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INSTRUMENTATION OF REPLACEMENT BASE INSULATOR ASSEMBLY

VLF EAST TOWER, LUALUALEI, HAWAII

CIVIL ENGINEERING LABORATORY (NAVY)

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INSTRUMENTATION OF REPLACEMENT BASE INSULATOR ASSEMBLY - VLF EAST TOWER, LUALUALEI, HAWAII

By

S. K. Takahashi

April 1976

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INSTRUMENTATION OF REPLACEMENT BASE INSULATOR ASSEMBLY – VLF EAST TOWER, LUALUALEI, HAWAII (Final),
by S. K. Takahashi

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1. Guy tower	2. Tower base insulator	I. YF53.534.011.01.001F	

The cone-type base insulators beneath a 1,500-foot-high guyed VLF antenna was replaced with station post-type base insulators. Strain gages were mounted on both types of insulators during the tower raising and lowering operations to determine the distribution of load on the base insulator assembly. The maximum strain deviation for the cone-type insulators from the average strain was 6%, which indicated that the load was distributed almost equally on the three insulators at the midtier. The strain deviation for the station post-type insulators varied from -36 to +52% when compared with the average strain value. Finite element computer analyses were performed for both the cone and post insulators subjected to a direct axial load. The vertical and circumferential stresses compared very well with the average values of the experimental strain readings.

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INTRODUCTION

In the past decade, the U. S. Navy has constructed several Very Low Frequency (VLF) antennas throughout the United States: the most recent ones were at Annapolis, Maryland, and Lualualei, Hawaii. For these locations, the antenna consists of the tower and portions of the tophat radial guy wires in contact with the tower. The base insulators were Lapp cone-shaped, ceramic type and were arranged in three tiers; each tier had three insulators arranged in the shape of an equilateral triangle.

Numerous internal cracks were discovered in most of the base insulators already placed beneath the towers at Annapolis and at Lualualei. Consequently, the transmitting operation at both sites was immediately suspended. A ad-hoc VLF Study Group, assembled by the Naval Electronics System Command (NAVELEX), determined that the base insulator assemblies were not suitable to carry the full voltage load,[a] and this group later found the assemblies had material defects. It was decided to replace the cone-type insulators with post-type insulators.

As part of the basic insulator research, the Civil Engineering Laboratory (CEL) was authorized to take strain measurements of the existing and replacement base insulators during the raising and lowering of the east tower at Lualualei. This report describes the testing program, and the resulting measurements acquired from the replaced cone-type and installed post-type base insulators. The objective of this task was to determine the efficiency of the structural load-distribution arrangement of the base insulator assembly (BIA).

DESCRIPTION OF THE VLF EAST TOWER, LUALUALEI, HAWAII

The tower is 1,500-ft high, is guyed at six levels (see Figures 1 and 2), and rests on three tiers of Lapp cone-type ceramic base insulators (Figure 3). The first five guy levels support the tower in three directions with bridge strands of various diameters. At the sixth level, the upper half of the guy wire is made of Alumoweld cable, and the lower half is made of bridge strands; there are 16 top radials. The three main legs of the tower are triangular in plan and are fabricated from 5-1/2- to 9-3/4-inch-diameter solid round bars. The material is of high-strength, low-alloy steel with a minimum yield point of 45,000 psi. The

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[a] Although the insulators are to be used at VLF frequencies of 10 to 30 kHz, they are tested by the manufacturer at 60 Hertz; adequate test facilities are not available.

majority of the horizontal chords are made from two angles 4 x 3 x 5/16 inch (at the guy levels, four angles are used). The diagonal bracing rods vary in diameter from 1-1/4 to 2-1/2 inches. The distance from the top of the base plate to the bottom of the tower base is approximately 11 feet 7 inches. This is the space where the three tiers of cone insulators were located and were later replaced by two tiers of post insulators (each replacement tier has 8 insulators, Figure 4).

During original construction of the tower, a feedline was run from the transmitter building about 1/2 mile away and was attached to the tower at the fourth guy level; this caused a ''kink'' at this level with a displacement of about 41 inches (Figure 5). This displacement was carefully monitored during the raising and lowering of the tower.

BASE INSULATOR INSTRUMENTATION

Lapp Cone Insulators

Prior to raising the tower for the base insulator replacement, the middle tier of the Lapp cone insulator was instrumented with strain gages as shown in Figure 6. The strain gages used were Micro-Measurements type EA-01-250BG-120, 120 ohms ± 0.3%, and 2.095 gage factor ± 0.5%. Strain gages 1 to 6 were mounted to measure vertical strains, and strain gage 7 was mounted to measure the circumferential strain.

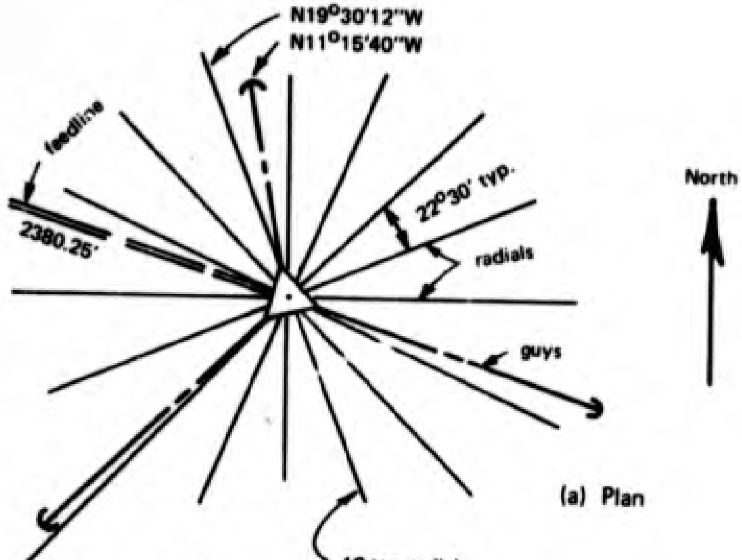
Rosenthal-Stemag Station Post Insulators

Prior to moving the station post base insulator assembly beneath the tower, the lower tier insulators were strain gaged with the same type of gages as on the Lapp-cone insulators at the locations shown in Figure 7. The first 24 gages were located at the mid height of the straight sidewall below the lowest shed so that the effect of strain concentration was minimal. Strain gages 25, 26, and 27 were located at midheight on leg L1 between the sheds for comparison with strain gages 1, 2, and 3, respectively. Strain gage 28 was placed on the shed to measure circumferential strain.

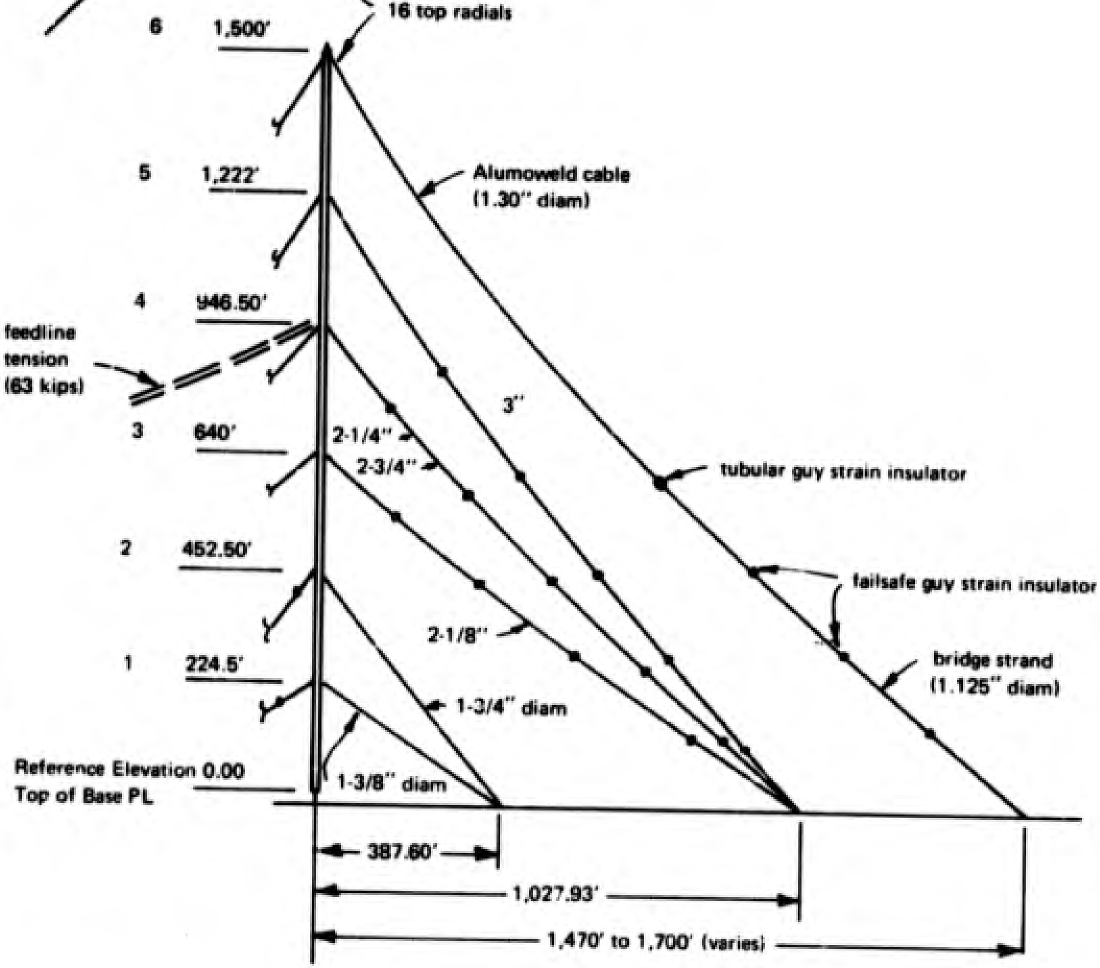
LOAD MEASUREMENT

Tower Load

The base insulator assembly (BIA) replacement operation required the raising of the 1,500-ft tower a distance of less than an inch. However, this called for very thorough planning and preparation several days before tower jacking (TJ) day and knowledge of up-to-the-minute weather conditions. The tower was supported by the stanchions as shown in Figure 8. Beneath each of the three stanchion columns were two load cells (500 ton capacity each) that were hard wired to a paper tape recorder to monitor the weight of the tower as it was raised. The load cell measurements were recorded on the console shown in Figure 9.



(a) Plan



(b) Elevation

Figure 1. VLF east tower, Lualualei, Hawaii.

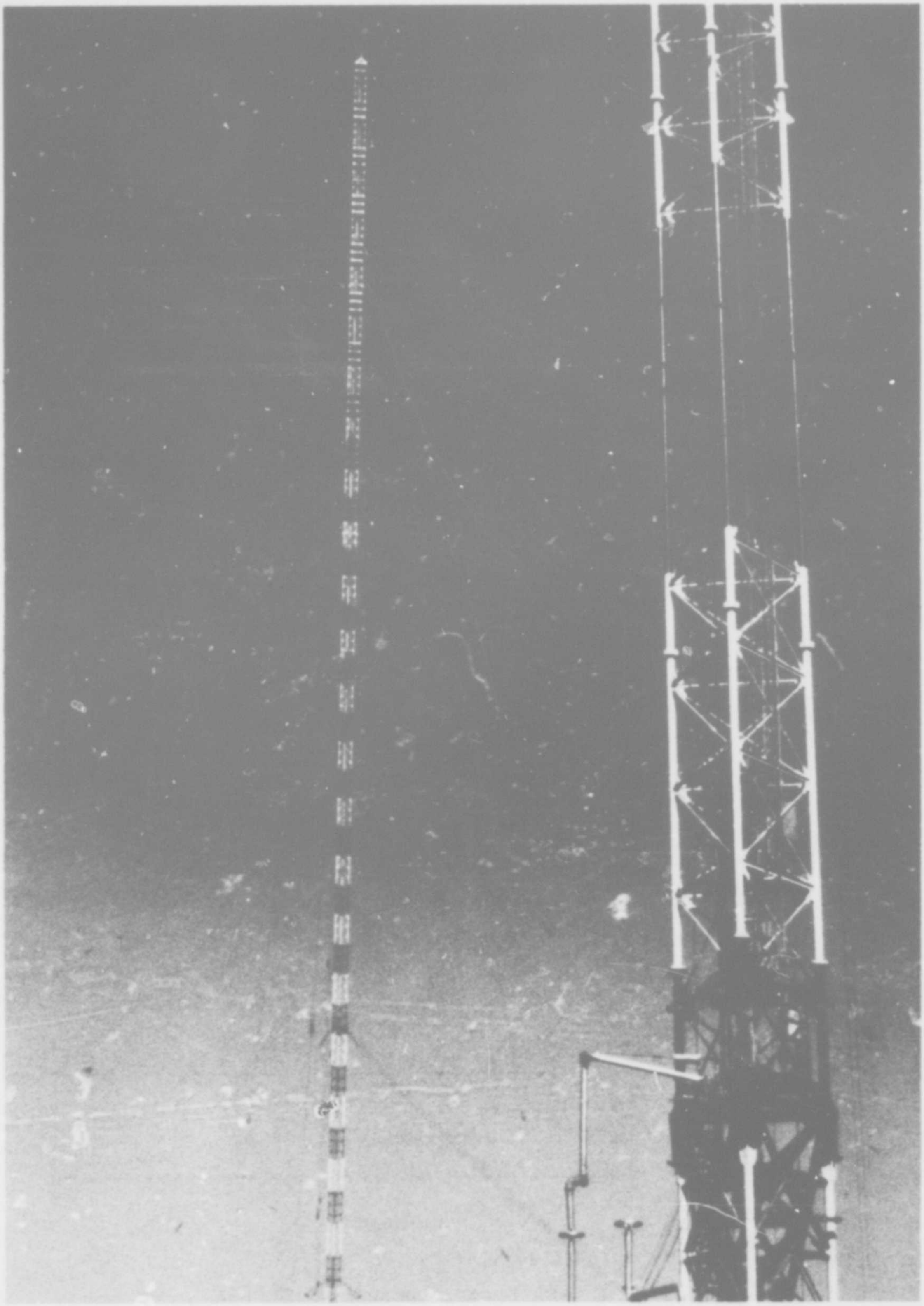


Figure 2. Lualualei 1,500-foot VLF guyed towers; east tower in foreground, west tower in background.

