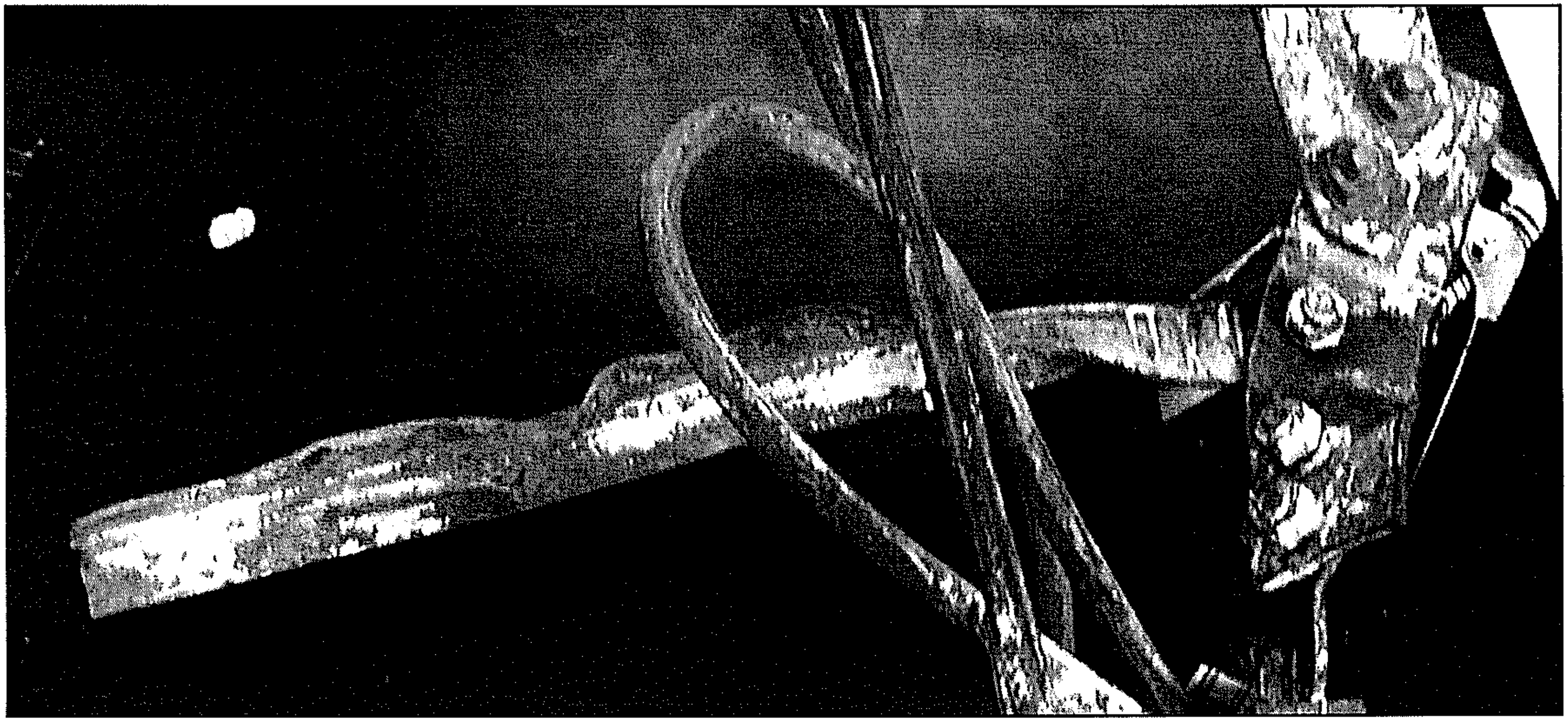


Figure 6: Horizontal brace 14.4A as attached to the West leg gusset

Figure 7: Center connectors on diagonal 14.5A2

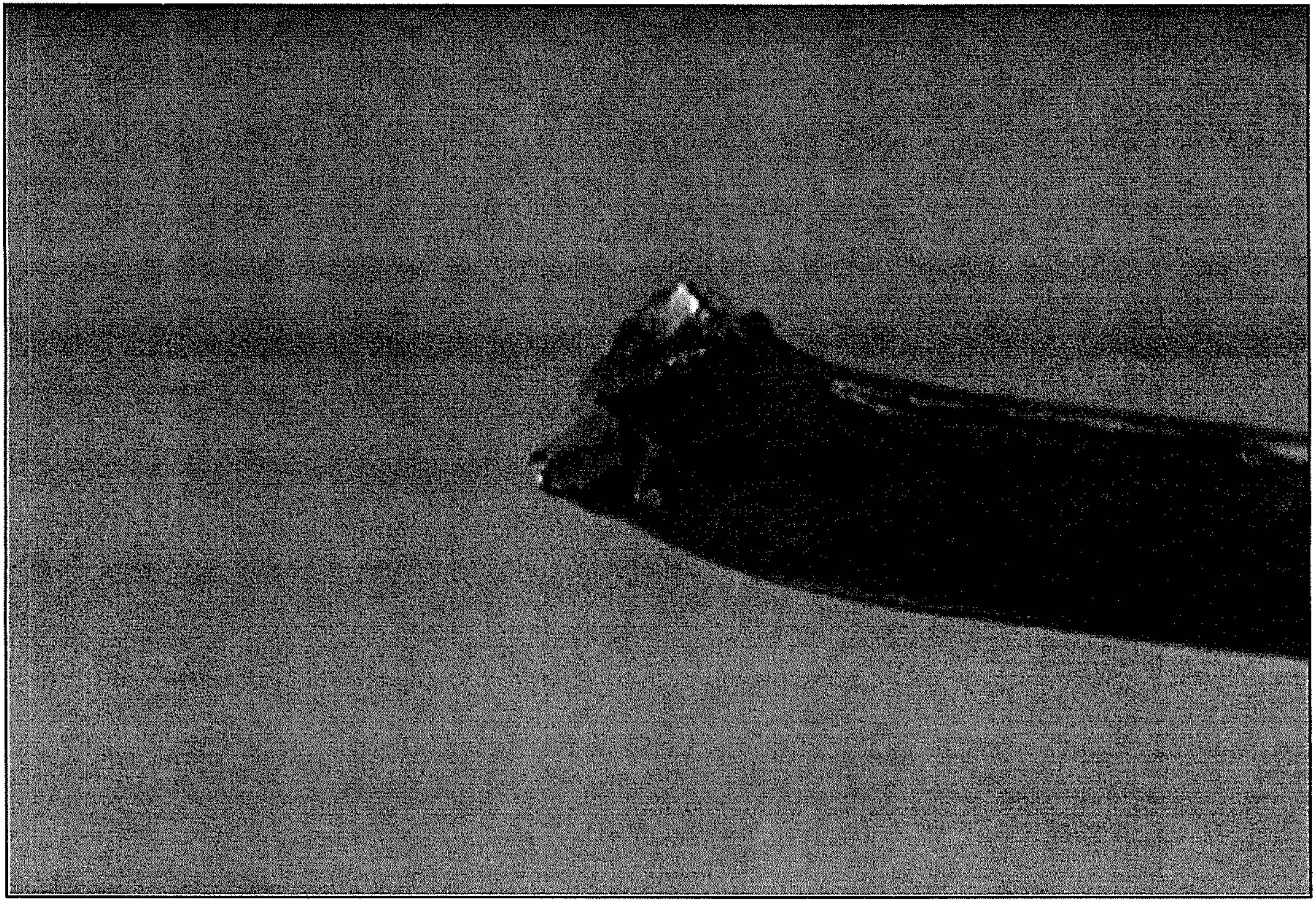


Figure 8: Broken end of 14.5A2 at 15.0 North

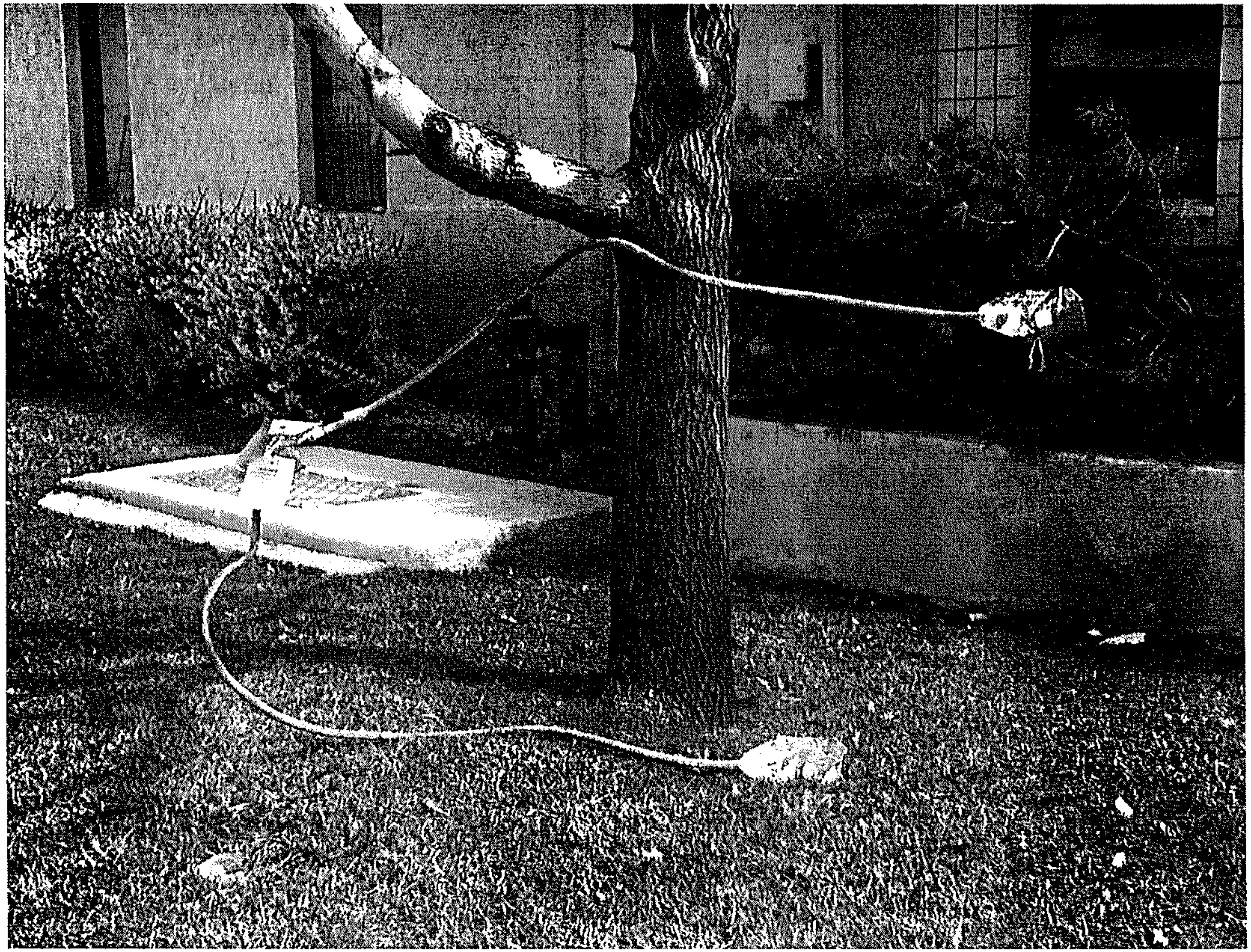


