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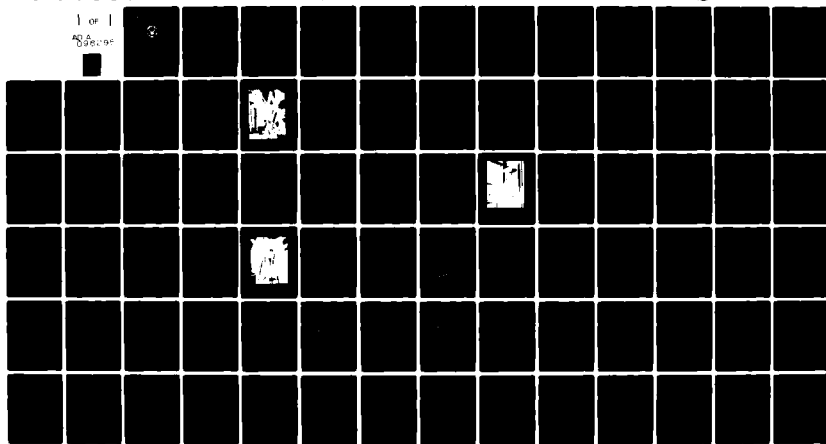
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## THESIS

PHOTOELASTIC STUDY OF ELASTIC AND PLASTIC STRESS FIELDS IN THE VICINITY OF A NOTCH.

by

10 Frank E. Stenstrom

11 Dec 1980

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Thesis Advisor: G. H. Lindsey

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STRESS FIELDS IN THE VICINITY OF A NOTCH

by

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Submitted in partial fulfillment of the  
requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

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## ABSTRACT

The ability to calculate stresses in critical areas by measuring strains at far-field locations will be essential to the success of new fatigue monitoring equipment currently being developed. In this thesis the photoelastic method was utilized to study plastic zone characteristics and residual compressive stresses in critical areas modeled by notched specimens. Data reduction methods for photoelastic measurements were developed by a thorough investigation of reinforcement effects and by a careful determination of material properties of PS-1C Photoelastic Material and 7075-T6 aluminum. A modified Ramberg-Osgood data reduction method was developed for determining stresses from strains measured in the plastic region. Stresses obtained from slip-line theory for rigid-perfectly-plastic material were compared to the experimental results, and differences noted. Notch tip stresses and strains were compared to predictions using Neuber's relation. The measured data indicated stress concentrations 20.9% lower than predicted by Neuber.

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## I. INTRODUCTION

Modern Naval aircraft instruments are capable of recording several types of data in flight among which is the capability to measure nominal strains near fatigue critical areas during maneuvers. Due to gage fatigue limitations it is not possible to mount strain gages right at the critical areas, and it becomes important, therefore, to understand the relationship between a nominal, far-field strain measurement and the local strain at the critical subject area. Previous methods have utilized Neuber's relationship [Ref. 1], which could have significant error at low strain levels as shown by Garske in Ref. 2. Furthermore, several investigators have shown that if a sufficient stress concentration is introduced to produce a plastic zone around a notch, the unloading of the material will produce a residual compressive stress around the notch tip and increase the fatigue life of the material [Refs. 3, 4, 5].

An experimental investigation was undertaken to statically load flat plate notched specimens, which simulated wing skins or other aircraft structure containing stress concentrations. Photoelastic measurements were made in the vicinity of the notch to study the elastic stress distribution, the plastic yield zone and the residual compressive stresses remaining after unloading. Initial phases of the work included a

complete characterization of the photoelastic material, a detailed analysis of unbound effects, evaluation of the Poisson's ratio mismatch, and the effects of reinforcement of the specimen by the bonded photoelastic material. A modified Ramberg-Osgood method was used to reduce biaxial strains to stresses in the plastic regions. Stresses in the plastic zone were compared to classical plane stress slip-line theory and Neuber's relation was evaluated using the plastic zone stress and strain concentration factors.

## II. CHARACTERIZATION OF PS-1C PHOTOELASTIC MATERIAL

Two uniaxial tensile test specimens were prepared from a single sheet of PS-1C Photoelastic Material. The first specimen was 1.0 inch wide and was used for thickness measurement, longitudinal strain data, and was eventually bonded to an aluminum test specimen. The second 2.0 inch wide specimen was used for transverse strain data and for measuring photoelastic coating fringe value,  $F_{\sigma}$ .

### A. THICKNESS DETERMINATION

One longitudinal edge of the 1.0 inch wide specimen was lightly sanded to create a smooth, uniform cross-section of the photoelastic material. The specimen was then mounted such that a traveling microscope could be used to measure thickness. With the capability of measuring thickness and the contrast in appearance between the reflective coating and the base material, it was possible to accurately determine the thickness of both. For the specimen viewed, the base thickness was measured to be 0.0382 inches and the reflective coating to be 0.0051 inches. These numbers were obtained by measuring eight separate points along the edge and averaging the results. The total thickness of 0.0433 inches fell within the range of the advertised  $0.044 \pm 0.002$  inches. It was, therefore, concluded that the labeled

thickness included both the base and the reflective coating after two similar specimens of different marked thicknesses were checked. For calculation purposes, the thickness of the original specimen was taken to be 0.0382 inches since the path of polarized light does not penetrate the reflective coating of the photoelastic material, and it was assumed that the reflective coating does not contribute to the strength of nor does it reinforce the base material.

#### B. YOUNG'S MODULUS

Two lines were lightly etched on the surface of the 1.0 inch wide specimen in the horizontal direction in order to accommodate a Tuckerman Optical Strain Gage. The specimen was then loaded in tension. The readings taken with an auto-collimater were recorded in Table I (all tables are in Appendix A). Using American Instrument Company calibration factors, the strain was calculated with the following formula taken from Ref. 6.

$$S = \frac{F A L R}{1000e}$$

where S = Strain in micro inches per inch

F = Lozenge calibration factor, 1.002

A = Auto-collimater calibration factor, 1.004

L = Lozenge length, 2.0 inches

R = Net reading

e = Gage length, 1.0 inch

With the measured strain, the measured load at each point and the known cross-sectional area, Young's Modulus, E, was determined from the slope of the stress-strain curve shown in Figure 1, using a linear regression analysis.

$$\sigma = 357079.18\varepsilon_1 - 4.3407$$

$$R = .9988$$

where R = correlation coefficient.

Dropping the non-zero intercept, Young's modulus was taken to be 357,079.18 psi. Photolastic Inc. information shows this number to be nominally 360,000 psi. Using thin specimens, such as the photoelastic material, requires very accurate thickness measurements because E is directly proportional to thickness.

#### C. POISSON'S RATIO

Using the 2.0 inch wide PS-1C specimen, two lines were lightly etched into the surface in the longitudinal direction one inch apart. With the Tuckerman Optical Strain Gage mounted in the transverse direction as shown in Figure 2, the specimen was loaded in tension. The data points from Table I were used in a linear regression analysis with the following results:

$$\sigma = -941487.02\varepsilon_2 - 1.00708$$

$$R = .99991$$

Poisson's ratio was then determined by dropping the non-zero intercept and dividing the negative of the slope by E as

indicated in Figure 1. The measured Poisson's ratio is 0.37927 which compares with a nominal value of 0.38 supplied by Photolastic Inc.

D. COATING FRINGE VALUE IN TERMS OF STRESS,  $F_{\sigma}$

Prior to etching lines on the 2.0 inch wide specimen, it was loaded in tension in the elastic region, and the fringe number, N, was determined using a reflection polariscope. With several load points and known dimensions, the stress was calculated and plotted against the fringe number. Using the data from Table II, a linear regression analysis yielded

$$\sigma = 456.6661N + 1.92740$$

$$R = .99932$$

Dropping the non-zero intercept,  $F_{\sigma}$  was taken to be 456.67 psi/fringe.

PS-1C CHARACTERIZATION  
STRESS-STRAIN CURVE

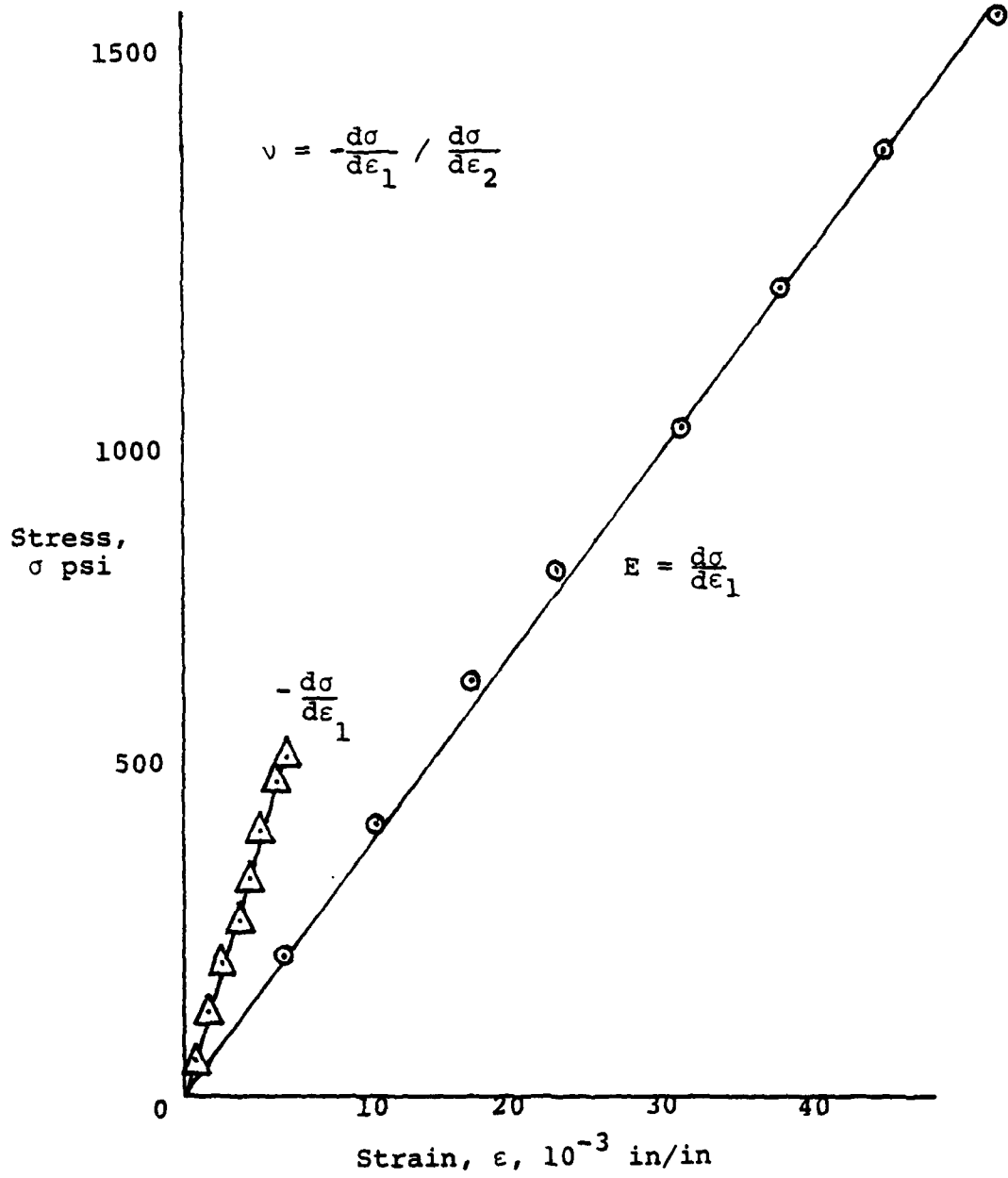


Figure 1

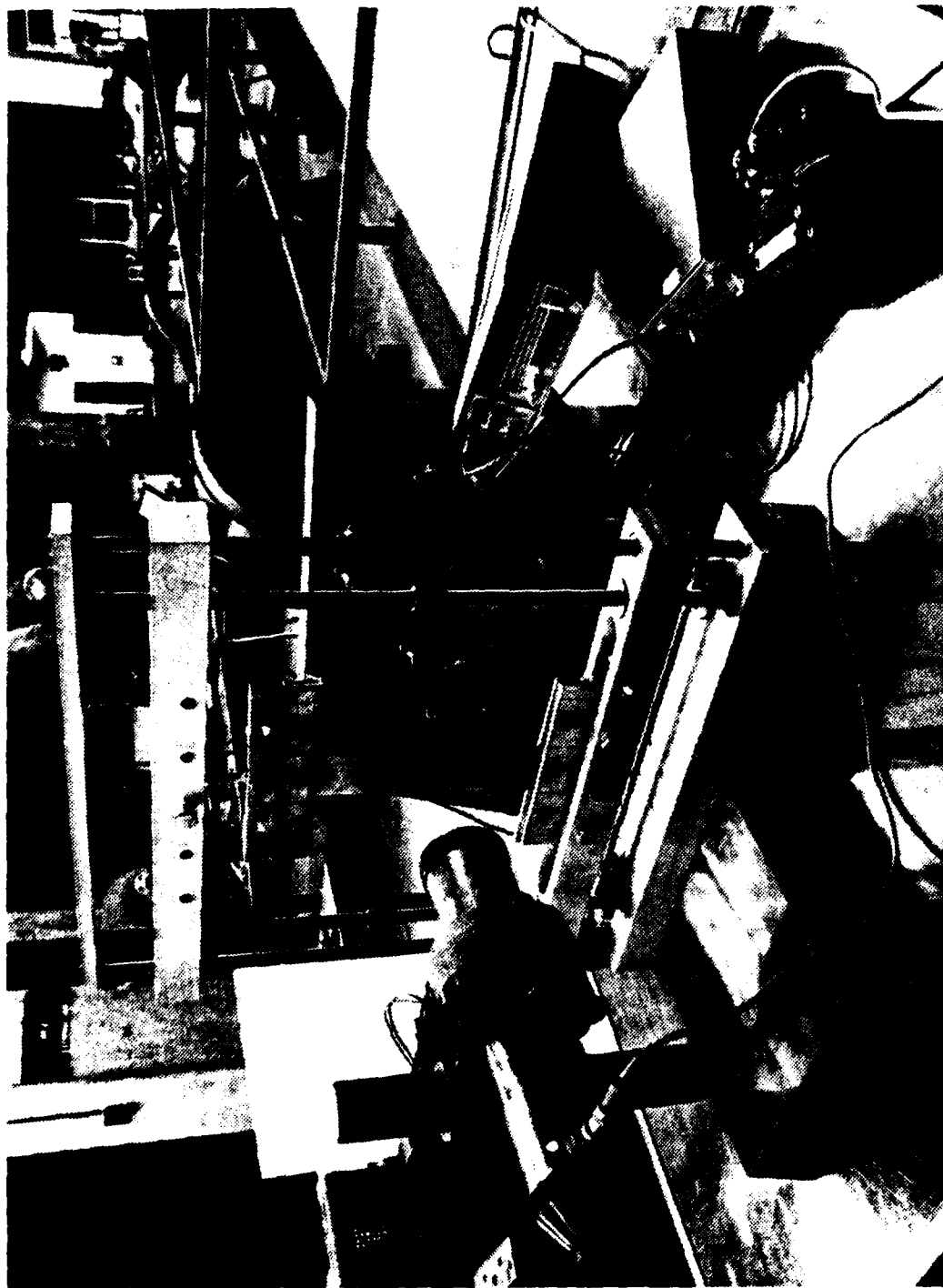


Figure 2. TUCKERMAN OPTICAL STRAIN GAGE SET-UP

### III. CHARACTERIZATION OF 7075-T6 ALUMINUM

This characterization was performed on a uniaxial tensile test specimen of 7075-T6 aluminum to establish material properties for use in analytically deriving correction factors for a bonded specimen. Although nominal material properties were readily available from several sources, the ultimate desire was for superior accuracy of measured data.

#### A. YOUNG'S MODULUS

A rosette type strain gage was bonded to the aluminum specimen shown in Figure 3. The specimen was then mounted in a RIEHLE Test Machine with only transverse and longitudinal leads connected to a Switching and Balancing Unit. Readings were taken on an SR-4 Strain Indicator at the points shown in Table III. Width and thickness measurements were made with a micrometer. With the dimensions of the cross-section and with measured loads, stresses were calculated and plotted against strain. The slope of the resulting linear relation was determined by linear regression.

$$\sigma = 10.41518 \times 10^6 \epsilon_1 + 242.076$$

$$R = .99992$$

Dropping the non-zero intercept, Young's Modulus was taken to be  $10.42 \times 10^6$  psi for the unbonded aluminum specimen.