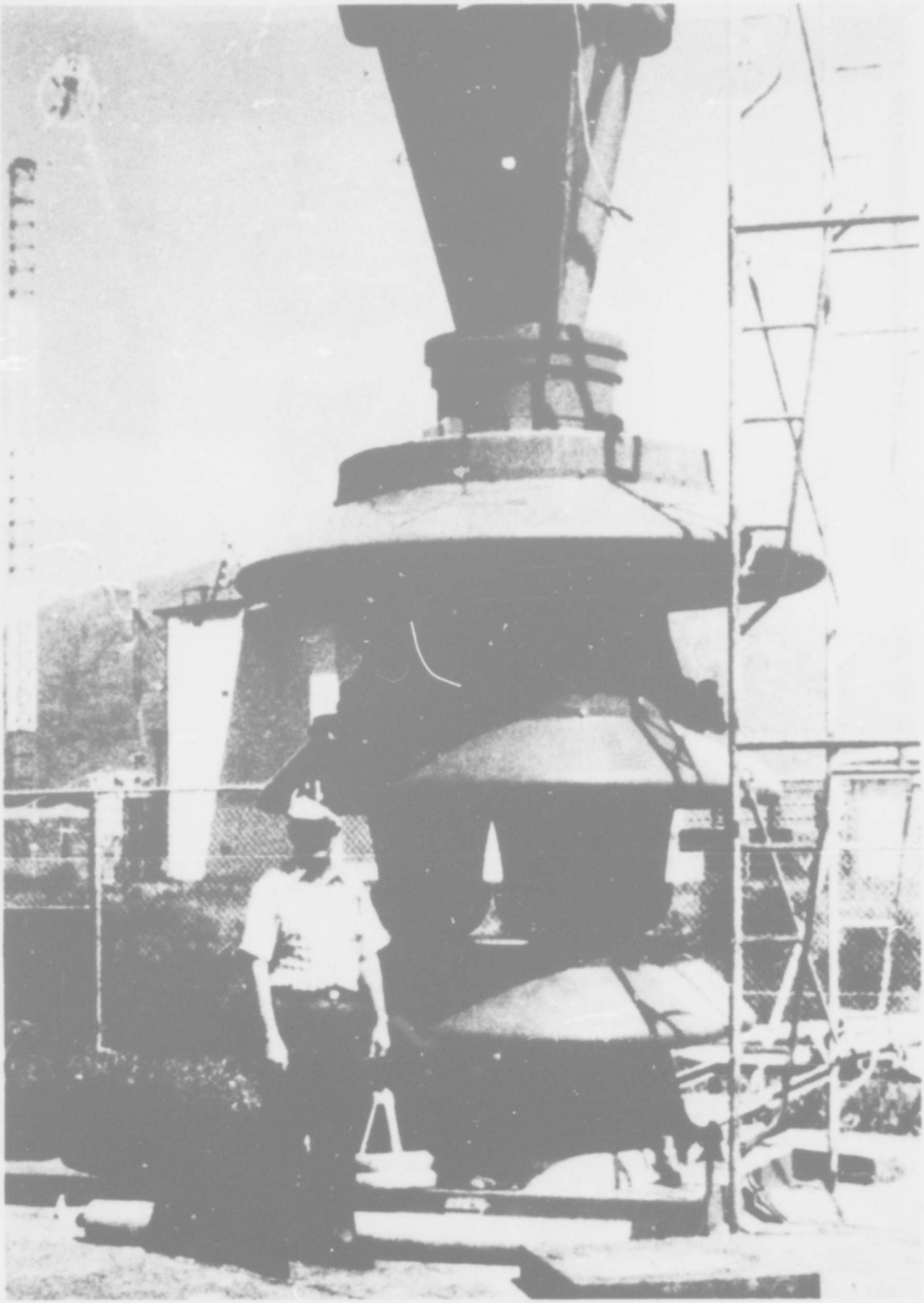


Figure 3. Lapp cone base insulator in Lualualei.

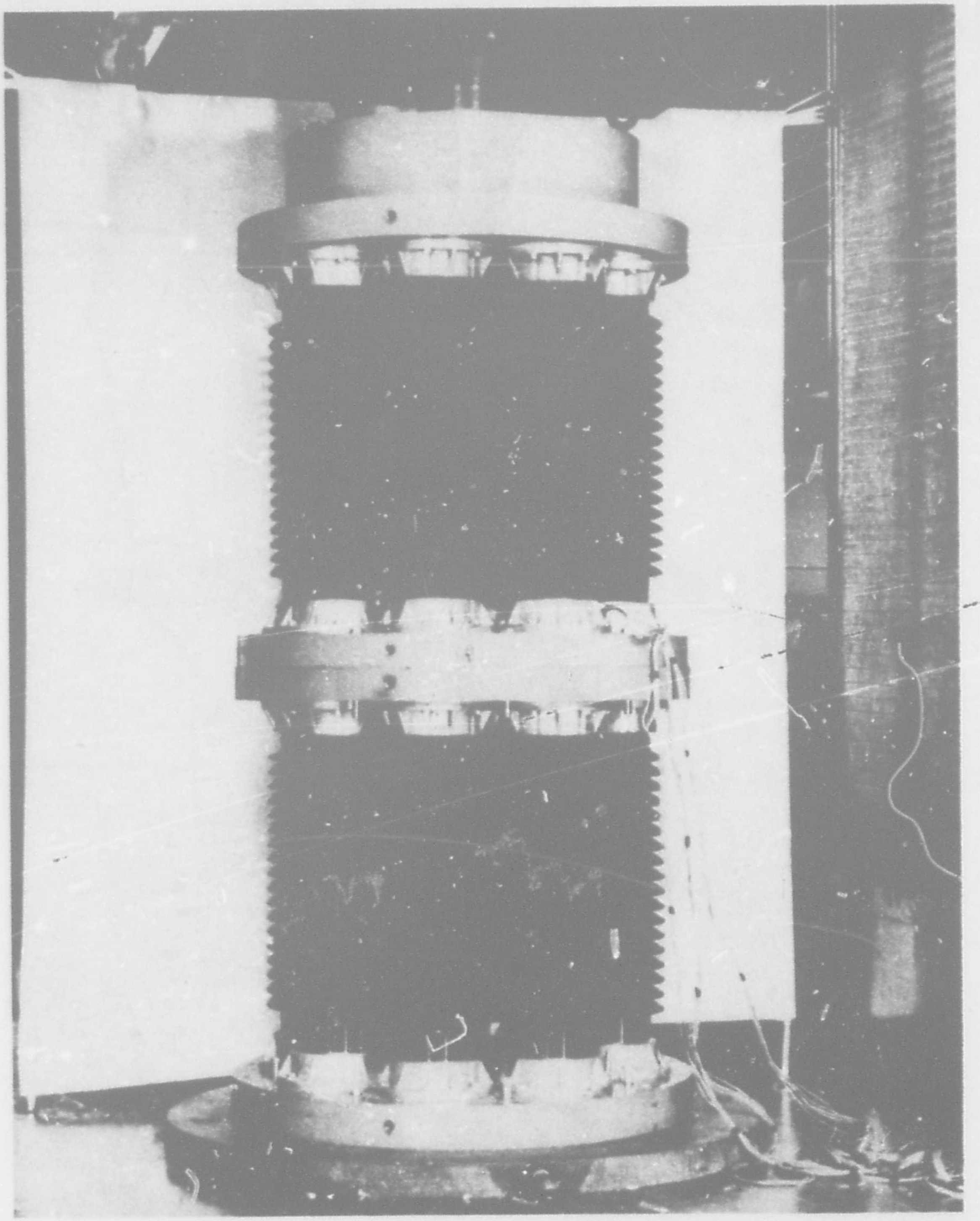


Figure 4. Rosenthal-Stemag base insulator assembly.

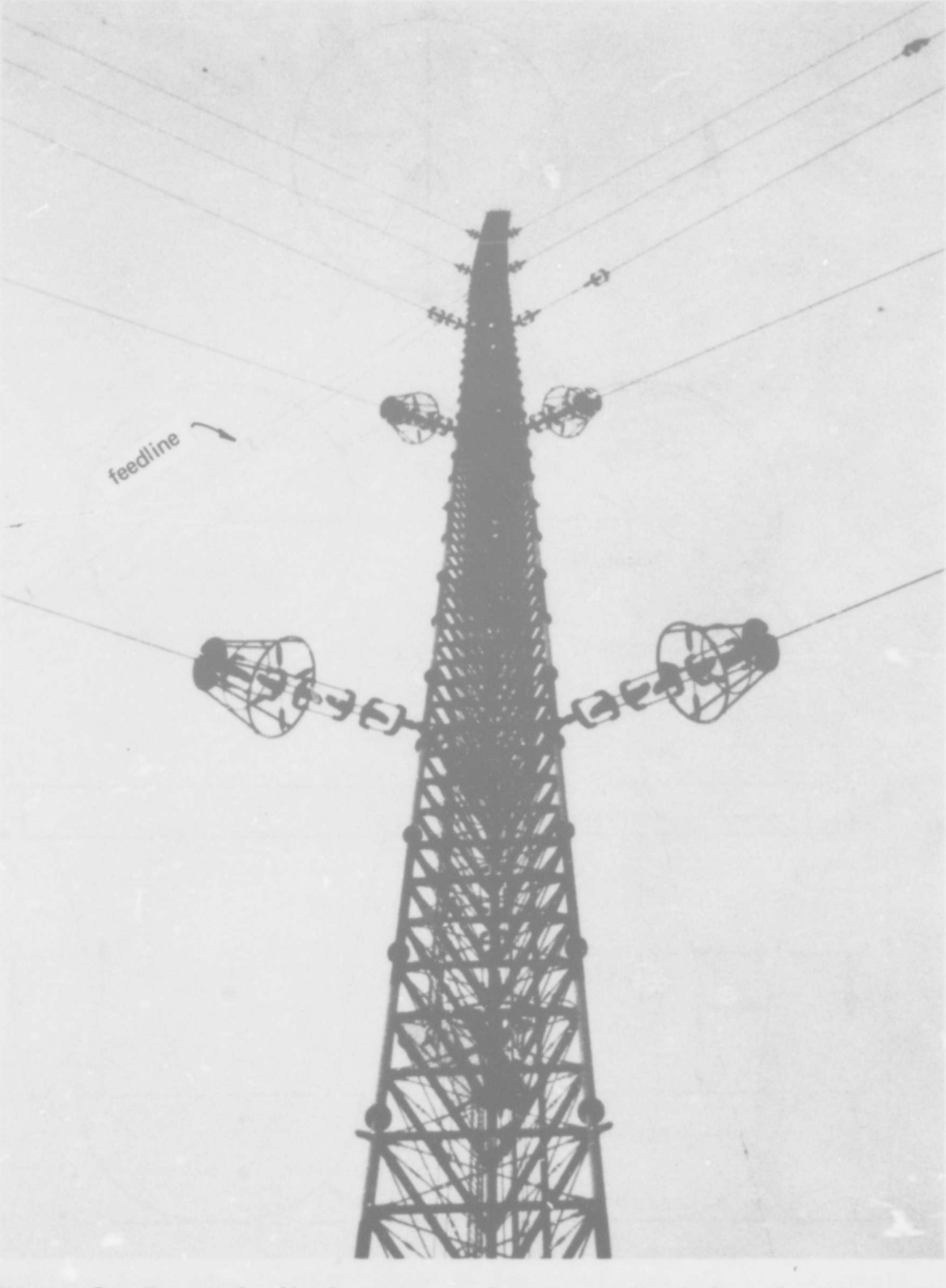


Figure 5. Eccentric displacement at fourth guy level from feedline pull.

