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NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

AN INVESTIGATION OF RESIDUAL STRESS
CHARACTERIZATION OF 7075-T6 ALUMINUM
FOR APPLICATION IN FATIGUE ANALYSIS

by

Gary Leland Stuart

December 1978

Thesis Advisor: G. H. Lindsey

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An Investigation of Residual Stress Characterization of 7075-T6 Aluminum For Application in Fatigue Analysis

by

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Lieutenant, United States Navy
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ABSTRACT

Residual stresses induced by a stress concentration have been shown to increase the fatigue life of materials. An experimental investigation was undertaken to establish a relationship which would allow for the prediction of local residual stresses at a notch from known geometrical stress concentration factors and applied loads. Notched flat plate specimens were tested utilizing photoelastic coatings for measurement of stress concentration factors and residual stresses. Handbook values for stress concentration factors were found to be accurate within seven percent for the geometrics tested. The residual stress characterization consisted of a plot of nominal stress versus residual stress. These plots predicted residual stresses to within ten percent of the measured values for typical flight load histories.

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I. INTRODUCTION

Fatigue life prediction has increased in importance with the long service life planned for current Naval aircraft. Considerable effort has gone into obtaining actual flight load histories for application in fatigue life prediction and testing. Currently, a fatigue monitoring system is being flight tested, which utilizes strain gages to record strains at critical locations in the aircraft structure [Ref. 1]. Because they will fatigue, the strain gages cannot be placed directly at the location of a stress riser, therefore, the local stress must be calculated from strains measured with gauges placed some distance from the stress concentration point. The stresses are usually found using Neuber's relationship [Ref. 2]. Garske used strain gage measurements to evaluate Neuber's rule and to calculate the stress at a notch tip using far field strains [Ref. 3]. He found considerable error in some instances which created a need for a more accurate method.

As a result of stress concentrations, there can be plastic deformation (yielding) in a small region at the notch tip where the local stress exceeds the yield stress. Upon unloading, the unyielded material compresses the yielded area, causing a residual stress. This residual stress has been shown to increase the fatigue life of the material [Refs. 4, 5, and 6].

An experimental investigation for residual stress characterization was followed using photoelastic coatings on notched flat plate specimens. Photoelastic coatings were chosen for two reasons. The first of these was that the photoelastic coating covered the entire area around the notch, allowing for the maximum residual strain to be measured. Had strain gages been used, the residual stress calculations could be significantly in error due to improper gage location in the rapidly varying stress field at the notch tip. The second reason was that a specimen could be set aside and then re-examined after a specific period of time to determine any change in the residual stress. This could not easily be done using strain gages.

The results of the residual stress characterization can be applied to fatigue testing. The applications involve modifying a fatigue test program to lower individual loads by accounting for residual stresses. Another application could be to determine the effect on fatigue life of inducing various residual stress levels into the material.

II. EXPERIMENTAL TESTS

A. INTRODUCTION

Residual stress characterization testing was accomplished in four phases. The first consisted of specimen design and sizing. Uniaxial tension tests were used in the second phase to determine the stress-strain relationships of the 0.080-inch thick 7075-T6 aluminum from which the specimens were manufactured. The third phase was the stress concentration factor determination and residual stress measurement of the notched flat plate specimens. The fourth and final phase consisted of cyclic loading of the notched specimens to compare predicted and measured residual stresses from the known maximum nominal stress to which the specimen was subjected.

B. SPECIMEN DESIGN

Notched specimens were designed to cover a range of stress concentration factors of approximately 1.5 to 4.0. The notch geometries were determined from Ref. 7 for a stress concentration factor of 1.63 and Ref. 8 for stress concentration factors of 2.60 and 3.80. In order to minimize the end attachment effects, photoelastic models of varying lengths and widths were used. A length-to-width ratio of approximately four to one resulted in a relatively uniform stress distribution for the middle half of the specimen. To keep the notch radius of curvature as large as possible, the specimens were made four feet by one foot. The actual specimen dimensions and notch geometries are shown in Fig. 1.

C. MATERIAL CHARACTERIZATION

Material characterization consisted of two uniaxial tension tests to determine a stress-strain curve and the modulus of elasticity.

1. Description of Procedure

Two tensile specimens were manufactured in accordance with ASTM standards. The specimen dimensions are shown in Fig. 2. The specimens were tested in an Instron TD-D Universal Test Machine, and specimen elongation was measured using an Instron G-51-13 Strain Gauge Extensometer, having a two-inch gauge length and a maximum extension of ten percent. Specimen elongation and loads were recorded using the X-Y recorder in the test machine.

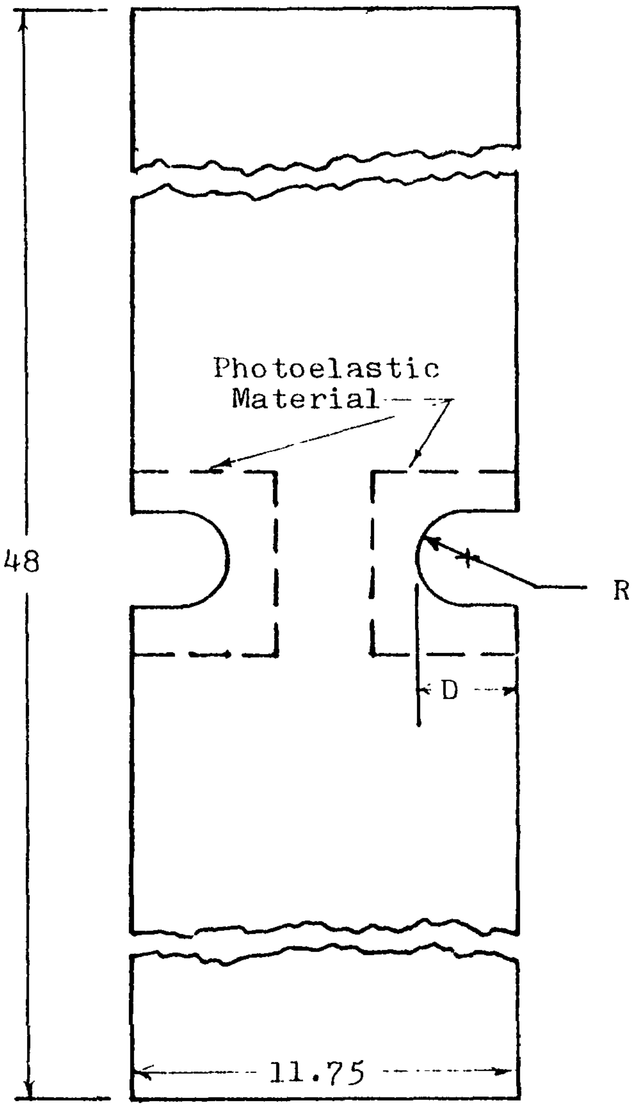
2. Test Results

The stress-strain curve for the uniaxial tensile test was obtained by scaling the load-elongation curves with the specimen geometries. The resulting stress-strain curve is shown in Fig. 3. From test results, the modulus of elasticity was determined to be 10,100 ksi, and the two-tenths percent (0.2%) offset yield point was determined to be 74.5 ksi.