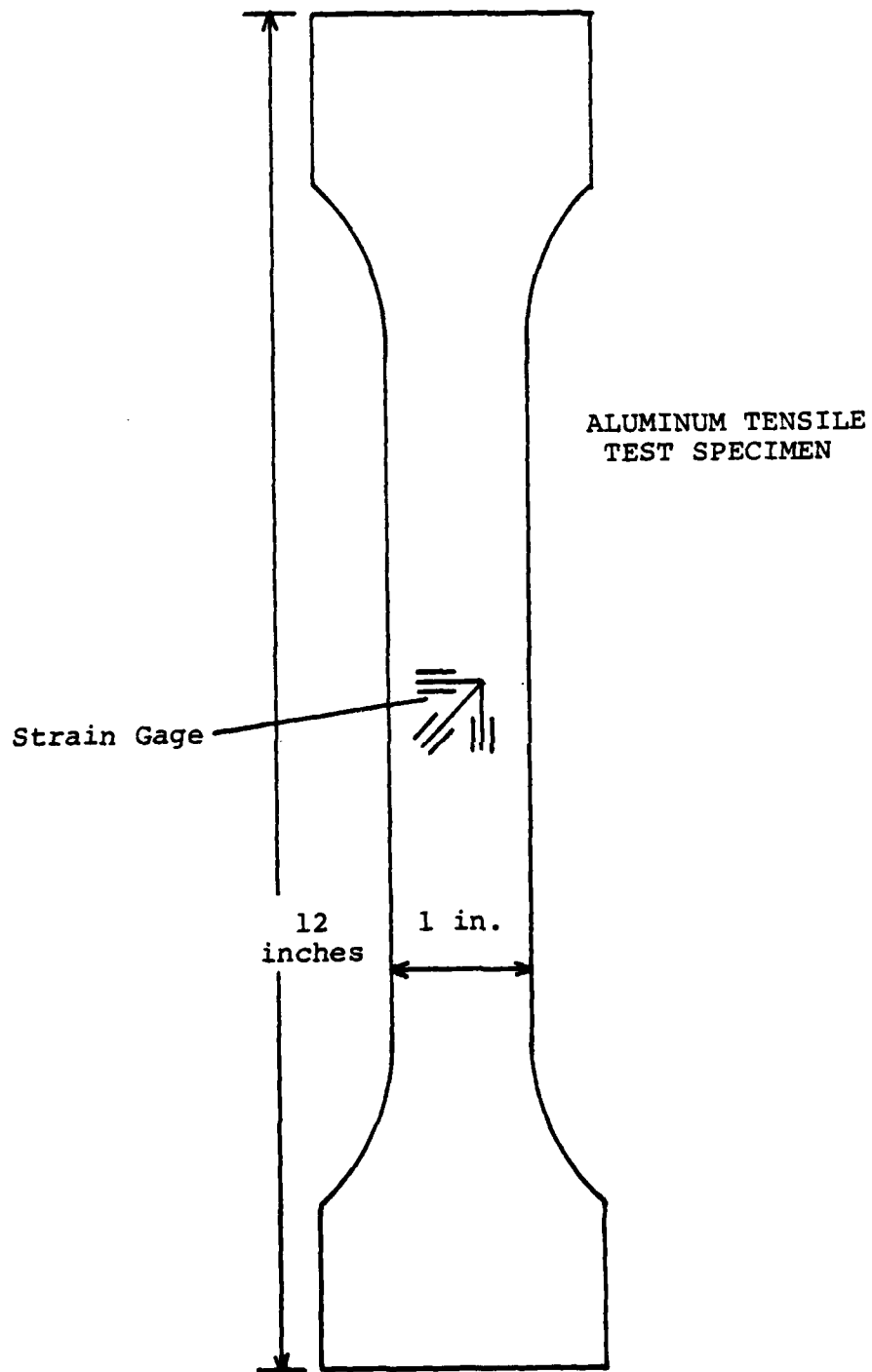


Figure 3

## B. POISSON'S RATIO

Using the transverse strain data from Table III and Young's Modulus determined above, Poisson's ratio was found by dividing E by the negative of the transverse slope, the same as in the PS-1C analysis. By linear regression

$$\sigma = 32.19308 \times 10^6 \epsilon_2 + 172.365$$

$$R = .999927$$

Dropping the non-zero intercept and proceeding as described above results in a Poisson's ratio of 0.32352.

#### IV. REINFORCEMENT EFFECT OF BONDED PHOTOELASTIC MATERIAL

Photoelastic material bonded to a specimen becomes, in effect, an extension of the specimen itself and consequently modifies certain material properties of the specimen. Error exists in the use of photoelastic data without accounting for these changes. This section will explore the effect on Young's Modulus and Poisson's ratio from the free boundary of a specimen to the fully reinforced interior regions. A correction factor for interior points will be obtained.

##### A. YOUNG'S MODULUS MODEL

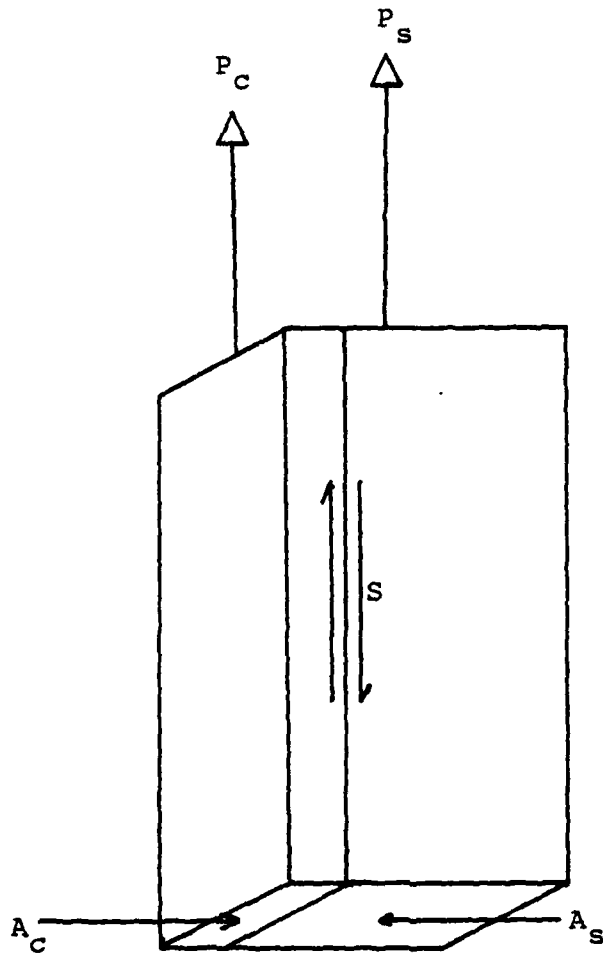
A model uniaxial bar with cross-sectional area,  $A^*$ , stress,  $\sigma^*$ , Young's Modulus,  $E^*$ , and strain,  $\epsilon^*$ , is introduced. This model is the combination described in Figure 4 where

$$A^* = A_c + A_s \quad (1)$$

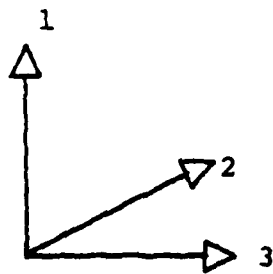
and

$$P = P_c + P_s \quad (2)$$

- $A^*$  = total cross-sectional area
- $A_c$  = coating cross-sectional area
- $A_s$  = specimen cross-sectional area
- $P$  = total load
- $P_c$  = load in the coating
- $P_s$  = load in the specimen



Sign Convention



MODEL UNIAXIAL BAR

Figure 4

To develop a model Young's Modulus which reflects the properties of a reinforced specimen, the basic equation

$$\sigma^* = \frac{P}{A^*} \quad (3)$$

is introduced. If the strain in the specimen equals that in the coating, it follows that the model strain,  $\epsilon^*$ , will also equal the other two. With the relation

$$\sigma^* = E^* \epsilon^*, \quad (4)$$

it follows from (2) that

$$\sigma^* A^* = \sigma_C A_C + \sigma_S A_S. \quad (5)$$

Since the strains are equal in the model, the coating, and the specimen

$$\sigma_C = E_C \epsilon_C = E_C \epsilon^* \quad (6)$$

and

$$\sigma_S = E_S \epsilon_S = E_S \epsilon^* \quad (7)$$

If equations (6) and (7) are substituted back into (5) and  $\epsilon^*$  cancelled, it follows that

$$E^* = \frac{E_C A_C + E_S A_S}{A^*} \quad (8)$$

At this point all the quantities on the right side of equation (8) are known.  $E^*$  is calculated to be  $9.083 \times 10^6$  psi using previously measured values.

## B. MODEL POISSON'S RATIO

To obtain a model quantity which reflects the Poisson effect of the combination of the specimen and bonded material, the basic definition of Poisson's ratio,  $\nu$ , is recalled where

$$\epsilon_2^* = \nu^* \epsilon_1^*, \quad \epsilon_{2c} = -\nu_c \epsilon_{1c}, \quad \epsilon_{2s} = -\nu_s \epsilon_{1s} \quad (9)$$

and the relationship

$$\epsilon_1^* = \frac{\sigma^*}{E^*}, \quad \epsilon_{1c} = \frac{\sigma_c}{E_c}, \quad \epsilon_{1s} = \frac{\sigma_s}{E_s} \quad (10)$$

where the 1 and 2 directions are those indicated in Figure 4.

It follows that

$$\epsilon_{2s} = -\nu_s \epsilon_{1s} = -\frac{\nu_s \sigma_{1s}}{E_s} \quad (11)$$

and

$$\epsilon_{2c} = -\nu_c \epsilon_{1c} = -\frac{\nu_c \sigma_{1c}}{E_c} \quad (12)$$

By solving for stress in equations (11) and (12) and substituting into (5),

$$\frac{-E^* \epsilon_2^* A^*}{\nu^*} = -\frac{E_s \epsilon_{2s} A_s}{\nu_s} - \frac{E_c \epsilon_{2c} A_c}{\nu_c} \quad (13)$$

Recalling that

$$\epsilon_{2s} = \epsilon_{2c} = \epsilon_2^*$$

and solving for  $\nu^*$ ,

$$\nu^* = \frac{E^* A^*}{\frac{E_s A_s}{\nu_s} + \frac{E_c A_c}{\nu_c}} \quad (14)$$

Now all of the quantities on the right side of Equation (14) are known, and  $v^*$  for this analysis using measured values becomes 0.3240.

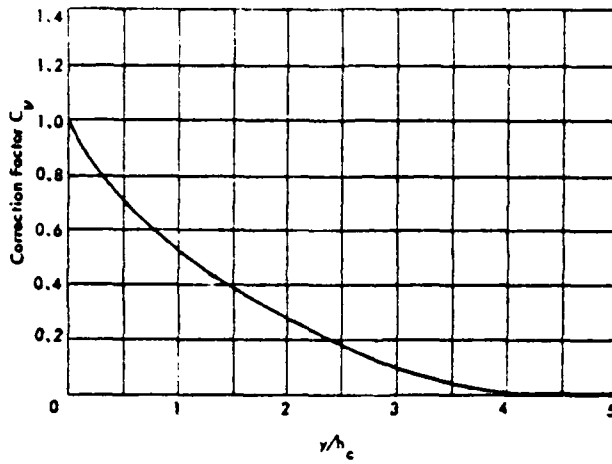
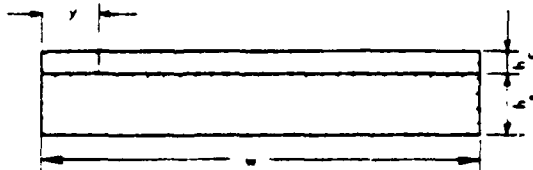
#### C. REINFORCEMENT EFFECT FOR INTERIOR REGIONS

One of the intermediate steps in determining the actual specimen strain at the interior points away from the free boundary is to develop a correction factor for the full reinforcement of the specimen. By referring to Figure 4, it follows that  $P_c$  does not equal zero but is actually equal to the shear in the interface between the coating and the specimen, which is the mechanism by which the load is transferred to the coating. As shown in Figure 5, Zandman et al [Ref. 7] have determined that the full reinforcement takes place approximately four coating thicknesses in from a free boundary. For this analysis, full reinforcement was assumed at the first measured interior point. The first interior point was at 0.125 inches in from the boundary. Using the measured coating thickness divided into 0.125 equals 3.27. This point on Figure 5 yields less than a 5% correction factor.

Zandman, et al [Ref. 7] made the following development for reinforcement effects. Recalling that

$$P = P_s + P_c$$

where



CORRECTION FACTOR C AS A FUNCTION OF POSITION  $y/h_c$  ACROSS THE TRANSITION ZONE [Ref. 7]

Figure 5

$$\begin{aligned}
 P &= \sigma_{1u} A_s \\
 P_s &= \sigma_{1s} A_s \\
 P_c &= \sigma_{1c} A_c
 \end{aligned}
 \tag{15}$$

where  $\sigma_{1u}$  = Stress in the uncoated specimen.

It follows from Equation (2) that

$$\sigma_{1u} A_s = \sigma_{1s} A_s + \sigma_{1c} A_c .
 \tag{16}$$

From Figure 5,

$$\begin{aligned}
 A_s &= h_s dy \\
 A_c &= h_c dy
 \end{aligned}
 \tag{17}$$

and therefore by substitution into (16)

$$h_s dy \sigma_{1u} = h_s dy \sigma_{1s} + h_c dy \sigma_{1c}
 \tag{18}$$

Rearranging terms,

$$\sigma_{1u} = \sigma_{1s} + \frac{h_c}{h_s} \sigma_{1c}
 \tag{19}$$

and by a similar development,

$$\sigma_{2u} = \sigma_{2s} + \frac{h_c}{h_s} \sigma_{2c} .
 \tag{20}$$

Recalling that

$$\epsilon_{1c} = \epsilon_{1s}, \quad \epsilon_{2c} = \epsilon_{2s}$$

and using the plane stress equations

$$\sigma_1 = \frac{E}{1-\nu^2} (\epsilon_1 + \nu \epsilon_2)
 \tag{21}$$

and

$$\sigma_2 = \frac{E}{1-\nu^2} (\epsilon_2 + \nu\epsilon_1), \quad (22)$$

substitution into Equations (19) and (20) and subtracting the results yields

$$\begin{aligned} \frac{E_s}{1-\nu_s^2} (\epsilon_{1u} - \epsilon_{2u}) (1 - \nu_s) = \\ \frac{E_s}{1-\nu_s^2} (\epsilon_{1s} - \epsilon_{2s}) (1 - \nu_s) + \\ \frac{h_c}{h_s} \frac{E_c}{1-\nu_c^2} (\epsilon_{1c} - \epsilon_{2c}) (1 - \nu_c) . \end{aligned} \quad (23)$$

Rearranging terms and letting

$$\epsilon_{1s} - \epsilon_{2s} = \epsilon_{1c} - \epsilon_{2c}$$

it follows that

$$\epsilon_{1u} - \epsilon_{2u} = \left[ 1 + \frac{E_c}{E_s} \frac{h_c}{h_s} \frac{(1 + \nu_s)}{(1 + \nu_c)} \right] (\epsilon_{1c} - \epsilon_{2c}) . \quad (24)$$

The quantities in the brackets are all known and Equation (24) becomes

$$\epsilon_{1u} - \epsilon_{2u} = 1.0051 (\epsilon_{1c} - \epsilon_{2c}) . \quad (25)$$

This basically says that the photoelastic results of the interior points must be multiplied by 1.0051 to obtain the true results for an unreinforced specimen.