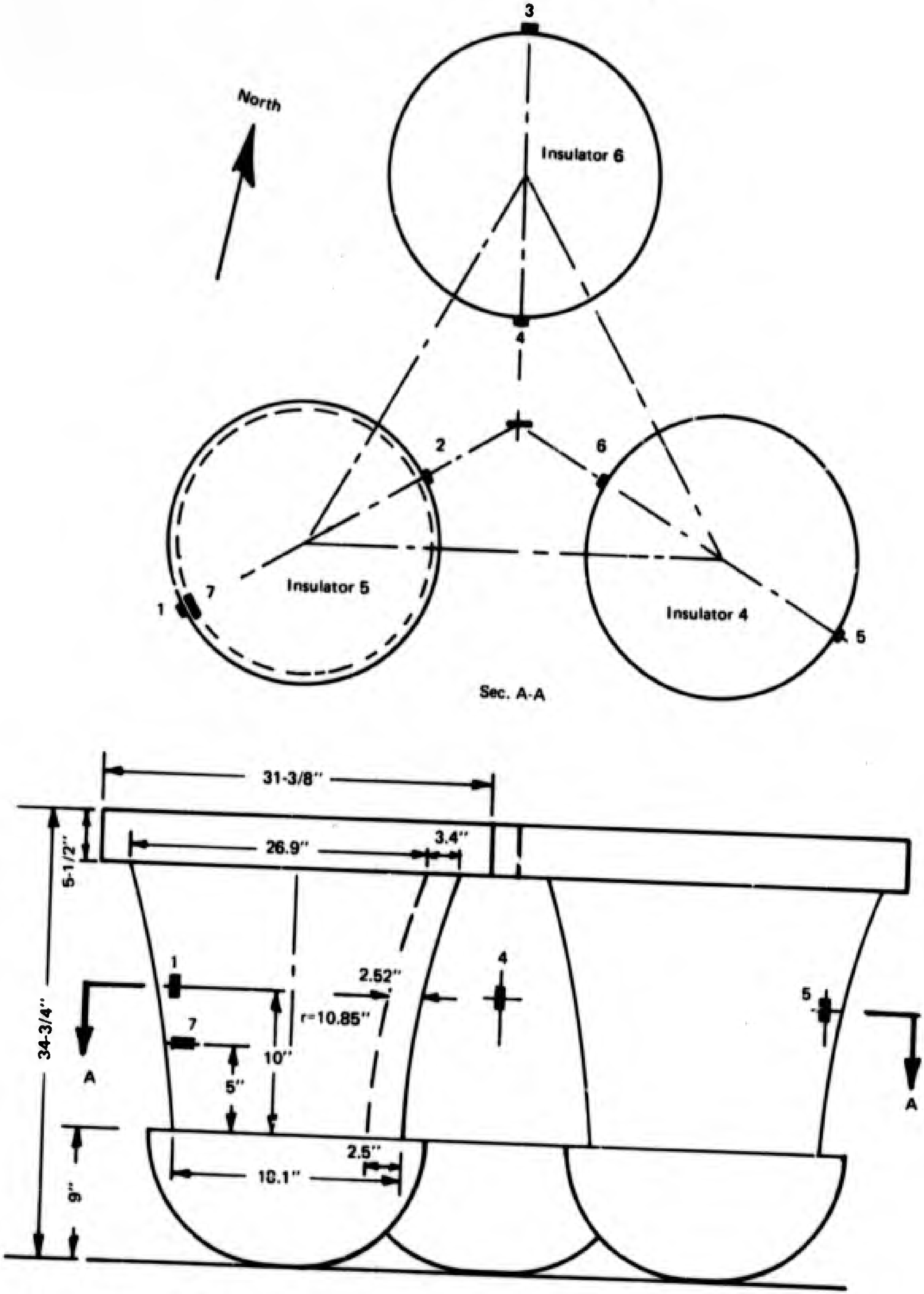


Figure 6. Strain gage locations on middle tier of Lapp cone insulator base at Lualualei.

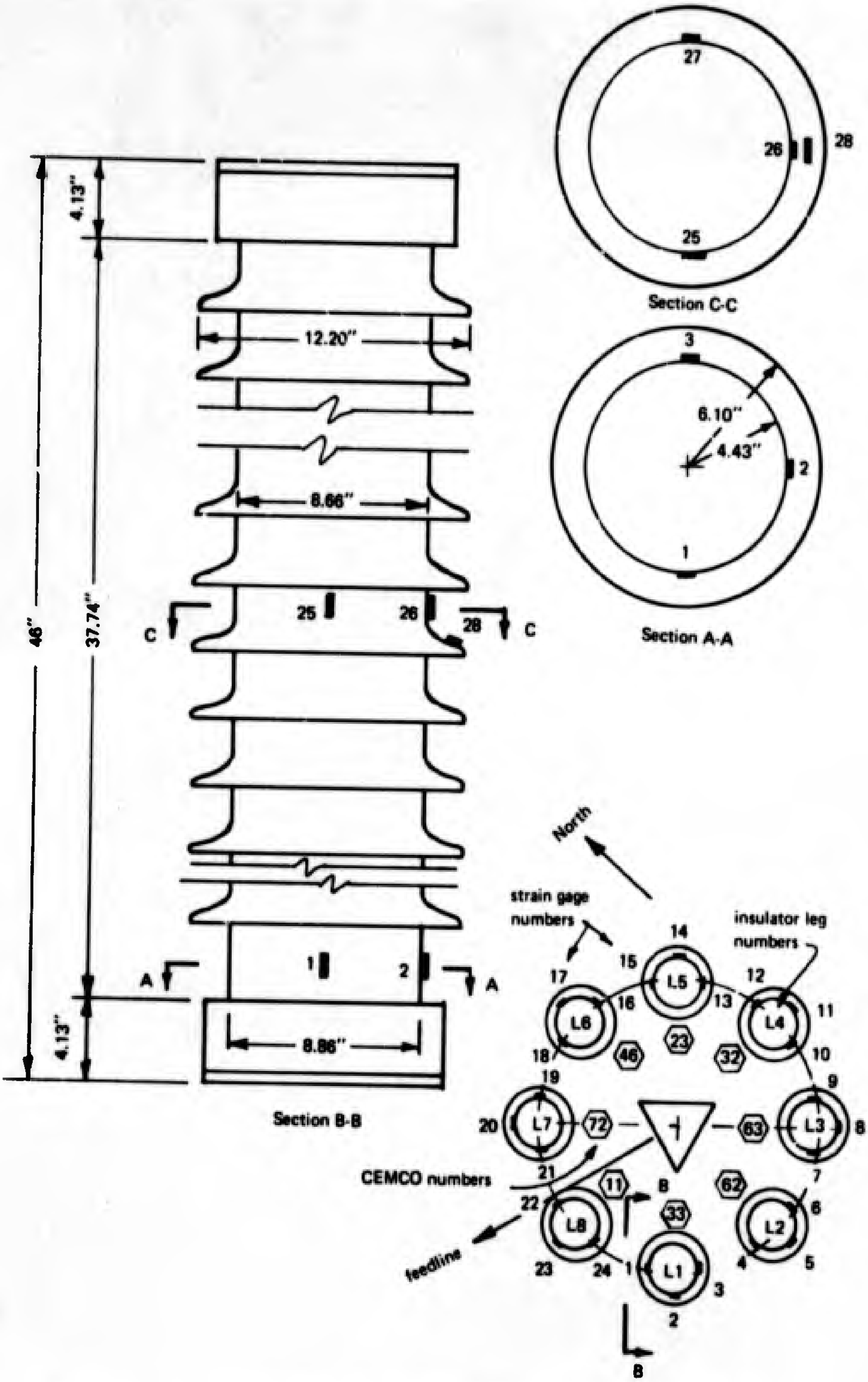


Figure 7. Locations of strain gages, BIA, Lualualei.

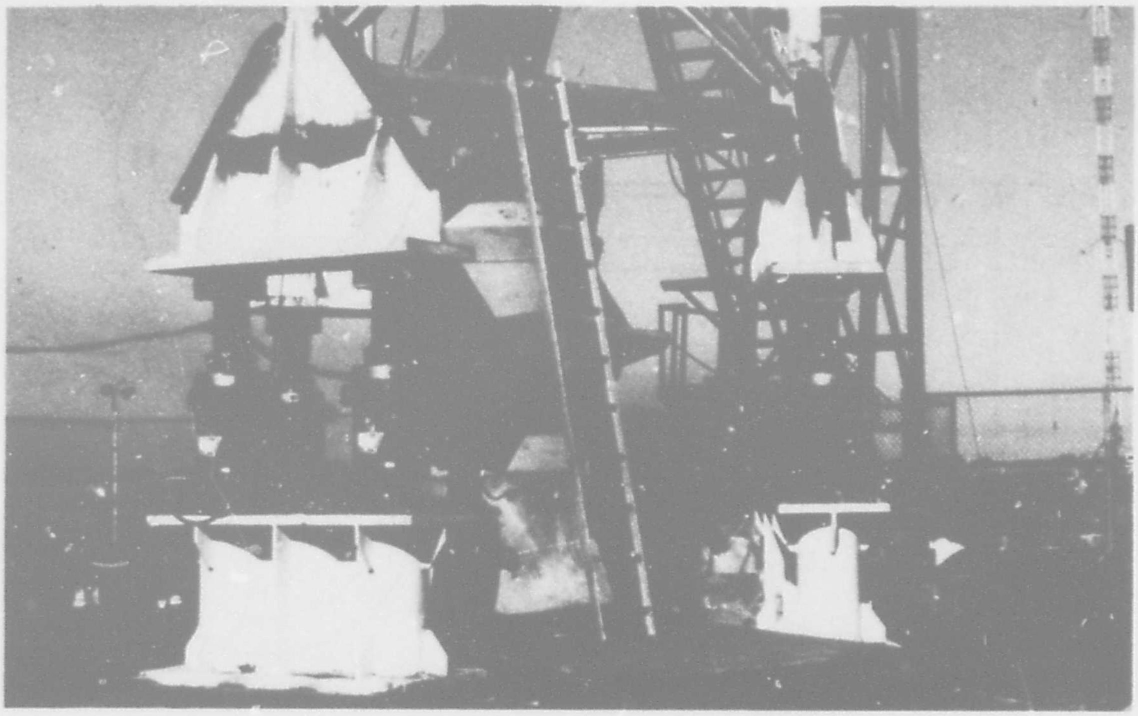


Figure 8. Stanchions used to raise tower.

Figure 9. Console for monitoring load cell and anemometer.

Wind Load

In addition to the weather forecasts to determine if the local weather conditions were favorable for starting the operation, a wind direction and velocity indicator was placed at the fourth guy level. The 3-cup anemometer, fabricated by Khal Scientific Instrumentation Corporation, and the vane are described below:

Item	Model No.	Type
Vane	TD 103	SN1049-17
Three-cup Anemometer	TV-114	SN1049-174

The magnitude and direction of the wind were displayed on the console at the left in Figure 9.

TOWER RAISING AND LOWERING OPERATIONS, DATA ACQUISITION

Raising

The tower load was taken off the Lapp cone insulator base system and was transferred in increments to the stanchions and load cell. The strain gage readings taken at each load increment are tabulated in Table 1, and plotted in Figure 10. Strain gage 7 recorded compressive values while the other gages recorded tensile values during the unloading operation. When the tower weight was removed from the base insulators, the load cells recorded a total load of 2,699 kips.

Lowering

After the Lapp cone base insulators were removed, the condition of the base hinge ball joint was inspected by others, and the ball joint was replaced. When the Stemag station post BIA was placed beneath the tower, the strain gage wires were connected to the strain indicators; and the readings were zeroed for no load. The weight of the tower was transferred in increments from the stanchions to the BIA; the pertinent strain gage readings are tabulated in Table 2. The gage readings for leg 1 are plotted in Figure 11. Only strain gage 28 recorded tensile values since it was placed to measure circumferential values; all the other gages measured vertical compressive strains. The total weight of the tower on the BIA was 2,699 kips.

Table 1. Summary of Strain Gage Readings for Lapp Cone Insulator

(Average strain, ϵ_{avg} = -818.5 μin./in.)

Leg No.	Gage No.	Strain (μin./in.) at Following Loads in kips –										Mean of 2.699-kip Load (μin./in.)	Deviation From ϵ_{avg} (%)
		63	487	719	969	1,162	1,542	1,784	2,114	2,321	2,699		
4	1	-56	-190	-286	-352	-398	-512	-572	-658	-718	-766	-799.5	-2
	2	-19	-168	-263	-335	-390	-537	-597	-683	-757	-823		
5	3	-20	-172	-308	-414	-486	-662	-728	-858	-944	-1,064	-789	-4
	4	-16	-69	-116	-150	-168	-276	-312	-382	-450	-514		
6	5	-30	-112	-188	-252	-278	-398	-450	-536	-620	-678	-867	+6
	6	-48	-226	-348	-454	-526	-708	-780	-883	-976	-1,056		
	7	+10	+42	+56	+56	+72	+72	+82	+94	+114	+94		

Table 2. Summary of Strain Gage Readings for New BIA Under the East Tower, Lualualei

(Average Strain, ϵ_{avg} = 344.2 μin./in.)

Leg No.	Gage No.	Strain (μin./in.) at Following Loads in kips –					Mean of 2.699-kip Load (μin./in.)	Deviation From ϵ_{avg} (%)
		164	604	1,160	2,042	2,699		
1	1	-3	-5	-40	-130	-185	-221	-36
	2	0	0	-39	-120	-207		
	3	-11	-25	-65	-165	-257		
2	4	-7	-23	-47	-137	-229	-244	-29
	5	-35	-120	-235	-397	-570		
	6	-7	-23	-83	-197	-259		
3	7	-20	-65	-133	-228	-326	-292	-15
	8	-71	-49	-105	-183	-251		
	9	-7	-47	-135	-231	-258		
4	10	-14	-60	-148	-244	-324	-310	-10
	11	-16	-58	-148	-256	-316		
	12	-24	-55	-150	-260	-296		
5	13	-54	-140	-266	-460	-618	-522.5	+52
	14	-26	-109	-209	-387	-525		
	15	-15	-52	-151	-309	-427		
6	16	-17	-83	-175	-377	-519	-489	+42
	17	-27	-90	-201	-343	-457		
	18	-20	-81	-195	-339	-459		
7	19	-22	-90	-214	-376	-498	-394	+14
	20	-16	-88	-194	-333	-282		
	21	-14	-55	-100	-198	-290		
8	22	-10	-62	-92	-180	-254	-281	-18
	23	-2	-10	-22	-92	-184		
	24	-10	-40	-100	-200	-308		
1	25	-10	-88	-210	-426	-626		
	26	-25	-106	-210	-412	-594		
	27	-36	-102	-210	-398	-595		
	28	+10	+42	+94	+148	+220		

