Fracture Evaluation of
Reactor Coolant Pump Motor
Seismic Snubber Lugs

for

Arkansas Nuclear One Unit 2

Combustion Engineering, Inc.

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1. INTRODUCTION

A fracture mechanics evaluation of the reactor coolant pump (RCP) motor seismic snubber lugs was performed to assist the NRC to complete their evaluation of the fracture toughness of these lugs for Arkansas Nuclear One Unit 2 (Reference 1). This report describes the analysis of the integrity of the RCP snubber subject to the maximum faulted condition design load.

Both two and three dimensional finite element analyses are used to evaluate the effect of hypothetical cracks in the lug emanating radially from the pin hole. These results are compared to simplified analysis methods previously recommended by CE.

A literature search to determine a lower bound material toughness for the integrity evaluation was also performed. A comparison of the analysis results and the material toughness demonstrates that the integrity of the lug is assured.

2. DESCRIPTION OF PROBLEM

The dimensions and the mounting of the seismic snubber lug are shown in figures 1 and 2. Each lug is bolted to the pump support plate by 12 bolts and pins and the snubber is connected to the clevis region of the lug by a 4.0 inch diameter pin. The maximum Design Basis Earthquake (DBE) loads applied to the lug are ± 200 kips in the radial direction. Only the positive (tensile) force is considered in this analysis which would tend to cause crack opening in the lug.

In order to perform a fracture mechanics analysis, cracks must be assumed in the structure. In response to NUREG 0577 (Reference 2), CE has proposed that the reference flaw size for fracture mechanics analysis of unwelded structures with pin holes be established as 10%

of the ligament from the edge of the pin hole to the outer edge of the structure (Reference 3). For the RCP lug this reference flaw size is 1.3 inches. In the three dimensional analysis a larger flaw (2.0 inches) is also evaluated to demonstrate the lack of sensitivity of this geometry to crack size.

From a previous two dimensional fracture mechanics study of lugs (Reference 3), it was observed that the maximum stress intensity factor occurs for cracks extending from the pin hole, perpendicular to the direction of maximum tensile load. At all other locations around the inside surface of the hole, the J integral value and the stress intensity factors are lower. Therefore, a conservative evaluation of all hypothetical cracks can be conducted by evaluating the consequences of cracks extending perpendicular to the load.

3. METHOD OF ANALYSIS

The finite element analyses were performed using the MARC general purpose finite element program (Reference 4). All the analyses presume linear elastic material behavior. The region surrounding the crack tip is modeled using the triangular-shaped quarter-point elements according to Barsoum (Reference 5). These elements are used to incorporate the correct elastic singularity in the crack tip region for determining the stress intensity factor, K_I. The crack tip stress intensity is calculated in the 2-D analyses using the J-integral technique available in the MARC program (Reference 6). J is an energy term which is used to express the change in potential energy per unit change in crack extension. For the case of linear elastic fracture mechanics analyses, the parameter J is identical to the strain energy release rate, G, which is defined according to the relation:

$$J = G = \frac{1-\nu^2}{E} K_I^2 \qquad \text{(for plane strain)}$$

where K_I is the stress intensity factor, E is Young's modulus, and ν is Poisson's ratio.

Since the J-integral concept is limited to two-dimensional cracked geometries, the determination of K_I for the three-dimensional analysis was computed from the crack opening using the relation (Reference 7)

$$K_I = \frac{\delta_r E \sqrt{2\pi}}{4\sqrt{r}(1-\nu^2)}$$

where δ_r is the opening displacement at a distance r from the crack tip. The triangular quarter-point crack tip elements were also used for the three-dimensional case, therefore, the distance r is measured from the crack tip to the location of the quarter-point node along the line of the crack. In the case of linear elastic analysis, the two methods used in the calculation of K_I produce virtually identical results.

4. TWO DIMENSIONAL ANALYSIS

A two dimensional analysis of one arm of the lug was performed first without any crack. Only one half the section of the arm beyond the centerline of the pin hole was modelled using 8 noded isoparametric plane stress quadrilateral elements available in the MARC program. The model was generated using a separate computer program and consists of 280 nodes and 81 elements. Details of the finite element mesh and boundary conditions used are shown in Figure 3. A sinusoidal pressure distribution.

$$P(\theta) = \frac{2P}{\pi R_i} \sin\theta$$

acting normal to the inner circular boundary of the hole was used in the analysis. Here P is the total load applied by the pin on the lug in tension,

R_i is the inside radius of the pin hole and θ is the angle measured from centerline of the lug hole.

The normal stress distribution along the centerline of the hole on which the hypothetical crack is placed is plotted in Figure 4. This stress distribution is used to compute the stress intensity factor for the reference flaw according to the procedure of Reference 3. A maximum stress of .425 Ksi for an applied P of 1000 lbs is observed at the hole surface. The stress distribution gradually decreases to a small negative value at 8" from the center of the hole and remains almost constant. From this figure, values of membrane stress σ_m = -1. Ksi and bending stress σ_b = 1.425 Ksi are computed for the reference flaw of 1.3 inches, according to Reference 3. The stress intensity factor is given by:

$$K_I = \sigma_m M_m \sqrt{\pi a/Q} + \sigma_b M_b \sqrt{\pi a/Q}$$

$$= (-1.)(1.2)\sqrt{\pi\, 1.3/.8} + (1.425)(1.03)\sqrt{\pi\, 1.3/.8}$$

$$= .605 \text{ Ksi}\sqrt{\text{in}} \text{ per kip load per inch thickness}$$

For a total load of 200 kips and 2 arms of 2" thick each, K_I is given by:

$$K_I = .605 \times 200/(2 \times 2) = 30.25 \text{ Ksi}\sqrt{\text{in}}$$

In order to evaluate the simplified analysis, the reference flaw (10% of the ligament length) was placed along the centerline of the finite element model. This time, since the crack structure is not symmetric, the entire lug section beyond the centerline of the hole was included in the model. The finite element mesh shown in Figures 5 and 6 consists of 477 nodes and 140 elements. At the crack tip, quadrilateral elements with cc ncident nodes were used. The mid side nodes along the sides joining at the crack tip are moved to the quarter point to similate the crack tip stress singularity. The stress intensity factor at the crack tip is computed from the J value calculated by the program.

$$K_I = \sqrt{JE/(1-\nu^2)} = 0.488 \text{ Ksi} \sqrt{\text{in}} \text{ per kip load per inch thickness}$$

The corresponding value for the actual load on the lug is 24.38 Ksi $\sqrt{\text{in.}}$

5. 3-D ANALYSIS OF LUG

A three-dimensional analysis of the lug containing a radial crack was performed to determine the out-of-plane loading effects caused by the bolted attachment to the pump support plate. A half-symmetry finite element model was constructed from isoparametric 20-node brick type elements, and a hypothetical crack was considered emanating from the pin holes in the direction normal to the maximum tensile loading. A plane view of the finite element model is shown in Figure 7. An isometric view showing the three-dimensional nature of the model is shown in Figure 8. Only one-half of the lug was analyzed because of the mirror-plane of symmetry, and symmetry boundary conditions were applied along this plane. In addition, boundary conditions constraining all degrees of freedom were applied along the bottom surface of the lug at the locations of bolted attachment to the support plate. Loading of the lug was accomplished by applying a traction along the vertical line of contact at the lug pin hole. Variations in load along the load line were also considered to represent the effect of bending of the pin.