D. NOTCHED SPECIMEN CHARACTERIZATION TEST

1. Specimen Preparation

The notched flat plate specimens were machined from 0.080-inch thick aluminum sheet. After the specimens were



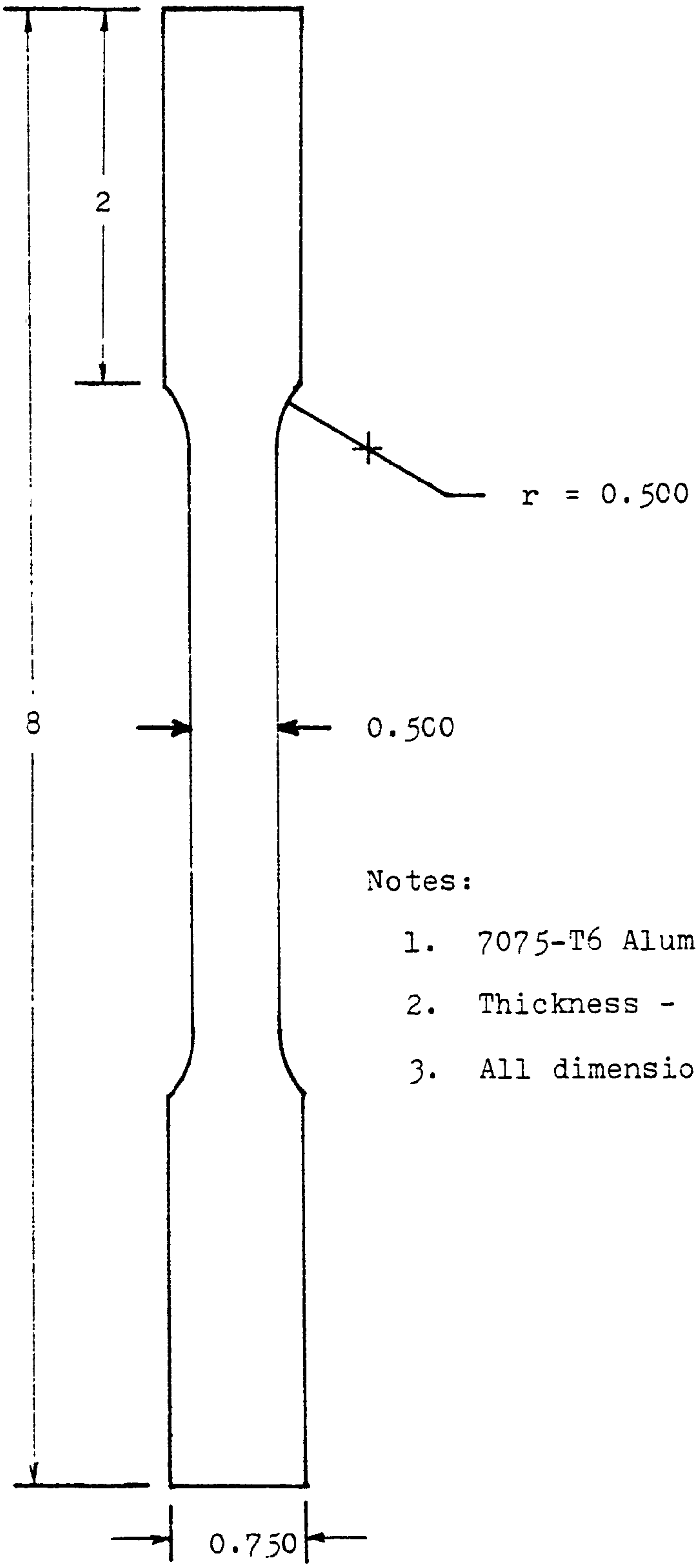
SPECIMEN GEOMETRIES

K_t	1.63	2.60	3.80
R	3.000	0.900	0.3125
D	0.500	0.415	1.963
Reduced Cross-section	0.860	0.740	0.626

Notes:

1. 7075-T6 Aluminum
2. Thickness - 0.080 inches
3. Photoelastic Material - Photolastic Inc, PS-1C
4. All dimensions inches