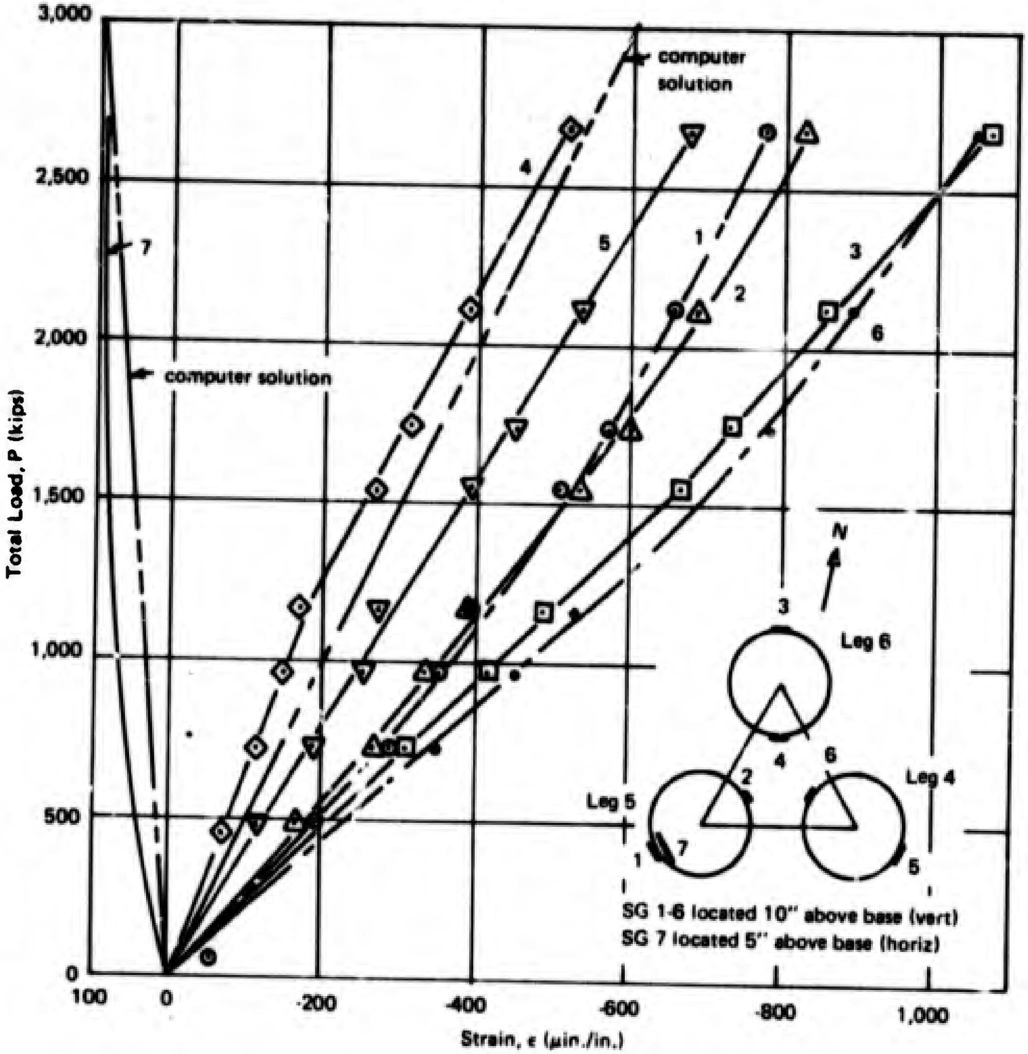


Figure 10. Strain versus total load on Lapp cone insulators at Lualualei.

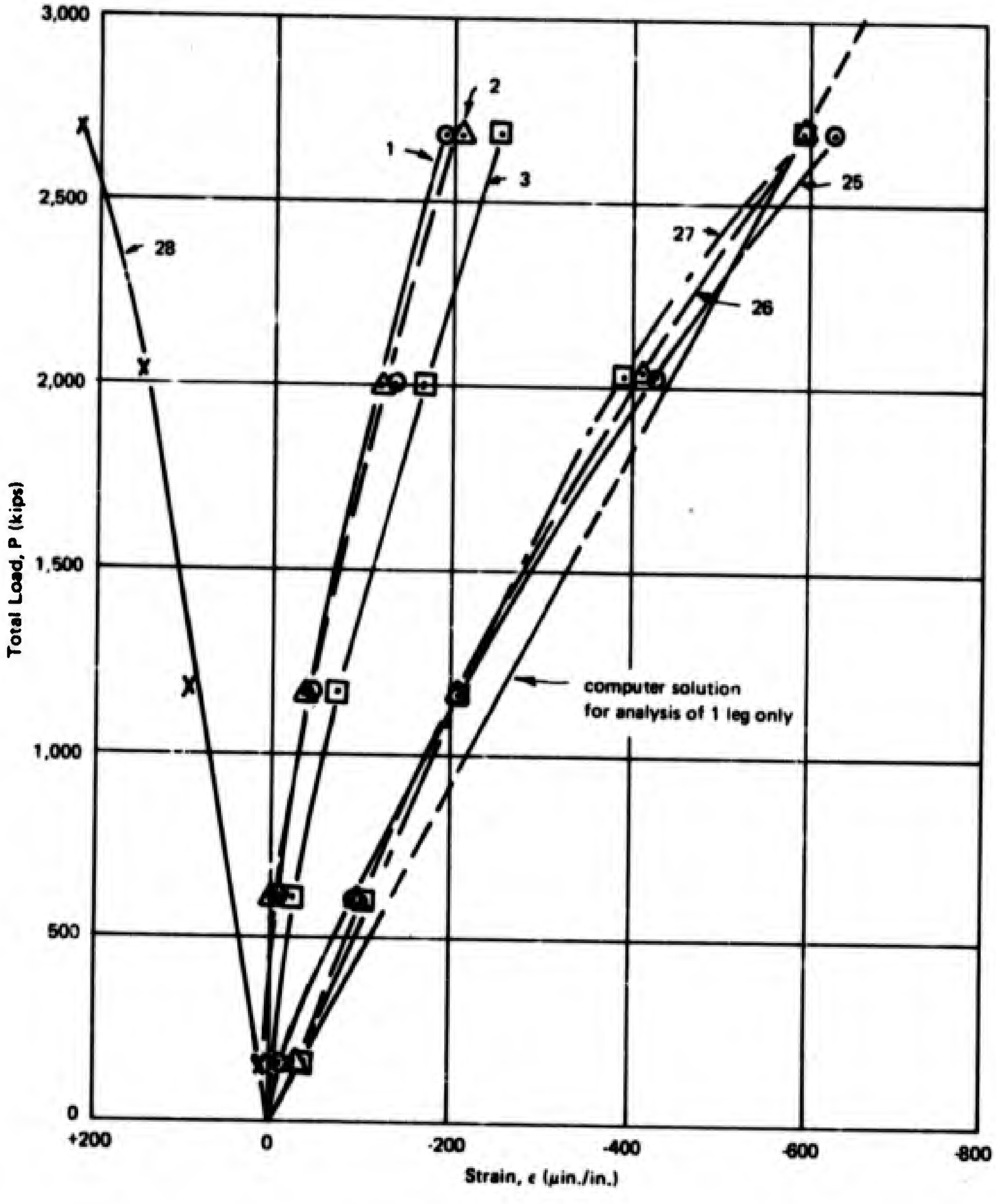


Figure 11. Load versus strain in leg 1 of BIA at Lualualei.

EXPERIMENTAL RESULTS AND DISCUSSION

Lapp Cone Insulators

For the total load of 2,699 kips on the cone insulators, Table 1 shows that the maximum and minimum compressive strains were -1,064 and -514 μin./in., respectively. However, using the average strain in each leg, the values were calculated to be -800, -789, and -867 μin./in., respectively, for legs 4, 5, and 6. The average deviation of each leg from the average value of -818 μin./in. was -2, -4, and +6%, respectively, indicating that the tower load was quite uniform on the Lapp cone base insulator assembly. However, the deviation of the maximum compressive strain of -1,064 μin./in. from the average was about 30%.

The strain gage plots in Figure 10 indicate that the neutral axis of the BIA was approximately on the line drawn through strain gages 1 and 2.

Since the inside surface of the cone insulator was not accessible for instrumentation during the unloading phase of the tower, a finite element analysis [1] was made of the model shown in Figure 12. A total vertical load of 1,000 kips was applied on the insulator cap. For the insulator an assumed modulus of $E = 10^7$ psi and a Poisson ratio of 0.23 was used. The interface between the end caps and the insulator was assumed to be bonded. The size and dimensions of the insulator are indicated in Figure 6.

The results show that the vertical strains in the center of elements 44 and 48 (Figure 12) are 607 μin./in. and 620 μin./in., respectively. Extrapolating these stresses to the outside surface of the cone insulator to nodal point 60 (Figure 12), a value of 600 μin./in. is obtained (Figure 13) for a total load of 3,000 kips; this is shown in Figure 10 for comparison with gages 1 to 6. A higher value would be obtained if a lower modulus of elasticity is used. Cracks in the insulator could contribute to some deviation of the compared data.

By extrapolating the computer strains in the circumferential direction, the surface hoop strain was computed to be 96 μin./in. The experimental strain at this location (gage 7 in Figure 10) was approximately 100 μin./in. under a load of 3,000 kips.

Rosenthal-Stemag Station Post Insulators

Once the base insulator assembly (BIA) was placed beneath the raised tower, the tower load was placed on the BIA in increments as described in Table 2. The strain gage values of leg 1 are plotted against load, as shown in Figure 11.

Unlike the laboratory load test performed by Continental Electronics Mfg. Co. (CEMCO) at Lehigh University [2] in which the load distribution between columns and insulators was less than 10% variance from the average strain value, the variation for the field test at Lualualei had a maximum deviation from the average value (344 μin./in.) of +52%. In

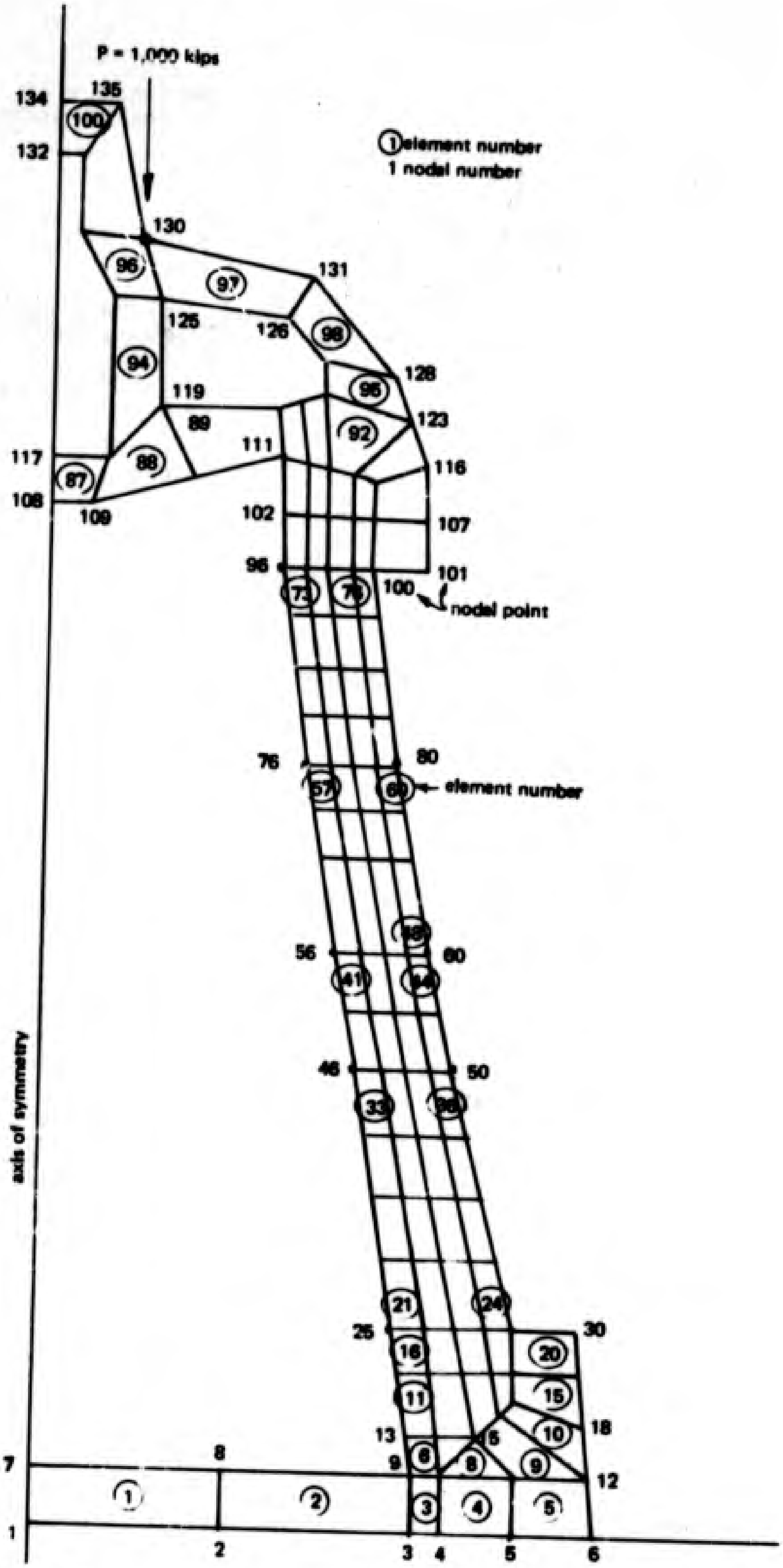


Figure 12. Finite element model of Lapp cone insulator, nodal points, and element numbers.