The results of the analysis demonstrate that three-dimensional effects are present even for a uniform axial loading. This is because the mounting of the snubber lug does not eliminate out-of-plane bending which produces a variation in stress distribution through the thickness of the lug during loading. For example, the equivalent (Mises) stress distribution at the bottom surface of the lug (i.e. the surface in contact with the support plate) is shown in Figure 9. Stress concentrations in the region of the bolts are apparent, as well as a high concentration of stress at the point of loading and at the crack tip location. For comparison, the equivalent stress distribution at the top surface of the lug is shown in Figure 10. These results also include the effect of non-uniform loading due to bending of the pin which produces the load-line variation in stress as shown in Figure 11.

The results of the three-dimensional analysis also show a variation in the crack tip stress intensity factor through the thickness of the lug. The value for K_I was computed at different locations through the thickness from the output of displacements using the crack-opening-displacement relation given in Section 2. The average stress intensity, K_I, for the 1.3 inch long reference flaw was calculated to be 23.3 Ksi $\sqrt{in}$, which is consistent with the results of the two-dimensional analysis. The through-thickness variation in K_I for the three-dimensional case is caused by the out-of-plane bending effects and the non-uniformity of the axial load transmitted from the pin. As a result, K_I determined at the crack tip was calculated to vary from 20.38 Ksi $\sqrt{in}$ to 27.55 Ksi $\sqrt{in}$. across the thickness of the lower arm of the lug. K_I in the upper arm varied only slightly from 22.28 Ksi $\sqrt{in}$ to 22.66 Ksi $\sqrt{in}$.

A similar analysis for the lug with a 2.0 inch long crack produced an average stress intensity value of 25.12 Ksi $\sqrt{in}$. The minimum and maximum values in the lower arm were calculated to be 22.43 Ksi $\sqrt{in}$ and 29.38 Ksi $\sqrt{in}$., respectively. Correspondingly, in the upper arm of the lug with a 2.0 inch long crack, the minimum value for K_I was determined to be 24.23 Ksi $\sqrt{in}$ and the maximum value was 24.43 Ksi $\sqrt{in}$.

These results indicate that the stress intensity factor is not sensitive to crack length since the crack is extending beyond the region of stress concentration near the pin. Larger cracks need not be considered since the two inch long crack is clearly far longer than any crack which could possibly exist in the lug.

6. FRACTURE TOUGHNESS OF RCP LUG MATERIAL

The RCP snubber lug was manufactured from a normalized 10.5 inch thick plate produced by Lukens Steel Co. to General Electric internal specification G.E. B 50A357A-58 69. This specification is essentially identical to SA 515 Gr 55. Chemical requirements are:

Specification	Carbon	Manganese	P	S	Si
SA-515 Gr 55	0.28 max.	0.9 max.	0.035 max.	0.04 max.	0.15-0.30
GEB50G357A-58	0.27 max.	0.50-0.90	0.04 max.	0.05 max.	0.14-0.30
Actual Plate	0.16	0.75	0.008	0.022	0.23

Mechanical requirements and the actual test results are:

Specification	Yield Strength KSI	Tensile Strength KSI	Elongation % in 2 inches
SA 515 Gr 55	30 min.	55 - 75	27 min.
GEB50A357-58	30 min.	55 in.	27 min.
Actual Plate	42.5	67.3	32

No impact testing was required by the GE specification so correlation to a fracture toughness value via the Barsom or Irwin relationships cannot be performed. Data for this class of plain carbon steels was, however, collected from available literature in NUREG 0577 (Reference 2). A lower bound value from this study is 32 Ksi $\sqrt{in}$ at $75^{o}F$. This value is based on very limited data from plain carbon steels (ASTM A-7 and A 212B) at low temperatures (- 75^oF and - 20^oF respectively) and some atypical material results (AISI 1020 high phosphorous steel at 60^oF and cold worked AISI 1018 steel at room temperature). More typical material toughness data from normalized AISI 1020 steel, ASTM A 106B and A212 B at or near room temperature would be in the range of 50 to 90 Ksi $\sqrt{in}$.

The K_{IC} value of 32 Ksi $\sqrt{in}$, suggested by NUREG 0577 is clearly conservative for the RCP lug material. This conservative low value, therefore, is used for the fracture evaluation.

7. FRACTURE EVALUATION

The stress intensity factor K_I, for the reference flaw of 1.3 inches was computed to be less than 30 Ksi $\sqrt{in}$ by a variety of computational methods for the design basis earthquake loading condition. Reference 3 recommends that a favorable comparison of K_I with the fracture toughness, K_{IC}, would be an adequate demonstration of sufficient fracture toughness because of the conservatism inherent in the selection of the reference flaw.

The lower bound fracture toughness value, at the conservative lowest service temperature of 75^oF, is shown in Section 6 to be 32 Ksi $\sqrt{in}$. Since K_I is less than K_{IC} the integrity of the lug is assured even if it contained the reference flaw. This assurance demonstrates an adequate safety margin against brittle fracture.

8. CONCLUSIONS

The fracture mechanics analysis of the RCP snubber lugs has been performed using simplified methods as well as two and three dimensional finite element analysis. All of the analyses are in reasonable agreement as expected. The fracture evaluation, comparing the stress intensity factor computed assuming large flaws to the lower bound toughness suggested in NUREG-0577, demonstrates an adequate safety margin against brittle fracture.

9. REFERENCES

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2. "Potential for Low Fracture Toughness and Lamellar Tearing on PWR Steam Generator and Reactor Coolant Pump Supports", NUREG 0577 for comment, U.S. NRC October, 1979.

3. "Fracture Mechanics Procedures for Primary Component Support Toughness Evaluations", Combustion Engineering, Inc. February 27, 1981

4. MARC-CDC, Non-linear Finite Element Analysis Program, Control Data Corp., Minneapolis, Minn.,1976

5. Barsoum, R. S., "Triangular Quarter-Point Elements as Elastic and Perfectly-Plastic Crack Tip Elements:, Int. J. for Numerical Meth. in Engineering, Vol. 11, pp. 85-98, 1977.