Figure 1

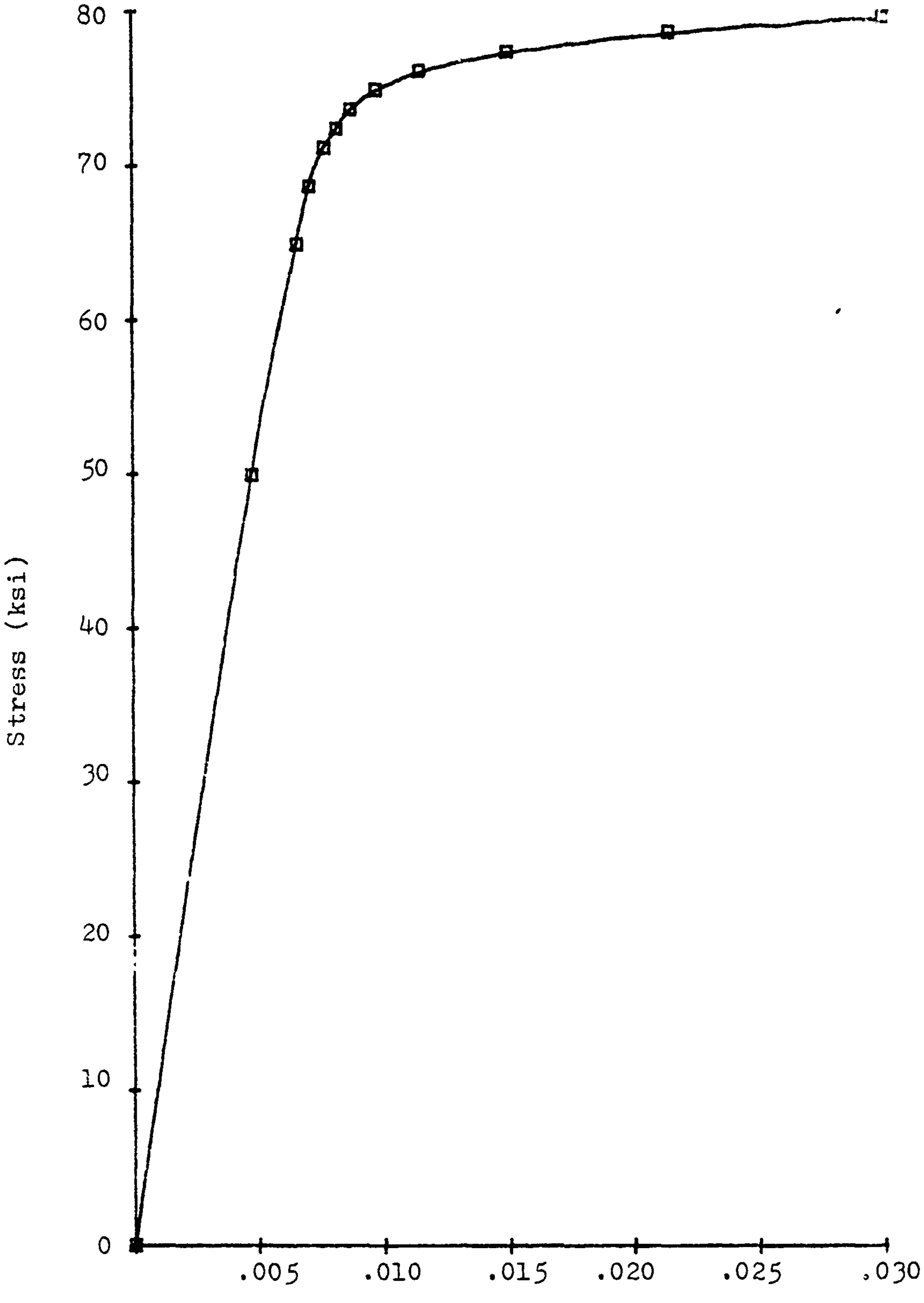


Notes:

1. 7075-T6 Aluminum
2. Thickness - 0.080 in.
3. All dimensions in inches

Uniaxial Tensile Specimen

Figure 2



Stress-Strain Curve

Figure 3

machined, PS-1C photoelastic material, by Photolastic Inc., was bounded with epoxy to the specimen around the notch as shown in Fig. 1. The photoelastic material sensitivity factor (K) and thickness are listed in Table 1 of Appendix A for each specimen. Once the epoxy has cured, the photoelastic material was trimmed to match the notch geometry.

2. Description of Procedure

After specimen preparation was complete, the specimen was mounted in the MTS 810 testing machine and loaded to give a 10,000 psi nominal stress (applied load/reduced cross-section). A Photolastic Inc. Model 031 Reflection Polariscope, equipped with a Model 137 Telemicroscope and a Model 232 Linear Compensator, was used for photoelastic measurement of the strain at the notch tip. The test set up is shown in Fig. 4. The compensator readings for both the left and the right sides were recorded for use in the calculation of stress concentration factors and are listed in Tables 2-4 of Appendix A.

After the compensator reading was recorded, the specimen was loaded to a large enough stress level to cause yielding at the notch tip. The largest localized strain at the notch was measured with the polariscope. The compensator reading and load were recorded. The specimen was then unloaded and the residual strain was measured using the photoelastic equipment. The load and two compensator readings were recorded in Tables 5-7 of Appendix A.