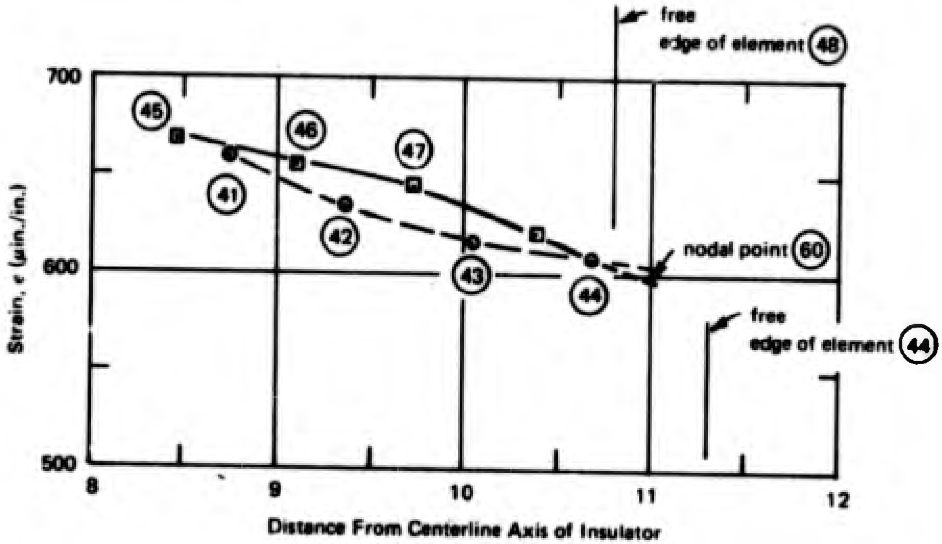


Figure 13. Vertical strain distribution across wall of Lapp cone insulator.

Reference 2, the average strain for the lower tier (for a load of 2,500 kips) was 400 μin./in. If this strain reading is extrapolated to the total field test load of 2,699 kips, the value becomes 431 kips. The field test results are, therefore, about (100)(344/431)=80% of the Laboratory test results. This difference is not too unusual considering that the field test was conducted late in the afternoon causing the insulators to cool off rapidly when the sun went down. Other unknown factors could also contribute to the difference.

In Figure 11 the average value from strain gages 25, 26, and 27 is about 600 μin./in. This is almost three times the values of the strains recorded at the bottom of the insulator on the straight vertical section and seems very excessive. The tensile strain value of strain gage 28 also seems quite high. No explanation is offered.

To obtain some idea of strain ratios of the curved portion between the sheds and of the straight vertical sides at the bottom of the insulator, a finite element analysis [1] was made of the model shown in Appendix A, Figure A-1; the applied load was 100 kips. The usual computer graphic output information is shown in Figures A-2 through A-13. Figures A-2, A-3, and A-4 are the material properties, the node point numbers, and element number plots, respectively. The stresses and strains obtained from the center of the element for element numbers 50 to 65 are plotted in Figure 14. The average stress for the 100-kip load is 1,697 psi; the ratio of the extrapolated vertical stress value of 2,720 psi at the surface of the insulator between the sheds and the average value of 1,697 psi, is 1.6. The computer surface strain value was 176 μin./in. Increasing this value to an equivalent load of 2,699 kips gives (2,699 x 176)/800 = 594 μin./in. A similar plot of stresses and strains near the bottom of the insulator (elements 20 to 25) gives a surface stress of 1,675 psi and a surface strain of 110 μin./in. For an equivalent load of 2,699 kips, this surface strain is increased by the factor to give 373 μin./in. and is comparable to the average field test strain of 344 μin./in. It must be remembered that this run was made for a modulus of elasticity value of 15 x 10^6 psi and a Poisson ratio of 0.23. Changing the modulus of elasticity to another value will have an effect on the resulting stress and strain values. Also, the accuracy of the finite element analysis solution depends upon the size of mesh used; i.e., the smaller the size of the mesh, the more accurate the solution becomes.

The strain readings at the maximum tower load of 2,699 kips were used in the program presented in Appendix B to determine the thrust and moments in the individual legs. For this program, three independent strain gage readings 90 degrees apart on each leg of the BIA are required. The output results presented in Table 3 indicate that the maximum thrust of 482.2 kips occurred in leg 5; the moment corresponding to this thrust was 97.5 in.-kips.

SUMMARY AND CONCLUSIONS

The strain measurements of the Lapp cone BIA made during the raising of the tower and in the Rosenthal-Stemag (R-S) station post BIA during the lowering of the tower were obtained at the Naval Radio Station, Lualualei, during the summer of 1974. Results of the measurements show that the tower load was distributed almost equally on the Lapp cone BIA but was quite eccentric when the load was placed on the R-S post BIA. The ratio of the average strain gage measurements from the Lualualei tower operation to the average strain gage measurements from the CEMCO Lehigh laboratory test at the bottom of the lower tier insulators was about 80%. The maximum strain deviation from the mean was about +52%, which indicated a load eccentricity on the new BIA.

Finite element computer analyses were performed for both types of insulators to supplement the experimental data and to give indications of the stress distributions within and on the surface of the insulators.

It can be concluded that:

1. The objective to determine the efficiency of the load distribution arrangement of the existing and replacement BIA was satisfied.

2. Finite element analyses were performed on individual Lapp cone and Stemag post insulators to support the strain gage data taken in the field. The vertical and circumferential stresses showed good correlation between the theoretical and experimental values.

3. The stress concentration factor between the sheds for the Stemag post insulators was calculated to be 1.6.

Table 3. Calculations of Thrust, Moment, and Stresses in BIA

1,500-foot east VLF tower load = 2,699,000 lb
Number of insulators = 8
Diameter of insulator = 8.86 in.
Young's Modulus = 15,000,000 psi
Axial strain concentration factor = 1

	ϵ_1	ϵ_2	ϵ_3	Reference Angle	Final Angle	Thrust	Moment	Maximum Stresses	Minimum Stresses
1	185	207	257	0.0	-68.7	204,381	39,562	3,894	2,736
2	229	570	259	45.0	-132.4	225,652	334,248	8,555	-1,235
3	326	251	258	90.0	129.7	270,042	54,553	5,179	3,581
4	324	316	296	135.0	248.2	286,689	15,600	4,878	4,422
5	618	525	427	180.0	271.5	483,209	97,846	9,270	6,405
6	519	457	459	225.0	268.2	452,228	44,926	7,993	6,677
7	498	452	290	270.0	389.1	364,372	121,964	7,696	4,124
8	254	184	308	315.0	299.4	259.869	103,126	5,725	2,705

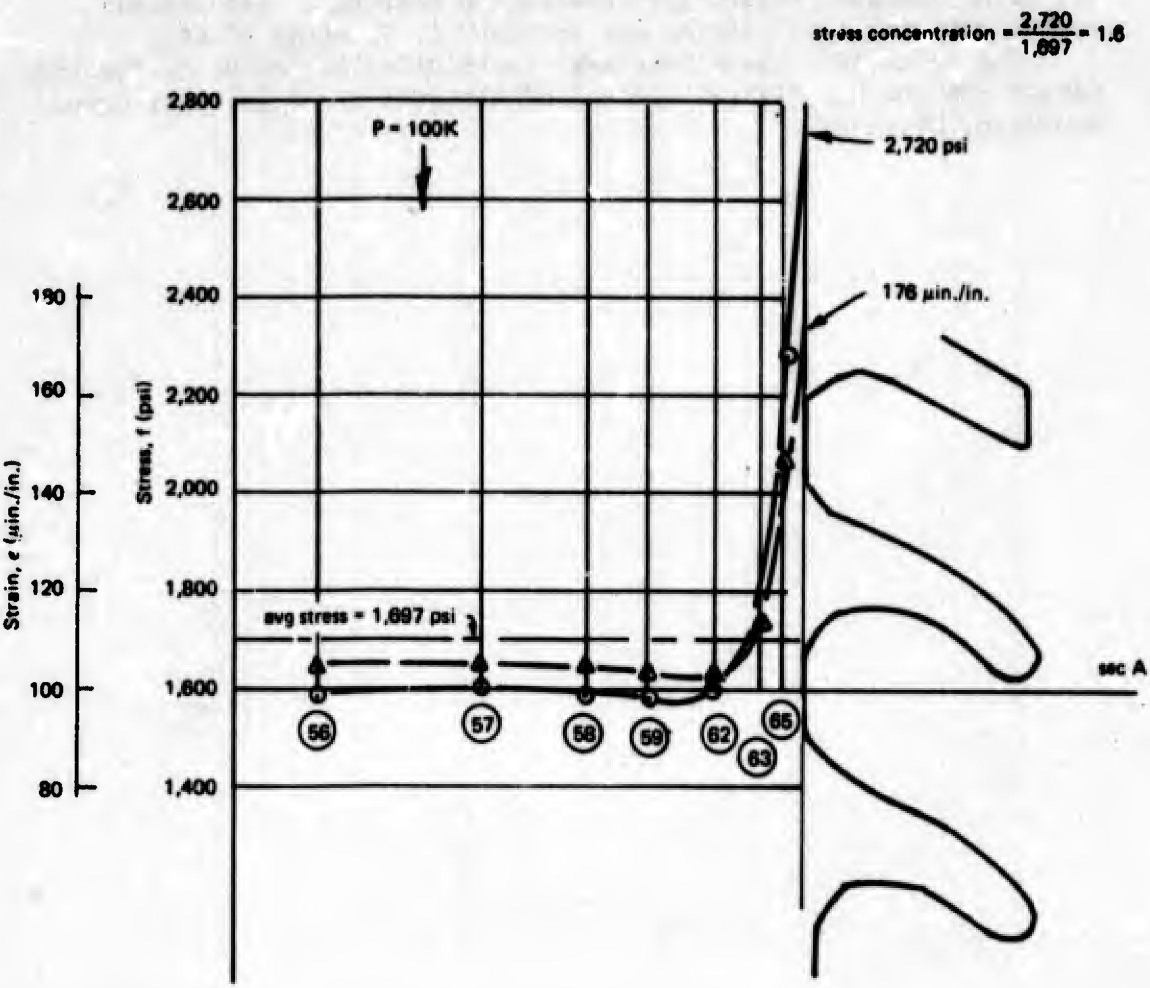


Figure 14. Stress and strain distribution of cross section between sheds, section A.

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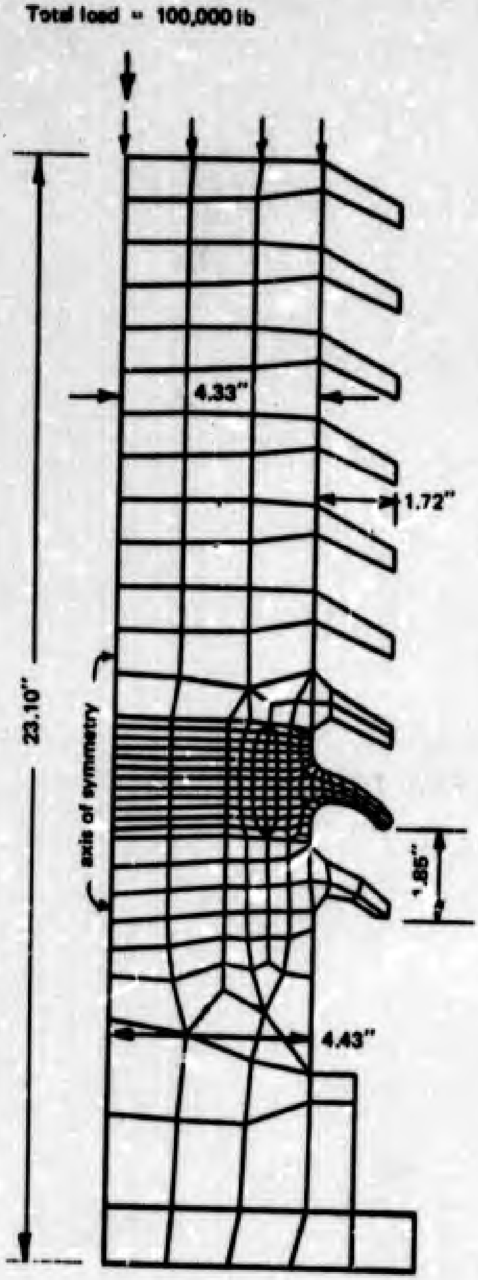
Computer analyses support from Mr. T. K. Lew, Research Structural Engineer and Mr. D. T. Corrente, Structural Engineering Technician, is gratefully acknowledged. The instrumentation support was provided by Mr. D. H. Johnson, Senior Instrumentation Engineer. The overall coordinator for this program was Mr. John A. Norbutas of CEL.

The tower lift operations were coordinated by CDR H. C. Sherrod, NAVFAC PC6 and Mr. William Lambert of National Steel Erectors Corp., Muskogee, Oklahoma.

Appendix A

Computer Plots of Station Post Insulator



Summary of:

Circumferential Stress and Strain

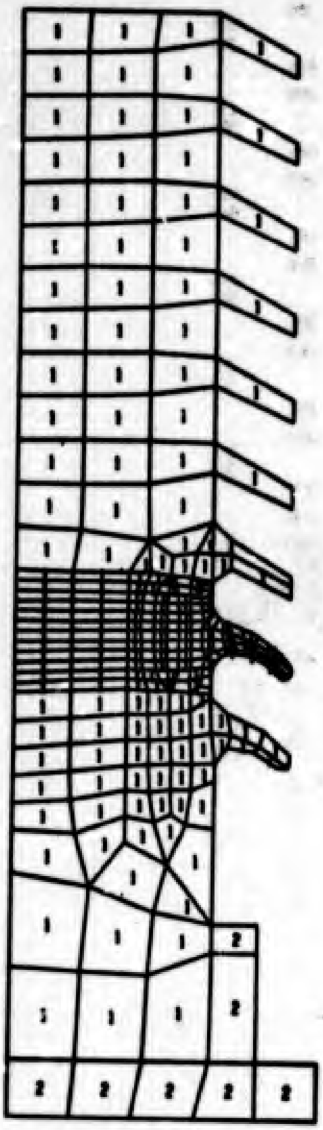
Computer stress (el 144) = +334 psi
Computer strain (el 144) = $+22.5 \times 10^{-6}$ in./in.
Computer stress (el 65) = -235 psi
Computer strain (el 65) = $+20.6 \times 10^{-6}$ in./in.