Figure 9: View of diagonal 14.5A1 at Salt Lake Technical Center

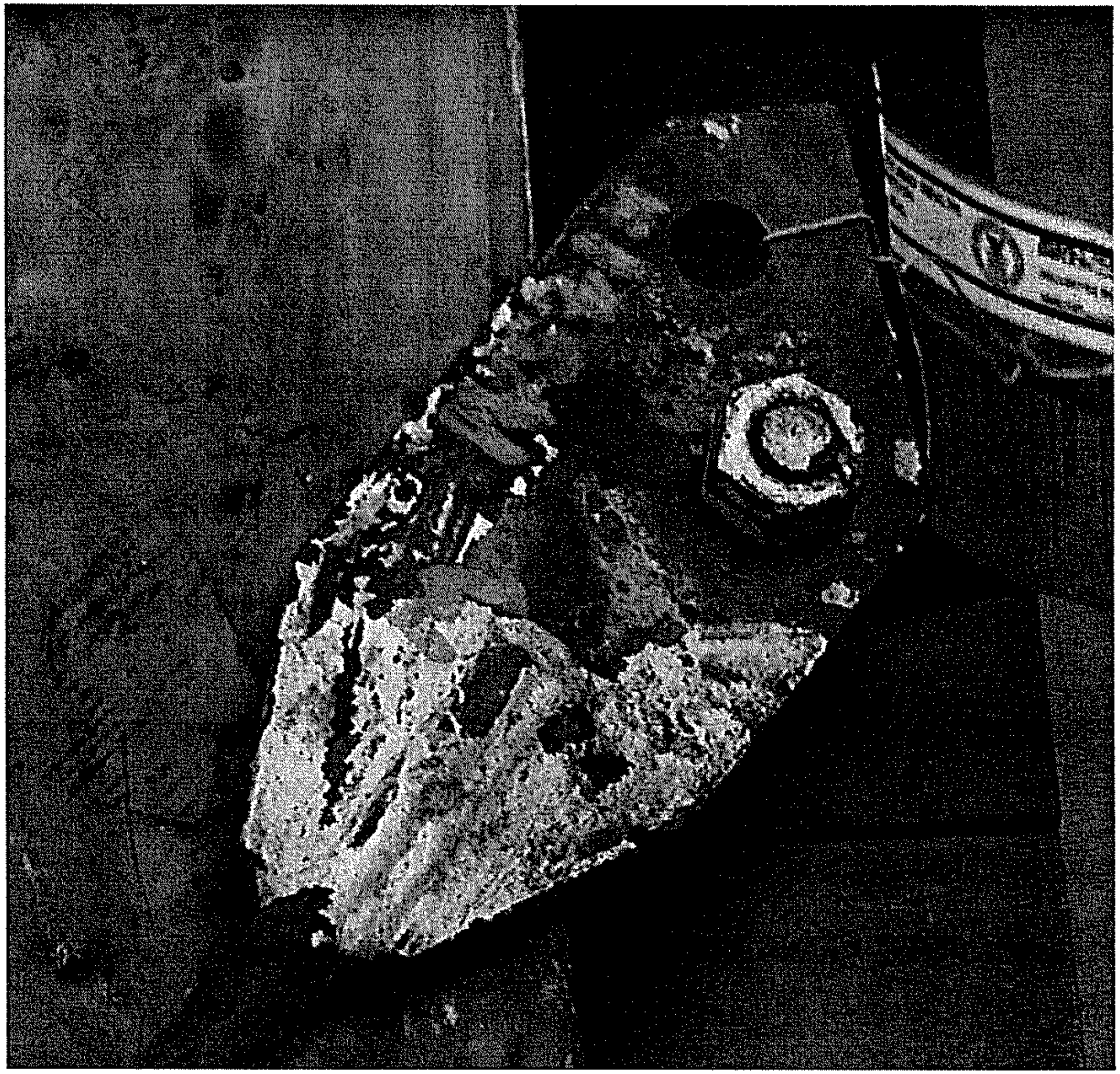


Figure10: Diagonal 14.5A1 W. Note the bolt with the spring-loaded nut was replaced into the hole

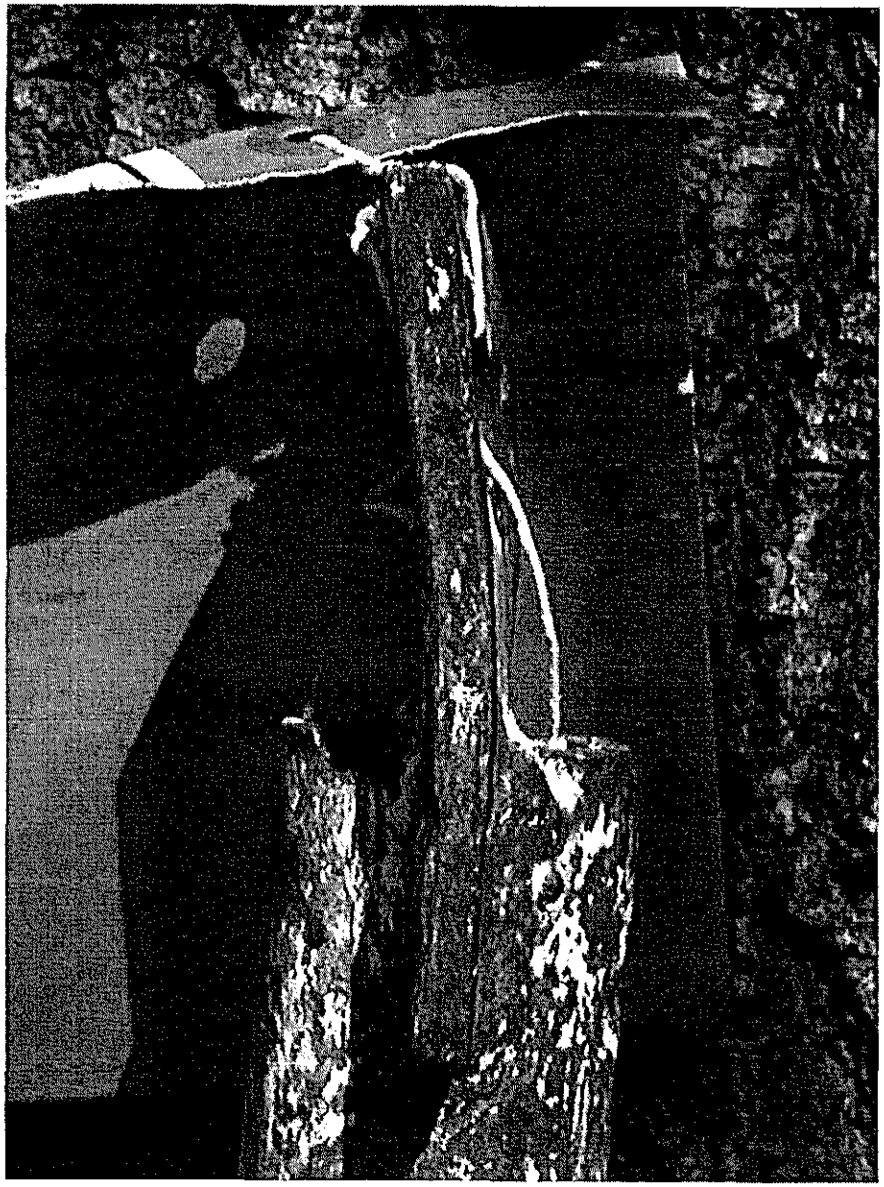


Figure 11: West end of 14.5A redundant showing bend in the direction of the attachment lug on West leg 14.