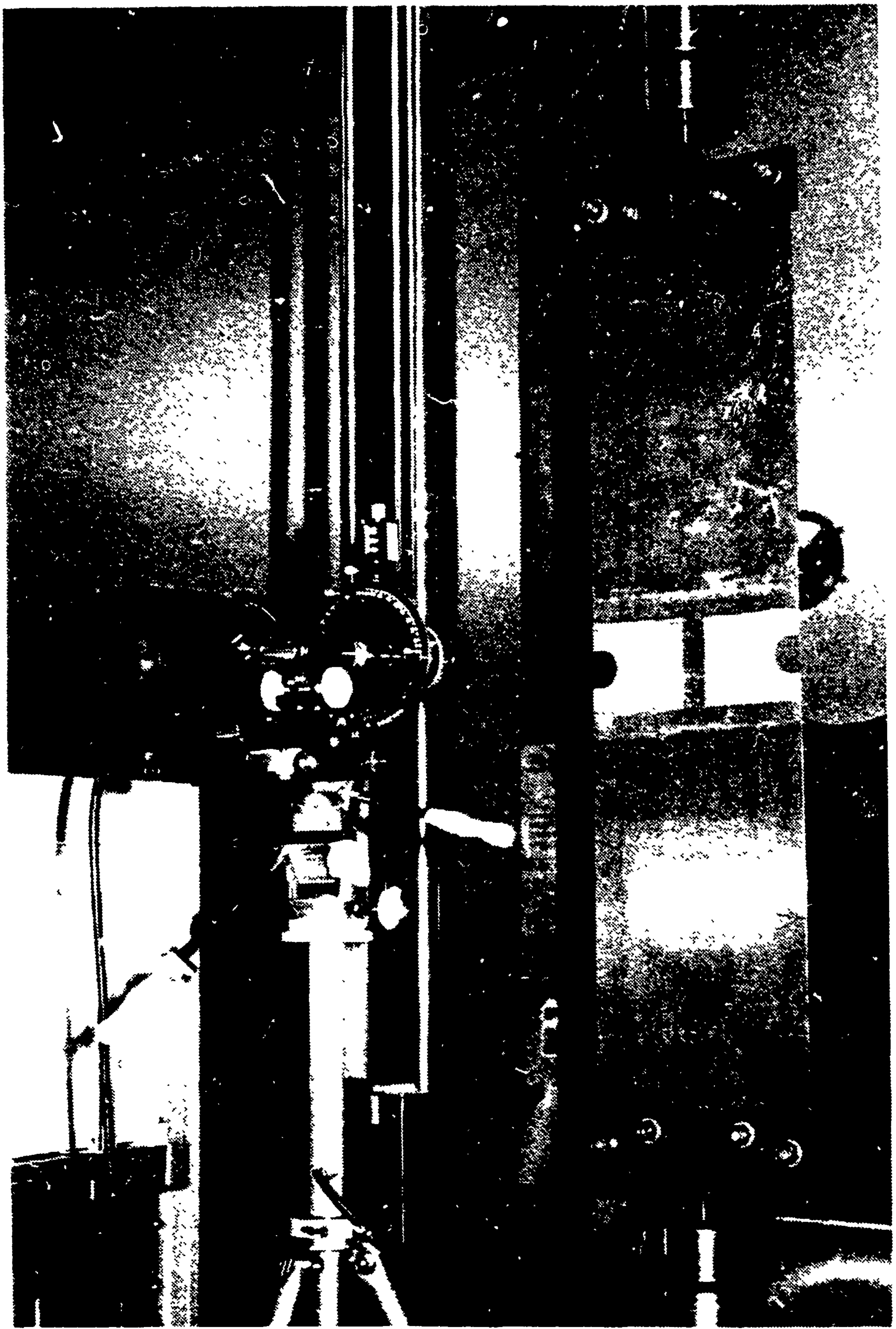


Figure 4 Test Set Up

3. Problems During Testing

Two minor problems developed during the testing procedure, neither of which were due to the photoelastic equipment or coatings. The first of these had to do with misalignment of the specimen mounting holes. This produced a moment in the speciment, resulting in one notch having a considerably higher stress than the other. This problem was resolved by remachining the mounting holes to achieve the proper alignment. The second problem arose in the specimens having a stress concentration factor of 1.63. The attachment holes caused a smaller cross section at the ends of the specimen than at the reduced cross section. This resulted in the shear out at the specimen ends. Due to time considerations, the specimens could not be redesigned. This accounts for only five specimens being tested for this stress concentration factor.

4. Data Reduction

In order to calculate the stresses from the measured strains, several assumptions has to be made. The first of these was that uniaxial tension existed in a small region at notch tip as shown in Fig. 5. Since photoelastic measurements measure a bi-directional state of strain, it follows that,

$$\epsilon_y = -\nu \epsilon_x \tag{1}$$

where ϵ_x and ϵ_y are strains and ν is Poisson's ratio. The stress could be then determined by applying Hooke's law,

$$\sigma_x = E \epsilon_x \tag{2}$$

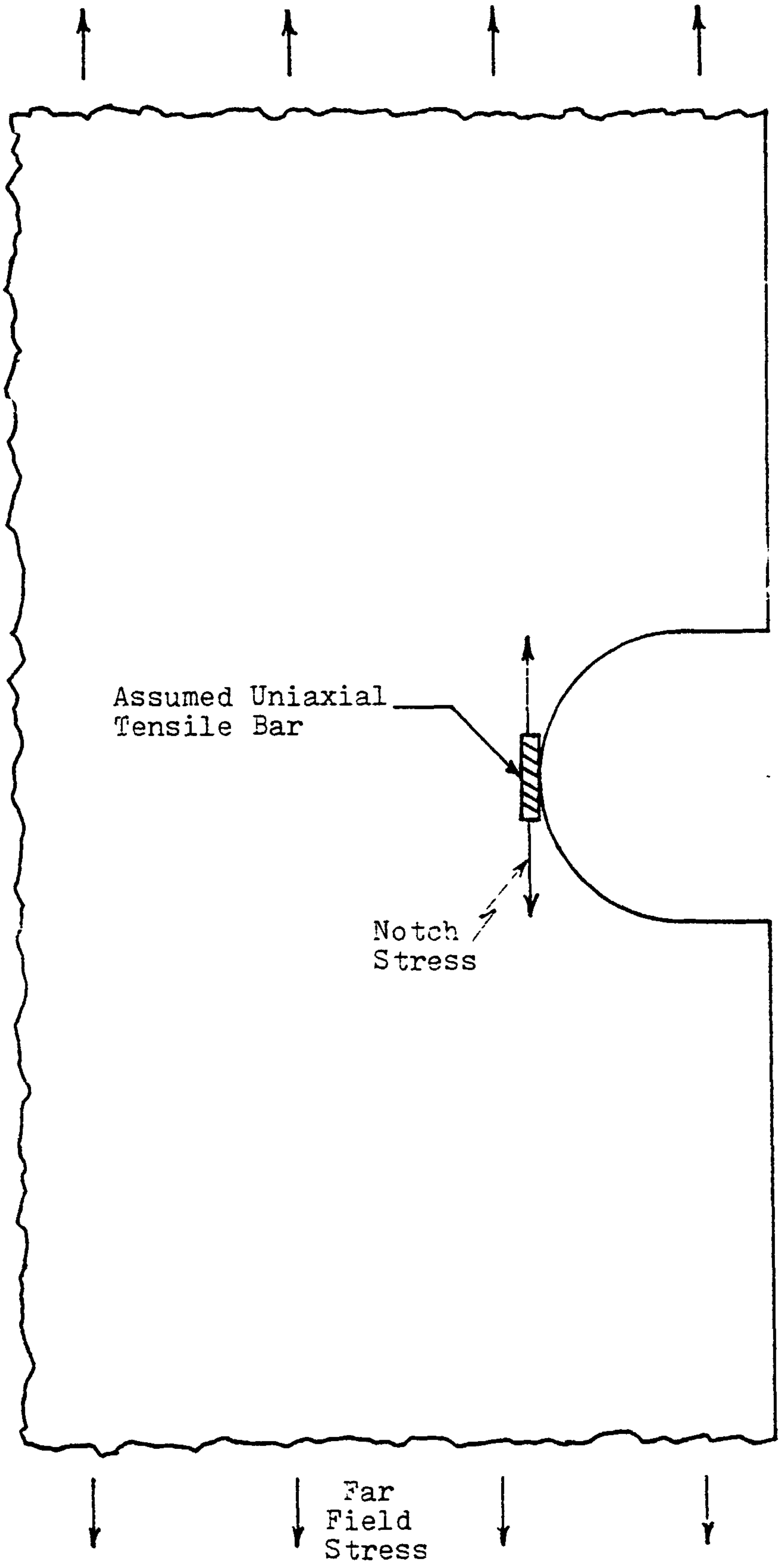


Figure 5 Uniaxial Tension Assumption

where σ_x is the stress and E is the modulus of elasticity.

a. Stress Concentration Factor Determination

The stress concentration factors were determined using data from Tables 1-4 of Appendix A. The fringe order at the notch was found by dividing the compensator reading by forty-seven and adding the appropriate fringe reference number (zero for stress concentration factors and residual stress measurements). The total strain was calculated using the following photoelastic equation from Ref. 9.

$$\epsilon_x - \epsilon_y = \frac{\lambda}{2tK} N \qquad (3)$$

where λ is the wavelength of the light source ($\lambda = 22.7 \times 10^{-6}$ in.)

t is the photoelastic material thickness (inches)

N is the fringe order

K is the sensitivity of the plastic

Substituting for ϵ_y from eq. (1) and collecting terms

$$\epsilon_x = \frac{1}{1+\nu} \frac{\lambda}{2tK} N \qquad (4)$$

The stress at the notch (σ_n) is

$$\sigma_n = \frac{E}{1+\nu} \frac{\lambda}{2tK} N \qquad (5)$$

The stress concentration factor (K_t) is

$$K_t = \frac{\sigma_n}{\sigma} \qquad (6)$$

where σ is the nominal stress (applied load/minimum cross-section). The stress concentration factors are shown in Table 8 of Appendix A.