#### D. POISSON'S RATIO MISMATCH NEAR THE EDGE

Now that the interior reinforced regions have been corrected, it is appropriate to resolve the Poisson's ratio mismatch from the free boundary to approximately four thicknesses in. First by subtracting Equation (20) from (19), the relation

$$\sigma_{1u} - \sigma_{2u} = (\sigma_{1s} - \sigma_{2s}) + \frac{h_c}{h_s} (\sigma_{1c} - \sigma_{2c}) \quad (26)$$

results. By using the plane stress equations, it follows that

$$\begin{aligned} \sigma_{1s} - \sigma_{2s} &= \frac{E_s}{(1 - \nu_s^2)} [(\epsilon_{1s} - \epsilon_{2s}) + \nu_s (\epsilon_{2s} - \epsilon_{1s})] \\ &= \frac{E_s}{(1 + \nu_s)} [\epsilon_{1s} - \epsilon_{2s}] \\ &= \frac{E_s}{(1 + \nu_s)} [\epsilon_{1c} - \epsilon_{2c}] . \end{aligned} \quad (27)$$

As implied above, near the boundary  $\nu_c$  is not homogeneous.

Let  $\nu_c = \bar{\nu}(x)$ . In the coating

$$\sigma_{1c} = \frac{E_c}{(1 - \bar{\nu}^2)} [\epsilon_{1c} - \bar{\nu}\epsilon_{2c}] \quad (28)$$

and

$$\sigma_{2c} = \frac{E_c}{1 - \bar{\nu}^2} [\epsilon_{2c} + \bar{\nu}\epsilon_{1c}] . \quad (29)$$

By subtracting and cancelling as above

$$\sigma_{1c} - \sigma_{2c} = \frac{E_c}{1 + \bar{\nu}} [\epsilon_{1c} - \epsilon_{2c}] . \quad (30)$$

Substituting Equation (30) into (26)

$$\sigma_{1u} - \sigma_{2u} = \left[ \frac{E_s}{1 + \nu_s} + \frac{E_c}{1 + \bar{\nu}} \right] (\epsilon_{1c} - \epsilon_{2c}) . \quad (31)$$

Since

$$\epsilon_{1c} - \epsilon_{2c} = F_\epsilon N$$

and

$$F_\epsilon = \left( \frac{1 + \bar{\nu}}{E_c} \right) F_\sigma ,$$

it follows that

$$\sigma_{1u} - \sigma_{2u} = \left[ \frac{E_s}{E_c} \frac{1 + \bar{\nu}}{1 + \nu_s} + \frac{h_c}{h_s} \right] F_\sigma N . \quad (32)$$

By using the graph from Figure 5 and letting the variable on the curve be  $C(x)$ ,

$$\bar{\nu} = \nu^* + C(x) (\nu_c - \nu^*) . \quad (33)$$

Equation (33) will give the Poisson's ratio,  $\bar{\nu}$ , needed to find the solution to Equation (32) since all other quantities will be known. For  $C(x) = 1$  at the free boundary and for previously determined values of  $\nu^*$  and  $\nu_c$ , it follows that  $\bar{\nu} = \nu_c$ . For the first interior point at 0.125 inches,  $C(x) = 0$  and  $\bar{\nu} = \nu^*$ .

## V. DETERMINATION OF STRAINS USING OBLIQUE INCIDENCE MEASUREMENTS

The use of the oblique incidence adapter on the reflection polariscope provided the additional data necessary to calculate the longitudinal and transverse strains at given points away from the edge of the notch. Two types of data points are possible in this study since the first interior point away from the notch tip was assumed fully reinforced. A set of equations for the edge and a set for the interior regions were developed.

With the previous developments and those in Zandman, et al [Ref. 7], it is now possible to determine the working equations which will reduce fringe values to actual strain in a non-reinforced specimen. Beginning with Equations 2.24 [Ref. 6] and letting  $v_c$  in those equations be  $\bar{v}$ .

$$\epsilon_1 = \frac{f_\epsilon}{2h_c} \frac{1}{(1+\bar{v}) \sin^2 \theta} [N_\theta (1-\bar{v}) \cos \theta - N (\cos^2 \theta - \bar{v})] \quad (32)$$

$$\epsilon_2 = \frac{f_\epsilon}{2h_c} \frac{1}{(1+\bar{v}) \sin^2 \theta} N_\theta (1-\bar{v}) \cos \theta - N (1-\bar{v} \cos^2 \theta)$$

where  $F_\epsilon = \frac{f_\epsilon}{2h_c}$ .

$N_\theta$  = Oblique incidence fringe reading

An equation can be derived which will reduce to the desired form where  $\theta$  is  $31^\circ$  for the oblique incidence adapter used.

Using the results from the previous section for  $\bar{\nu}$  at the edge,  $\bar{\nu} = 0.2793$ , the strains at the edge of the notch are given by

$$\epsilon_1 = f_e [1.4540N_\theta - .9712N] \quad (33)$$

$$\epsilon_2 = f_e [1.4540N_\theta - 1.9712N]$$

For the interior points where  $\bar{\nu} = 0.3240$ ,

$$\epsilon_1 = f_e [1.6497N_\theta - 1.1692N] \quad (34)$$

$$\epsilon_2 = f_e [1.6497N_\theta - 2.1692N] .$$

These two equations now accurately describe the actual strain in the unbonded specimen using PS-1C Photoelastic Material bonded to 7075-T6 aluminum.

## VI. EXPERIMENTAL COMPARISON OF STRESS CONCENTRATION IN A STRIP WEAKENED BY A CIRCULAR HOLE

To test the validity and accuracy of data taken utilizing the photoelastic method, a test case using a circular hole specimen of finite width was selected. R. C. J. Howland [Ref. 8] determined the stress distribution around the circular hole and with the known theoretical solution and the data points measured, it was possible to determine the accuracy of the photoelastic method.

### A. EXPERIMENTAL PROCEDURE

A specimen was designed to accommodate a 2.0 inch diameter hole in the center. To determine a reasonable width and length which would allow a uniaxial field to exist between the center hole and the end grips, a 1/8 scale PS-1C model was tested under various tensile load conditions. It was determined that a minimum of a five-to-one ratio for length-to-width must exist to eliminate interference of fringe patterns. Figure 6 shows the full-scale 7075-T6 aluminum specimen and dimensions.

The aluminum specimen was placed under an 8000 pound load in the MTS machine, and both normal and oblique compensator readings were taken with a Model 032 Photoelastic Compensator at 0.125 inch intervals at the 90° position on each side of the hole. Figure 7 shows the actual set-up

CIRCULAR HOLE SPECIMEN

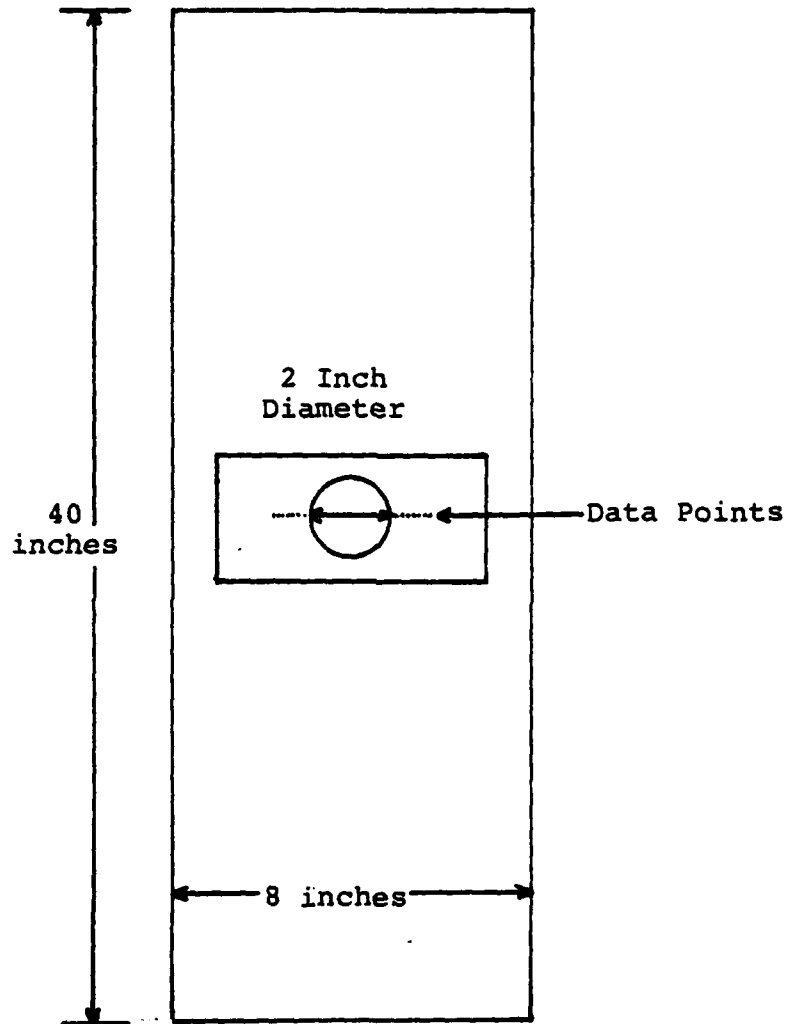
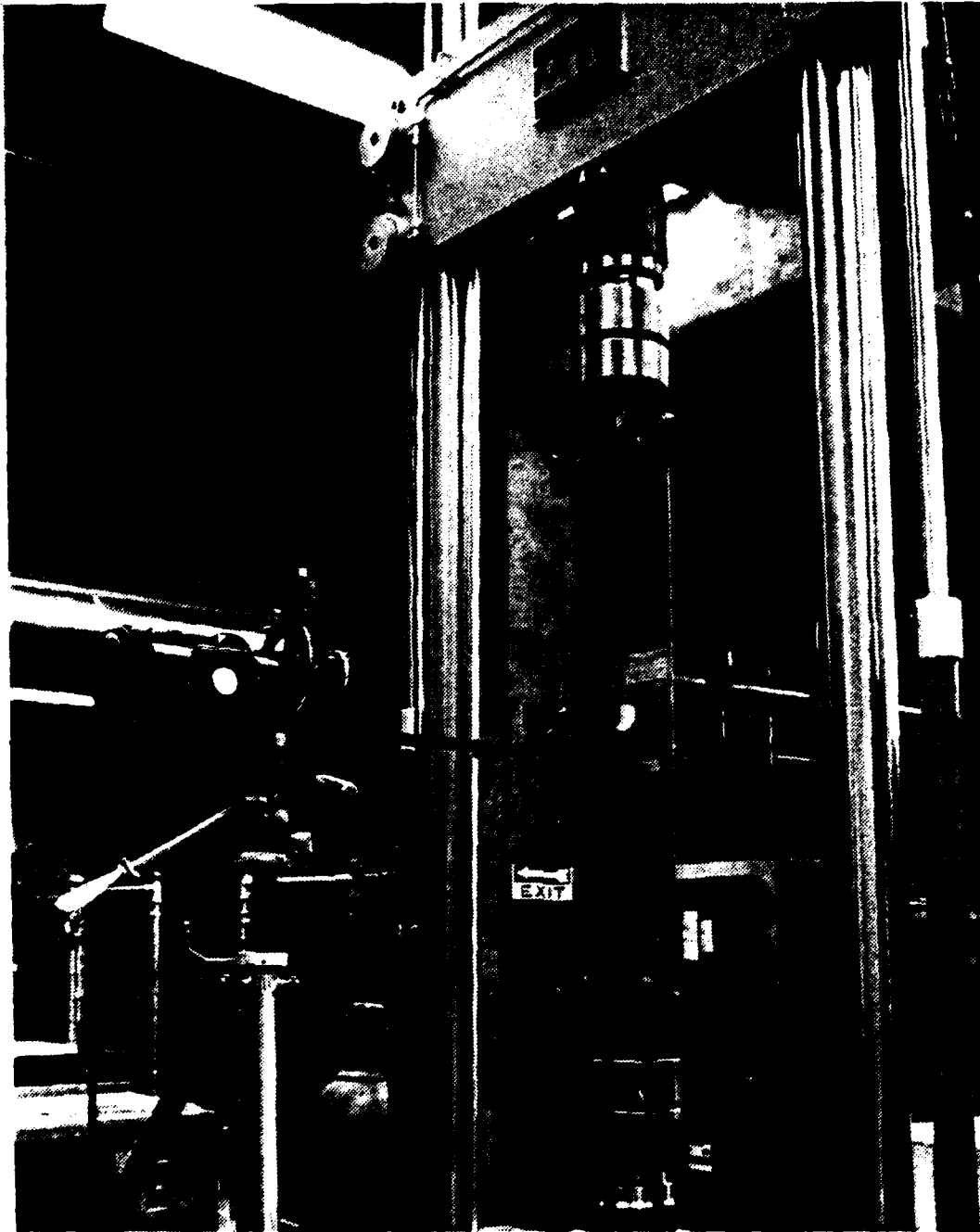


Figure 6



MTS MOUNTED CIRCULAR HOLE SPECIMEN

Figure 7

used. Figure 6 shows the data points, and Table V lists the compensator readings on both the left and right sides of the hole.

#### B. DATA COMPARISON

For the comparison to theory, the hole solution required was for  $\lambda = 0.25$ , where

$$\lambda = \frac{r}{b}$$

and

$r$  = radius of the hole

$b$  = half width of the strip.

Only the solutions for  $\lambda = 0.2$  and  $\lambda = 0.3$  were provided in Ref. 8; therefore, these two curves were plotted as shown in Figure 8, and the data points for  $\lambda = 0.25$  were graphically determined by using the points on a curve midway between  $\lambda = 0.2$  and  $\lambda = 0.3$ . Using the resulting  $K_T$  values and knowing that Howland [Ref. 8] used the far-field cross-sectional area of the specimen to determine  $K_T$ , the comparisons in Table VI were generated. From the comparison, a range of 0.2% to 1.4% difference resulted.

#### C. PHOTOELASTIC METHOD ACCURACY

In the references used for this thesis, the general consensus is that photoelastic methods are accurate to within 5.0%. The accuracy attained in this comparison was much better, even with the graphical interpolation of the  $\lambda = 0.25$

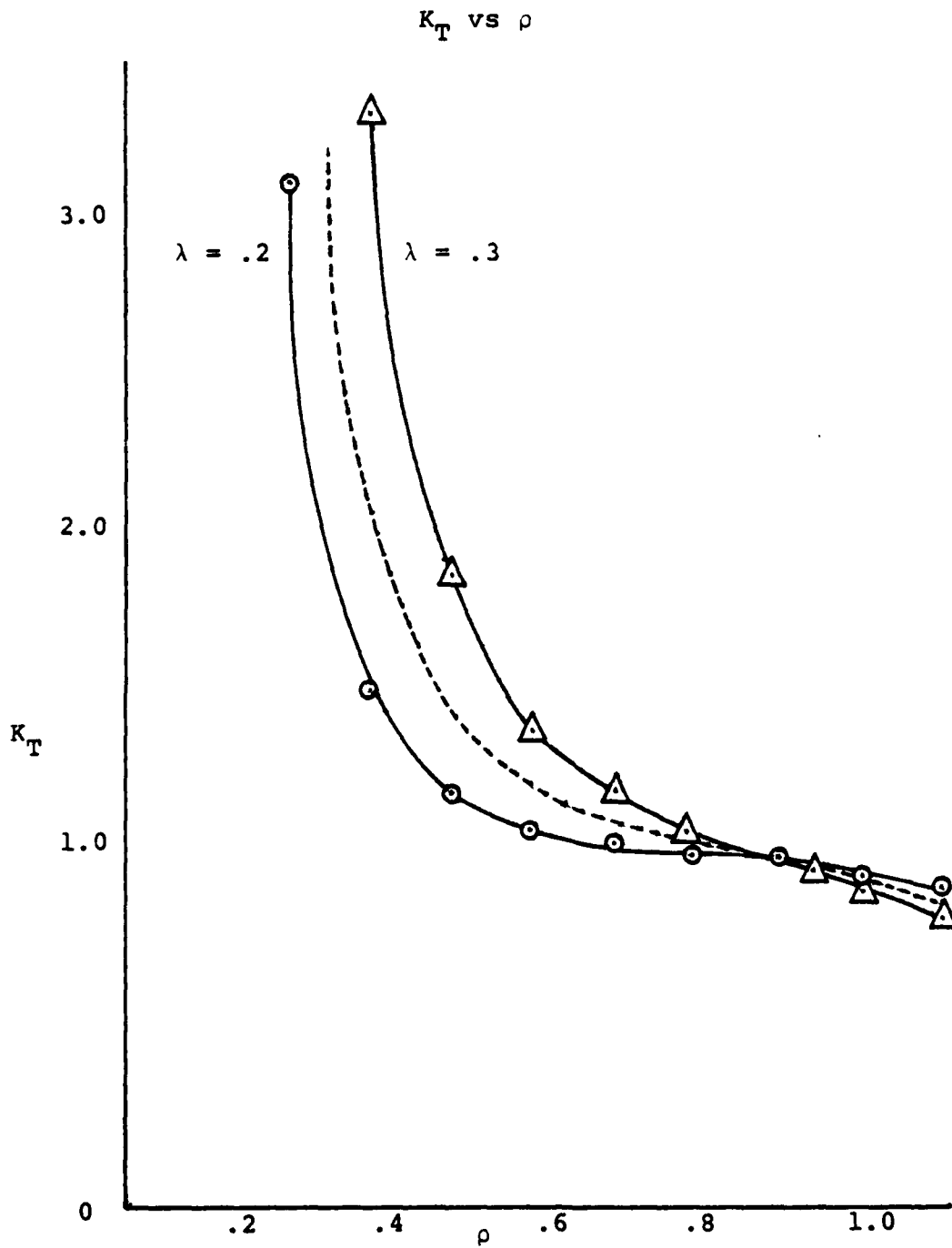


Figure 8

curve. The explanation offered for this close correlation is the use of the telemicroscope in conjunction with a procedure wherein each data point was measured three times, and the value itself was taken as the average of the three readings. Also, the careful measurement of all material properties improved the accuracy several percent over that which could be obtained with published, nominal values.