Figure 12: End-on view of the west end of 14.5A redundant showing bowing.

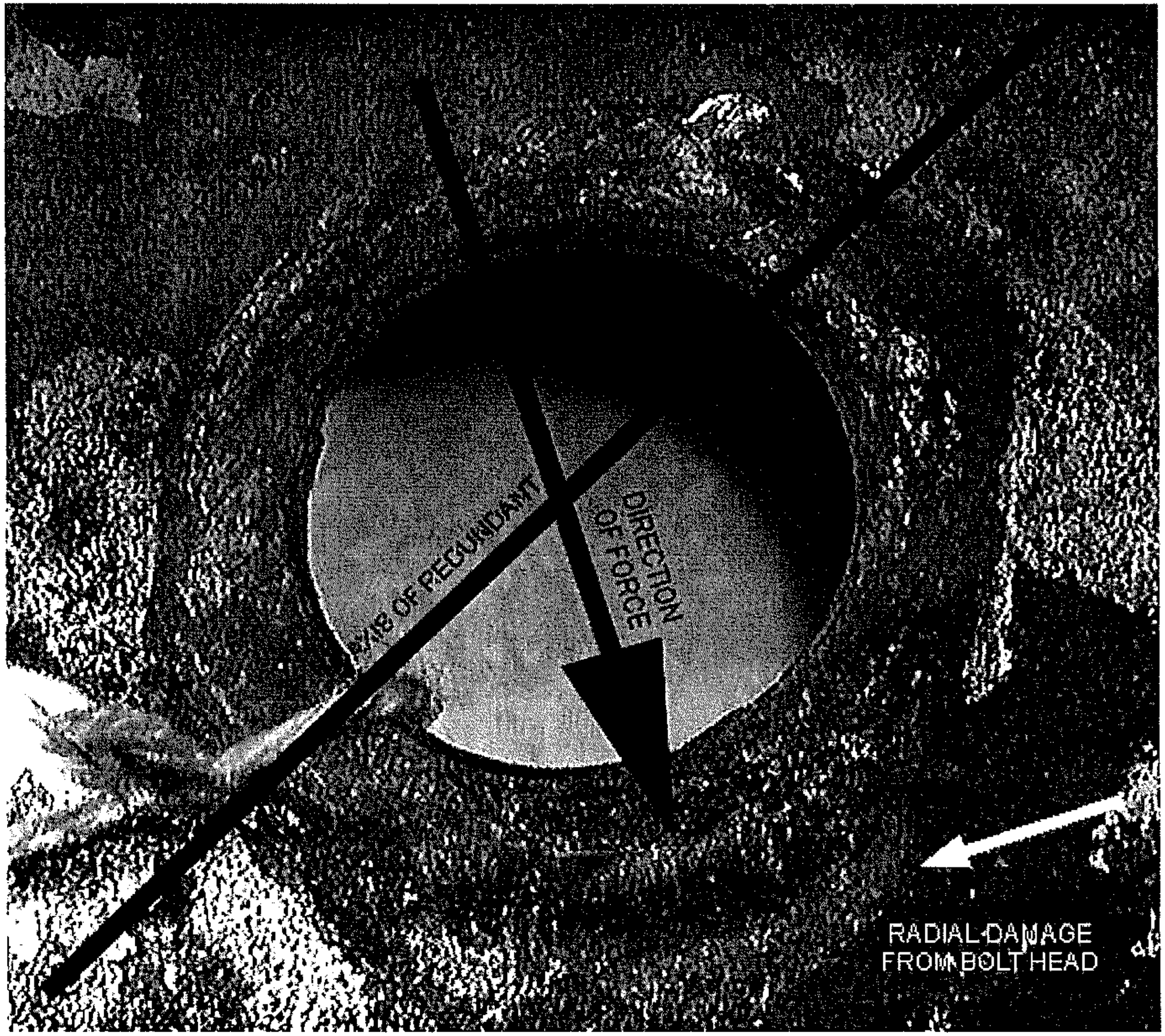


Figure 13: Direction of force relative to the axis of the redundant 14.5A also showing radial damage due to bolt head gouging during bolt failure.

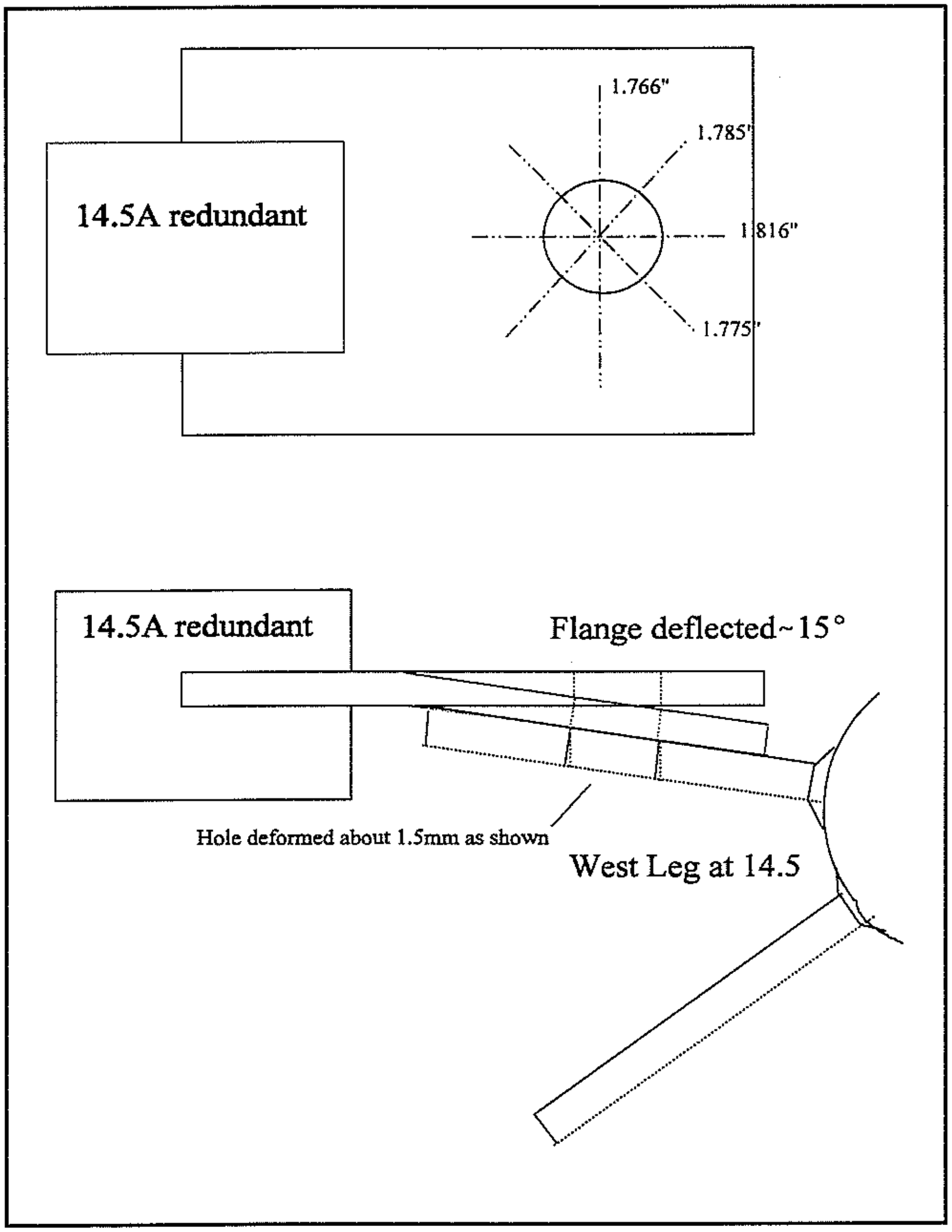


Figure 14: Attachment of 14.5A redundant to West leg at 14.5. The top diagram shows the hole distortion and the bottom shows the flange bend and the hole distortion in the attachment gusset to 14 W. The redundant member is not shown in the position in which it finally failed.