b. Residual Stress Determination

The residual stress was determined using Fig. 3 and data from Tables 1 and Tables 5-7 of Appendix A. Since there was plastic deformation at the notch tip, the notch stress was determined by first calculating the local strain using eq. (4). Knowing this value of strain, the stress was determined from Fig. 2. It was assumed that the yielded area unloaded along a line paralled to the elastic portion of the stress strain curve as illustrated in Fig. 6. With this assumption, the residual stress could be calculated using the residual strain from eq. (4) and the following

$$\sigma_r = E(\epsilon_r - \epsilon_n) + \sigma_n \quad . \tag{7}$$

where σ_r is the residual stress

ϵ_r is the residual strain

ϵ_n is the strain at the notch under load

σ_n is the notch stress corresponding to strain

The nominal, notch and residual stresses are listed in Tables 9-11 of Appendix A.

5. Test Results

The measured stress concentration factors are shown in Table 8. As can be seen, the stress concentration factors vary considerably from specimen to specimen. The average stress concentration factors were found to be 1.62, 2.69, and 4.05, with standard deviations of 0.132, 0.187, and 0.219 respectively. The error between theoretical and measured stress concentration factors was less than seven percent for all three notch geometries.

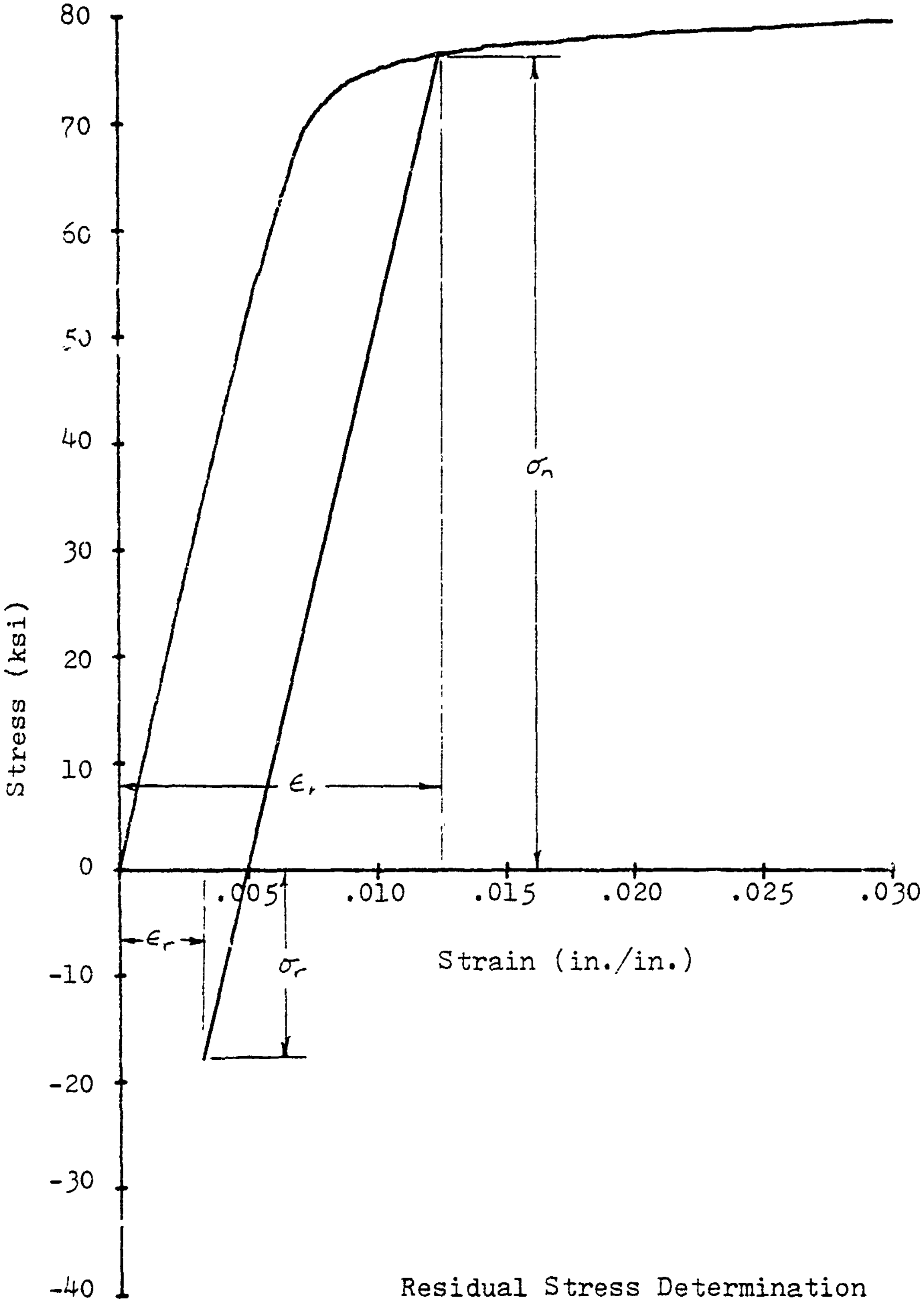
A plot of residual stress versus nominal stress was made for each specimen series using data from Tables 9-11 of Appendix A. Figure 7 shows the considerable scatter of the data. The HP 9830 calculator polynomial regression routine was used to fit a straight line to each of the three groups of data. The curve fit resulted in R square values of 0.692, 0.796, and 0.701 for stress concentration factors of 1.63, 2.60, and 3.80, respectively. These three curves allow for the prediction of residual stress by cross-plotting for a known stress concentration factor and using the nominal stress.

E. NOTCHED SPECIMEN CYCLIC TESTS

In order to verify the residual stress characterization results, two specimens were tested to compare the predicted and measured residual stresses in specimens which were subjected to elements of a flight load sequence. One specimen was also subjected to sinusoidal loading to determine the effect of this type of loading on the induced residual stress.