6. Parks, D. M., "A Stiffness Derivative Finite Element Technique for Determination of Elastic Crack Tip Stress Intensity Factors, Int. J. of Fracture, Vol. 10, No. 4, 1974.

7. Tracey, D. M., "Finite Element for Determination of Crack Tip Elastic Stress Intensity Factors", Eng. J. of Fracture Mechanics, Vol. 3, pp. 255-265, 1971.

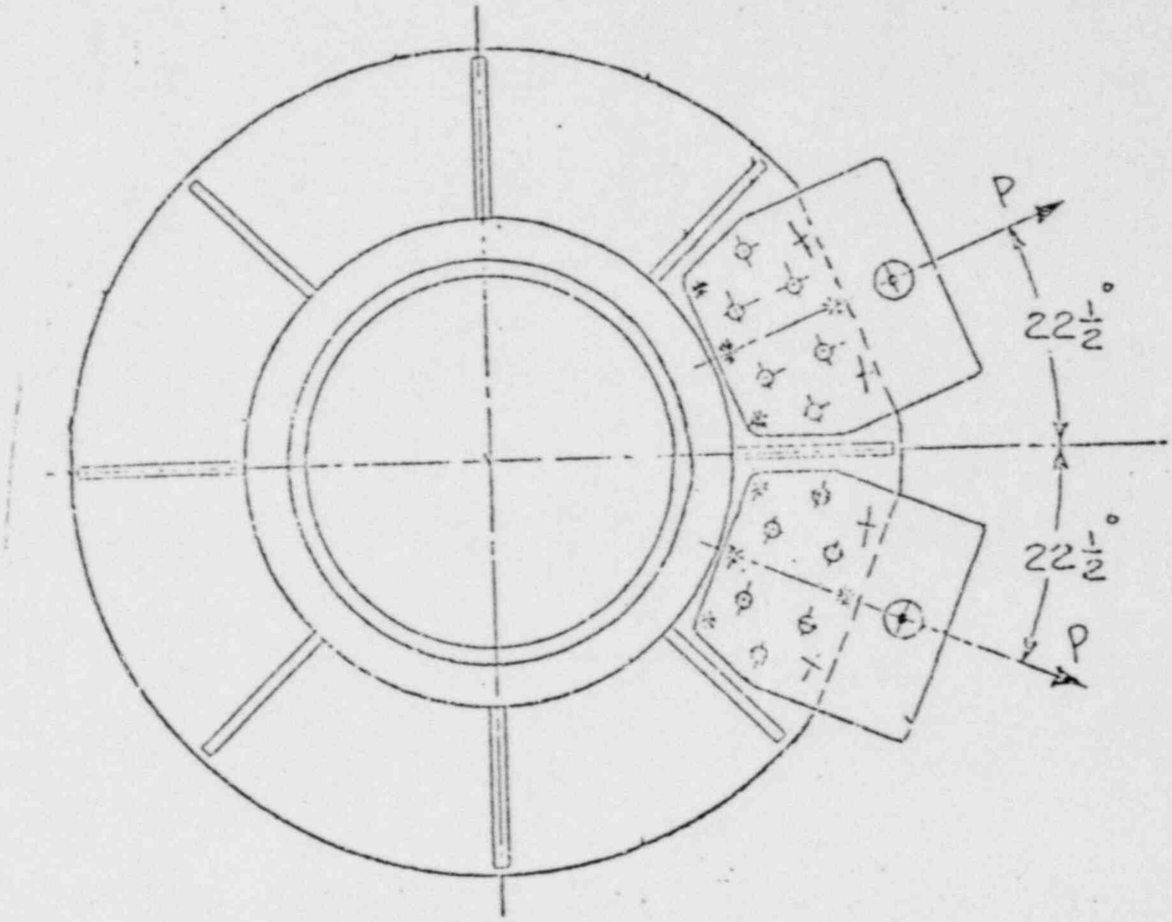

Figure 1. Configuration of Seismic Snubber Lugs of Arkansas Nuclear power plant Reactor Coolant pump.