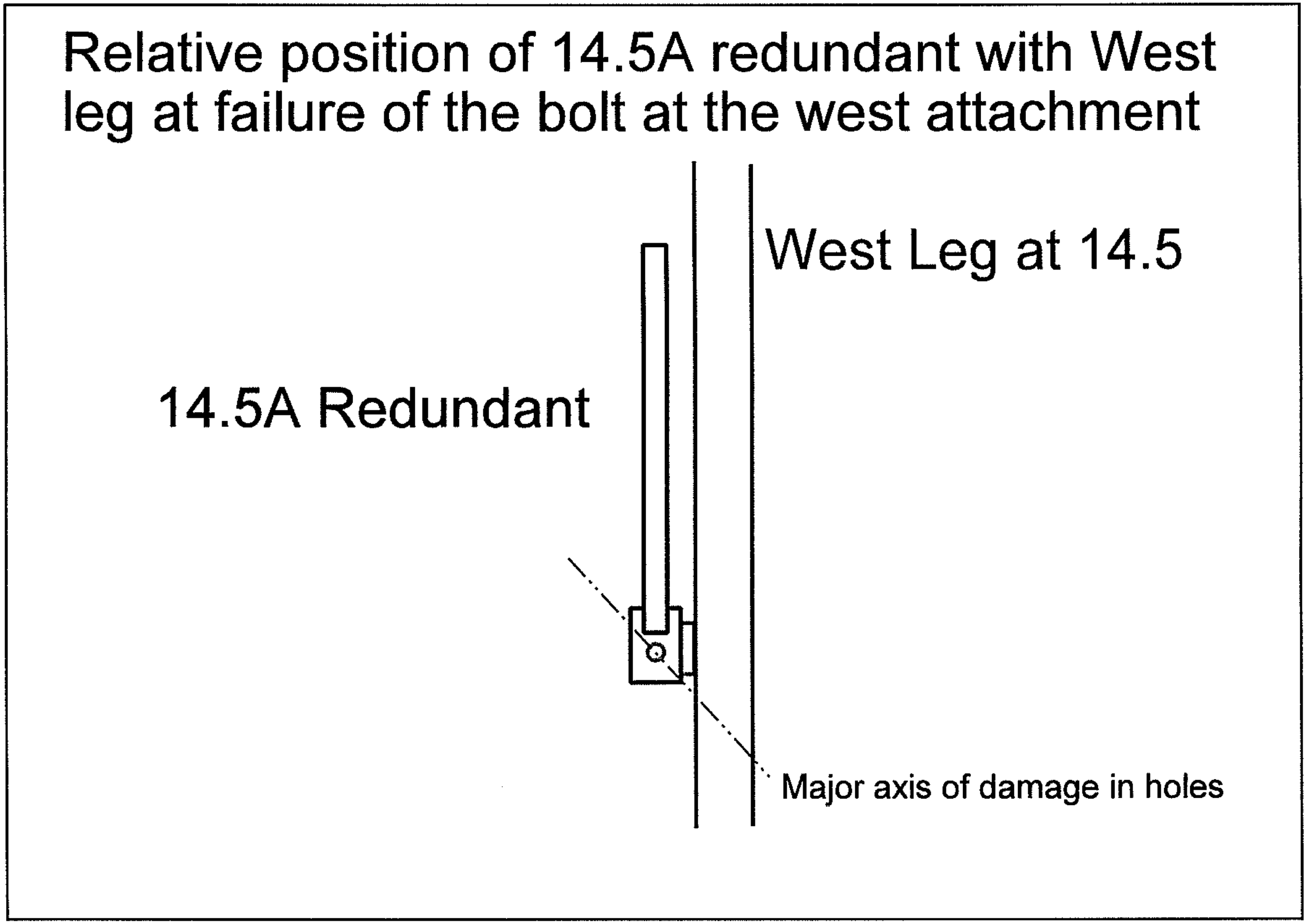


Figure 15: Diagram of 14.5 redundant at failure.

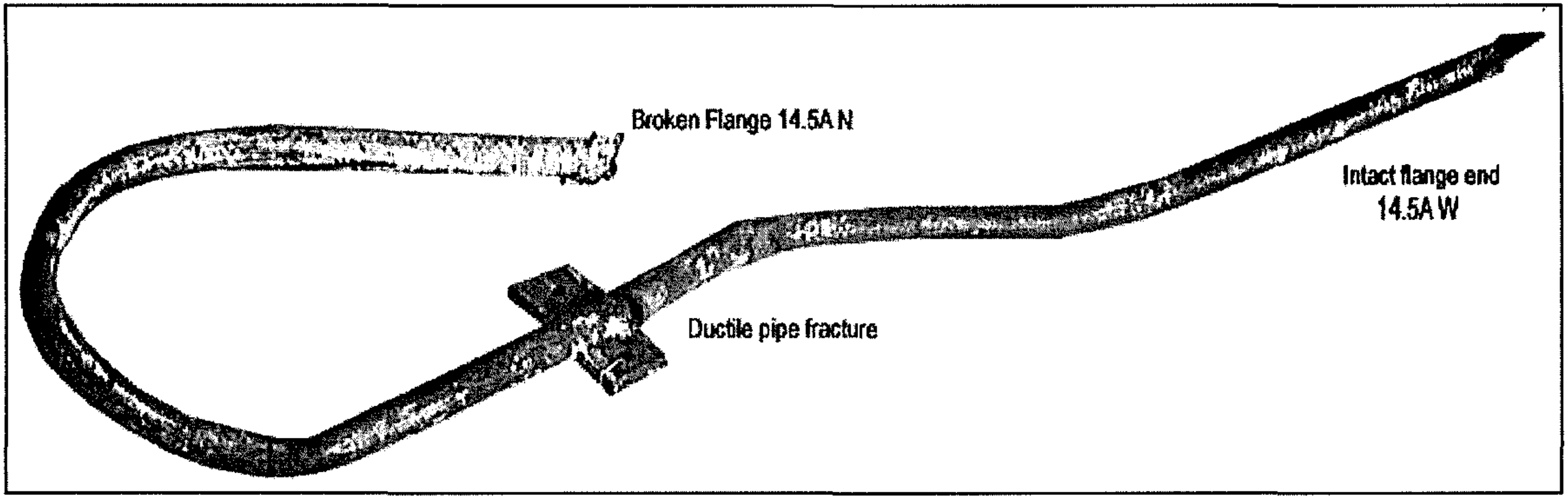


Figure 16: Layout of the pieces of redundant member 14.5A identifying the fracture points.

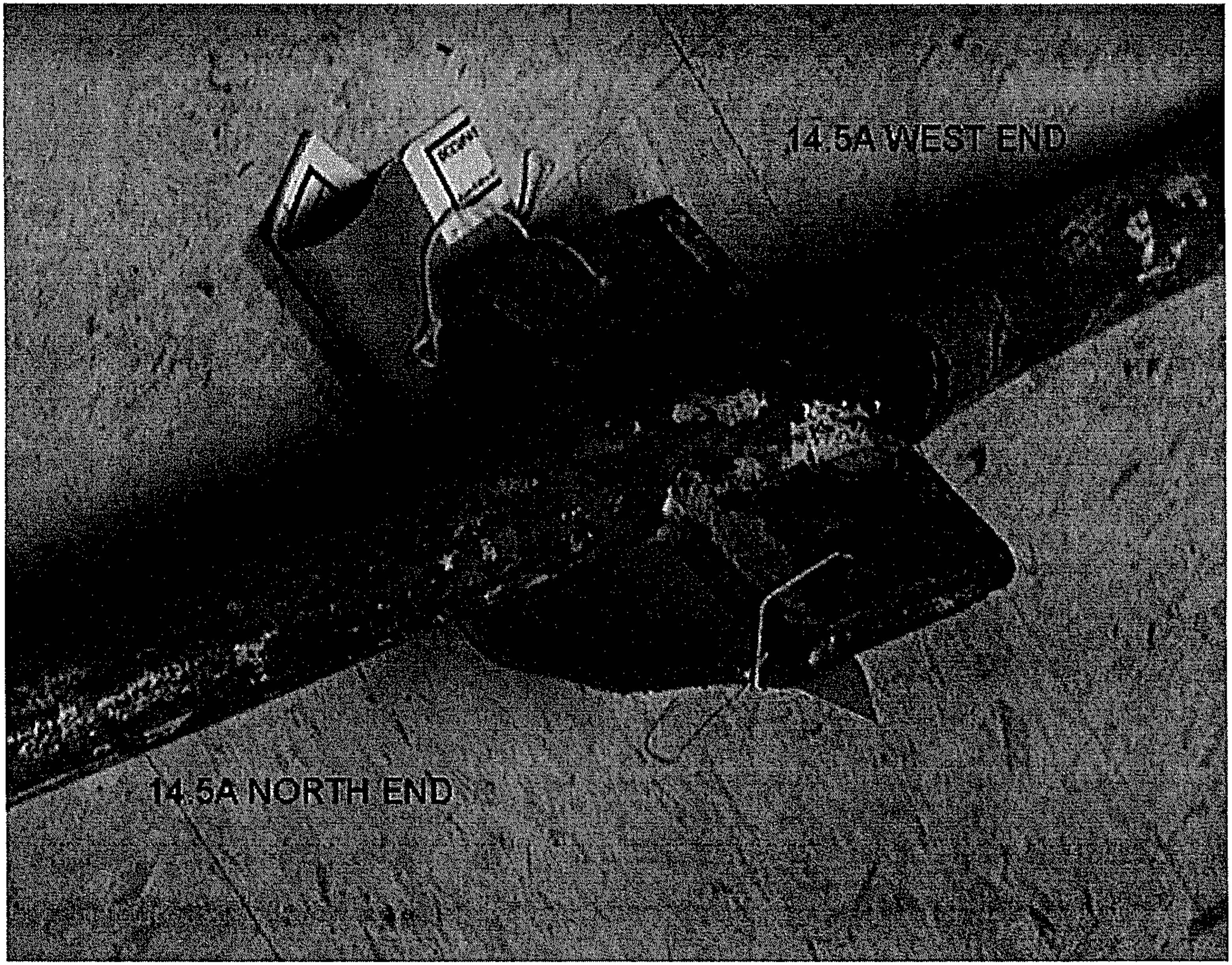


Figure 17: Close-up of the fracture at the center of redundant 14.5A.

Figure 18: The north end of 14.5A redundant showing ductile fracture.