## VII. UNBOND CHARACTERISTICS OF A NOTCHED SPECIMEN

During specimen preparation, it is possible to inadvertently introduce a weak bond area between a specimen and the photoelastic material, which would cause a change in the fringe number in that weak area. This study was undertaken to determine the amount of bond failure required to show significant change in fringe values.

### A. EXPERIMENTAL PROCEDURE

As indicated in Figure 9, an aluminum specimen with PS-1C Photoelastic Material bonded to it was prepared with intentionally created unbond areas of known size between the PS-1C and the aluminum. The 0.5 inch diameter paper discs with adhesive backing were applied at the points indicated in Figure 9. Enough oil to cover each disc with a thin film was applied prior to bonding material application. Preparation and photoelastic material application were done according to instructions provided by Photoelastic Inc. After proper drying time, the specimen was loaded in 1000 pound increments up to 15,000 pounds in the MTS machine, and compensator readings were taken in the normal direction. This selection of points allowed for both elastic and plastic region investigation. A second specimen was prepared with no known unbonds or weak areas and loaded according to the same schedule as a control specimen.

UNBOND SPECIMEN

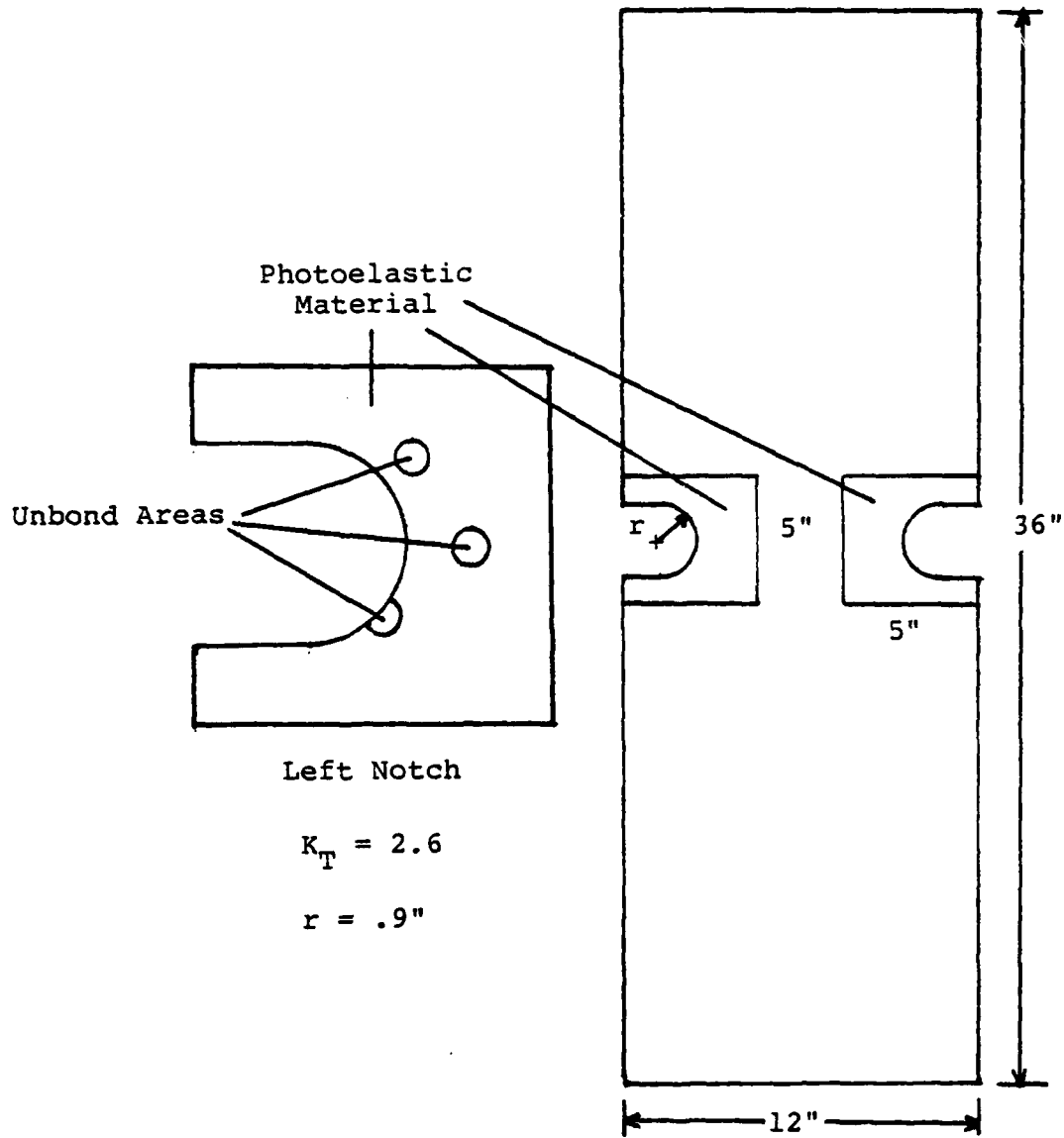


Figure 9

## B. UNBOND TEST RESULTS

Figure 10 clearly shows a problem with the unbond specimen. Close visual examination of photos taken of each specimen at similar loads showed a clearer, more uniform pattern in the control specimen. The unbond specimen showed rough, fuzzy fringes with barely discernable changes in pattern shape at the interior unbond areas. The area at the notch tip displayed the most significant pattern difference. As indicated by Figure 10, above the 5000 pound load, or in a 5320.0 psi stress level in the principle direction, this particular unbond specimen dropped off at the rate of 0.2 fringes for 10,000 pounds of load.

## C. UNBOND CHARACTERISTICS

Weak bonds of the type studied are difficult to detect, but they can be seen if the operator is familiar with the rough pattern characteristics of the weak bond. The problem with the unbond is confined to the immediate vicinity of the weak area and does not appear to effect the surrounding areas. Weak bond areas can be tolerated only if they are located at distances sufficiently far from points of interest so that they do not distort or interfere with local fringe patterns.

FRINGE NUMBER VS LOAD

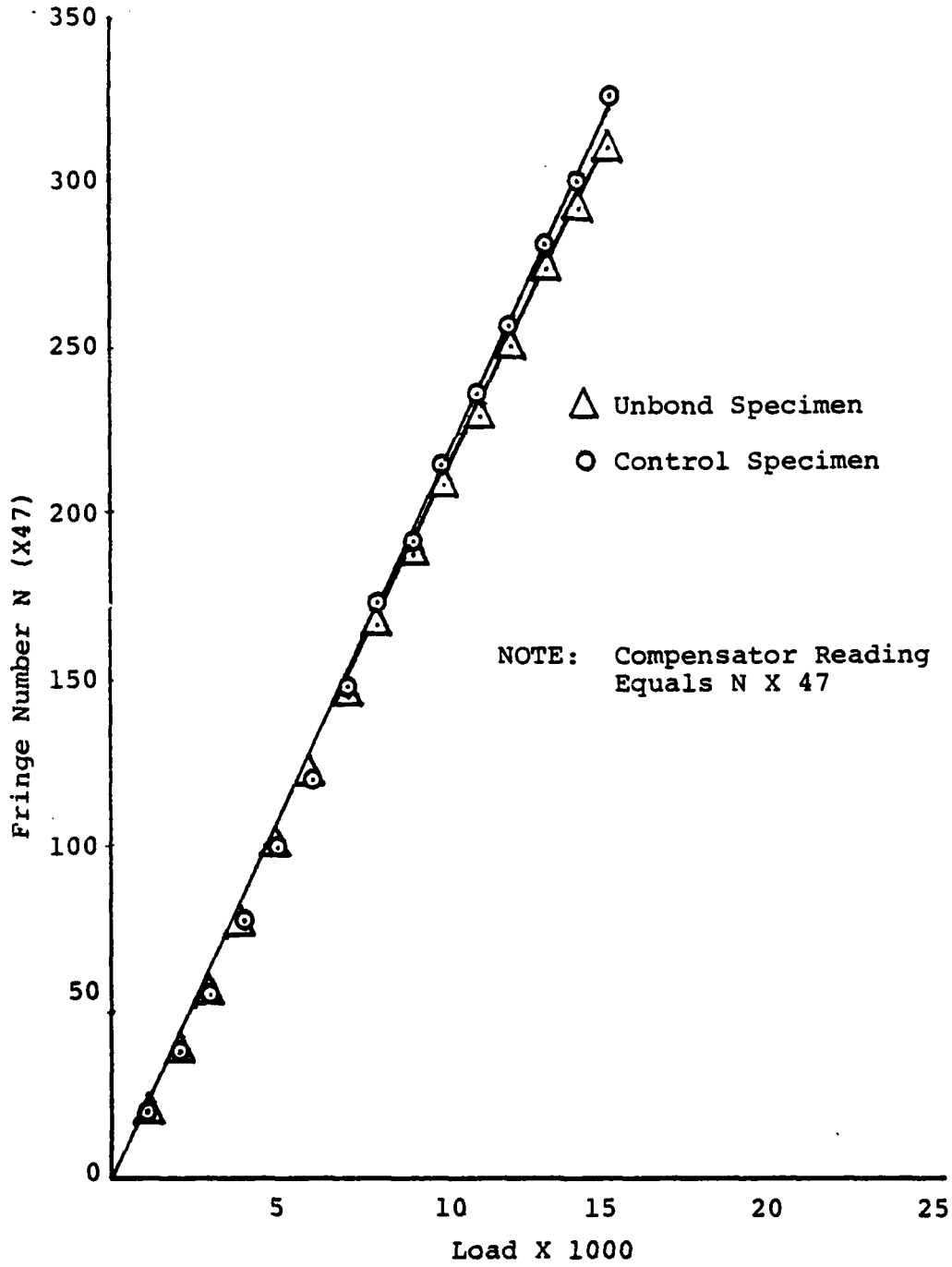


Figure 10

## VIII. LINEARLY ELASTIC ZONE INVESTIGATION OF A NOTCHED SPECIMEN

Several proposals in the area of fracture theory analysis have indicated that in addition to stress concentration factors, information on the stress distribution at a notch is required. This study provides carefully measured longitudinal and transverse stress distributions of that area obtained by the photoelastic method. Oversized specimens were used to increase the accuracy of photoelastic results.

### A. SPECIMEN PREPARATION

The basic dimensions of the specimens used by Stuart [Ref. 9] and Engle [Ref. 10] were doubled in size as shown in Figure 11. The stress concentration factors of 3.8 and 2.6 were retained in order to compare data points. Each specimen was bonded with photoelastic material from the same lot number and nominal thickness as that used in the characterization to retain the accuracy of correction factors and data reduction techniques.

### B. EXPERIMENTAL PROCEDURE

Each specimen was loaded in tension in the linearly elastic zone using the Tinius-Olsen set-up shown in Figure 12. Normal and oblique compensator readings were taken at 0.125 inch intervals from the notch tip for loads of 15,000

LARGE SPECIMEN GEOMETRIES

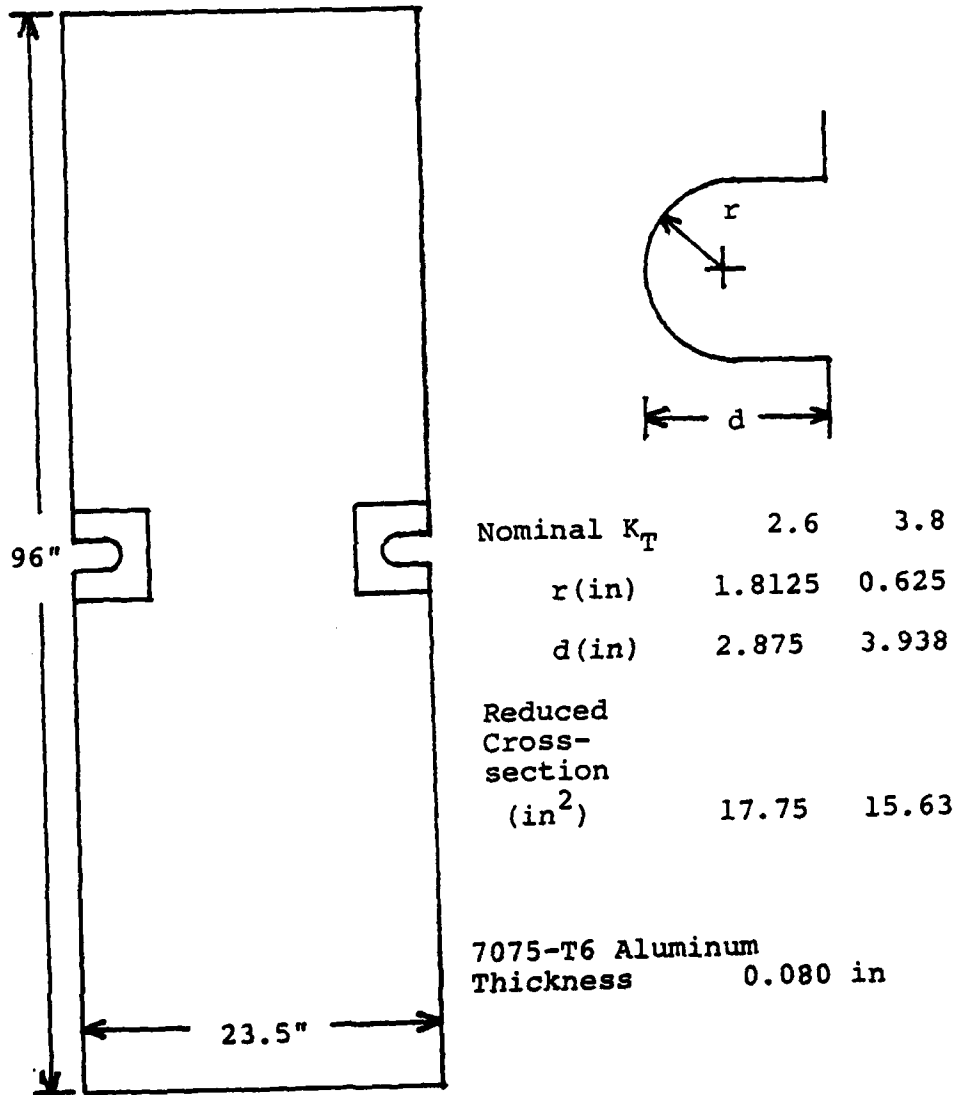


Figure 11



LARGE SPECIMEN MOUNTED IN THE TINIUS-OLSEN

Figure 12

and 20,000 pounds for the  $K_{T} = 3.8$  notch and loads of 10,000, 15,000 and 20,000 pounds for the  $K_{T} = 2.6$  notch. The results of the  $K_{T} = 3.8$  notch loads are tabulated in Tables VIII and IX while the  $K_{T} = 2.6$  notch results are shown in Tables XIII, XIV, and XV. Figures 13 and 14 depict the stress distributions at positions on the line of symmetry extending outward from the notch tip for both the longitudinal and transverse directions. Normalized curves are also indicated in Figures 13 and 14.