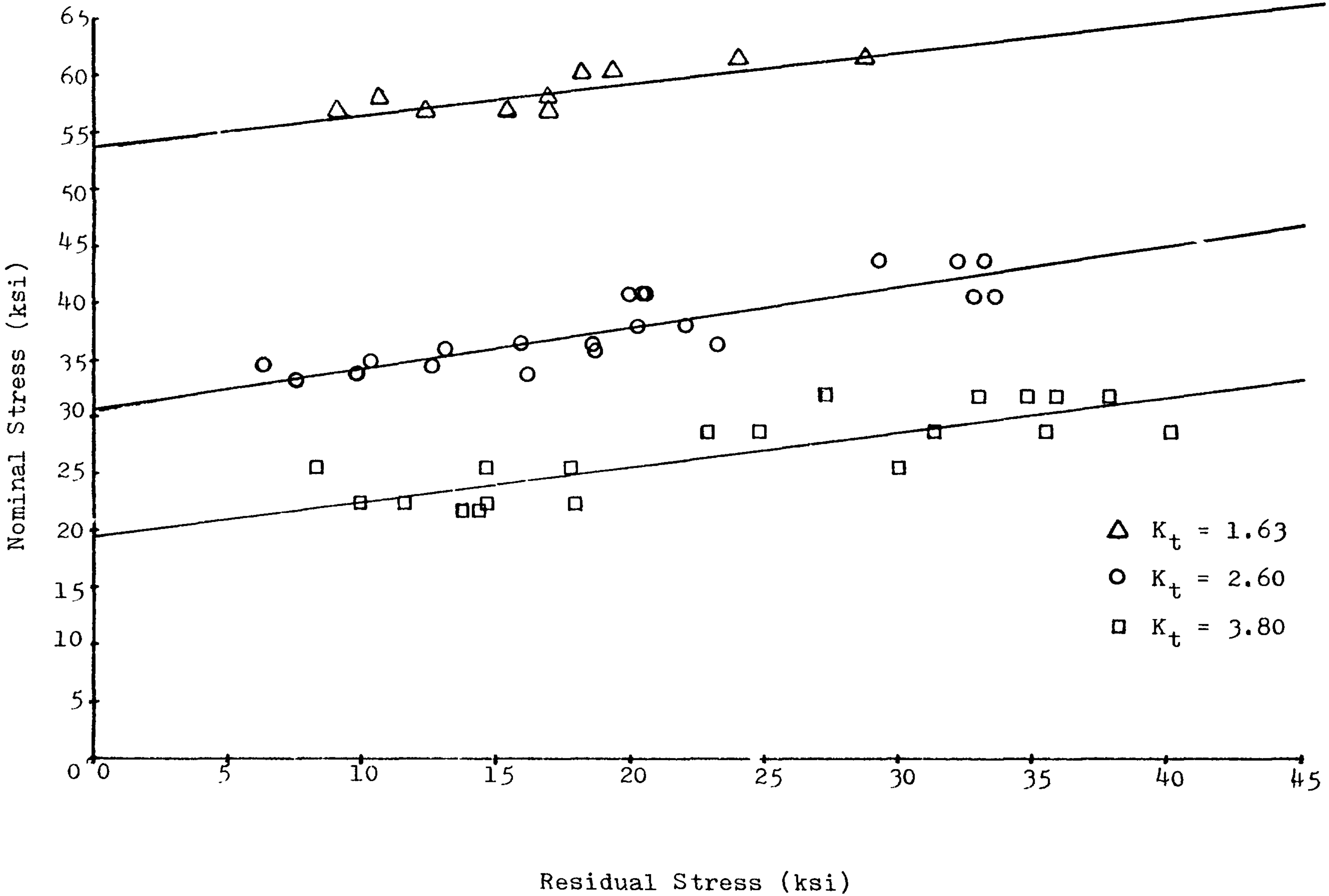
1. Description of Procedure

Two of the specimens with stress concentration factors of 2.60 (specimens 3 and 12), which had been



Residual Stress Determination

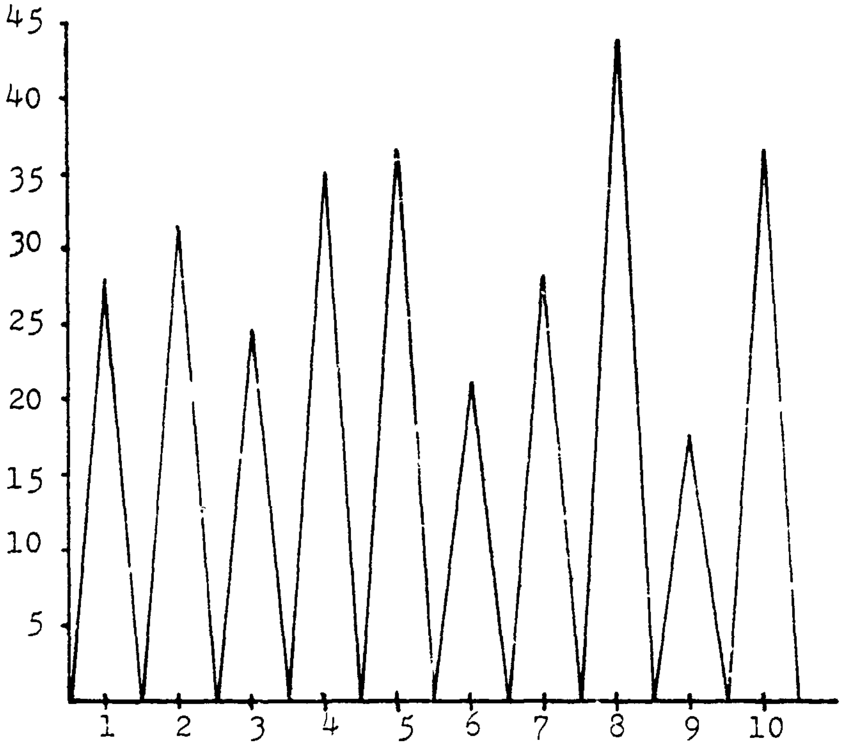
Figure 6



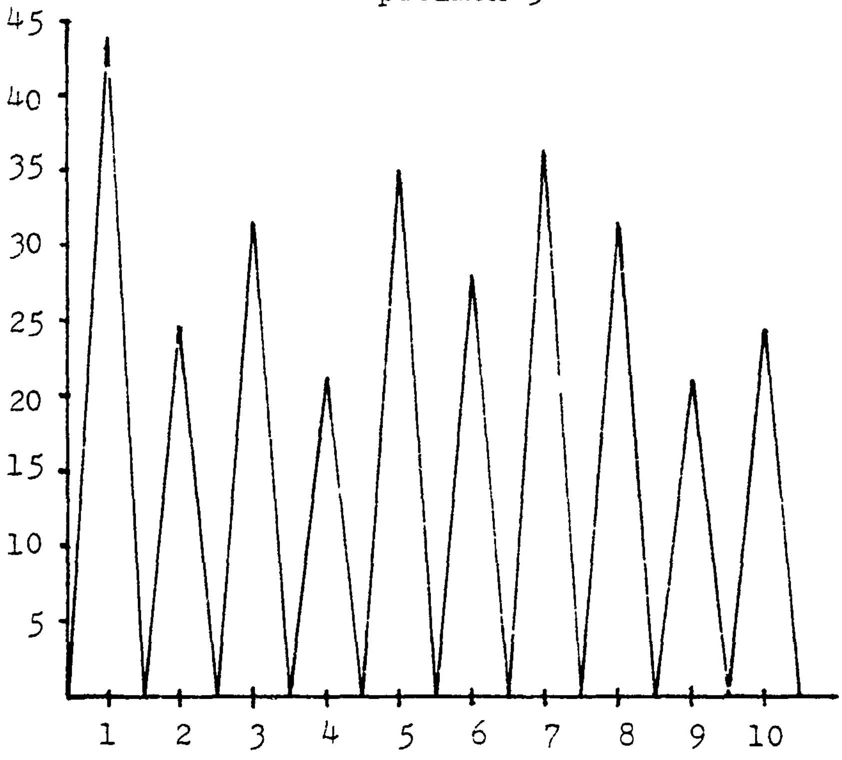
Residual Stress Characterization
Figure 7