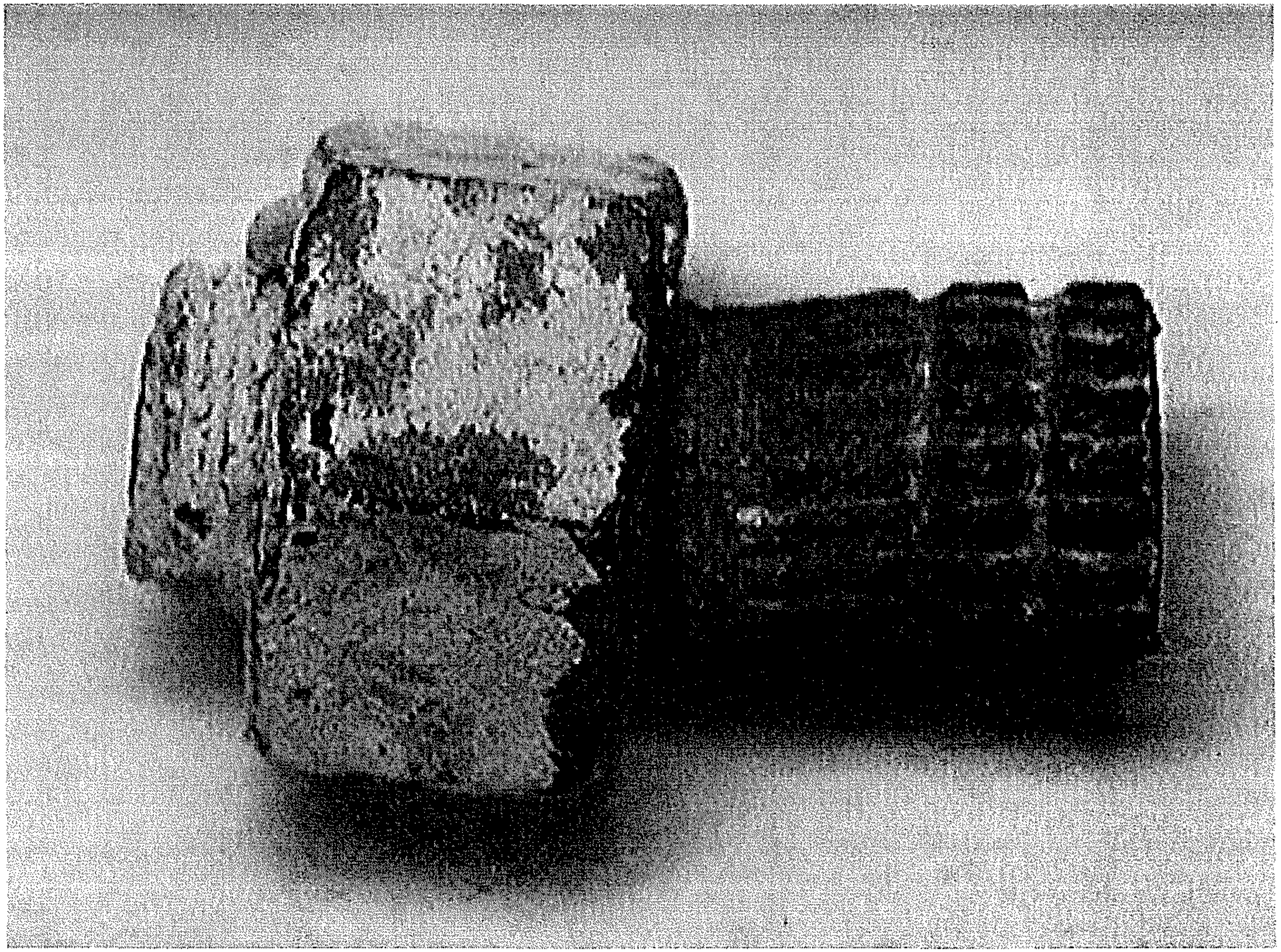


Figure 19: Bolt collected from Tower collapse site. It shows a little bending, little stretching and has apparently failed when the head sheared off.

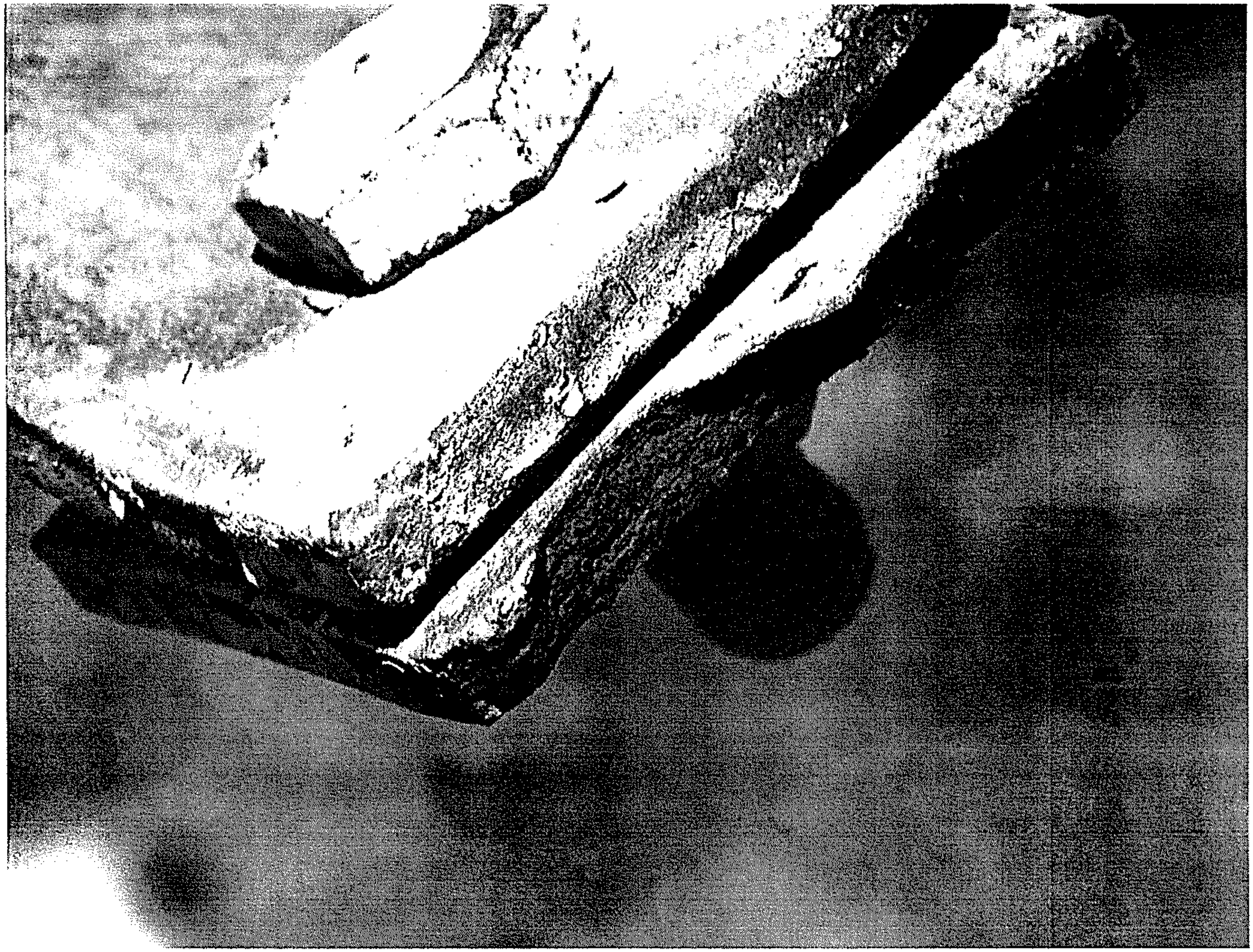


Figure 20: Gusset on North 14 leg at 14.5 with remnant of redundant flange showing ductile fracture.