POOR ORIGINAL

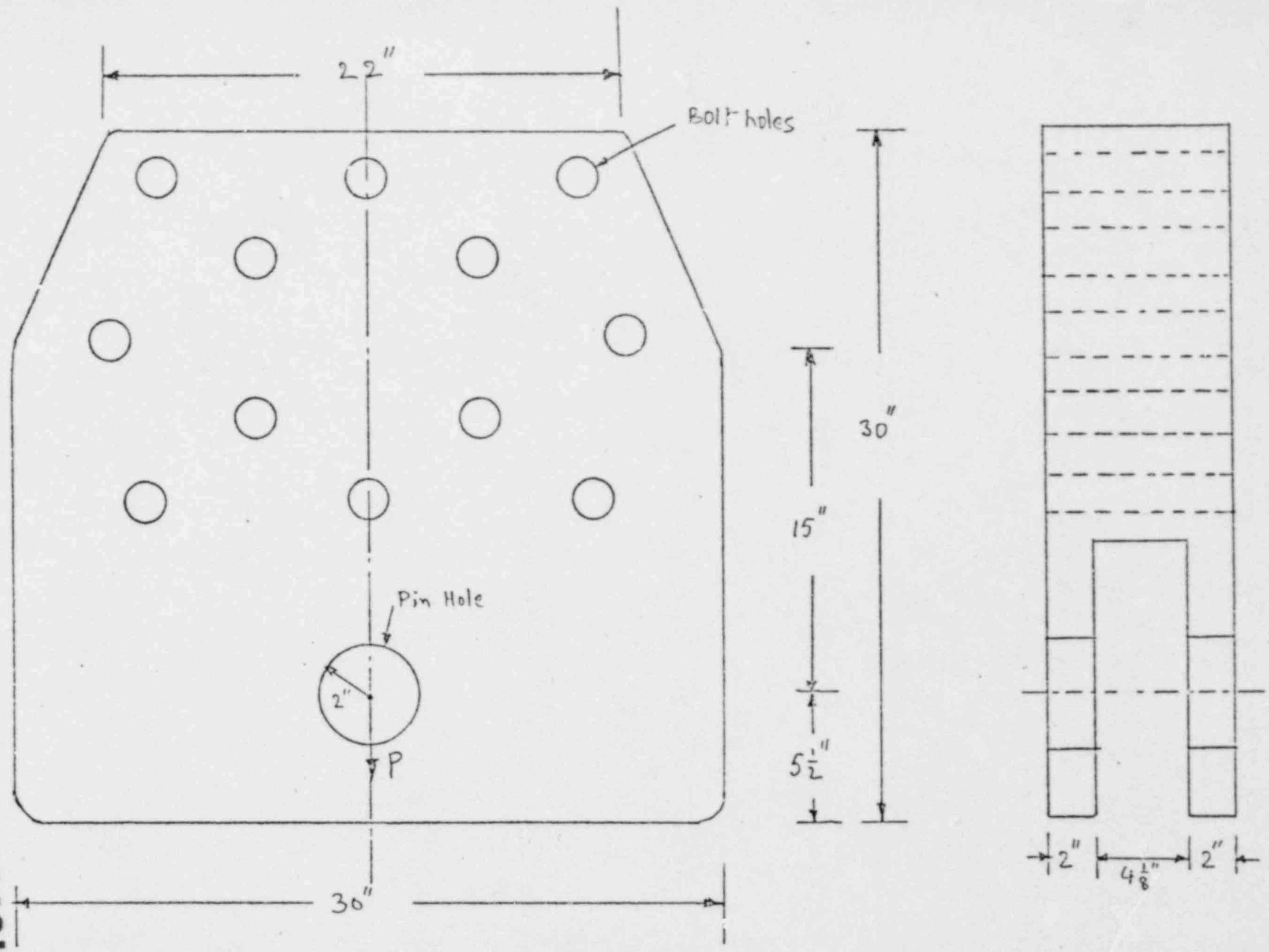

Figure 2. Seismic Snubber Lug Details

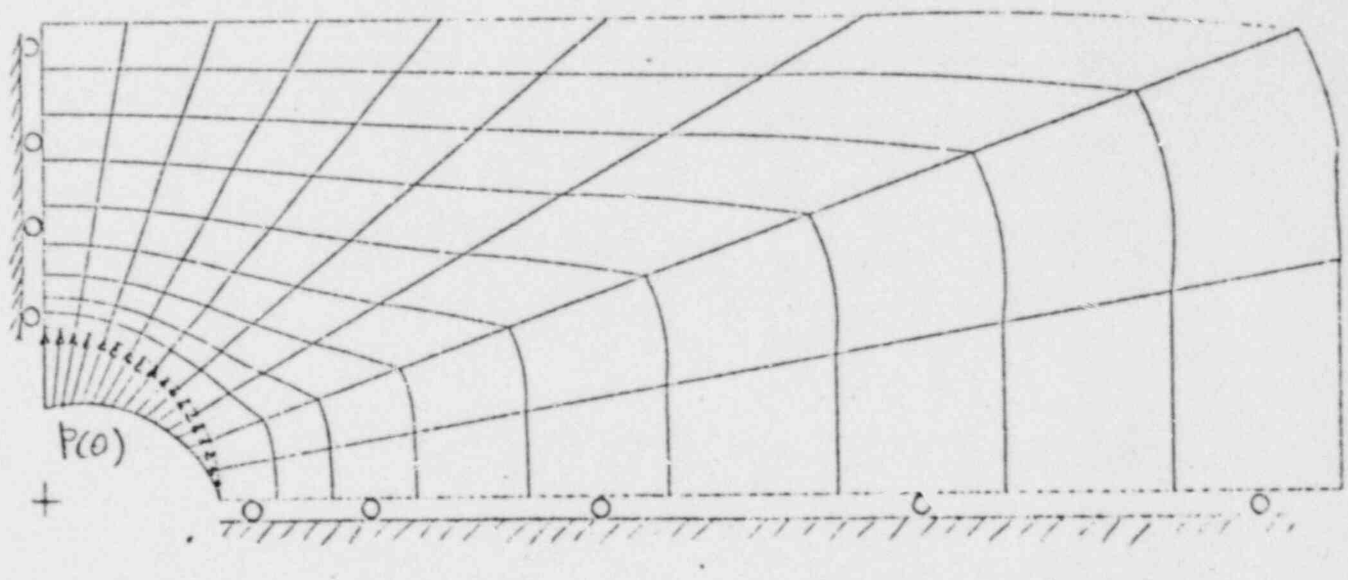

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Figure 3 Finite Element Mesh of Uncracked Lug
(Two Dimensional Model)