subjected to relatively low nominal stresses were tested further. The cyclic tests were performed in the MTS 810 test machine, using an SBC 80/10 microprocessor for control [Ref. 10]. Two load programs of ten cycles were designed, one for each specimen. Specimen 3 was run with varying loads with the maximum load giving a nominal stress peak of 43,810 psi at the end of the ten cycles. Specimen 12 was run similarily but with the same maximum load coming at the beginning of the ten cycles. The two load programs are shown in Fig. 8. After the specimen had completed ten cycles the residual strain was measured using the photoelastic equipment and was recorded in Table 12 of Appendix A. The specimen was then loaded to the maximum load of the cyclic test, and the strain was measured, and the compensator reading was recorded in Table 12 of Appendix A.

Specimen 5 was used to determine if the induced residual stress was altered when the specimen was subjected to sinusoidal cyclic loading, using a maximum load lower than the load used to initially induce the residual stress. The specimen was mounted in the MTC 810, and residual strain was measured. The specimen was loaded to a maximum load of 24,000 pounds and a mean load of 12,500 pounds, which gave maximum and mean stresses of 33,632 psi and 17,517 psi respectively. The residual strain was measured every 100 cycles for the first 500 cycles, again at 1,000 cycles, and then at 1,000 cycle intervals. These measurements were recorded in Table 13 of Appendix A.



Load Cycle
Specimen 3



Load Cycle
Specimen 3

Figure 8 Cyclic Load Programs

2. Test Results

The residual stresses were calculated in the same manner as outlined previously. The measured residual stresses varied from a minimum magnitude of -31,980 psi to a maximum of -37,130 psi with the average of the four notches being -34,000 psi. For a nominal stress of 43,810 psi, the predicted residual stress would be -37,500 psi. The maximum error between the predicted and measured stresses was 10.4 percent, with the average residual value having an error of 4.8 percent.

Specimen 5, which was subject to sinusoidal loading, showed no changes in residual stress through 1,000 cycles. The specimen failed after 1,970 cycles, just prior to the next planned measurement. Time considerations did not allow for further testing in this manner.

III. CONCLUSIONS AND RECOMMENDATIONS

The results of the notched flat plate specimens showed that residual stresses could be measured at the notch tip using photoelastic coatings. Furthermore, the resulting residual stress verus nominal stress curves could be used to predict the residual stress to within ten percent of the measured stress. After a residual stress was induced into the material, it was found to be constant during a low cycle fatigue test at a relatively high stress level.

The residual stress characterization could be applied to fatigue testing in several ways. One application would be to modify the cyclic loading by reducing the load by the residual stress induced by the highest load previously encountered in the program. This type of testing lends itself to microprocessor control of the fatigue testing machine. Another application would be to determine the effect that various residual stress levels would have on the fatigue life of the material for both low cycle and random load fatigue. This could be accomplished by preloading the specimen to obtain the desired residual stress and then performing the fatigue test. Another variation would be to induce residual stresses at various times in the fatigue test and see the resulting effect on fatigue life.

One other area of interest would be to determine the relaxation rate of the residual stress. Several specimens could be tested, some sitting with no load while others were subjected to a compressive load, thereby determining the relaxation rate for various load levels. The relaxation of the residual stress could have a significant impact on the fatigue life prediction, especially if the prediction was based on the presence of a residual stress.

APPENDIX A

EXPERIMENTAL DATA

TABLE 1

PHOTOELASTIC MATERIAL THICKNESS*

Specimen	$K_t = 1.63$	Thickness (inches) $K_t = 2.60$	$K_t = 3.80$
1	0.041	0.040	0.040
2	0.041	0.040	0.040
3	0.041	0.040	0.040
4	0.041	0.040	0.040
5	0.041	0.040	0.040
6		0.043	0.040
7		0.043	0.040
8		0.043	0.040
9		0.043	0.040
10		0.043	0.044
11		0.040	0.044
12		0.040	0.044
13		0.040	
14		0.040	

*Sensitivity factor, K = 0.15

TABLE 2

STRESS CONCENTRATION DATA FOR $K_t = 1.63$

MTS Load Scale: 50 Load Reading: 1.720

Specimen	Compensator
1	47.0/53.5*
2	56.0/57.5
3	55.0/58.0
4	55.5/59.0
5	46.0/53.5

*LEFT/RIGHT

TABLE 3

STRESS CONCENTRATION DATA FOR $K_t = 2.60$

MTS Load Scale: 50 Load Reading: 1.428

Specimen	Compensator
1	83.0/85.0*
2	88.0/88.0
3	90.0/87.0
4	78.0/80.0
5	90.0/87.0
6	99.0/103.0
7	84.5/101.0
8	93.5/93.5
9	84.0/84.0
10	94.0/96.0
11	92.0/88.0
12	90.5/83.0
13	97.5/97.0
14	94.0/96.0

TABLE 4

STRESS CONCENTRATION DATA FOR $K_t = 3.80$

MTS Load Scale: 20 Load Reading: 3.132

Specimen	Compensator
1	138.5/136.0*
2	119.0/ 88.0
3	137.0/134.0
4	41.0/136.0
5	137.0/147.5
6	132.0/141.0
7	134.5/133.0
8	104.0/141.0
9	139.0/145.5
10	148.0/144.0
11	132.0/131.0
12	134.5/145.0