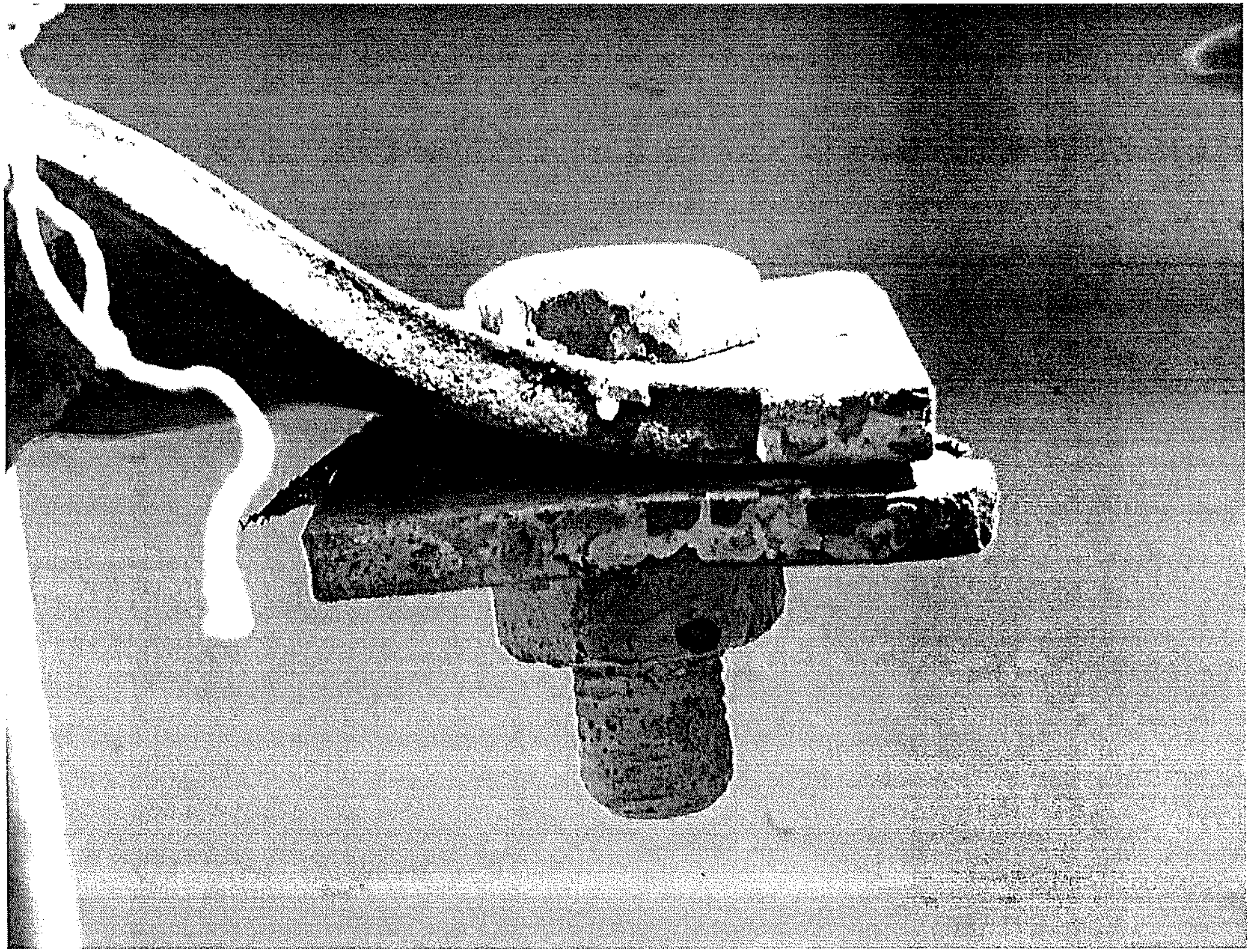


Figure 21: View of remnant of redundant flange attached to North leg at 14.5.

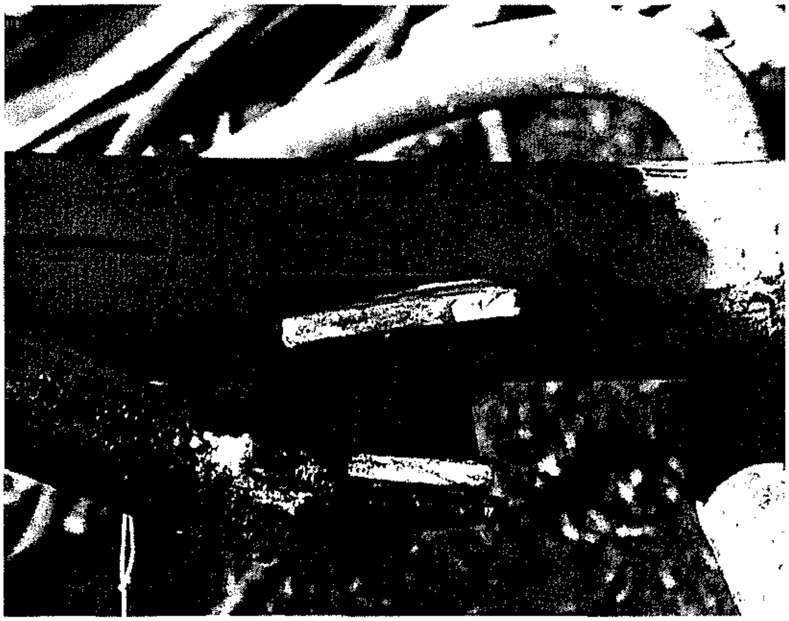


Figure 22: Attachment lug at 14.5 West leg for redundant.

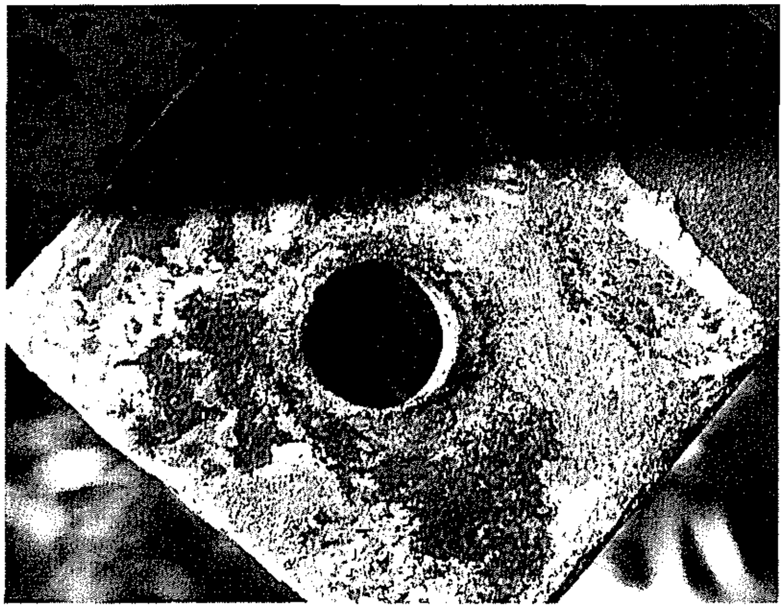


Figure 23: Close-up of attachment lug at 14.5 West
showing hole distortion left to right from bolt failure

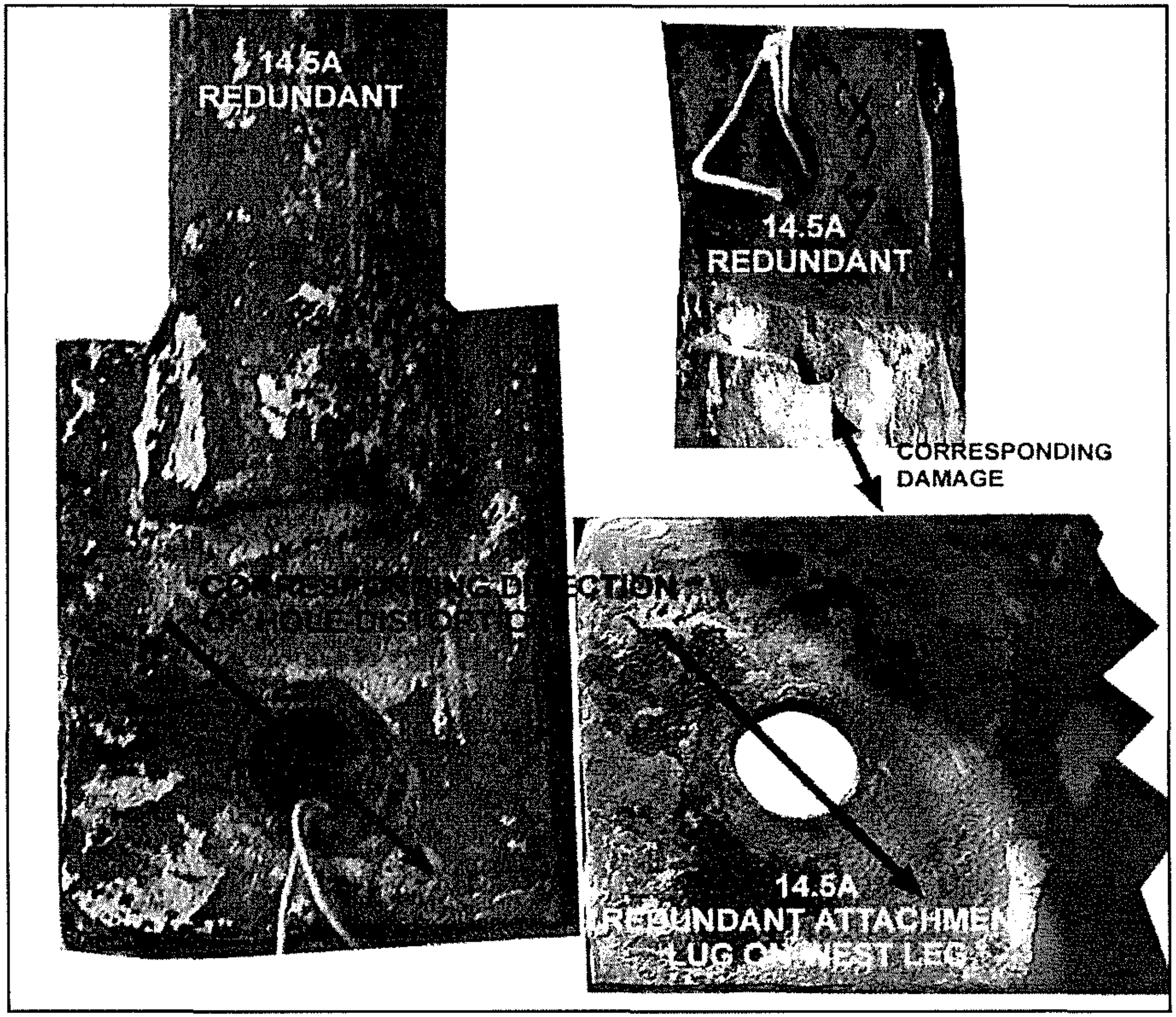


Figure 24: This is a composite showing the relative position of the redundant 14.5A at the time of failure along with damage caused by contact of the redundant with the gusset on the west leg at 14.5. Also noted is the relative direction of the hole distortion.