Vertical Stress and Strain

Cross-sectional area
$A_{4.33}$ = 58.901 in.^{2}
$A_{4.43}$ = 61.653 in.^{2}
Average stress
$f_{4.33}$ = -1,697 psi
$f_{4.43}$ = -1,621 psi
Computer stress (el 65) = -2,280 psi
Stress concentration = 2,720/1,697 = 1.6
Computer strain (el 65) = -147×10^{-6} in./in.

Note: See Figure A-7 for location of elements.

Figure A-1. Mesh of German insulator.



No.	Modulus of Elasticity	Poisson Ratio
1	15×10^6 psi	0.23 porcelain
2	30×10^6 psi	0.30 steel

Figure A-2. Material property numbers.

Figure A-3. Nodal point numbering scheme.

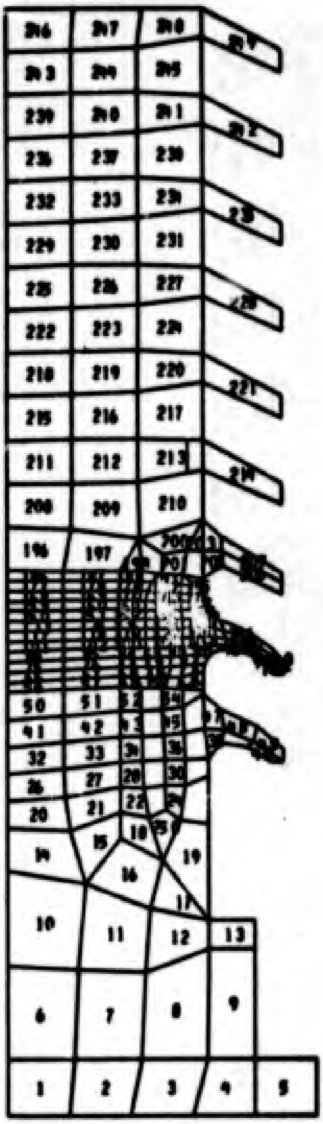
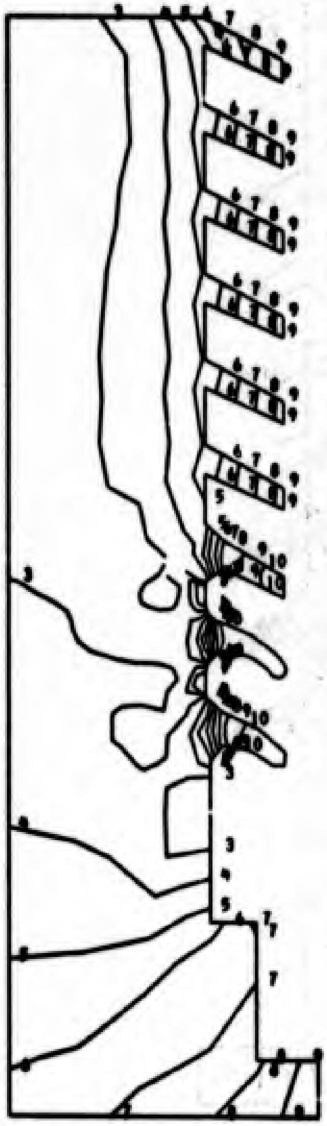
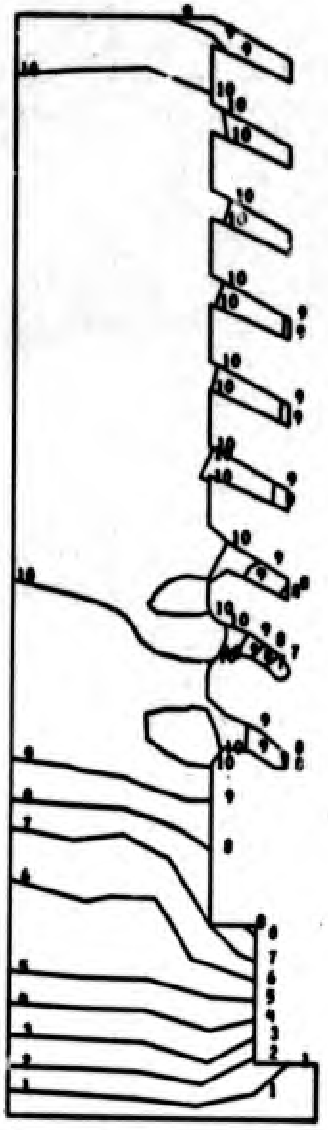


Figure A-4. Element numbering scheme.



Contour No.	Strain (in./in.)
1	1.30×10^{-04}
2	1.18×10^{-04}
3	1.05×10^{-04}
4	9.24×10^{-05}
5	7.96×10^{-05}
6	6.67×10^{-05}
7	5.39×10^{-05}
8	4.11×10^{-05}
9	2.82×10^{-05}
10	1.54×10^{-05}

Figure A-5. Vertical strains.



Contour No.	Strain (in./in.)
1	1.48×10^{-06}
2	3.78×10^{-06}
3	6.08×10^{-06}
4	8.38×10^{-06}
5	1.06×10^{-05}
6	1.29×10^{-05}
7	1.52×10^{-05}
8	1.75×10^{-05}
9	1.98×10^{-05}
10	2.21×10^{-05}

Figure A-6. Circumferential strains.

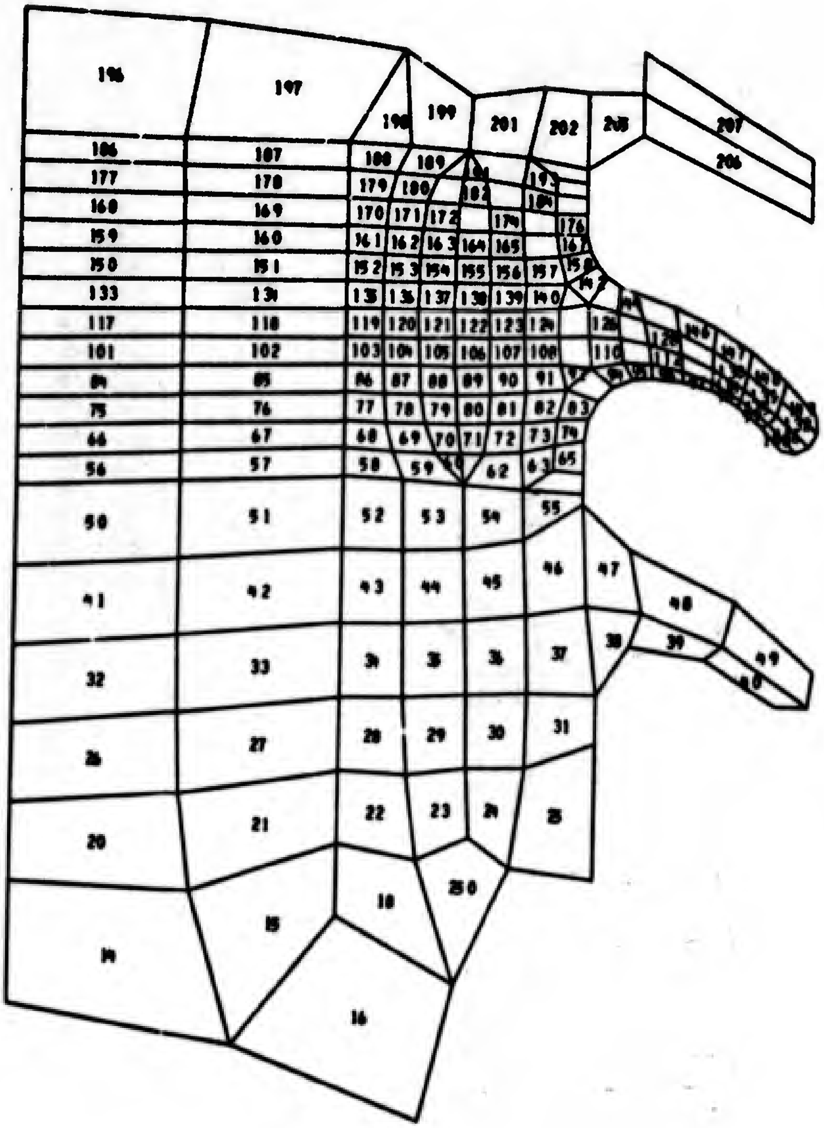


Figure A-7. Expanded mesh, element numbering scheme.

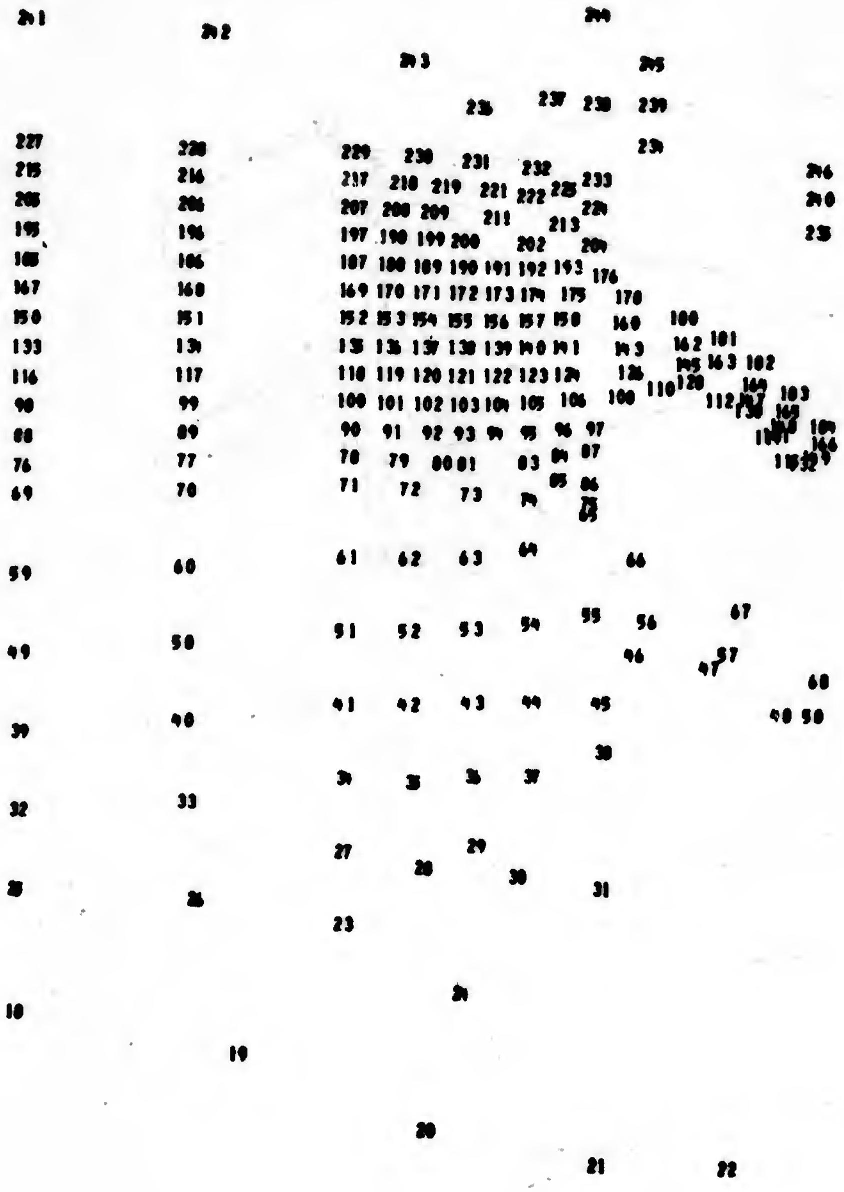
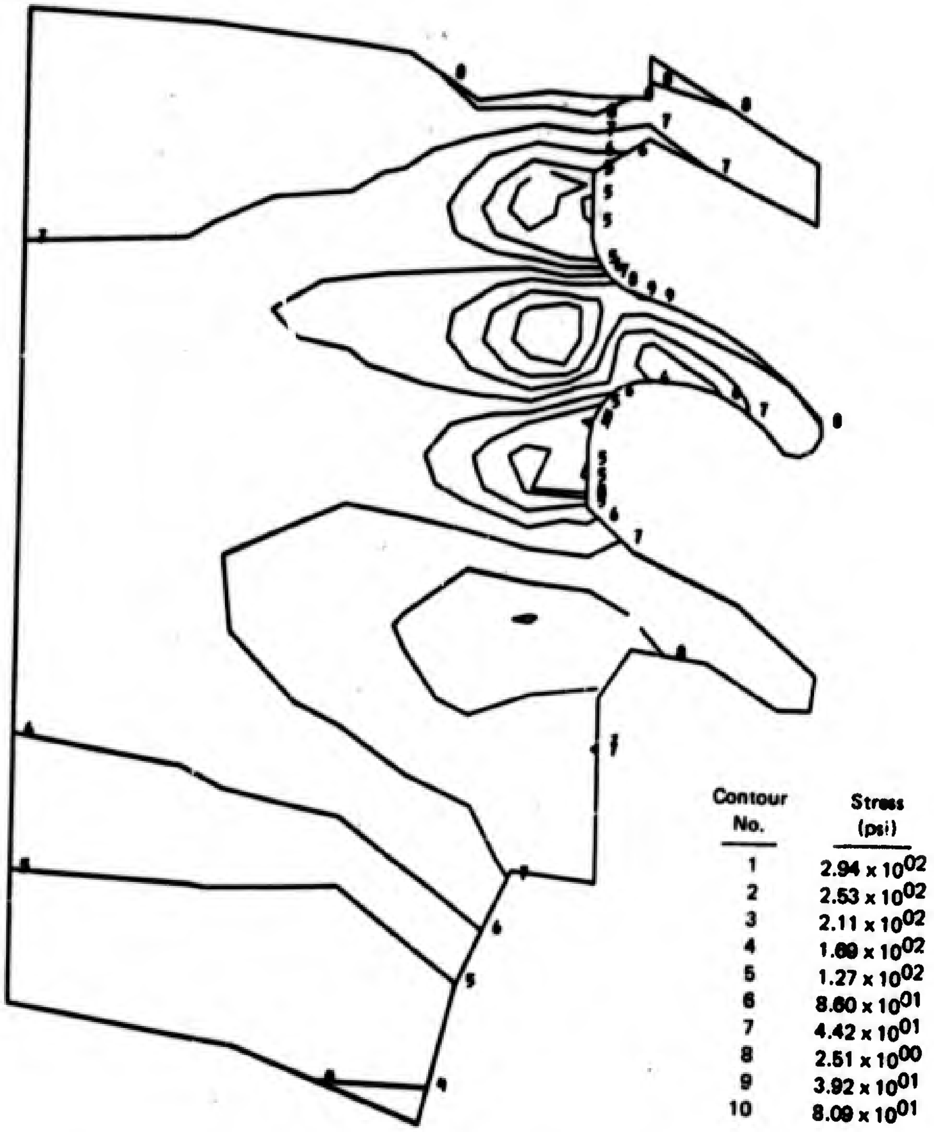


Figure A·8. Expanded mesh, nodal point numbering scheme.