### C. ELASTIC ZONE CHARACTERISTICS

The use of large specimens provided a much more detailed view of the notch tip region and allowed for an accurate assessment of the stress gradient near the notch tip in the elastic zone. No other data was available to compare measurements with theory, but the characteristic shape of the stress curve compares favorably with that of Kim et al in Ref. 11. The normalized curve plots on Figures 13 and 14 demonstrate the proportionality and consistency of the measured data.

ELASTIC REGION  
 $K_T = 3.8$   
STRESS vs DISTANCE

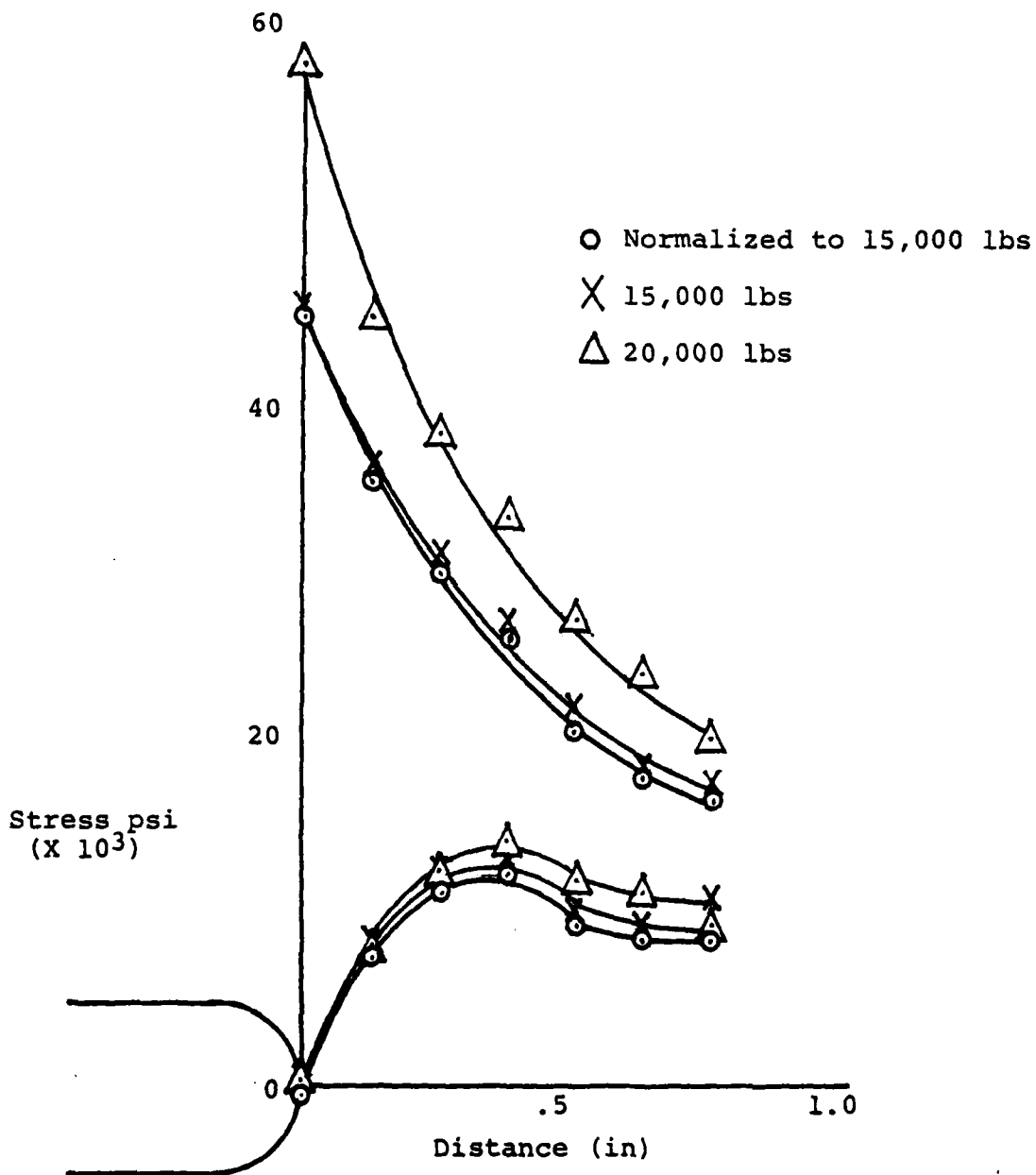


Figure 13

ELASTIC REGION  
 $K_T = 2.6$   
Stress vs Distance

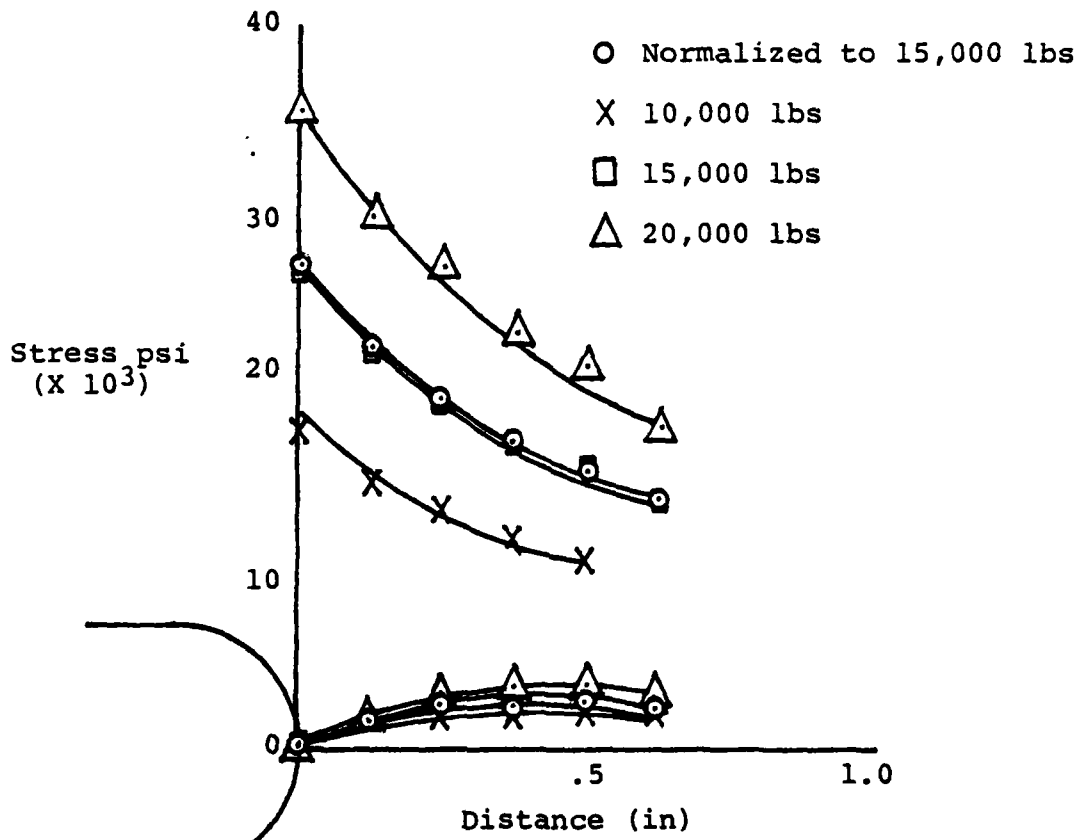


Figure 14

IX. EXPERIMENTAL DETERMINATION OF THE PLASTIC ZONE AND RESIDUAL COMPRESSIVE STRESS

If a notched specimen is subjected to a large tensile load below the yield point of the material in the far-field regions, it is possible to cause the area in the vicinity of a notch to yield and create a plastic zone. When the specimen is unloaded, the surrounding unyielded portion of the specimen will cause a residual compressive stress to be produced around the notch. Using a modified Ramberg-Osgood approach, an attempt was made to characterize the plastic zone and compare the results to slip-line theory and Neuber's relation.

A. EXPERIMENTAL PROCEDURE

The  $K_T = 2.6$  specimen used for the elastic zone analysis was loaded to strain levels well into the plastic region which coincided with loads of 60,000, 65,000 and 70,000 pounds. Normal and oblique compensator readings were taken at each load level and at the no load condition. The no load condition was measured as each load level was taken back down to zero. Tables XVI, XVII, and XVIII contain the measured and reduced data, while Figure 16 shows the graphical results for the plastic region. The residual compressive stresses were plotted in Figure 21.

The  $K_T = 3.8$  specimen was lost on the first load into the plastic region due to a bond failure. For the  $K_T = 2.6$  specimen, a higher elongation percentage bonding agent was chosen, PC-8, which allowed more flexibility in choosing strain levels. Tables X and XI were retained to provide data for the  $K_T = 3.8$  notch beyond the elastic region and into the early plastic region prior to bond separation.

#### B. DATA REDUCTION METHOD

In order to reduce fringe values to stresses, it becomes necessary to develop a method of data reduction which fits both the elastic and the plastic regions. The previous photoelastic development, derived to handle the purely elastic region which uses the linear stress-strain law, has been applied to the data in that range. To reduce the fringe numbers in the plastic range to stresses, the data was first reduced to strain by the previous method. To obtain stresses, a nonlinear stress-strain law was used where it was assumed that the total strain was equal to the strain in the elastic region plus the strain in the plastic region.

$$\epsilon = \epsilon_e + \epsilon_p \quad (35)$$

The total stress-strain expressions in the 1 and 2 directions, due to longitudinal and transverse loading, are derivable using linear superposition of the elastic strains. Referring to Figure 15a,

REPRESENTATIVE LOADING

Figure 15a

Longitudinal Load

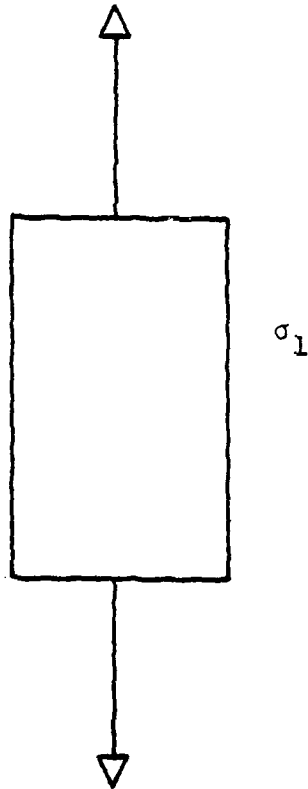
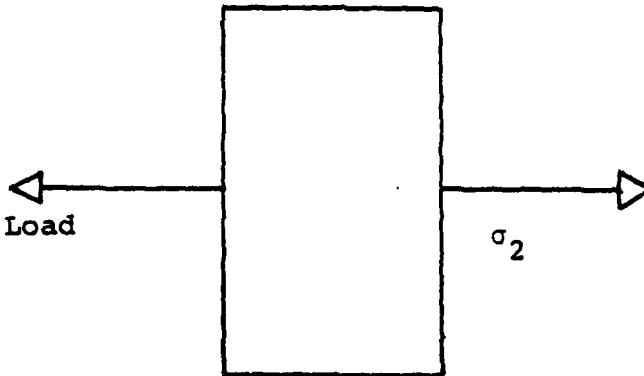


Figure 15b

Transverse Load



$$\epsilon_1 = \frac{\sigma_1}{E}$$

and

(36)

$$\epsilon_2 = -\nu\epsilon_1 = -\nu\frac{\sigma_1}{E}$$

for a longitudinal load. A transverse load from Figure 15b yields

$$\epsilon_2 = \frac{\sigma_1}{E} \quad (37)$$

and

$$\epsilon_1 = \nu\epsilon_2 = -\nu\frac{\sigma_2}{E}$$

Substitution back into Equation (35) now gives

$$\epsilon_1 = \epsilon_{p1} - \nu\epsilon_{p2} + \frac{1}{E} [\sigma_1 - \nu\sigma_2] \quad (38)$$

and similarly

$$\epsilon_2 = \epsilon_{p2} - \nu\epsilon_{p1} + \frac{1}{E} [\sigma_2 - \nu\sigma_1] \quad (39)$$

The strain in the plastic regions is handled using a modified Ramberg-Osgood method such that

$$\epsilon_p = \beta \left(\frac{\sigma}{E}\right)^n \quad (40)$$

Substitution into Equation (39) yields

$$\epsilon_1 = \beta \left(\frac{\sigma_1}{E}\right)^n - \nu\beta \left(\frac{\sigma_2}{E}\right)^n + \frac{1}{E} [\sigma_1 - \nu\sigma_2] \quad (41)$$

$$\epsilon_2 = \beta \left(\frac{\sigma_2}{E}\right)^n - \nu\beta \left(\frac{\sigma_1}{E}\right)^n + \frac{1}{E} [\sigma_2 - \nu\sigma_1] \quad (42)$$

For this analysis  $E = 10.11 \times 10^6$  psi which was measured by Engle [Ref. 10] on material from the same lot. It was

developed from strain gage data and had a 0.999994 correlation coefficient, and  $\nu = 0.3238$  from the same strain data measured into the plastic region. Using a power curve fit on Garske's data [Ref. 2] measured on the same material in the plastic range resulted in  $\beta = 3.8776 \times 10^{45}$  and  $n = 22.678$ .

To solve for the two unknown stresses in Equations (41) and (42) simultaneously, a nonlinear, simultaneous equation, FORTRAN program developed by K. M. Brown at Purdue was used. The program was listed in the Naval Postgraduate School computer's IMSL as a subroutine named NLNSYS.

The results of the computer analysis were tabulated in Tables XIX, XX, and XXI. Figures 16 and 17 depict the results of the stress and strain data reductions.

#### C. COMPARISON OF EXPERIMENTAL DATA WITH SLIP-LINE THEORY RESULTS

Classical slip-line theory for rigid, perfectly plastic materials as developed by Kachanov [Ref. 12] indicated that as the distance from the notch tip increases, the stresses at those points increase slightly as shown in Figure 18. As can be seen, the experimental data reduced by the modified Ramberg-Osgood method does not increase at any point beyond the tip value and as the distance from the tip increases, the two lines grow further apart. The transverse stress appears to have the same trend as the theory but also falls off.