Appendix C

Upper Air Weather Data

JACKSON, MISSISSIPPI   OB TIME(HOUR) 23(UTC) 22 OCT 1997 SONDE TYPE:
WBAN NO. 03940 WMO NO. 722350   RELEASE TIME(HRMN) 2302(UTC)   00999999+019751+99999
LATITUDE 32.32N(.01DEG)   LONGITUDE 090.08W(.01DEG)   STATION ELEVATION   91.0 M.
TROPOPAUSE DATA - PRESS (HPA): 207.0   HEIGHT (M-MSL): 11765   TEMP (DEG C):-56.2
MAXIMUM WIND DATA - DIR:282 DEG   SPD: 093 KTS   HEIGHT (MSL): 11736

LVL QUAL	LVL TYP	ELAP TIME	PRESS (HPA)	HEIGHT (M-MSL)	TEMP (DEG C)	DEW PT. (DEG C)	RH %	WIND DIR	WIND SPD(KTS)	ELEMENT FLAGS PR	HGT	TMP	DPT	RH	WIND
0	31	0.0	1008.9	91	15.8	4.5	47.0	040	4	00	00	00	00	00	00
0	39	0.1	1005.2	122	16.3	1.9	38.1	039	5	00	00	00	00	00	00
0	32	0.3	1000.0	166	16.3	1.8	37.9	038	6	00	00	00	00	00	00
0	43	1.0		350				033	10	51	00	51	51	51	00
0	21	1.9	950.0	598	12.3	1.0	46.6	026	9	01	01	01	01	01	01
0	43	2.0		612				026	9	51	00	51	51	51	00
0	32	2.8	925.0	822	10.1	0.5	51.1	010	10	00	00	00	00	00	00
0	43	3.0		871				006	10	51	00	51	51	51	00
0	21	3.7	900.0	1049	8.1	-0.5	54.2	004	9	01	01	01	01	01	01
0	38	4.0	892.6	1117	7.5	-0.9	55.2	003	8	00	00	00	00	00	00
0	39	4.3	884.1	1195	7.9	-9.8	27.7	006	6	00	00	00	00	00	00
0	39	4.6	875.9	1272	8.0	-15.8	16.7	010	4	00	00	00	00	00	00
0	43	5.0		1371				014	2	51	00	51	51	51	00
0	32	5.6	850.0	1520	8.6	-14.4	18.0	346	2	00	00	00	00	00	00
0	43	6.0		1626				326	2	51	00	51	51	51	00
0	39	6.4	828.4	1732	7.2	-8.7	31.6	316	3	00	00	00	00	00	00
0	38	7.0	813.1	1885	6.7	-9.6	30.2	302	4	00	00	00	00	00	00
0	21	7.5	800.0	2017	5.7	-9.9	32.1	313	3	01	01	01	01	01	01
0	43	8.0		2139				328	3	51	00	51	51	51	00
0	43	9.0		2393				313	4	51	00	51	51	51	00
0	38	9.1	761.6	2418	2.7	-10.3	38.0	311	5	00	00	00	00	00	00
0	21	9.5	750.0	2541	2.1	-11.2	37.1	300	9	01	01	01	01	01	01
0	39	9.7	746.6	2578	1.8	-11.6	36.7	298	10	00	00	00	00	00	00
0	43	10.0		2652				292	13	51	00	51	51	51	00
0	39	10.1	737.6	2676	1.5	-6.4	55.5	292	14	00	00	00	00	00	00
0	39	10.6	725.3	2811	0.8	-5.2	63.7	291	19	00	00	00	00	00	00
0	39	11.0	716.4	2910	0.9	-8.5	49.5	291	23	00	00	00	00	00	00
0	32	11.7	700.0	3096	0.0	-9.0	50.7	290	27	00	00	00	00	00	00
0	43	12.0		3178				289	29	51	00	51	51	51	00
0	38	12.1	690.5	3205	-0.6	-11.2	44.4	289	29	00	00	00	00	00	00
0	39	12.2	688.2	3232	-0.8	-13.4	38.2	290	29	00	00	00	00	00	00
0	39	12.3	685.5	3263	-0.5	-20.6	20.2	290	29	00	00	00	00	00	00
0	38	12.5	680.5	3322	-0.4	-20.2	20.6	291	30	00	00	00	00	00	00
0	43	13.0		3465				292	30	51	00	51	51	51	00
0	38	13.6	654.1	3637	-2.5	-21.3	22.2	291	31	00	00	00	00	00	00
0	21	13.7	650.0	3687	-2.7	-21.5	21.8	291	31	01	01	01	01	01	01
0	43	14.0		3747				291	31	51	00	51	51	51	00

JACKSON, MISSISSIPPI OB TIME(HOUR) 11(UTC) 22 OCT 1997 SONDE TYPE:
WBAN NO. 03940 WMO NO. 72235 RELEASE TIME(HRMN) 1100(UTC) 42007000+018466-06550
LATITUDE 32.32N(.01DEG) LONGITUDE 090.08W(.01DEG) STATION ELEVATION 91.0 M.
TROPOPAUSE DATA - PRESS (HPA): 127.8 HEIGHT (M-MSL): 14795 TEMP (DEG C):-64.7
MAXIMUM WIND DATA - DIR:267 DEG SPD: 096 KTS HEIGHT (MSL): 13710

50

LVL QUAL	LVL TYP	ELAP TIME	PRESS (HPA)	HEIGHT (M-MSL)	TEMP (DEG C)	DEW PT. (DEG C)	RH %	WIND DIR	WIND SPD(KTS)	ELEMENT FLAGS PR	HGT	TMP	DPT	RH	WIND
0	31	0.0	1010.2	91	11.1	9.3	89.0	020	6	00	00	00	00	00	00
0	32	0.3	1000.0	176	10.8	9.0	88.4	024	9	00	00	00	00	00	00
0	43	1.0		381				032	16	51	00	51	51	51	00
0	39	1.1	972.2	410	8.6	8.0	96.0	033	16	00	00	00	00	00	00
0	38	1.7	952.7	578	7.5	5.7	88.0	039	17	00	00	00	00	00	00
0	21	1.7	950.0	601	7.5	5.1	85.0	040	17	01	01	01	01	01	01
0	39	2.0	942.5	665	7.3	3.6	77.0	042	17	00	00	00	00	00	00
0	32	2.5	925.0	821	7.3	3.6	77.3	038	14	00	00	00	00	00	00
0	39	2.8	916.5	897	7.3	3.6	76.4	036	13	00	00	00	00	00	00
0	43	3.0		951				035	12	51	00	51	51	51	00
0	38	3.2	904.5	1005	6.7	6.3	97.7	025	11	00	00	00	00	00	00
0	21	3.3	900.0	1047	7.7	7.6	99.0	017	10	01	01	01	01	01	01
0	38	3.4	899.2	1054	7.9	7.8	99.2	016	10	00	00	00	00	00	00
0	38	3.8	886.7	1169	8.3	8.1	98.7	355	8	00	00	00	00	00	00
0	43	4.0		1223				345	7	51	00	51	51	51	00
0	43	5.0		1491				318	11	51	00	51	51	51	00
0	32	5.1	850.0	1518	6.7	6.5	98.5	317	12	00	00	00	00	00	00
0	43	6.0		1770				306	17	51	00	51	51	51	00
0	21	6.8	800.0	2015	4.7	4.3	97.5	293	20	01	01	01	01	01	01
0	38	7.0	796.7	2049	4.5	4.1	97.4	292	20	00	00	00	00	00	00
0	43	8.0		2332				282	23	51	00	51	51	51	00
0	21	8.7	750.0	2538	1.7	1.4	97.9	281	24	01	01	01	01	01	01
0	43	9.0		2615				281	25	51	00	51	51	51	00
0	39	9.3	735.2	2700	0.6	0.3	98.0	282	25	00	00	00	00	00	00
0	39	9.7	724.8	2814	0.4	-3.0	78.0	283	26	00	00	00	00	00	00
0	25	9.9	719.6	2872	0.0	-3.6	76.4	284	26	00	00	00	00	00	00
0	43	10.0		2900				284	26	51	00	51	51	51	00
0	32	10.7	700.0	3093	-1.6	-3.8	84.0	285	25	00	00	00	00	00	00
0	43	11.0		3180				286	25	51	00	51	51	51	00
0	39	11.5	679.8	3325	-3.2	-3.5	98.2	286	26	00	00	00	00	00	00
0	43	12.0		3474				286	28	51	00	51	51	51	00
1	39	12.2	662.1	3534	-5.3	-5.6	97.5	286	29	00	00	77	00	00	00
0	38	12.4	657.7	3586	-5.8	-7.1	90.5	286	29	00	00	00	00	00	00
0	39	12.6	652.7	3646	-5.9	-11.8	63.1	285	30	00	00	00	00	00	00
0	39	12.7	650.1	3677	-6.0	-12.5	60.2	285	30	00	00	00	00	00	00
0	21	12.7	650.0	3678	-6.0	-12.5	60.2	285	30	01	01	01	01	01	01
0	43	13.0		3761				285	31	51	00	51	51	51	00
0	33	14.0	620.4	[illegible]	-7.7	-14.7	57.1	[illegible]	[illegible]	00	00	00	00	00	00