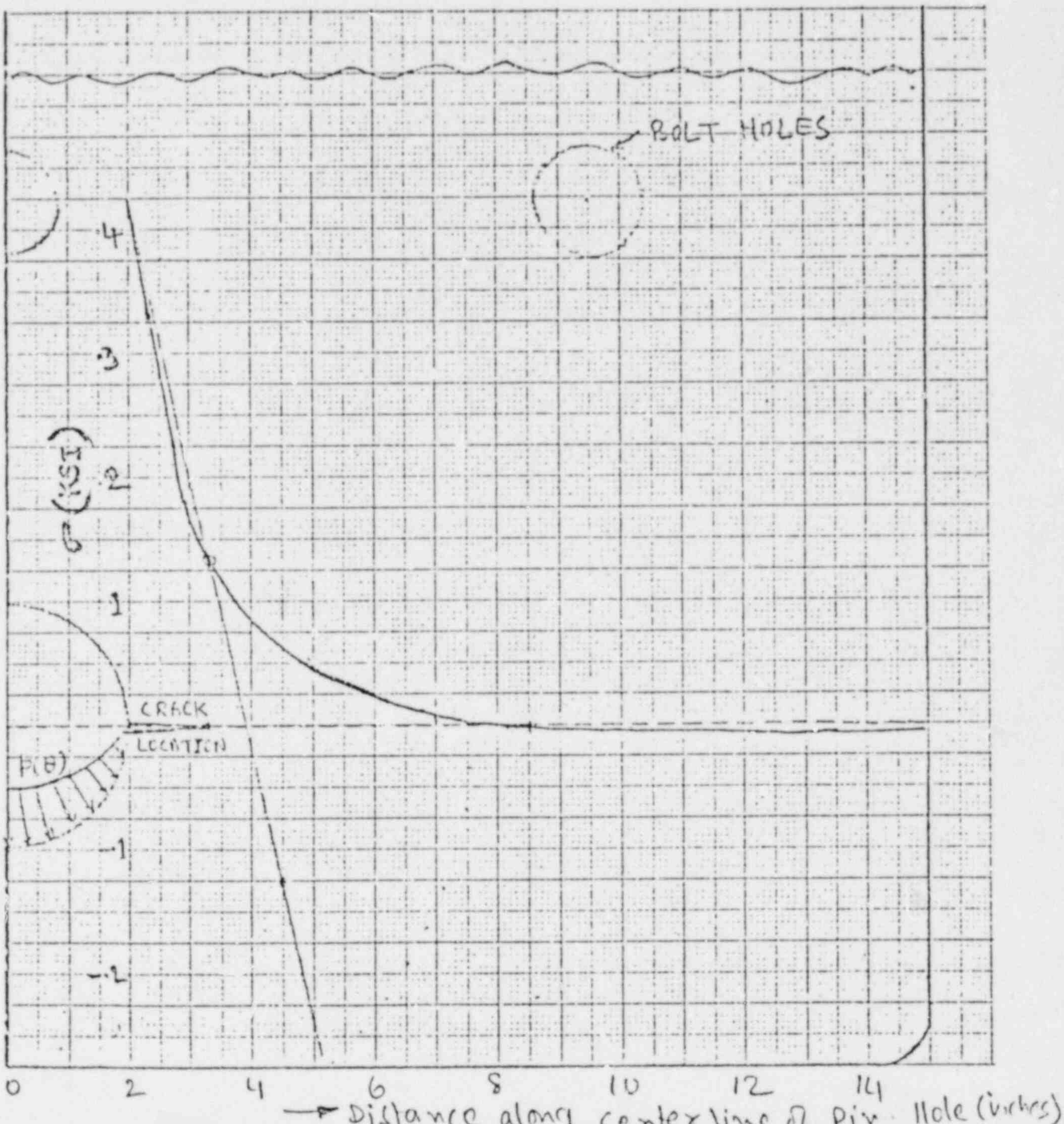

Figure 4 Normal Stress Distribution across Lug width in Uncracked Geometry (Two Dimensional Model)

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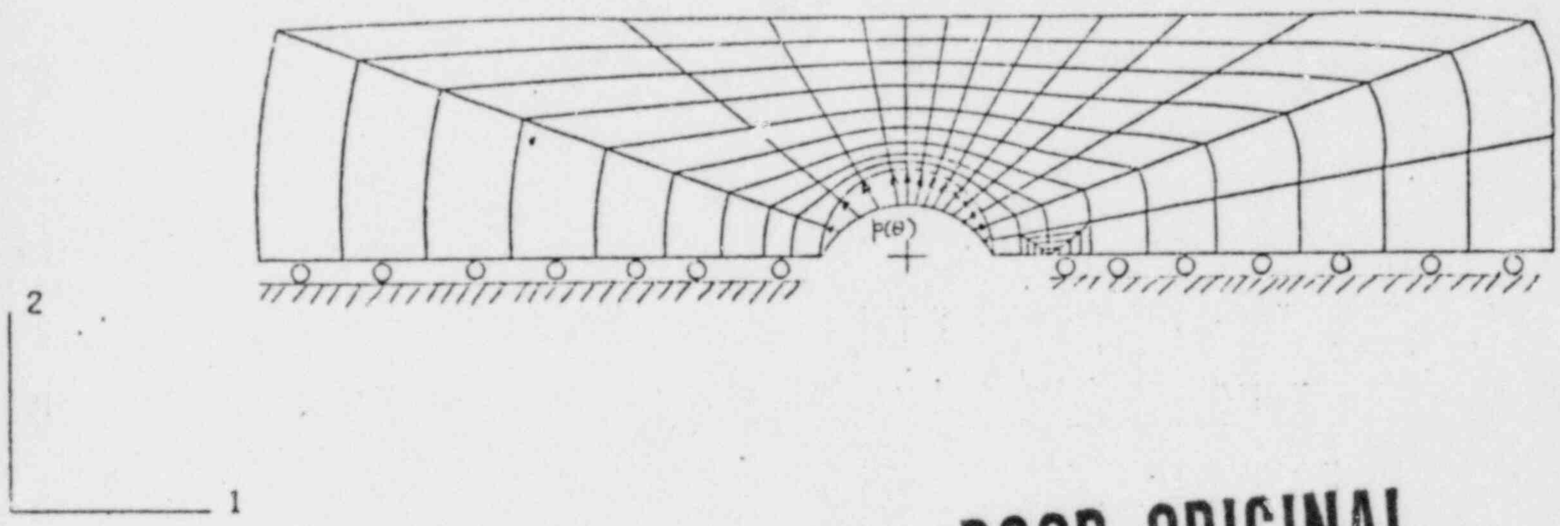

Figure 5. Finite Element Mesh of Lug with 1.3" crack
(Two Dimensional Model)