PLASTIC REGION

$K_T = 2.6$

STRESS vs DISTANCE

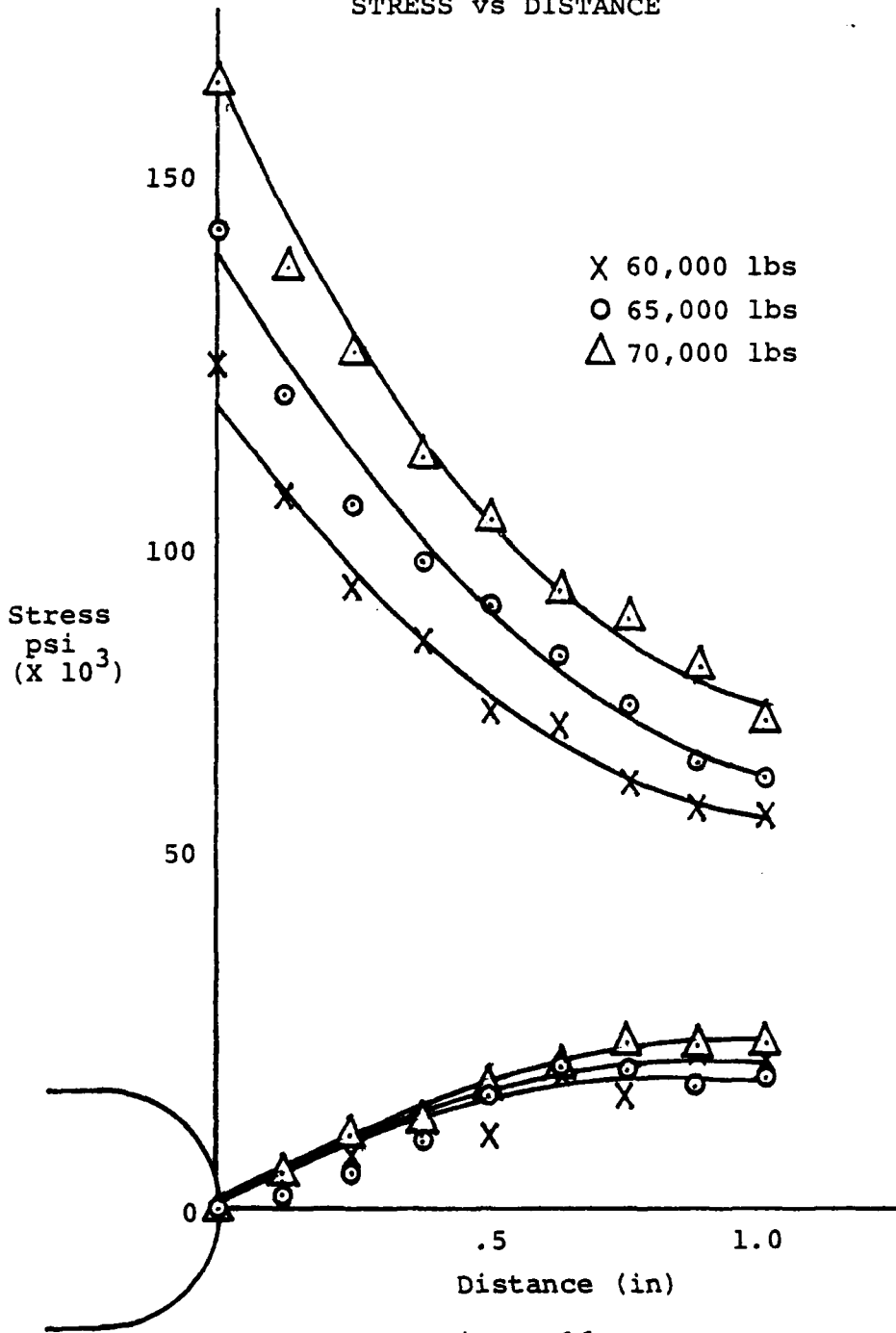


Figure 16

PLASTIC REGION  
 $K_T = 2.6$   
 STRAIN vs DISTANCE

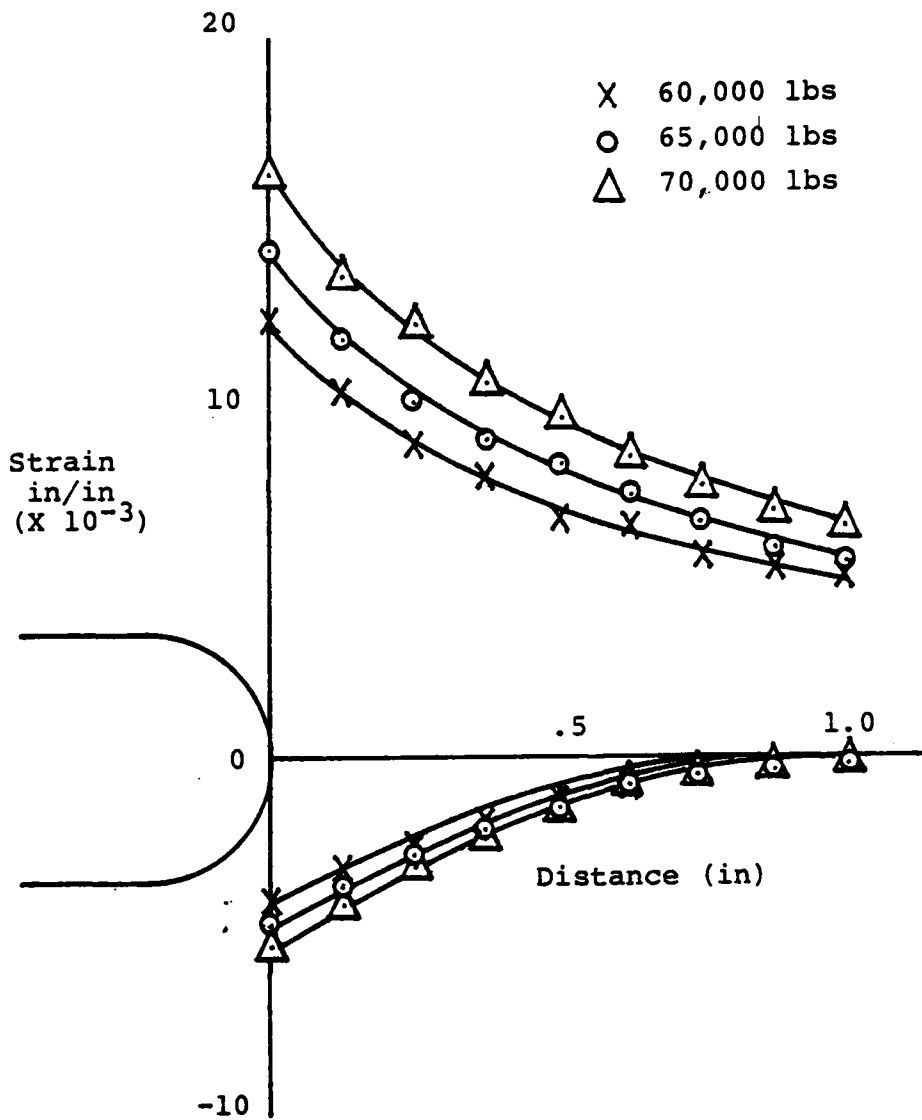
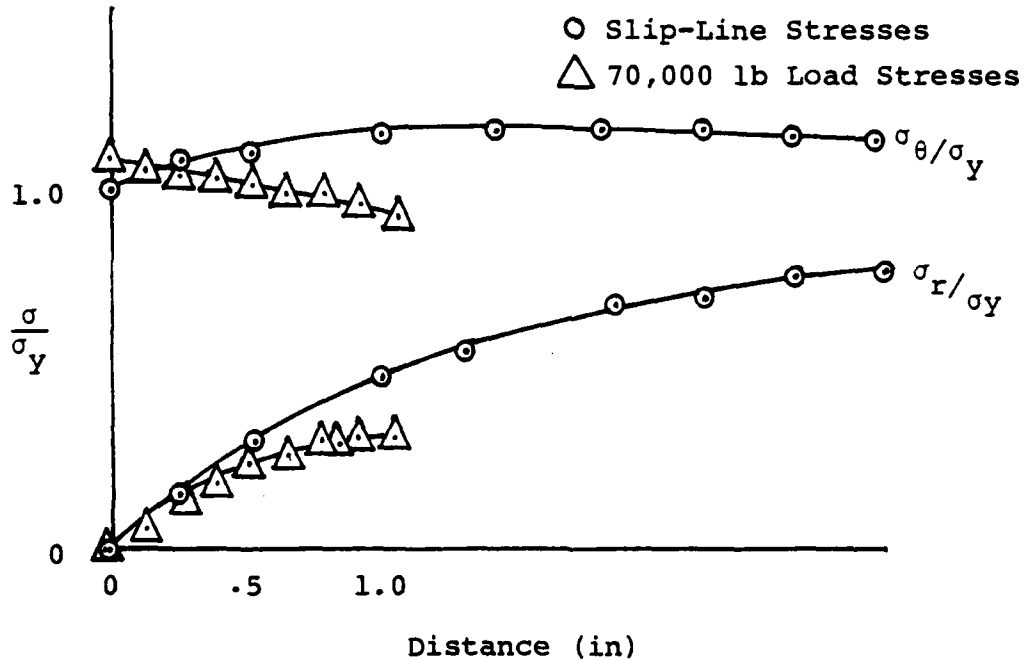


Figure 17

SLIP-LINE STRESSES COMPARED  
TO EXPERIMENTAL STRESSES

$K_T = 2.6$ , 70,000 lb Load

STRESS (NORMALIZED) vs DISTANCE



NOTE:  $\sigma_y = 74,500$  psi

Figure 18

#### D. PLASTIC ZONE DETERMINATION

To further understand the actual regions depicted by each of the load points, the Von Mises Theory was applied as shown in Figure 19. To determine which of the points on the experimental curves were fully plastic, the yield stress level was plotted as indicated, and the results show that for the highest load, only the first three points were fully plastic. Referring back to Figure 18, the longitudinal stress still appears to contradict the approximate theory in this range, while the transverse stress follows the theoretical curve closely.

#### E. COMPARISON OF PLASTIC ZONE RESULTS WITH NEUBER'S RELATION

Neuber [Ref. 1] theorized that the geometric mean of a stress concentration factor,  $K_{\sigma}$ , and a strain concentration factor,  $K_{\epsilon}$ , is equal to  $K_T$ , the elastic stress concentration factor

$$K_T^2 = K_{\sigma} K_{\epsilon}$$

where  $K_{\sigma} = \frac{\text{local stress}}{\text{nominal stress}}$

$$K_{\epsilon} = \frac{\text{local strain}}{\text{nominal strain}}$$

This relation applies only at the edge of a hole; in this case at the notch tip. Table XXII clearly depicts the consistent inaccuracy of the above relation for this set of load levels and the  $K_T = 2.6$  notch size. The design  $K_T$  value used in this study is calculated using the reduced

YIELD POINT PREDICTION

$$\sigma_r^2 - \sigma_r\sigma_\theta + \sigma_\theta^2 \text{ vs DISTANCE}$$

X 60,000 lbs

O 65,000 lbs

△ 70,000 lbs

$$\sigma_{eq} = \sigma_r^2 - \sigma_r\sigma_\theta + \sigma_\theta^2$$

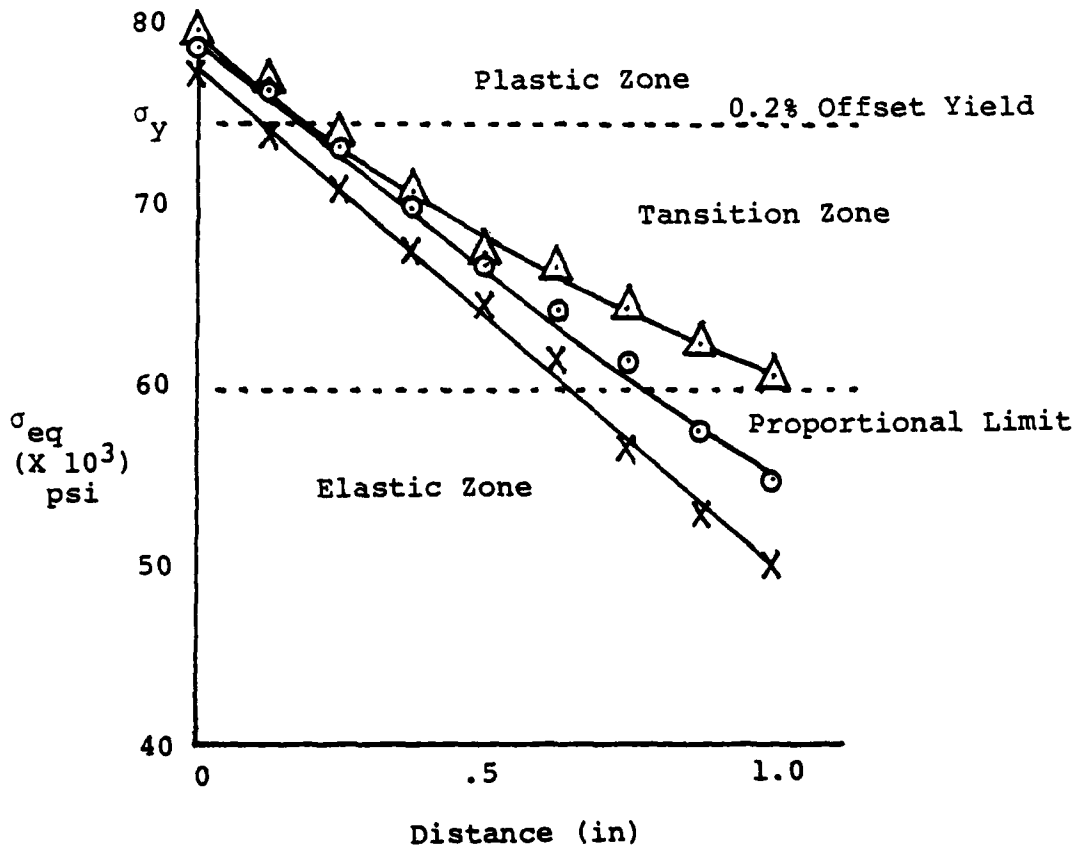


Figure 19

cross-section area while Neuber's  $K_T$  is based on the far-field area. For Neuber's  $K_T = 3.44$ , a spread of from 20.6% to 21.2% error resulted.

#### F. STRESS CURVE ANALYSIS FOR COMBINATION ELASTIC AND PLASTIC CURVES

If the classical stress-strain curve is recalled for 7075-T6 aluminum, it follows that a mapping of the stresses through a plastic zone into the elastic portion of the specimen, going outward from the notch tip, would display the characteristics of a nonlinear plastic stresses, then a transition from plastic to elastic stresses, and finally a linear elastic field. This is the essential explanation of Figure 20. Assuming that the data taken was accurate past the characteristic plastic zone around the notch, Figure 20 depicts an interesting result in the range of  $D = 0.65$  in. when compared to pure elastic curves. It is seen that the material in that elastic region exhibits elastic characteristics, and it is interesting to note the similarity to the elastic curve and that on the continually changing curve a rather abrupt change to elastic-like behavior occurs. This study did not attempt to match those curvature similarities.

#### G. RESIDUAL COMPRESSIVE STRESS

After each loading into the plastic region, a complete unload was performed to obtain residual compression fringe values around the  $K_T = 2.6$  notch. The resulting stresses

RAMBERG-OSGOOD PLASTIC REGION  
SOLUTION COMPARED TO ELASTIC  
REGION SOLUTION

STRESS vs DISTANCE

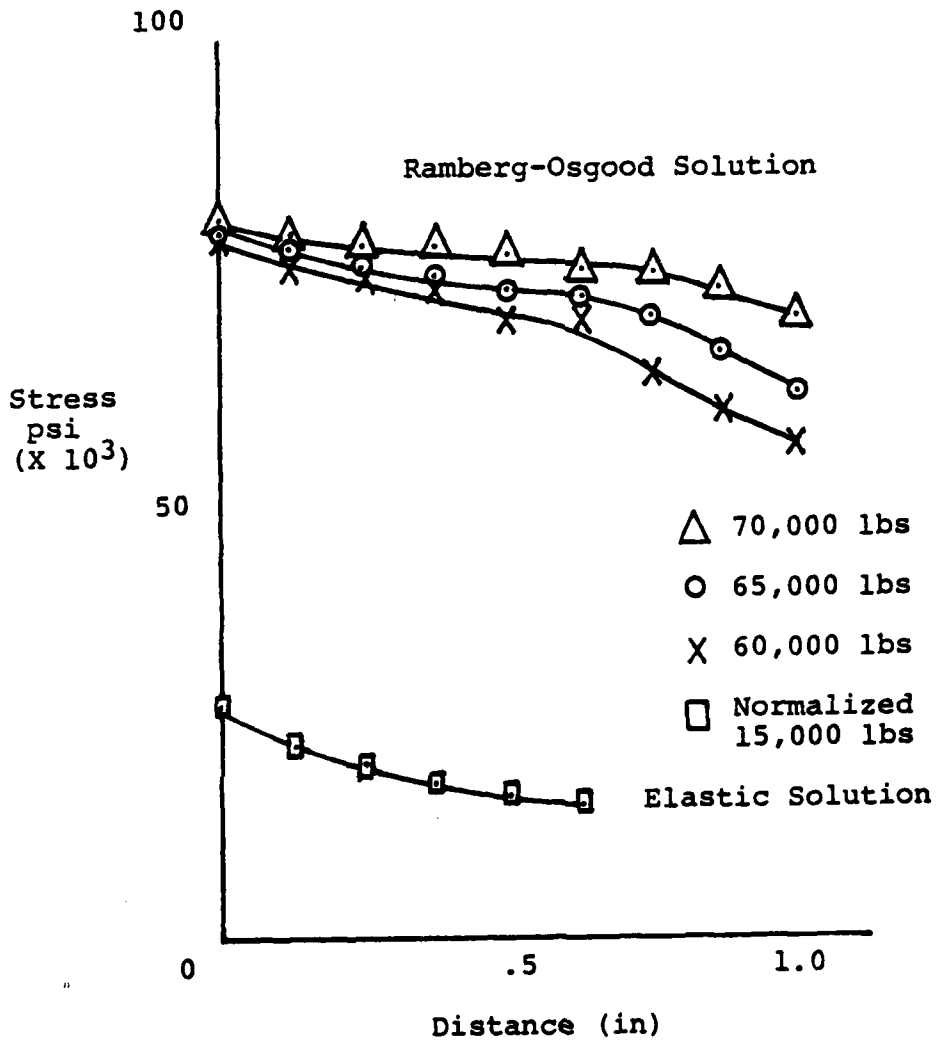


Figure 20

from Tables XVI, XVII, and SVIII were plotted against the distance from the notch tip in Figure 21. The stress levels in each case appear to converge on an unplotted point beyond  $D = 0.625$  in where  $\sigma_1$  and  $\sigma_2$  are equal. Since the residual stresses were non-zero, this would indicate that yielding had occurred up to that point. Referring back to the regions indicated on Figure 19, it can be inferred that the plastic zone around the notch includes points in the transition zone. Washout of fringes at a possible convergent point precluded its exact determination.