JACKSON, MISSISSIPPI OB TIME(HOUR) 11(UTC) 23 OCT 1997 SONDE TYPE:
WBAN NO. 03940 WMO NO. 722350 RELEASE TIME(HRMN) 1105(UTC) 00999999+019463+99999 505 1
LATITUDE 32.32N(.01DEG) LONGITUDE 090.08W(.01DEG) STATION ELEVATION 91.0 M.
TROPOPAUSE DATA - PRESS (HPA): 220.4 HEIGHT (M-MSL): 11390 TEMP (DEG C):-56.0
MAXIMUM WIND DATA - DIR:274 DEG SPD: 093 KTS HEIGHT (MSL): 11670

LVL QUAL	LVL TYP	ELAP TIME	PRESS (HPA)	HEIGHT (M-MSL)	TEMP (DEG C)	DEW PT. (DEG C)	RH %	WIND DIR	WIND SPD(KTS)	ELEMENT FLAGS PR	HGT	TMP	DPT	RH	WIND
0	31	0.0	1008.4	91	5.5	3.8	89.0	000	0	00	00	00	00	00	00
0	32	0.2	1000.0	160	8.1	3.6	72.5	105	3	00	00	00	00	00	00
0	38	0.6	985.1	285	12.4	0.3	43.2	131	9	00	00	00	00	00	00
0	38	0.7	981.5	315	12.6	0.8	44.7	137	11	00	00	00	00	00	00
0	43	1.0		405				156	15	51	00	51	51	51	00
0	38	1.4	957.3	525	12.5	1.9	48.6	168	13	00	00	00	00	00	00
0	21	1.6	950.0	589	12.1	2.7	53.2	174	12	01	01	01	01	01	01
0	43	2.0		716				187	11	51	00	51	51	51	00
0	32	2.3	925.0	812	10.6	5.2	69.0	201	9	00	00	00	00	00	00
0	39	2.8	909.4	953	9.6	8.3	91.4	221	7	00	00	00	00	00	00
0	43	3.0		1010				229	6	51	00	51	51	51	00
0	21	3.1	900.0	1039	9.6	6.4	80.2	231	6	01	01	01	01	01	01
0	39	3.3	893.9	1096	9.6	5.1	72.9	236	6	00	00	00	00	00	00
0	43	4.0		1307				254	5	51	00	51	51	51	00
0	38	4.1	868.3	1337	8.6	3.8	71.5	255	6	00	00	00	00	00	00
0	39	4.4	859.0	1426	9.0	3.5	67.5	259	8	00	00	00	00	00	00
0	32	4.7	850.0	1514	9.9	-1.4	45.4	262	9	00	00	00	00	00	00
0	43	5.0		1590				265	11	51	00	51	51	51	00
0	38	5.1	839.7	1615	9.9	-4.6	36.0	266	11	00	00	00	00	00	00
0	43	6.0		1884				278	14	51	00	51	51	51	00
0	38	6.3	804.0	1974	7.0	-2.8	49.7	280	14	00	00	00	00	00	00
0	39	6.4	801.7	1997	6.9	-1.6	54.5	281	14	00	00	00	00	00	00
0	21	6.4	800.0	2014	6.8	-1.8	53.7	281	14	01	01	01	01	01	01
0	43	7.0		2183				286	15	51	00	51	51	51	00
0	38	7.9	757.4	2463	5.3	-9.6	33.7	284	18	00	00	00	00	00	00
0	43	8.0		2494				284	18	51	00	51	51	51	00
0	21	8.1	750.0	2543	4.9	-10.9	31.3	284	18	01	01	01	01	01	01
0	39	8.7	734.7	2711	4.0	-13.8	26.3	285	19	00	00	00	00	00	00
0	43	9.0		2795				286	19	51	00	51	51	51	00
0	43	10.0		3074				295	19	51	00	51	51	51	00
0	32	10.1	700.0	3102	1.0	-11.3	39.6	295	19	00	00	00	00	00	00
0	25	10.6	689.0	3229	0.1	-12.5	38.2	295	19	00	00	00	00	00	00
0	43	11.0		3341				295	19	51	00	51	51	51	00
0	39	11.5	667.6	3480	-1.8	-11.4	47.7	290	18	00	00	00	00	00	00
0	43	12.0		3611				286	17	51	00	51	51	51	00
0	38	12.2	652.3	3664	-3.2	-14.0	43.2	285	17	00	00	00	00	00	00
0	21	12.3	650.0	3692	-3.2	-15.0	40.6	285	17	01	01	01	01	01	01
0	39	13.0	634.8	3879	-4.0	-22.3	22.5	282	16	00	00	00	00	00	00

JACKSON, MISSISSIPPI   OB TIME(HOUR) 23(UTC) 23 OCT 1997   SONDE TYPE:
WBAN NO. 03940   WMO NO. 722350   RELEASE TIME(HRMN) 2303(UTC)   00999999+018988+99999
LATITUDE 32.32N(.01DEG)   LONGITUDE 090.08W(.01DEG)   STATION ELEVATION   91.0 M.
TROPOPAUSE DATA - PRESS (HPA): 190.2   HEIGHT (M-MSL): 12351   TEMP (DEG C):-61.2
MAXIMUM WIND DATA - DIR:263 DEG   SPD: 097 KTS   HEIGHT (MSL): 12438

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LVL QUAL	LVL TYP	ELAP TIME	PRESS (HPA)	HEIGHT (M-MSL)	TEMP (DEG C)	DEW PT. (DEG C)	RH %	WIND DIR	WIND SPD(KTS)	ELEMENT FLAGS PR	HGT	TMP	DPT	RH	WIND
2	31	0.0	999.8	91	20.6	13.4	63.0	120	9	00	00	27	00	00	00
8	31	0.0	999.8	91	19.6	12.4	63.0	120	9	00	00	00	00	00	00
0	38	0.1	995.6	127	19.8	12.6	62.7	123	11	00	00	00	00	00	00
0	43	1.0		384				142	27	51	00	51	51	51	00
0	21	1.5	950.0	528	16.7	11.7	72.7	146	26	01	01	01	01	01	01
0	43	2.0		670				150	26	51	00	51	51	51	00
0	32	2.3	925.0	756	14.9	11.2	78.3	152	27	00	00	00	00	00	00
0	43	3.0		944				155	28	51	00	51	51	51	00
0	21	3.1	900.0	987	12.9	10.2	82.7	157	28	01	01	01	01	01	01
0	39	3.4	893.1	1052	12.3	9.7	83.9	159	29	00	00	00	00	00	00
0	38	3.5	890.2	1080	12.1	10.6	90.5	160	29	00	00	00	00	00	00
0	43	4.0		1213				165	30	51	00	51	51	51	00
0	38	4.3	867.9	1293	12.1	6.6	69.0	169	29	00	00	00	00	00	00
0	32	4.9	850.0	1467	10.9	3.9	61.7	178	28	00	00	00	00	00	00
0	43	5.0		1493				179	28	51	00	51	51	51	00
0	38	5.5	834.3	1622	9.8	5.6	74.8	183	28	00	00	00	00	00	00
0	43	6.0		1762				188	28	51	00	51	51	51	00
0	39	6.1	817.6	1790	9.1	6.2	82.3	188	28	00	00	00	00	00	00
0	21	6.7	800.0	1970	8.3	3.3	68.0	190	30	01	01	01	01	01	01
0	39	6.8	798.1	1990	8.8	3.0	66.5	190	30	00	00	00	00	00	00
0	43	7.0		2044				190	31	51	00	51	51	51	00
0	38	7.2	787.8	2098	8.5	3.0	67.4	190	31	00	00	00	00	00	00
0	43	8.0		2320				188	31	51	00	51	51	51	00
0	38	8.6	751.4	2487	5.7	0.9	70.8	191	30	00	00	00	00	00	00
0	21	8.6	750.0	2502	5.5	0.8	71.4	191	30	01	01	01	01	01	01
0	43	9.0		2587				193	30	51	00	51	51	51	00
0	39	9.5	730.9	2713	4.3	1.1	79.0	198	30	00	00	00	00	00	00
0	43	10.0		2848				204	31	51	00	51	51	51	00
0	32	10.8	700.0	3064	2.6	-1.4	74.9	213	33	00	00	00	00	00	00
0	43	11.0		3128				216	33	51	00	51	51	51	00
0	39	11.4	683.7	3255	1.7	-2.7	72.3	219	33	00	00	00	00	00	00
0	39	11.7	676.9	3335	1.5	-5.2	60.7	221	32	00	00	00	00	00	00
0	43	12.0		3422				223	32	51	00	51	51	51	00
0	39	12.2	664.8	3480	0.6	-6.8	57.7	221	32	00	00	00	00	00	00
0	39	12.6	655.6	3592	0.4	-12.2	38.7	219	31	00	00	00	00	00	00
0	21	12.8	650.0	3660	0.2	-11.8	40.5	217	31	01	01	01	01	01	01
0	25	13.0	647.6	3690	0.1	-11.5	41.2	216	31	00	00	00	00	00	00
0	43	14.0		[illegible]				[illegible]	30	[illegible]	00	[illegible]	[illegible]	[illegible]	00