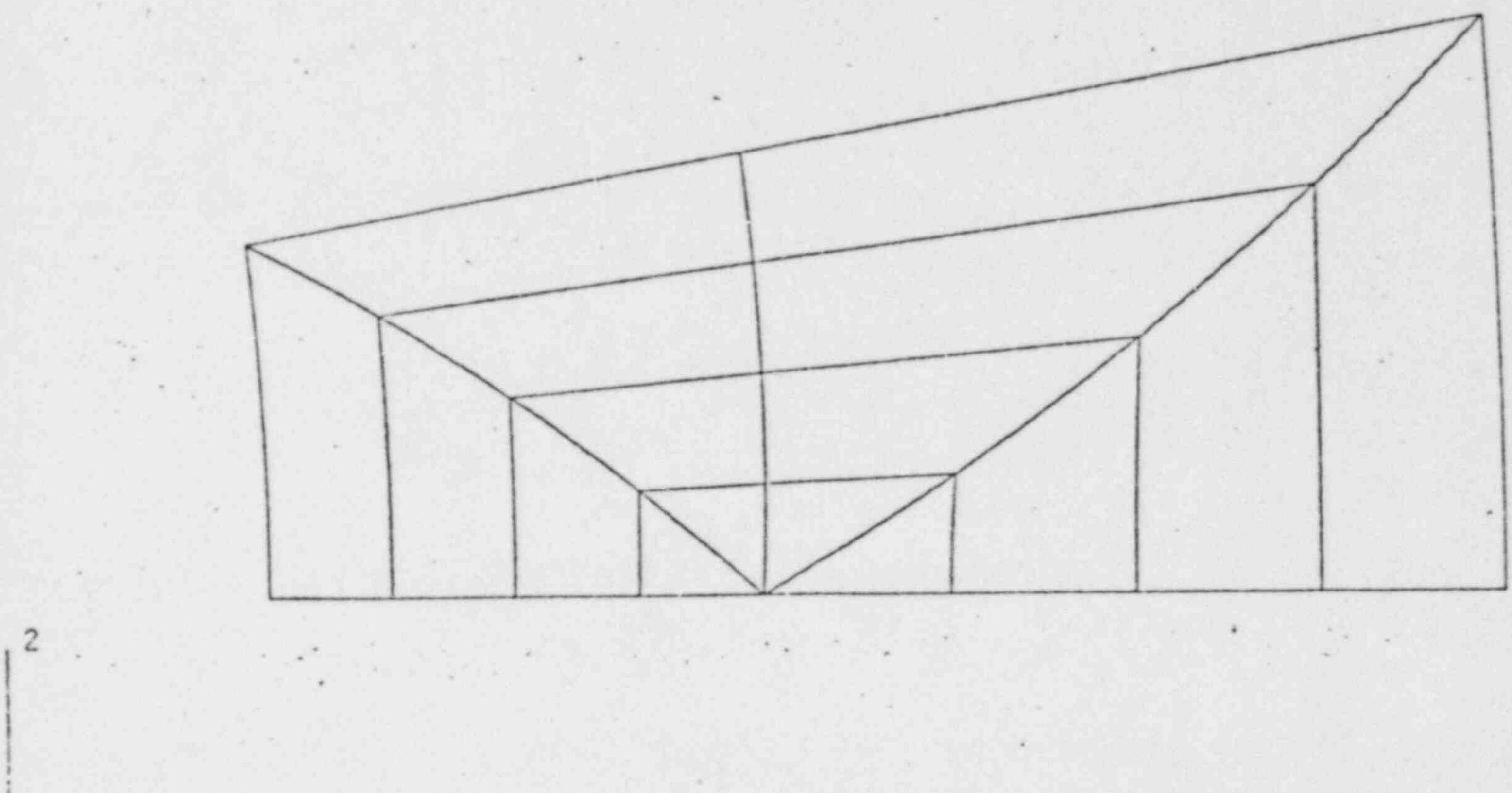

Figure 6. Mesh at crack Tip

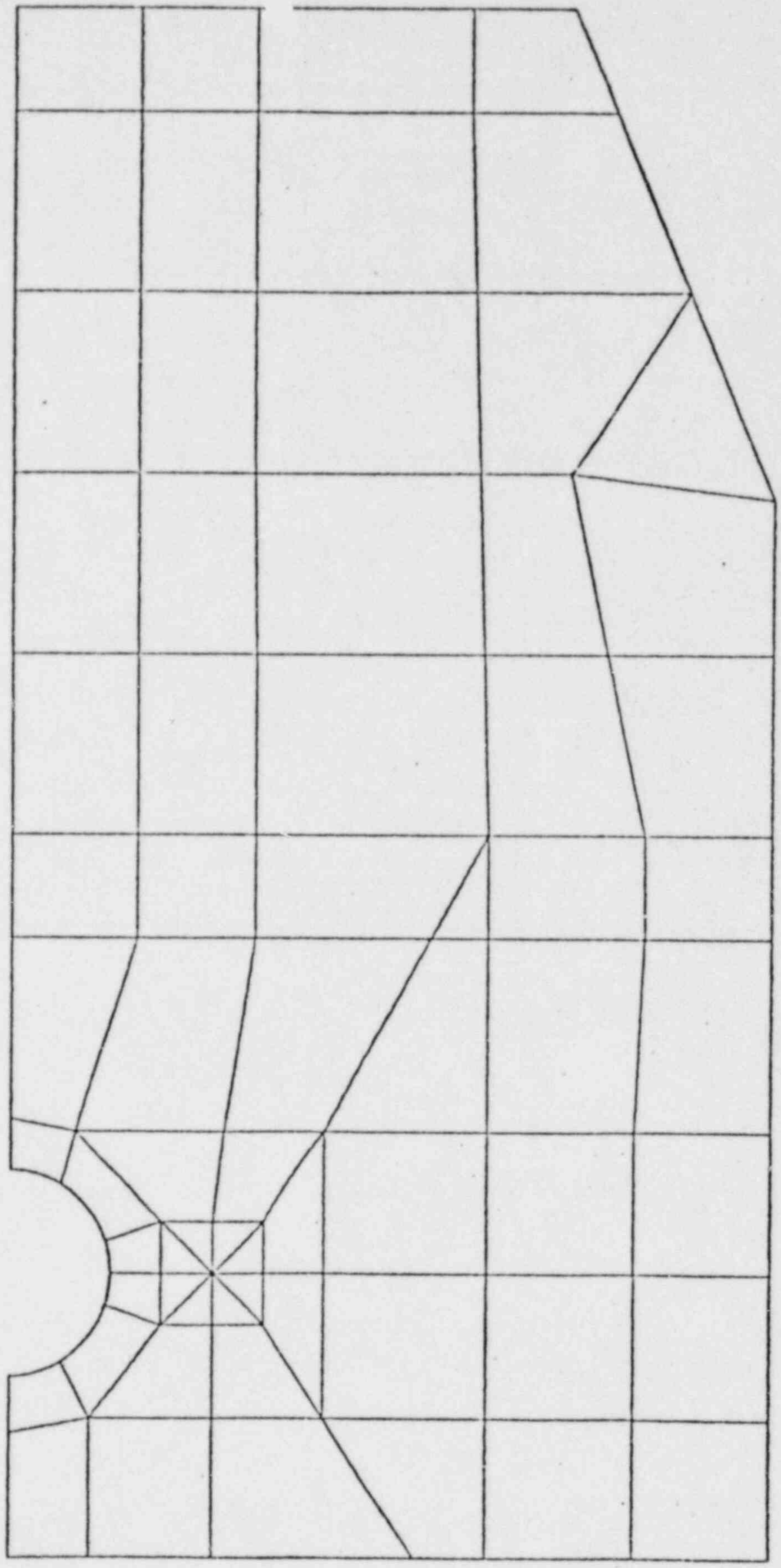

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Figure 7. Top View of 3-D Mesh