Contour No.	Stress (psi)
1	2.94×10^{02}
2	2.53×10^{02}
3	2.11×10^{02}
4	1.69×10^{02}
5	1.27×10^{02}
6	8.60×10^{01}
7	4.42×10^{01}
8	2.51×10^{00}
9	3.92×10^{01}
10	8.09×10^{01}

Figure A-9. Expanded mesh, radial (horizontal) stresses.

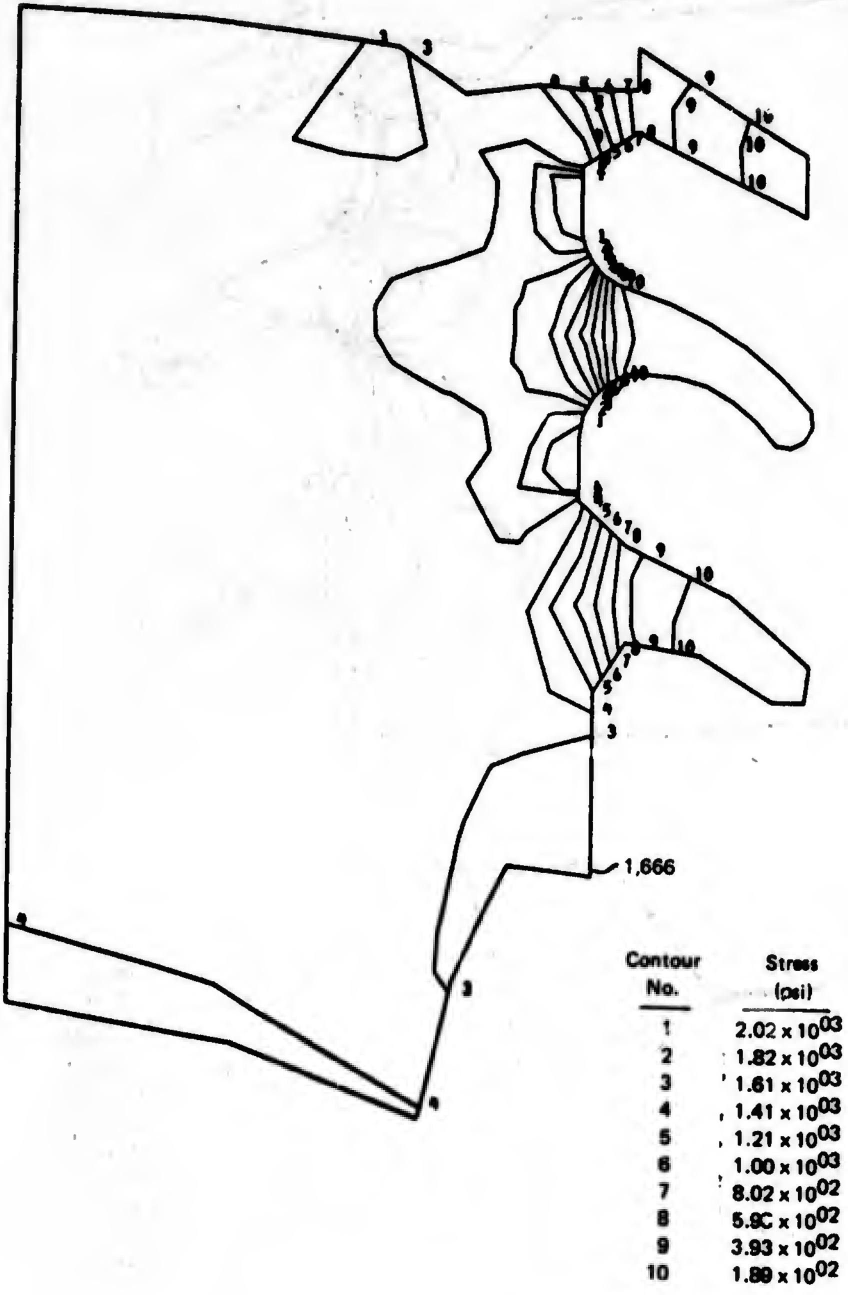
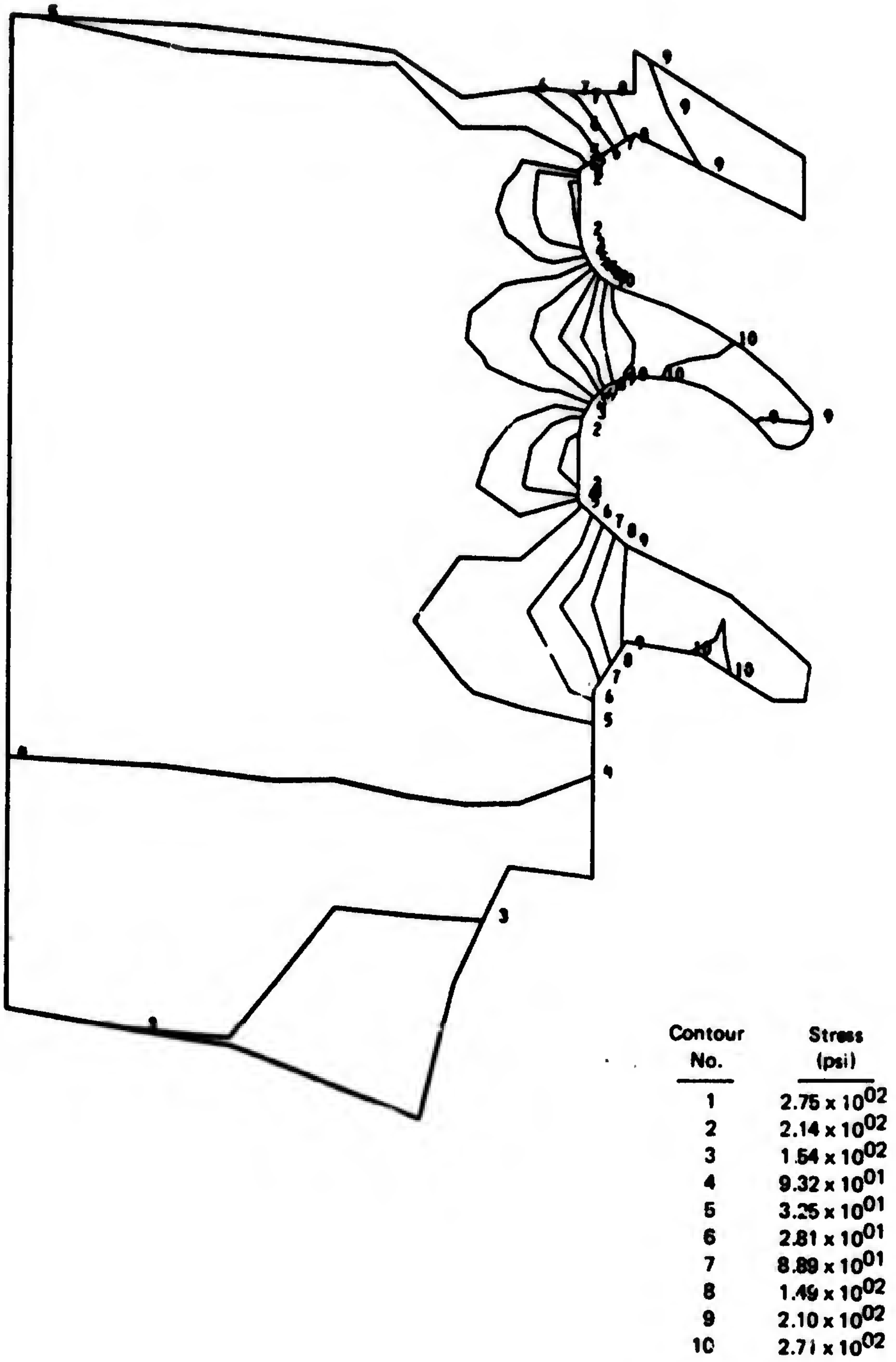
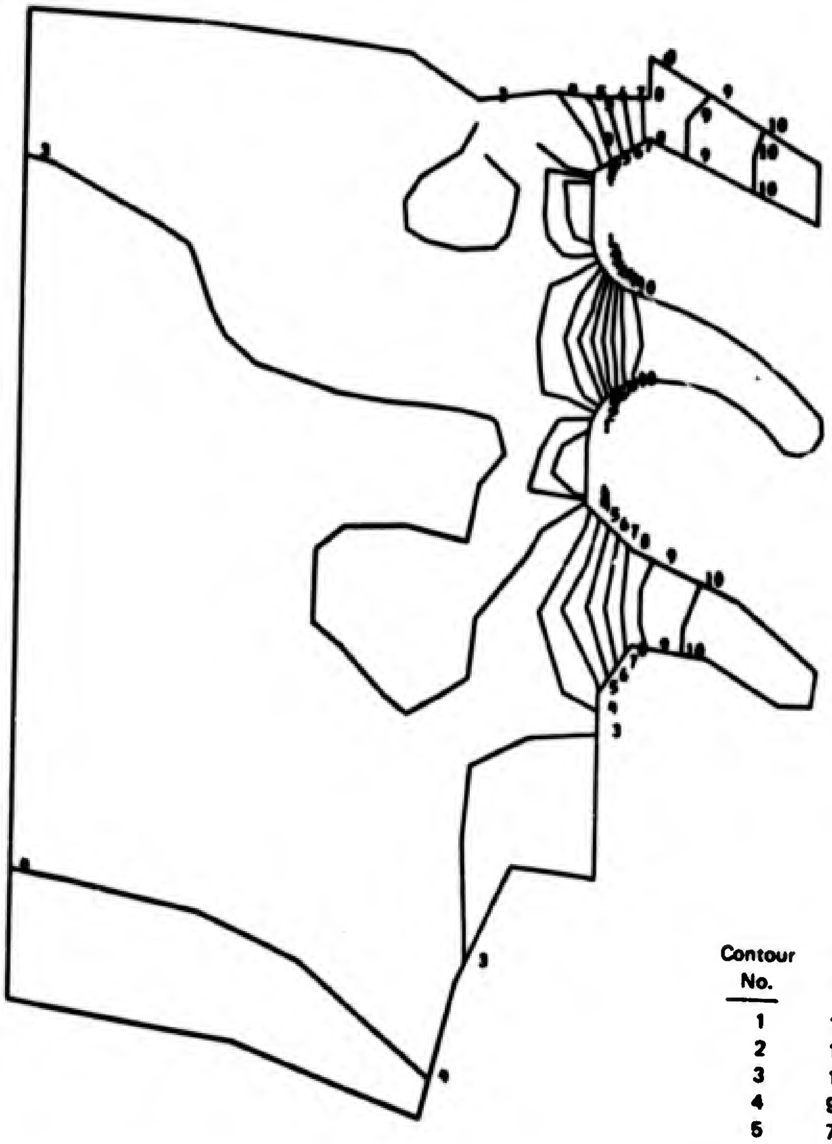


Figure A-10. Expanded mesh, vertical (axial) stresses.



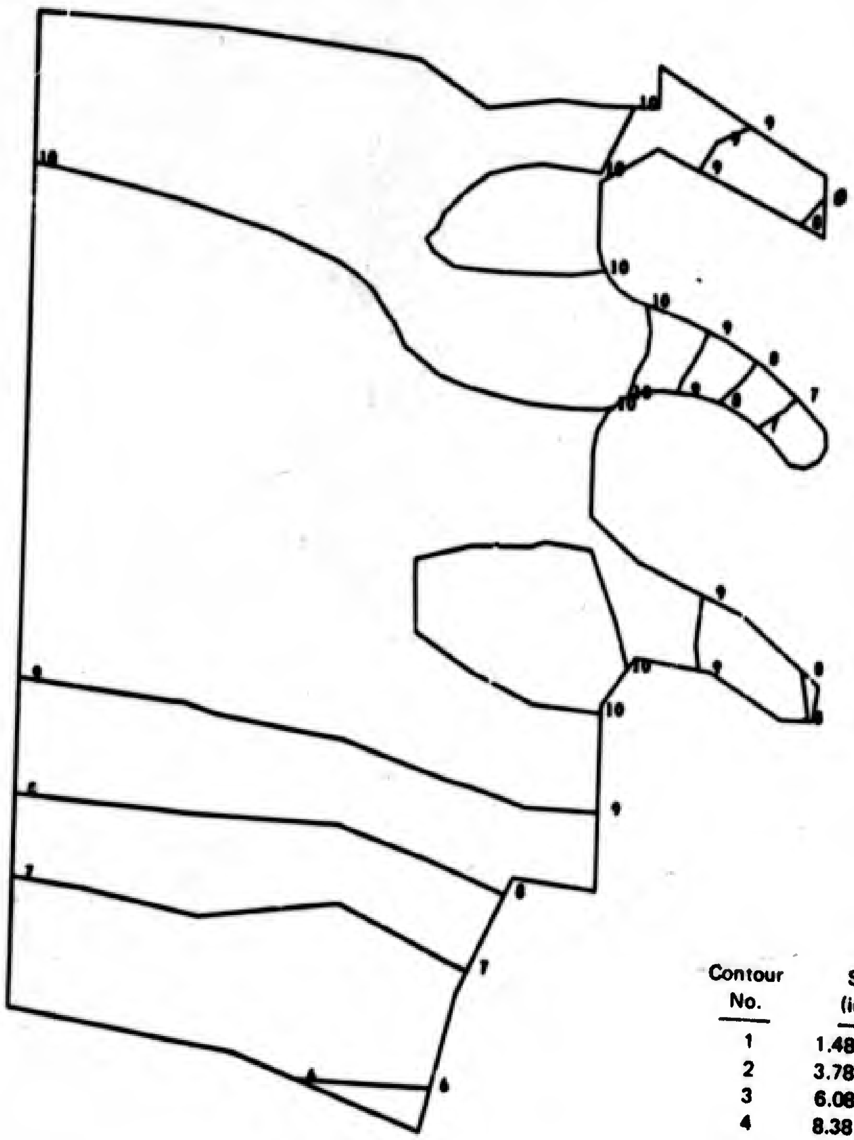
Contour No.	Stress (psi)
1	2.75×10^{02}
2	2.14×10^{02}
3	1.54×10^{02}
4	9.32×10^{01}
5	3.25×10^{01}
6	2.81×10^{01}
7	8.89×10^{01}
8	1.49×10^{02}
9	2.10×10^{02}
10	2.71×10^{02}

Figure A-11. Expanded mesh, circumferential stresses.