RESIDUAL COMPRESSIVE STRESS

STRESS vs DISTANCE

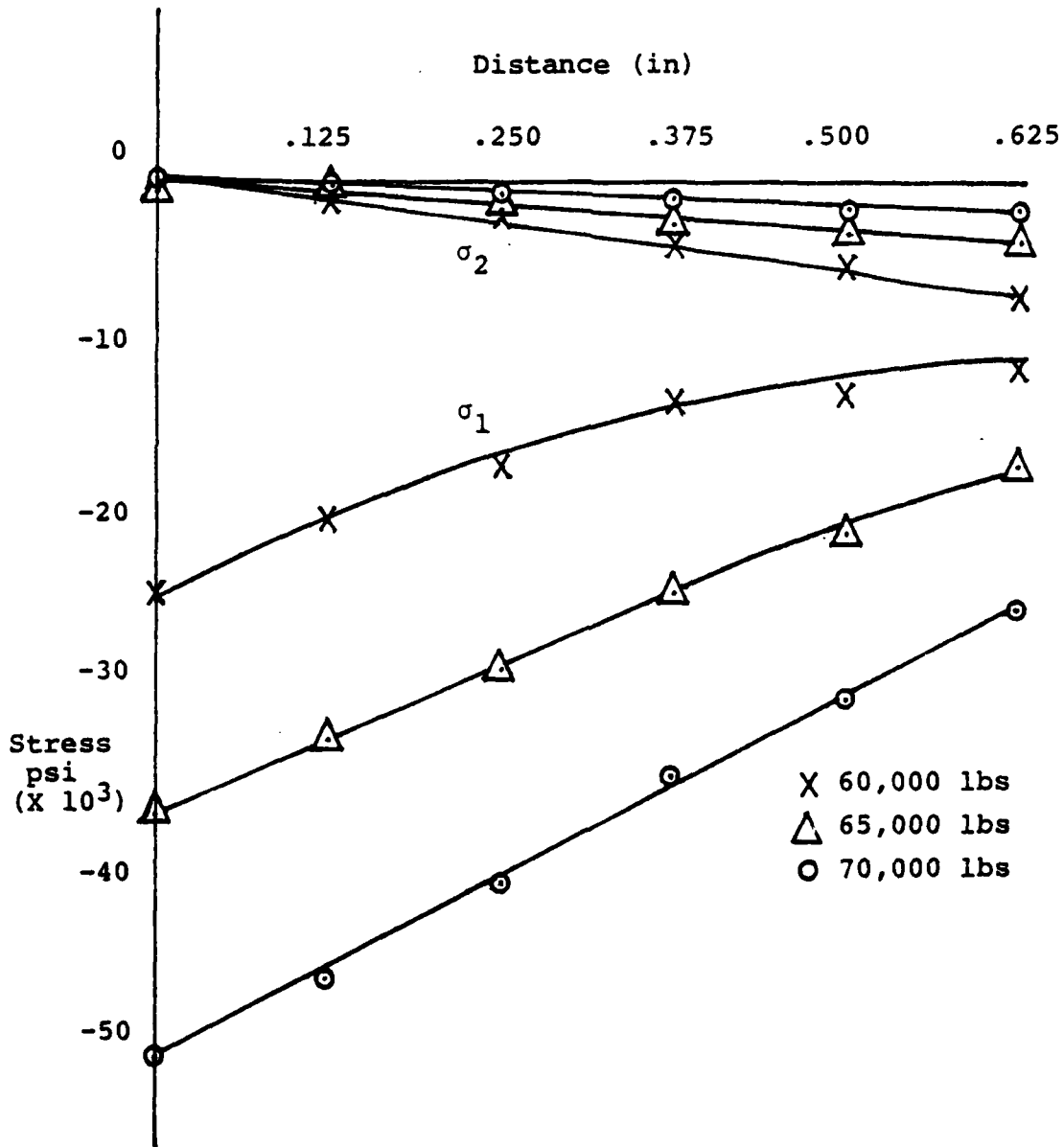


Figure 21

## X. CONCLUSIONS

It has been clearly established that the photoelastic method of stress analysis can be accurate to within 2% by a comparison to the theoretical circular hole solution. Applying the same experimental methods to a notched specimen facilitated reliable evaluations of classical slip-line theory and Neuber's relation. Slip-line theory for a rigid-perfectly-plastic material indicated a gradual increase in stress levels beyond the tip, while data reduced by the modified Ramberg-Osgood method consistently exhibited the maximum stress levels at the notch tip. Although an error may have been introduced right at the notch tip by the over-sensitive photoelastic material used, the data did not exhibit erratic results in that region. Neuber's relation for the same region was applied at three separate stress levels and resulted in errors that varied very little. However, the level of the error, 20.9%, coupled with the results of Garske [Ref. 2], lead to the conclusion that methods of calculating stresses using Neuber's relation are subject to large inaccuracies.

This study also revealed the realities of working with materials that do not exhibit perfectly elastic or perfectly plastic properties. A transition zone exists between the two regions and creates difficulties in determining actual

plastic zone boundaries. Residual compressive stresses were present after a plastic region was produced with definite indications that the plastic zone at a yielded notch extends outward through strain levels that would be in the transition region of a uniaxial specimen.

APPENDIX A: EXPERIMENTAL DATA

TABLE I

PS-1C PHOTOELASTIC MATERIAL CHARACTERIZATION

| $\sigma$<br>psi | Net<br>Reading | $\epsilon$<br>in/in | $\sigma$<br>psi | Net<br>Reading | $\epsilon$<br>in/in |
|-----------------|----------------|---------------------|-----------------|----------------|---------------------|
| 0.0             | 0.0            | 0.0                 | 0.0             | 0.0            | 0.0                 |
| 202.37          | 2.76           | 0.000555            | 65.78           | 0.32           | 0.000064            |
| 408.42          | 5.74           | 0.001155            | 131.58          | 0.70           | 0.000141            |
| 610.26          | 8.47           | 0.001704            | 197.37          | 1.04           | 0.000209            |
| 785.26          | 11.02          | 0.002217            | 263.16          | 1.38           | 0.000278            |
| 990.53          | 14.80          | 0.002978            | 328.95          | 1.75           | 0.000352            |
| 1189.21         | 16.32          | 0.003284            | 394.74          | 2.08           | 0.000418            |
| 1407.63         | 19.38          | 0.003899            | 460.53          | 2.43           | 0.000489            |
| 1606.32         | 22.27          | 0.004481            | 526.32          | 2.76           | 0.000555            |

LINEAR REGRESSION:

$$\sigma = 357079.18\epsilon - 4.3407$$

$$R = .9988$$

$$\nu = .37927$$

$$\sigma = 941487.02\epsilon_2 + 1.00708$$

$$R = .99991$$

TABLE II  
PS-1C  $F_{\sigma}$  DETERMINATION

| <u><math>\sigma</math></u><br><u>psi</u> | <u>Compensator</u><br><u>Reading</u> | <u>N</u> |
|--|--------------------------------------|----------|
| 0.0                                      | 0.0                                  | 0.0      |
| 202.37                                   | 23.0                                 | 0.489    |
| 408.42                                   | 39.0                                 | 0.830    |
| 610.26                                   | 63.0                                 | 1.340    |
| 785.26                                   | 79.5                                 | 1.691    |
| 990.53                                   | 102.0                                | 2.170    |
| 1189.21                                  | 123.0                                | 2.617    |

LINEAR REGRESSION:

$$\sigma = 456.6661N + 1.92740$$

$$R = .99932$$

TABLE III

## 7075-T6 ALUMINUM CHARACTERIZATION

| $\sigma$<br><u>psi</u> | $\epsilon_1$<br><u>in/in</u> | $\epsilon_2$<br><u>in/in</u> |
|------------------------|------------------------------|------------------------------|
| 12072.6                | 1138                         | -368                         |
| 15090.8                | 1415                         | -465                         |
| 18108.9                | 1710                         | -552                         |
| 21127.1                | 1985                         | -650                         |
| 24145.3                | 2290                         | -740                         |
| 27163.4                | 2568                         | -838                         |
| 30181.6                | 2880                         | -930                         |
| 33199.7                | 3160                         | -1032                        |
| 36217.9                | 3470                         | -1115                        |
| 39236.0                | 3760                         | -1220                        |

## LINEAR REGRESSION:

$$\sigma = 10.41518 \times 10^6 \epsilon_1 + 242.076$$

$$R = .999921$$

$$\sigma = 32.19308 \times 10^6 \epsilon_2 + 172.365$$

$$R = .999927$$

$$\nu = .32352$$

TABLE IV  
UNBOND CHARACTERISTICS OF PS-1C

| <u>Load</u><br><u>lbs</u> | Compensator Readings             |                                   |
|---------------------------|----------------------------------|-----------------------------------|
|                           | <u>Unbond</u><br><u>Specimen</u> | <u>Control</u><br><u>Specimen</u> |
| 1027                      | 20                               | 18                                |
| 1982                      | 37                               | 38                                |
| 2990                      | 55                               | 56                                |
| 3996                      | 77                               | 77                                |
| 4997                      | 99                               | 101                               |
| 5996                      | 120                              | 121                               |
| 7008                      | 144                              | 146                               |
| 8006                      | 168                              | 173                               |
| 9001                      | 188                              | 192                               |
| 10003                     | 210                              | 215                               |
| 11001                     | 231                              | 237                               |
| 12002                     | 252                              | 256                               |
| 12999                     | 274                              | 282                               |
| 13998                     | 293                              | 303                               |
| 15001                     | 312                              | 328                               |

TABLE V

## CIRCULAR HOLE COMPENSATOR DATA

| Data Point<br>In. | Compensator Readings (corrected) |                         |
|-------------------|----------------------------------|-------------------------|
|                   | $C_n$ (Left/Right)               | $C_\theta$ (Left/Right) |
| 0.0               | 122.5/121.5                      | 143.0/143.5             |
| 0.125             | 91.5/92.0                        | 105.0/105.5             |
| 0.250             | 67.3/66.3                        | 78.9/78.4               |
| 0.375             | 53.8/54.3                        | 65.3/65.8               |
| 0.500             | 45.7/46.2                        | 57.3/57.3               |

TABLE VI

## CIRCULAR HOLE DATA COMPARISON

| Data Point<br>In. | $\sigma_{\theta/P}$ | $\sigma_{\theta}$<br>psi | Experimental Stress |       |
|-------------------|---------------------|--------------------------|---------------------|-------|
|                   |                     |                          | Left                | Right |
| 0.0               | 3.24                | 34827                    | 35188               | 35254 |
| 0.125             | 2.30                | 24723                    | 24606               | 24672 |
| 0.250             | 1.85                | 19886                    | 19644               | 19975 |
| 0.375             | 1.67                | 17951                    | 17766               | 17832 |
| 0.500             | 1.54                | 16554                    | 16786               | 16390 |

TABLE VII  
 CIRCULAR HOLE STRESSES AND STRAINS  
 FROM MEASURED DATA

| Left Side  |                                   |                                   |            |            |
|------------|-----------------------------------|-----------------------------------|------------|------------|
| Data Point | $\epsilon_1$                      | $\epsilon_2$                      | $\sigma_1$ | $\sigma_2$ |
| <u>In.</u> | <u><math>10^{-3}</math> in/in</u> | <u><math>10^{-3}</math> in/in</u> | <u>psi</u> | <u>psi</u> |
| 0.0        | 3.478                             | -1.119                            | 35188      | 88         |
| 0.125      | 2.485                             | -0.948                            | 24606      | -1612      |
| 0.250      | 1.931                             | -0.594                            | 19644      | 361        |
| 0.375      | 1.682                             | -0.337                            | 17766      | 2350       |
| 0.500      | 1.542                             | -0.173                            | 16786      | 3692       |
| Right Side |                                   |                                   |            |            |
| 0.0        | 3.487                             | -1.129                            | 35254      | 11         |
| 0.125      | 2.494                             | -0.958                            | 24672      | -1689      |
| 0.250      | 1.944                             | -0.543                            | 19975      | 978        |
| 0.375      | 1.691                             | -0.347                            | 17832      | 2273       |
| 0.500      | 1.520                             | -0.214                            | 16390      | 3152       |

TABLE VIII

## ELASTIC REGION LOADING

 $K_T = 3.8$  Notch, 15,000 lb. Load

| Data Pt.<br>In. | Corrected |            | $\epsilon_1$    | $\epsilon_2$    | $\sigma_1$ | $\sigma_2$ |
|-----------------|-----------|------------|-----------------|-----------------|------------|------------|
|                 | $C_n$     | $C_\theta$ | $10^{-3}$ in/in | $10^{-3}$ in/in | psi        | psi        |
| 0.0             | 161.0     | 191.0      | 4.554           | -1.488          | 45991      | -141       |
| 0.125           | 94.5      | 120.6      | 3.320           | -0.227          | 36668      | 9591       |
| 0.250           | 63.3      | 88.4       | 2.695           | 0.320           | 31613      | 13476      |
| 0.375           | 46.2      | 68.8       | 2.232           | 0.498           | 27036      | 13799      |
| 0.500           | 37.7      | 55.3       | 1.769           | 0.355           | 21283      | 10480      |
| 0.625           | 31.7      | 47.2       | 1.531           | 0.342           | 18544      | 9461       |
| 0.750           | 26.6      | 42.7       | 1.476           | 0.478           | 18425      | 10803      |

TABLE IX

## ELASTIC REGION LOADING

 $K_T = 3.8$  Notch, 20,000 lb. Load

| Data Pt.<br>In. | Corrected |            | $\epsilon_1$    | $\epsilon_2$    | $\sigma_1$ | $\sigma_2$ |
|-----------------|-----------|------------|-----------------|-----------------|------------|------------|
|                 | $C_n$     | $C_\theta$ | $10^{-3}$ in/in | $10^{-3}$ in/in | psi        | psi        |
| 0.0             | 213.0     | 253.0      | 6.041           | -1.951          | 61098      | 68         |
| 0.125           | 131.7     | 161.8      | 4.238           | -0.704          | 45293      | 7557       |
| 0.250           | 90.0      | 119.1      | 3.424           | 0.470           | 38850      | 13062      |
| 0.375           | 66.8      | 93.5       | 2.857           | 0.351           | 33558      | 14418      |
| 0.500           | 52.8      | 74.9       | 2.320           | 0.339           | 27447      | 12318      |
| 0.625           | 44.2      | 64.9       | 1.716           | 0.283           | 20423      | 9477       |