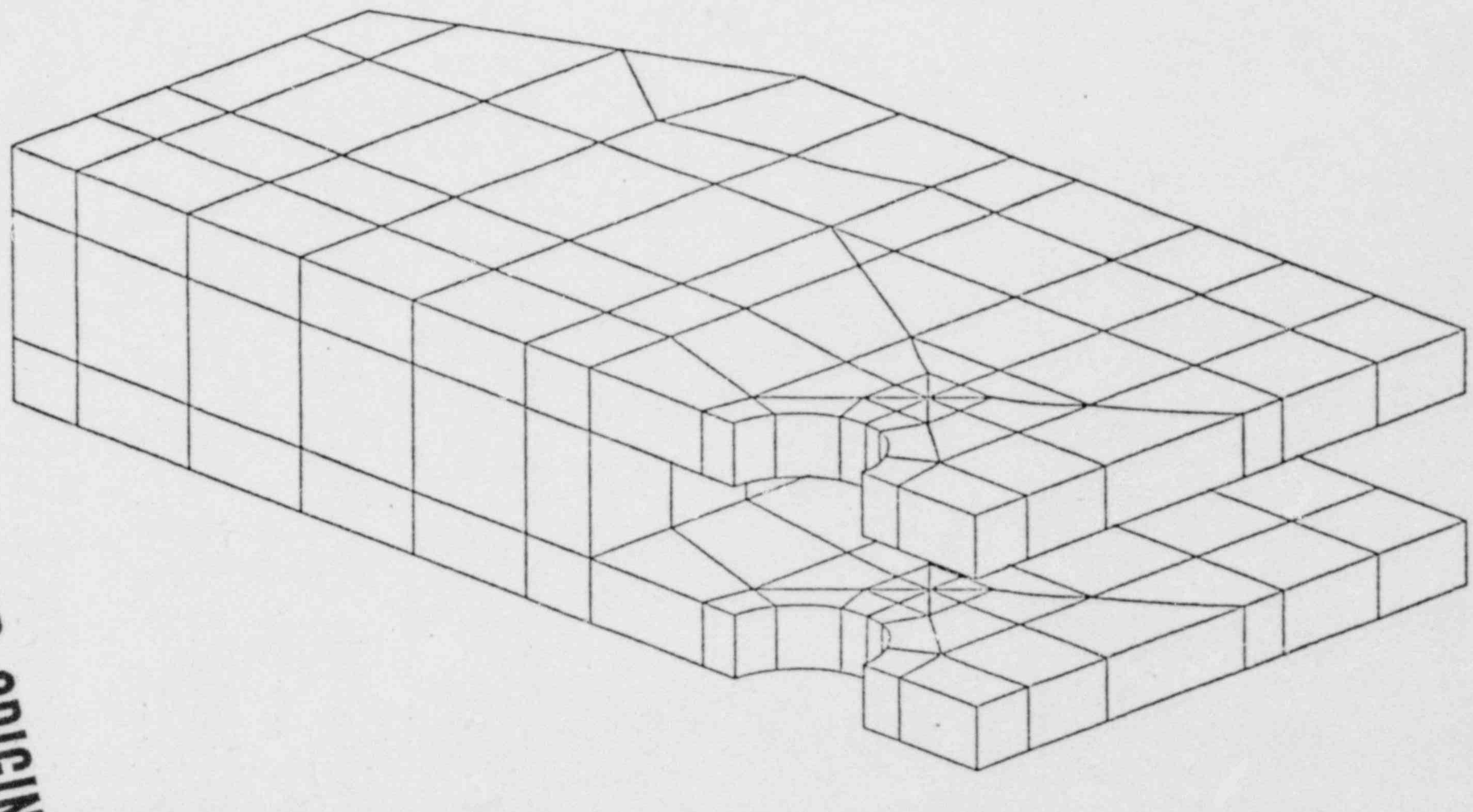

Figure 8. Isometric View of 3-D Finite Element Mesh

Contour Levels (psi)

1 = .250E 4
2 = .125E 5
3 = .225E 5
4 = .325E 5
5 = .425E 5
5 = .525E 5
7 = .625E 5
8 = .725E 5
9 = .825E 5
10 = .925E 5
11 = .102E 6
12 = .112E 6

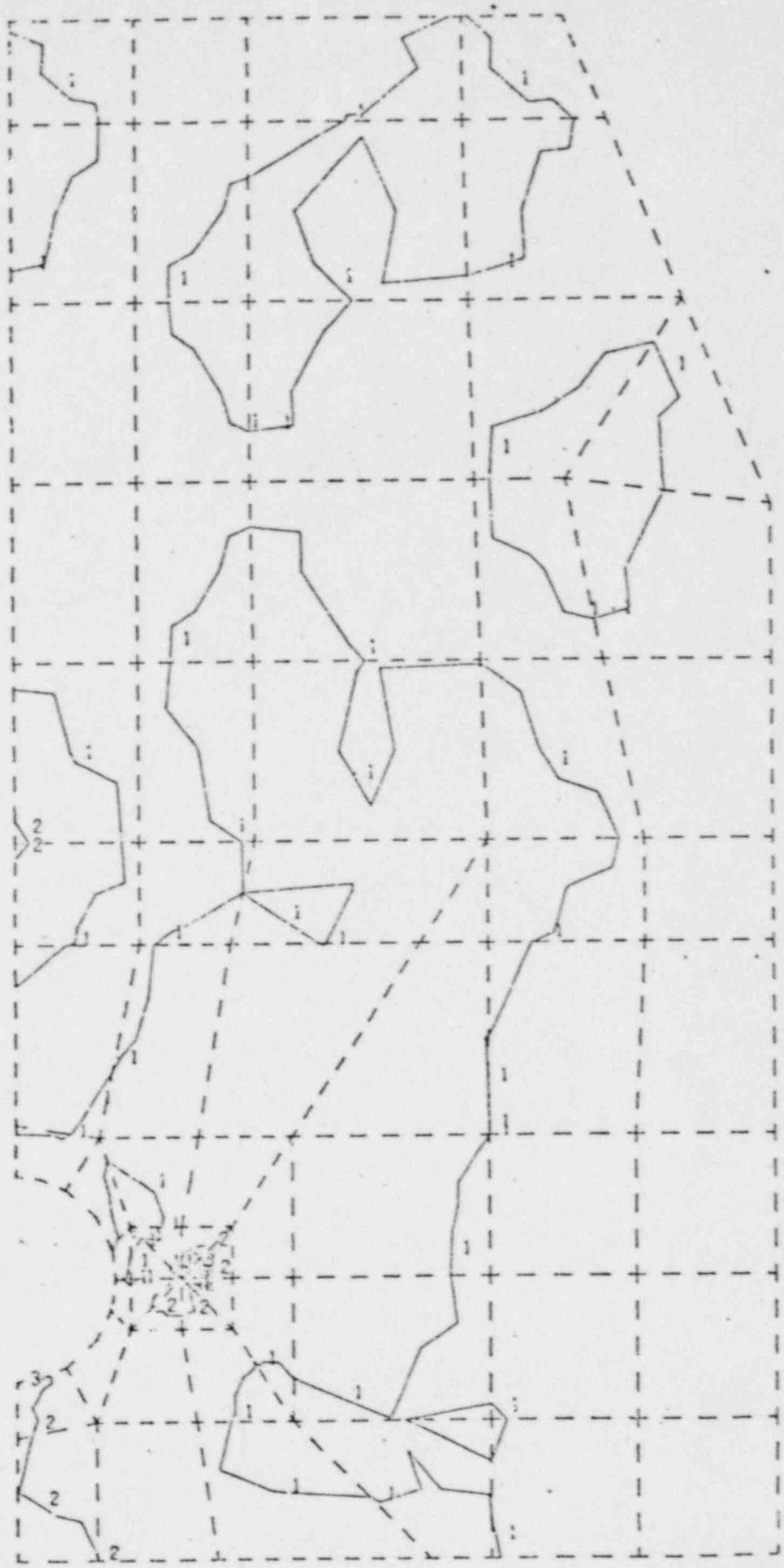

Figure 9. Equivalent Stress Contours at Bottom Section of Lug

Contour Levels (psi)

1 = .250E 4
2 = .125E 5
3 = .225E 5
4 = .325E 5
5 = .425E 5
6 = .525E 5
7 = .625E 5
8 = .725E 5
9 = .825E 5
10= .925E 5
11= .102E 6
12= .112E 6