*LEFT/RIGHT

TABLE 5

RESIDUAL STRESS DATA FOR $K_t = 1.63$

Specimen	Load Scale	Load Reading	Compensator (Loaded)	Fringe Read	Compensator (Residual)
1	50	9.800	173.5/187.5*	3/3*	13.0/23.0*
2	100	5.200	180.5/170.0	4/4	53.0/40.0
3	100	5.300	191.0/210.0	4/4	43.5/44.0
4	50	10.000	171.0/197.0	3/3	24.5/22.0
5	50	9.800	156.5/172.0	3/3	18.0/23.0

TABLE 6

RESIDUAL STRESS DATA FOR $K_t = 2.60$

MTS Load Scale: 50

Specimen	Load Reading	Compensator (Loaded)	Fringe Read	Compensator (Residual)
1	4.766	183.0/185.0*	2/2*	12.0/12.0*
2	5.143	189.5/168.5	3/3	23.0/23.0
3	5.202	218.0/197.0	3/3	35.0/27.0
4	4.977	188.5/192.5	2/2	9.0/0.0
5	4.851	171.0/149.0	3/3	16.0/14.0
6	5.821	177.0/185.0	4/4	29.0/34.0
7	6.253	225.0/225.0	5/5	75.0/84.5
8	6.253	** /225.0	** /5	79.0/71.5
9	4.938	149.5/187.0	3/3	14.0/21.0
10	6.253	/211.0	/5	89.0/74.0
11	5.821	/186.0	/4	67.0/60.0
12	5.202	184.0/181.0	3/3	27.0/22.5
13	5.438	183.0/189.0	4/4	49.0/59.0
14	5.821	160.0/177.5	4/4	35.5/54.0

*LEFT/RIGHT
**FRINGES COULD NOT BE MEASURED

TABLE 7

RESIDUAL STRESS DATA FOR $K_t = 3.80$

MTS Load Scale: 20

Specimen	Load Reading	Compensator Loaded	Fringe Read	Compensator (Residual)
1	6.801	205.5/210.5*	2/2*	13.0/12.0*
2	9.000	217.0/	4/	34.0/
3	7.000	185.5/164.5	3/3	19.0/11.5
4	8.000	/187.0	/3	/21.5
5	9.000	204.0/183.0	4/5	53.5/52.0
6	10.000	225.0/224.0	5/5	82.0/90.0
7	7.000	211.5/202.5	2/2	22.0/20.0
8	8.000	/184.0	/4	/26.5
9	9.000	183.0/186.0	5/5	59.5/57.0
10	10.000	214.0/217.0	6/6	91.0/98.0
11	10.000	208.5/222.0	6/5	95.5/85.5
12	8.000	152.0/175.5	4/4	41.0/41.0

TABLE 8

STRESS CONCENTRATION FACTORS

Specimen	$K_t = 1.63$	$K_t = 2.60$	$K_t = 3.80$
1	1.40/1.60*	2.54/2.60*	4.23/4.16*
2	1.67/1.72	2.69/2.69	3.63/
3	1.64/1.73	2.75/2.66	4.19/4.10
4	1.66/1.76	2.38/2.45	/4.16
5	1.37/1.60	2.75/2.66	4.19/4.36
6		2.18/2.93	4.04/4.31
7		2.40/2.87	4.11/4.07
8		/2.66	/4.31
9		2.38/2.38	3.86/4.04
10		/2.73	4.11/4.00
11		/2.67	3.67/3.64
12		2.77/2.54	3.74/4.03
13		2.98/2.97	
14		2.87/2.94	
AVERAGE	1.62	2.69	4.05
STD. DEV.	0.132	0.187	0.219

*LEFT/RIGHT

TABLE 9

RESIDUAL STRESS CHARACTERIZATION FOR $K_t = 1.63$

Specimen	Nominal	Notch	Residual
1	56,980	74,500/75,000*	-15,390/-16,910*
2	60,465	75,770/75,590	-18,160/-19,350
3	61,630	75,950/76,250	-24,040/-28,790
4	58,140	74,280/75,000	-10,590/-16,910
5	56,980	73,750/74,500	-9,070/-12,360

TABLE 10

RESIDUAL STRESS CHARACTERIZATION FOR $K_t = 2.60$

STRESSES (psi)

Specimen	Nominal	Notch	Residual
1	33,390	73,250/73,250*	-7,550/ -7,550*
2	36,040	75,250/74,750	-18,680/-13,120
3	36,450	75,770/76,350	-23,210/-18,590
4	34,990	73,500/73,500	-10,330/0
5	33,990	74,750/ 7,400	-16,150/ -9,830
6	40.790	75,410/75,530	-20,540/-20,420
7	43,810	76,850/76,850	-32,230/-33,240
8	43,810	/76,850	/-33,240
9	34,600	72,500/74,250	-6,280/-12,610
10	43,810	/76,750	/-29,300
11	40,790	/76,010	/-19,940
12	36,450	75,000/75,000	-15,900/-16,910
13	38,100	75,950/76,070	-22,020/-20,260
14	40,790	76,500/76,750	-33,590/-32,830

*LEFT/RIGHT

TABLE 11

RESIDUAL STRESS CHARACTERIZATION FOR $K_t = 3.80$

STRESSES (psi)

Specimen	Nominal	Notch	Residual
1	21,715	74,150/74,250*	-13,720/-14,360*
2	28,735	76,600/	-35,510/
3	22,350	75,000/74,250	-17,920/-14,630
4	25,540	/75,150	/-17,770
5	28,735	77,000/76,750	-40,160/-31,350
6	31,930	77,250/77,250	-37,890/-35,870
7	22,350	74,250/73,900	-11,600/ -9,930
8	25,540	/76,010	/-30,040
9	28 735	76,130/76,190	/-30,040
10	31,930	77,200/77,300	-35,920/-34,810
11	31,930	77,100/76,750	-32,990/-27,280
12	25,540	74,500/75,250	-8,320/-14,640

*LEFT/RIGHT

TABLE 12

PSEUDO-RANDOM CYCLIC LOAD DATA

Load Scale: 50 Max Load: 6.252

Specimen	Compensator (Loaded)	Fringe	Compensator (Residual)
3	183.0/212.0*	6/5*	101.0/73.0*
12	218.0/215.0	5/5	94.5/89.5

STRESSES

Specimen	Nominal	Notch	Residual
3	43,810	77,250/77,000*	33,850/37,130*
12	43,810	77,100.77,050	31,980/33,040

TABLE 13

SINUSOIDAL CYCLIC LOAD DATA

Specimen: 12
Mean Load: 12,500 lbs.
Max Load: 24,000 lbs.

CYCLES	COMPENSATOR
0	33.5/26.5*
100	33.5/26.5
200	33.5/26.5
300	33.5/26.5
400	33.5/26.5
500	34.0/27.5
1,000	33.5/26.5

Specimen failed at 1,970 cycles

*LEFT/RIGHT

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