TABLE X

## TRANSITION REGION LOADING

 $K_T = 3.8$  Notch, 25,000 lb. Load

| Data Pt.<br>In. | Corrected |            | $\epsilon_1$    | $\epsilon_2$    | $\sigma_1$ | $\sigma_2$ |
|-----------------|-----------|------------|-----------------|-----------------|------------|------------|
|                 | $C_n$     | $C_\theta$ | $10^{-3}$ in/in | $10^{-3}$ in/in | psi        | psi        |
| 0.0             | 269.0     | 319.0      | 7.601           | -2.493          | 76740      | -336       |
| 0.125           | 157.3     | 193.5      | 5.077           | -0.826          | 54328      | 9257       |
| 0.250           | 109.6     | 143.7      | 4.087           | -0.256          | 46072      | 14668      |
| 0.375           | 81.4      | 113.1      | 3.430           | 0.376           | 40119      | 16795      |
| 0.500           | 64.8      | 90.5       | 2.759           | 0.328           | 32367      | 13800      |
| 0.625           | 54.3      | 75.4       | 2.285           | 0.248           | 26719      | 11161      |
| 0.750           | 48.2      | 65.8       | 1.959           | 0.150           | 22672      | 8861       |

TABLE XI

## PLASTIC REGION LOADING

 $K_T = 3.8$  Notch, 30,000 lb. Load

| Data Pt.<br>In. | Corrected |            | $\epsilon_1$    | $\epsilon_2$    | $\sigma_1$ | $\sigma_2$ |
|-----------------|-----------|------------|-----------------|-----------------|------------|------------|
|                 | $C_n$     | $C_\theta$ | $10^{-3}$ in/in | $10^{-3}$ in/in | psi        | psi        |
| 0.0             | 319.0     | 378.5      | 9.025           | -2.945          | 91172      | -230       |
| 0.125           | 203.0     | 243.2      | 6.149           | -1.469          | 64078      | 5913       |
| 0.250           | 138.2     | 172.4      | 4.609           | -0.577          | 49949      | 10351      |
| 0.375           | 103.0     | 135.7      | 3.881           | 0.016           | 43903      | 14390      |
| 0.500           | 81.4      | 112.6      | 3.399           | 0.345           | 39656      | 16332      |
| 0.625           | 66.8      | 95.0       | 2.950           | 0.444           | 34946      | 15806      |
| 0.750           | 57.8      | 85.4       | 2.751           | 0.582           | 33200      | 16639      |

TABLE XII  
ELASTIC REGION NORMALIZATION

$K_T = 3.8$  Notch, Elastic Region

Normalized to a 15,000 lb. Load

| Data Pt.<br><u>In.</u> | Corrected               |                              | $\epsilon_1$                      | $\epsilon_2$                      | $\sigma_1$ | $\sigma_2$ |
|------------------------|-------------------------|------------------------------|-----------------------------------|-----------------------------------|------------|------------|
|                        | <u><math>C_n</math></u> | <u><math>C_\theta</math></u> | <u><math>10^{-3}</math> in/in</u> | <u><math>10^{-3}</math> in/in</u> | <u>psi</u> | <u>psi</u> |
| 0.0                    | 160.4                   | 190.4                        | 4.542                             | -1.476                            | 45907      | -45        |
| 0.125                  | 96.6                    | 121.0                        | 3.252                             | -0.373                            | 35372      | 7693       |
| 0.250                  | 65.4                    | 88.9                         | 2.634                             | 0.180                             | 30410      | 11671      |
| 0.375                  | 48.1                    | 69.5                         | 2.192                             | 0.387                             | 26177      | 12395      |
| 0.500                  | 38.6                    | 55.7                         | 1.754                             | 0.306                             | 20939      | 9879       |
| 0.625                  | 32.5                    | 47.7                         | 1.527                             | 0.307                             | 18373      | 9060       |
| 0.750                  | 27.6                    | 41.9                         | 1.383                             | 0.347                             | 16891      | 8984       |

TABLE XV

## ELASTIC REGION LOADING

 $K_T = 2.6$  Notch, 10,000 lb. Load

| Data Pt.<br>In. | Corrected |            | $\epsilon_1$    | $\epsilon_2$    | $\sigma_1$ | $\sigma_2$ |
|-----------------|-----------|------------|-----------------|-----------------|------------|------------|
|                 | $C_n$     | $C_\theta$ | $10^{-3}$ in/in | $10^{-3}$ in/in | psi        | psi        |
| 0.0             | 62.0      | 73.5       | 1.751           | -0.573          | 17696      | -10        |
| 0.125           | 48.7      | 57.8       | 1.441           | -0.386          | 14897      | 990        |
| 0.250           | 41.2      | 49.7       | 1.269           | -0.277          | 13350      | 1584       |
| 0.375           | 34.7      | 42.2       | 1.090           | -0.211          | 11562      | 1652       |
| 0.500           | 30.2      | 37.2       | 0.978           | -0.155          | 10503      | 1878       |

TABLE XIV

## ELASTIC REGION LOADING

 $K_T = 2.6$  Notch, 15,000 lb. Load

| Data Pt.<br>In. | Corrected |            | $\epsilon_1$    | $\epsilon_2$    | $\sigma_1$ | $\sigma_2$ |
|-----------------|-----------|------------|-----------------|-----------------|------------|------------|
|                 | $C_n$     | $C_\theta$ | $10^{-3}$ in/in | $10^{-3}$ in/in | psi        | psi        |
| 0.0             | 93.0      | 110.5      | 2.639           | -0.850          | 26749      | 190        |
| 0.125           | 73.4      | 86.9       | 2.159           | -0.595          | 22252      | 1291       |
| 0.250           | 61.8      | 74.4       | 1.894           | -0.425          | 19885      | 2236       |
| 0.375           | 52.3      | 63.3       | 1.624           | -0.339          | 17142      | 2207       |
| 0.500           | 45.2      | 55.8       | 1.471           | -0.225          | 15834      | 2926       |
| 0.625           | 41.2      | 50.3       | 1.306           | -0.240          | 13909      | 2143       |

TABLE XV  
ELASTIC REGION LOADING

$K_T = 2.6$  Notch, 20,000 lb. Load

| Data Pt.<br><u>In.</u> | Corrected |            | $\epsilon_1$    | $\epsilon_2$    | $\sigma_1$ | $\sigma_2$ |
|------------------------|-----------|------------|-----------------|-----------------|------------|------------|
|                        | $C_n$     | $C_\theta$ | $10^{-3}$ in/in | $10^{-3}$ in/in | psi        | psi        |
| 0.0                    | 124.0     | 147.0      | 3.501           | -1.152          | 35391      | -20        |
| 0.125                  | 97.5      | 115.6      | 2.888           | -0.780          | 29715      | 1871       |
| 0.250                  | 82.4      | 99.5       | 2.544           | -0.548          | 26793      | 3261       |
| 0.375                  | 69.4      | 84.4       | 2.190           | -0.424          | 23123      | 3304       |
| 0.500                  | 60.3      | 74.4       | 1.960           | -0.303          | 21085      | 3865       |
| 0.625                  | 54.8      | 66.3       | 1.700           | -0.356          | 17937      | 2288       |

TABLE XVI

## PLASTIC REGION LOADING

 $K_T = 2.6$  Notch, 60,000 lb. Load

| Data Pt.<br>In. | Corrected |            | $\epsilon_1$    | $\epsilon_2$    | $\sigma_1$ | $\sigma_2$ |
|-----------------|-----------|------------|-----------------|-----------------|------------|------------|
|                 | $C_n$     | $C_\theta$ | $10^{-3}$ in/in | $10^{-3}$ in/in | psi        | psi        |
| 0.0             | 431.0     | 511.0      | 12.173          | -3.999          | 123060     | -25        |
| 0.125           | 351.8     | 414.1      | 10.200          | -3.001          | 104413     | 3946       |
| 0.250           | 295.5     | 351.8      | 8.813           | -2.275          | 91403      | 7014       |
| 0.375           | 252.3     | 306.6      | 7.910           | -1.557          | 83847      | 11800      |
| 0.500           | 216.1     | 263.3      | 6.818           | -1.291          | 72460      | 10750      |
| 0.625           | 183.9     | 235.2      | 6.491           | -0.409          | 72038      | 19520      |
| 0.750           | 162.3     | 207.1      | 5.700           | -0.391          | 63134      | 16780      |
| 0.875           | 145.7     | 189.0      | 5.307           | -0.160          | 59549      | 17940      |
| 1.000           | 132.2     | 174.9      | 5.027           | 0.066           | 57211      | 19460      |

## RESIDUAL COMPRESSION

|       |      |      |        |        |        |       |
|-------|------|------|--------|--------|--------|-------|
| 0.0   | 83.5 | 99.0 | -2.258 | 0.775  | -23842 | 4     |
| 0.125 | 67.8 | 79.5 | -1.947 | 0.597  | -19837 | -475  |
| 0.250 | 53.8 | 63.8 | -1.589 | 0.430  | -16409 | -1044 |
| 0.375 | 39.2 | 47.2 | -1.202 | 0.269  | -12620 | -1426 |
| 0.500 | 25.6 | 35.2 | -1.056 | -0.095 | -12319 | -5008 |
| 0.625 | 15.6 | 25.1 | -0.869 | -0.284 | -10908 | -6453 |

TABLE XVII  
PLASTIC REGION LOADING

$K_T = 2.6$  Notch, 65,000 lb. Load

| Data Pt.<br>In. | Corrected |            | $\epsilon_1$    | $\epsilon_2$    | $\sigma_1$ | $\sigma_2$ |
|-----------------|-----------|------------|-----------------|-----------------|------------|------------|
|                 | $C_n$     | $C_\theta$ | $10^{-3}$ in/in | $10^{-3}$ in/in | psi        | psi        |
| 0.0             | 501.0     | 594.0      | 14.150          | -4.649          | 143052     | -23        |
| 0.125           | 411.1     | 480.4      | 11.700          | -3.724          | 118751     | 1349       |
| 0.250           | 344.7     | 407.0      | 10.070          | -2.863          | 103478     | 5038       |
| 0.375           | 293.5     | 352.8      | 8.963           | -2.051          | 93935      | 10118      |
| 0.500           | 249.4     | 308.6      | 8.166           | -1.189          | 88111      | 16920      |
| 0.625           | 215.1     | 272.4      | 7.425           | -0.646          | 81740      | 20310      |
| 0.750           | 186.9     | 239.2      | 6.607           | -0.406          | 73365      | 19990      |
| 0.875           | 165.8     | 212.1      | 5.855           | -0.366          | 64993      | 17640      |
| 1.000           | 148.8     | 194.0      | 5.481           | -0.103          | 61728      | 19230      |

RESIDUAL COMPRESSION

|       |       |       |        |       |        |       |
|-------|-------|-------|--------|-------|--------|-------|
| 0.0   | 128.0 | 152.0 | -3.628 | 1.175 | -36745 | -191  |
| 0.125 | 112.6 | 131.6 | -3.206 | 1.019 | -32543 | -387  |
| 0.250 | 93.5  | 110.6 | -2.744 | 0.764 | -28256 | -1554 |
| 0.275 | 75.4  | 90.4  | -2.288 | 0.541 | -23914 | -2381 |
| 0.500 | 61.3  | 74.3  | -1.910 | 0.390 | -20192 | -2686 |
| 0.625 | 45.2  | 56.3  | -1.502 | 0.194 | -16300 | -3392 |

TABLE XVIII  
 PLASTIC REGION LOADING  
 $K_T = 2.6$  Notch, 70,000 lb. Load

| Data Pt.<br>In. | Corrected |            | $\epsilon_1$    | $\epsilon_2$    | $\sigma_1$ | $\sigma_2$ |
|-----------------|-----------|------------|-----------------|-----------------|------------|------------|
|                 | $C_n$     | $C_\theta$ | $10^{-3}$ in/in | $10^{-3}$ in/in | psi        | psi        |
| 0.0             | 571.0     | 678.0      | 16.182          | -5.244          | 163866     | 800        |
| 0.125           | 464.4     | 545.8      | 13.410          | -4.014          | 137050     | 4426       |
| 0.250           | 393.9     | 472.4      | 11.960          | -2.819          | 125057     | 12570      |
| 0.375           | 339.7     | 410.1      | 10.480          | -2.264          | 110367     | 13360      |
| 0.500           | 294.5     | 361.8      | 9.476           | -1.576          | 101522     | 17420      |
| 0.625           | 253.3     | 314.6      | 8.362           | -1.143          | 90502      | 18160      |
| 0.750           | 219.1     | 281.4      | 7.807           | -0.415          | 86927      | 24360      |
| 0.875           | 193.0     | 250.3      | 7.027           | -0.215          | 78828      | 23710      |
| 1.000           | 170.9     | 225.3      | 6.436           | 0.024           | 73027      | 24220      |

RESIDUAL COMPRESSION

|       |       |       |        |       |        |       |
|-------|-------|-------|--------|-------|--------|-------|
| 0.0   | 178.0 | 211.0 | -5.025 | 1.654 | -50791 | 43    |
| 0.125 | 158.8 | 185.8 | -4.535 | 1.424 | -46086 | -736  |
| 0.250 | 139.7 | 163.7 | -4.004 | 1.238 | -40774 | -878  |
| 0.375 | 117.6 | 138.1 | -3.389 | 1.023 | -34600 | -1016 |
| 0.500 | 100.5 | 118.5 | -2.926 | 0.845 | -30017 | -1316 |
| 0.625 | 81.4  | 96.5  | -2.402 | 0.652 | -24798 | -1551 |

TABLE XIX

## MODIFIED RAMBERG-OSGOOD STRESSES

 $K_T = 2.6$  Notch, 60,000 lb. Load

| <u>Data Point</u><br><u>In.</u> | $\sigma_1$<br><u>psi</u> | $\sigma_2$<br><u>psi</u> |
|---------------------------------|--------------------------|--------------------------|
| 0.0                             | 77245                    | -690                     |
| 0.125                           | 75623                    | 3372                     |
| 0.250                           | 73913                    | 6503                     |
| 0.375                           | 72460                    | 11311                    |
| 0.500                           | 68752                    | 10326                    |
| 0.625                           | 68526                    | 19088                    |
| 0.750                           | 62501                    | 16409                    |
| 0.875                           | 59207                    | 17580                    |
| 1.000                           | 56473                    | 17614                    |

TABLE XX

## MODIFIED RAMBERG-OSGOOD STRESSES

 $K_T = 2.6$  Notch, 65,000 lb. Load

| <u>Data Point</u><br><u>In.</u> | $\sigma_1$<br><u>psi</u> | $\sigma_2$<br><u>psi</u> |
|---------------------------------|--------------------------|--------------------------|
| 0.0                             | 78463                    | -808                     |
| 0.125                           | 76922                    | 687                      |
| 0.250                           | 75520                    | 4455                     |
| 0.375                           | 74303                    | 9580                     |
| 0.500                           | 73332                    | 16402                    |
| 0.625                           | 71942                    | 19826                    |
| 0.750                           | 69139                    | 19551                    |
| 0.875                           | 64037                    | 17254                    |
| 1.000                           | 61237                    | 18861                    |

TABLE XXI

## MODIFIED RAMBERG-OSGOOD STRESSES

 $K_T = 2.6$  Notch, 70,000 lb. Load

| <u>Data Point</u><br><u>In.</u> | $\sigma_1$<br><u>psi</u> | $\sigma_2$<br><u>psi</u> |
|---------------------------------|--------------------------|--------------------------|
| 0.0                             | 79426                    | -104                     |
| 0.125                           | 78132                    | 3659                     |
| 0.250                           | 77379                    | 11855                    |
| 0.375                           | 76206                    | 12716                    |
| 0.500                           | 75291                    | 16828                    |
| 0.625                           | 73754                    | 17637                    |
| 0.750                           | 73097                    | 23835                    |
| 0.875                           | 71129                    | 23237                    |
| 1.000                           | 68978                    | 23775                    |

TABLE XXII

NEUBER'S RELATION COMPARISON,  $K_T = 2.6$ 

| $\sigma_{\text{nom}}$<br>psi | $\sigma_1$<br>psi | $\epsilon_1$<br>$10^{-3}$ in/in | $K_T$ | %<br>Error |
|------------------------------|-------------------|---------------------------------|-------|------------|
| 31915                        | 77245             | 12.173                          | 9.33  | 21.2       |
| 34575                        | 78463             | 14.150                          | 9.39  | 20.6       |
| 37234                        | 79426             | 16.182                          | 9.37  | 20.8       |

Neuber's Equivalent  $K_T$  3.44 (far-field)

$$K_T^2 = 11.83$$

$$K_T^2 = \frac{\sigma_1 E \epsilon_1}{\sigma_{\text{nom}}^2}$$

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