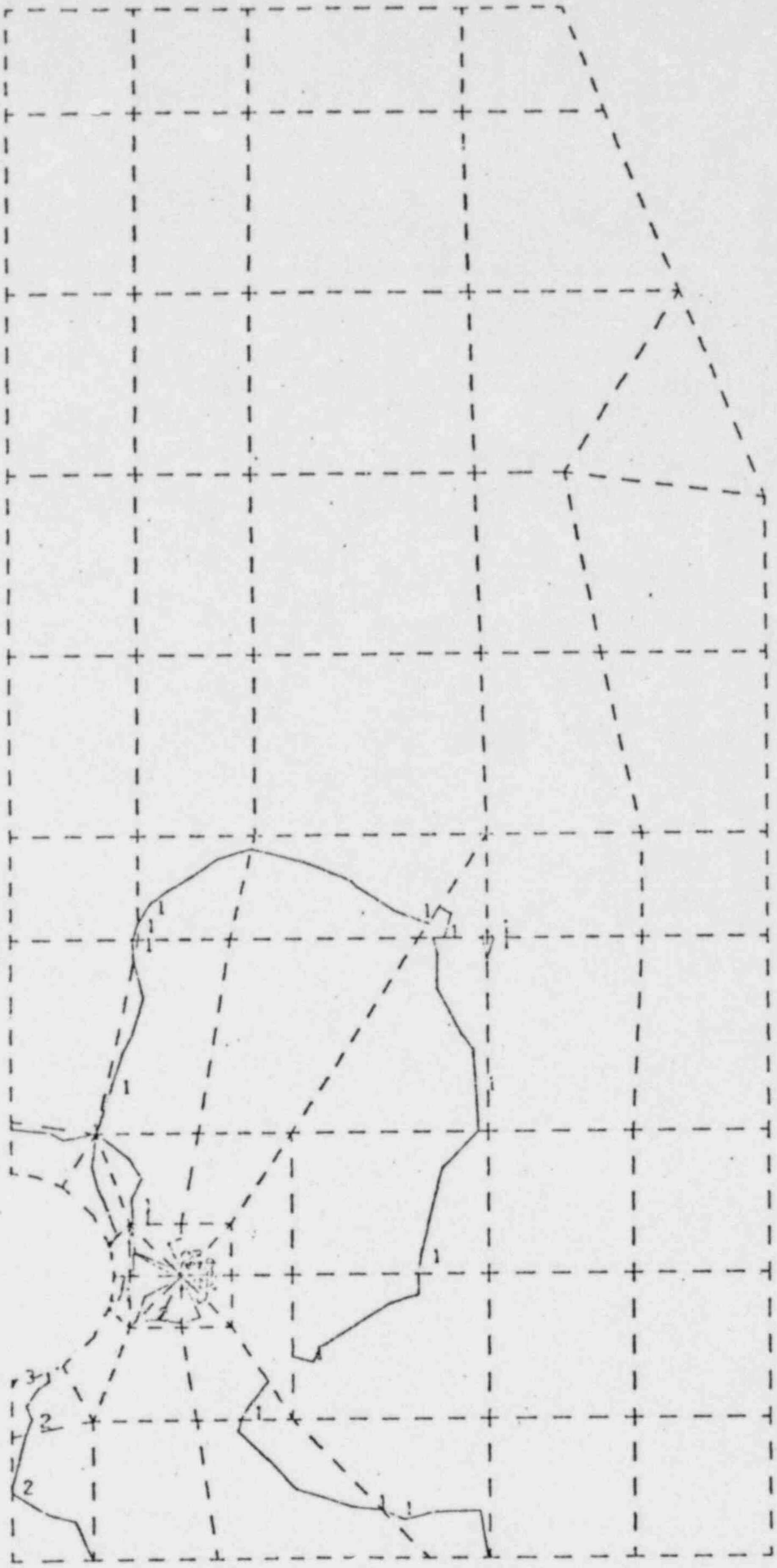

Figure 10. Equivalent Stress Contours at Top Section of Lug

Contour Levels (psi)

1 = .250E 4
2 = .125E 5
3 = .225E 5
4 = .325E 5
5 = .425E 5
6 = .525E 5
7 = .625E 5
8 = .725E 5
9 = .825E 5
10= .925E 5
11= .102E 6
12= .112E 6

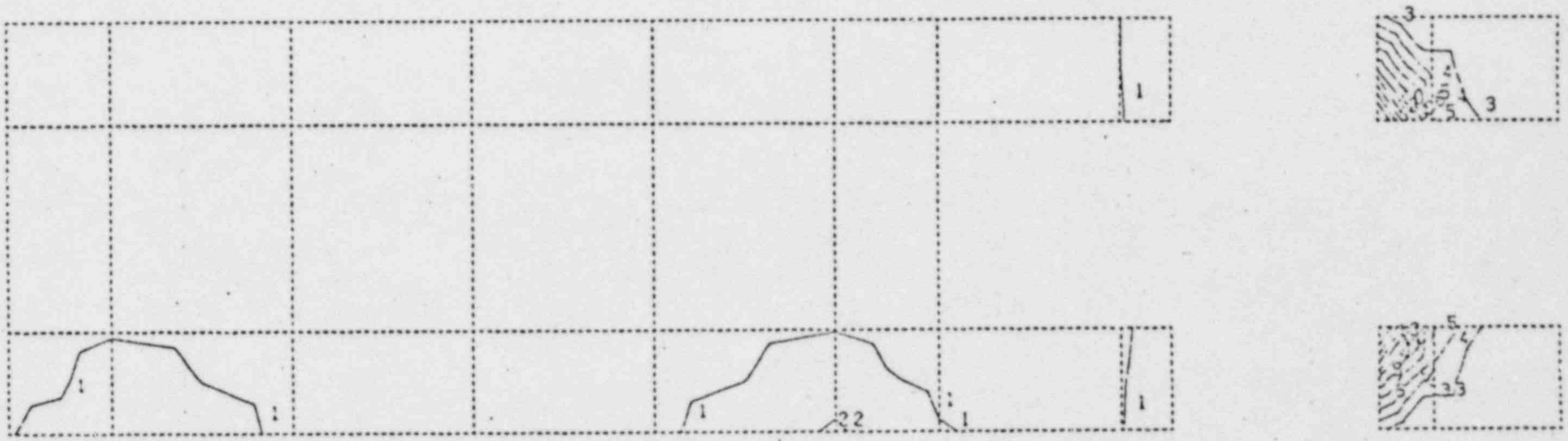

Figure 11. Equivalent Stress Contours at Symmetry Plane

ATTACHMENT 2