Contour No.	Strain (in./in.)
1	1.30×10^{-04}
2	1.18×10^{-04}
3	1.05×10^{-04}
4	9.24×10^{-05}
5	7.96×10^{-05}
6	6.67×10^{-05}
7	5.39×10^{-05}
8	4.11×10^{-05}
9	2.82×10^{-05}
10	1.54×10^{-05}

Figure A-12. Expanded mesh, vertical (axial) strains.



Contour No.	Strain (in./in.)
1	1.48×10^{-06}
2	3.78×10^{-06}
3	6.08×10^{-06}
4	8.38×10^{-06}
5	1.06×10^{-05}
6	1.29×10^{-05}
7	1.52×10^{-05}
8	1.75×10^{-05}
9	1.98×10^{-05}
10	2.21×10^{-05}

Figure A-13. Expanded mesh, circumferential strains.

Appendix B

Program DRPIE To Determine Axial Thrust and Moments From Strain Gage Readings in BIA

(User's Manual)

by T. K. Lew

In the development of the program, compressive strain is assumed to be positive. After the strains for the insulators are read in, the average strain for each insulator is computed from the expression:

$$SA = 0.5\ (\varepsilon 1 + \varepsilon 3) \tag{B-1}$$

Then, the program determines the direction of the principal bending with respect to the local x and y axes and angle Θ in Figure B-1. The logic used is according to the following cases:

a. If ($\varepsilon 1 = \varepsilon 3$), the principal bending is about the local x-axis

b. If ($\varepsilon 2 = SA$), the principal bending is about the y-axis

c. If ($\varepsilon 2 < SA$) and ($\varepsilon 1 < SA$), the principal bending direction makes a negative angle, Θ, with respect to the local x-axis

d. If ($\varepsilon 2 < SA$) and ($\varepsilon 1 \geq SA$), principal bending directions make a positive angle, Θ, with respect to the local x-axis

e. If ($S1 > SA$), principal bending direction makes a negative angle, Θ

f. If ($S1 \leq SA$), principal bending direction makes a positive angle, Θ, with respect to the local axis

The angle Θ is determined from

$$\Theta = \tan^{-1}\left(\frac{\varepsilon 2}{\varepsilon 1}\right) \tag{B-2}$$

for cases c and e, and from

$$\Theta = \tan^{-1}\left(\frac{\varepsilon 3}{\varepsilon 2}\right) \tag{B-3}$$

for cases d and f.

The bending strain for cases c and e is computed from

$$DS = 0.5 \left[(S2/\sin \Theta) + (S1/\cos \Theta)\right] \tag{B-4}$$

and for cases d and f from

$$DS = 0.5 \quad [(S2/\cos \theta) \; + \; (S3/\cos \theta)] \tag{B-5}$$

The final bending angle TF is computed by adding θ to the input reference angle TR for the insulator; i.e.,

$$TF = TR + \theta \tag{B-6}$$

Thrust in the insulator is computed from

$$T = E(A)(SA)/PF \tag{B-7}$$

where

E = Young's modulus of elasticity of insulator material
A = Area of insulator
SA = Average Strain
PF = Strain concentration factor of insulator under axial compression

Bending moment is computed from

$$BM = \frac{(E)(I)(DS)}{(C)(BMF)} \tag{B-8}$$

where

E = Young's modulus of elasticity of insulator material
I = Moment of inertia of insulator
DS = Bending strain
C = Distance from center of insulator to the surface of insulator between the sheds
BMF = Bending strain concentration factor of insulator

The maximum and minimum bending stresses in the insulator is determined from

$$f_{\substack{max\\min}} = (SA \pm |DS|)(E) \qquad \text{(B-9)}$$

where

SA = Average strain
$|DS|$ = Absolute value of bending strain
E = Young's modulus of elasticity of insulator material

The computer program for the above derivation and the user's manual are presented below.

USERS GUIDE FOR PROGRAM DRPIE

The following data cards are required for the program:

1. Title card (12A6)

cols.	
1-72	Identification information for strain data

2. Insulator card (I5, 4F10.0)

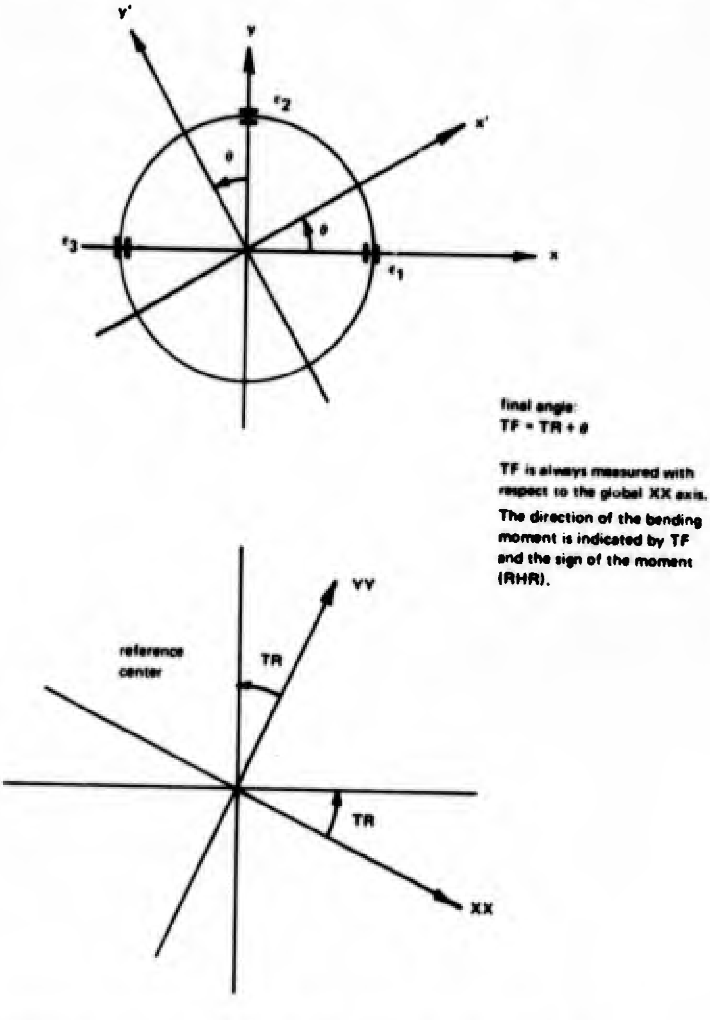
cols.	
1-5	NINS - No. of insulators in test
6-15	DIA - diameter of insulators
16-25	E - Young's modulus of elasticity of insulators
26-35	PF - axial strain concentration factor
36-45	BMF - bending strain concentration factor
	If PF and BMF are left blank, the program sets them = 1.0

3. Strain data cards (I5, 4F10.0)
NINS cards required

cols.	
1-5	J - insulator identification number
6-15	$\varepsilon 1$ - strain from strain gage no. 1 on insulator (μin./in.)

16-25	ε2 - strain from strain gage no. 2 on insulator (μin./in.)
26-35	ε3 - strain from strain gage no. 3 on insulator (μin./in.)
36-45	TR - reference angle (degrees)
	Two blank cards required at end of data deck required for normal exit.

The reference angle and final angle are illustrated in Figure B-1. The orientation of the bending moment in each insulator, as indicated by the final angle TF, is measured with respect to the global XX-axis. The sign of the bending moment is determined by the right hand rule.



final angle:
TF = TR + θ

TF is always measured with respect to the global XX axis.
The direction of the bending moment is indicated by TF and the sign of the moment (RHR).

Figure B-1. Reference and final angles.

A

```
      PROGRAM DHPIE (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C
C     MECHANICAL PROPERTIES FOR INSULATOR
C
C
      DIMENSION HED(12)
C
    1 READ (5,1000) HED,NINS,DIA,E,PF,BMF
 1000 FORMAT (12A6,/I5,4F10.0)
C
      IF (NINS.EQ.0) STOP
      IF (PF.EQ.0.) PF = 1.
      IF (BMF.EQ.0.) BMF = 1.
      WRITE (6,2000) HED,NINS,DIA,E,PF,BMF
 2000 FORMAT (1H1,12A6/
     1 1H0,30HNO. OF INSULATORS              = I15  /
     2 1H0,30HDIAMETER OF INSULATOR          = F15.4/
     3 1H0,30HYOUNG≠S MODULUS                = F15.4/
     4 1H0,30HAXIAL STRAIN CONC. FACTOR      = F15.4/
     5 1H0,30HBENDING STRAIN CONC. FACTOR    = F15.4///)
C
C     COMPUTE STIFFNESS PROPERTIES
C
      C = DIA/2.
      A = 3.14159265 * (C**2)
      XI = 3.14159265 * (DIA**4)/64.
C
      WRITE (6,2001)
 2001 FORMAT (1H0,12X,2HE1,8X,2HE2,8X,2HE3,10H REF ANGLE,10H FINAL ANG,
     1 9X,6HTHRUST,9X,6HMOMENT,9X,6HSIGMAX,9X,6HSIGMIN//)
C
      DO 500 I = 1,NINS
C
      READ (5,1001) J,E1,E2,E3,IR
 1001 FORMAT (I5,4F10.0)
      S1 = E1*1.E-06
      S2 = E2*1.E-06
      S3 = E3*1.E-06
C
      SA = 0.5*(S1+S3)
      SS1 = S1 - SA
      SS2 = S2 - SA
      SS3 = S3 - SA
C
      IF (S1.EQ.S3) GO TO 10
      IF (S2.EQ.SA) GO TO 20
      GO TO 30
C
   10 DIF = 0.
      IF (S2.GT.SA) DIF = 180.
      IF = IR + DIF
      DS = ABS(SS2)
   11 BM = E * DS * XI / (BMF * C)
```

```
      S1 = E1*1.E-06
      S2 = E2*1.E-06
      S3 = E3*1.E-06
C
      SA = 0.5*(S1+S3)
      SS1 = S1 - SA
      SS2 = S2 - SA
      SS3 = S3 - SA
C
      IF (S1.EQ.S3) GO TO 10
      IF (S2.EQ.SA) GO TO 20
      GO TO 30
C
   10 DIF = 0.
      IF (S2.GT.SA) DIF = 180.
      TF = TR + DIF
      DS = ABS(SS2)
   11 BM = E * DS * XI / (HMF * C)
      T = (E*A*SA)/FF
      SMAX = E * (SA + DS)
      SMIN = E * (SA - DS)
      GO TO 40
C
   20 IF (S1.GT.SA) DIF = 0.
      IF (S3.GT.SA) DIF = -180.
      TF = TR + 90. + DIF
      DS = ABS(SS1)
      GO TO 11
C
   30 IF (S2.LT.SA) GO TO 50
      IF (S1.GT.SA) GO TO 31
   32 THETA = ATAN2(SS3,SS2)
      DS = 0.5*((SS2/COS(THETA)) + (SS3/SIN(THETA)))
      DS = ABS(DS)
      TF = TR + (57.295779*THETA)
      IF (THETA.LT.0.) TF = TF + 180.
      IF (THETA.GT.0.) TF = TF - 180.
      GO TO 11
C
   31 CONTINUE
   33 THETA = ATAN2(SS2,SS1)
      TF = TR + 90. + (57.295779*THETA)
      DS = 0.5 * ((SS2/SIN(THETA)) + (SS1/COS(THETA)))
      DS = ABS(DS)
      GO TO 11
C
   50 IF (S1.LT.SA) GO TO 33
      GO TO 32
C
   40 WRITE (6,2002) J,E1,E2,E3,TR,TF,T,BM,SMAX,SMIN
 2002 FORMAT (I5,3F10.0,2F10.1,4F15.0)
C
  500 CONTINUE
C
      GO TO 1
C
      END
```

B

REFERENCES

1. Naval Civil Engineering Laboratory. Technical Report R-743: Stress analysis of multicomponent structures, by S. B. Nosseir, S. K. Takahashi and J. E. Crawford, Port Hueneme, CA, Oct 1971.

2. Naval Facilities Engineering Command. Assembly compression proof load test, report of base insulator assembly S/N 2. Dallas, TX, Continental Electronics Manufacturing Co., Sep 1974. (Contract N00039-74-C-0052)

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