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MAXIMUM STRESS CONCENTRATION FACTORS CAUSED BY TWO EQUAL CIRCULAR HOLES IN A PLATE SUBJECTED TO UNIFORM AXIAL LOADING

by

Matthew F. Borg

[redacted]

STRUCTURAL MECHANICS LABORATORY

RESEARCH AND DEVELOPMENT REPORT

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CDR S.R. Heller, Jr., USN

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ABSTRACT

Two specimens, designed to explore significant and insignificant interaction of the effects of two circular holes, were tested under uniform axial compression. The experimental data verify the maximum stress concentration factors obtained theoretically by Ling. The verified theoretical values are presented both in tabular form and in a chart suitable for engineering purposes.

INTRODUCTION

In almost all structures, openings of some sort are required, either for access or for passing piping, ventilation, or electrical systems to the various compartments. It, therefore, behooves the structural designer to make proper provisions for these requirements without adversely affecting the structure as a whole.

Because of its simplicity of construction, the circle has probably been used most widely for such penetrations. With the ever-increasing complexity of internal systems for ships, the structural designer has been faced with an ever-increasing number of penetrations. Similarly, the systems designer has found it desirable to group his penetrations in wireways, pipe tunnels, and the like. Hence, the structural designer is faced with a situation where circular holes are, for reasons beyond his control, spaced so closely that the effects of one have not dissipated before the appearance of another.

Admittedly, the ultimate problem is to choose a combination of hole spacing and reinforcement that permits economic assembly and safe structure. The first phase of this problem is, however, the determination of the effect of hole spacing. It is this facet that is reported here.

Theoretical and experimental investigations of stress distribution around various shaped openings date back to 1898 and Kirsch's classical work on a single circle. It remained, however, until 1921 for the effects of more than a single hole to be studied. Between 1921 and 1948, the effects of two equal circular holes in a plate were studied by Poschl,[1] Weber,[2] Weinel,[3] Frocht,[4] and Ghosh[5] for various types of loading. All these studies were based on bipolar coordinates, the use of which was first propounded by Jeffery.[6]

Finally, in 1948, Ling[7] published rigorous solutions for the effects of two equal circular holes in an infinite plate loaded with uniform tension normal to the line joining the centers (transverse), for uniform tension parallel to the line joining the centers (longitudinal), and for uniform all-around tension. Savin[8] confirmed Ling's findings photoelastically for the transverse loading of two equal circles separated by three diameters. It is the purpose of this report to compare experimental results for both transverse and longitudinal loadings with Ling's theoretical values.

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[1]References are listed on page 11.

THEORETICAL ANALYSIS

Ling developed a nondimensional expression for the stress at the edge of the holes:

$$\frac{\sigma_t}{T} = 2\,(\cosh\alpha - \cos\xi)\left\{K \sinh\alpha\left(1 + 4\sum_{n=1}^{\infty}\frac{\sinh n\alpha\ \cos n\xi}{\sinh 2n\alpha + n\sinh 2\alpha}\right)\right. \quad [1]$$

$$\left.\mp 2\sum_{n=1}^{\infty}\frac{n\,(n\sinh n\alpha\ \sinh\alpha - \cosh n\alpha\ \cosh\alpha\,)\cos n\xi}{\sinh 2n\alpha + n\sinh 2\alpha}\right\}$$

where K is a numerical coefficient, and the ambiguous sign of the second term within the braces are both dependent on the type of loading,

σ_t is the tangential stress at the edges of the hole, and

T is the applied uniform stress remote from the hole.

For all around loading:

$$K\left[\frac{1}{2} + \tanh\alpha\ \sinh^2\alpha - 4\sum_{n=2}^{\infty}\frac{e^{-n\alpha}\ \sinh n\alpha + n\sinh\alpha(n\sinh\alpha + \cosh\alpha)}{n\,(n^2 - 1)\,(\sinh 2n\alpha + n\sinh 2\alpha\,)}\right] = 1 \quad [1a]$$

and the second term within the braces of Equation [1] is zero.

For unidirectional loading:

$$K = \frac{\frac{1}{2} \pm \frac{1}{2} \mp 2\sinh^2\alpha \sum_{n=1}^{\infty}\frac{n}{\sinh 2n\alpha + n\sinh 2\alpha}}{\frac{1}{2} + \tanh\alpha\ \sinh^2\alpha - 4\sum_{n=2}^{\infty}\frac{e^{-n\alpha}\ \sinh n\alpha + n\sinh\alpha(n\sinh\alpha + \cosh\alpha)}{n\,(n^2-1)\,(\sinh 2n\alpha + n\sinh 2\alpha)}} \quad [1b]$$

where the ambiguous sign in K is interpreted as:

Upper sign for longitudinal loading.

Lower sign for transverse loading.

This same convention applies to the ambiguous sign in Equation [1].

In Equations [1], [1a], and [1b], α is defined in terms of the nondimensional distance between centers (see Figure 1) by the relation:

$$\lambda = \cosh\alpha \quad [2]$$

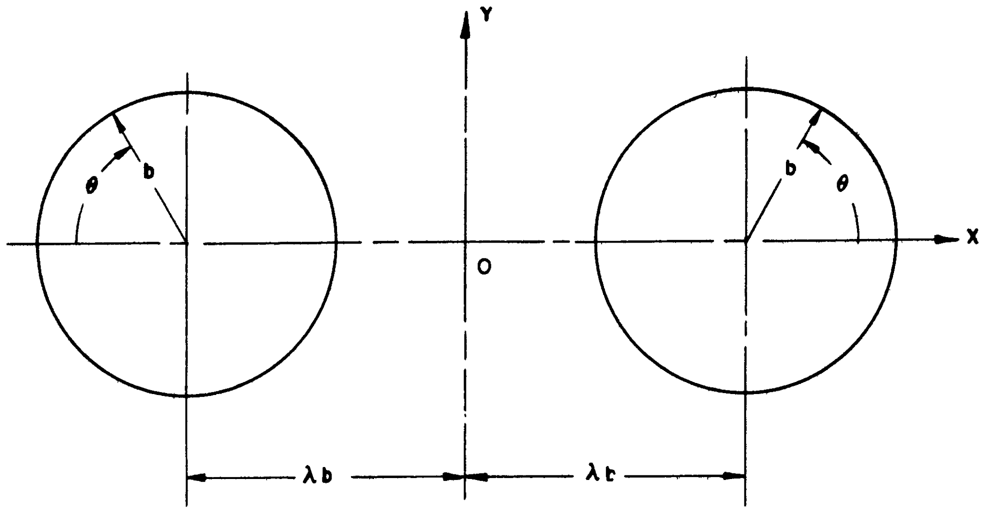


Figure 1 - Geometry and Notation of Two Equal Circles

TABLE 1

Maximum Stress Predicted by Equation [1]

λ	Stress Concentration Factor $(\sigma_t/T)_{max}$				
	Longitudinal Loading	Transverse Loading		All-Around Loading	
	$\theta = \pm\frac{\pi}{2}$	$\theta = 0$	$\theta = \pi$	$\theta = 0$	$\theta = \pi$
1	2.569	3.869	∞	2.894	∞
1.1	2.571	3.409	6.106	2.490	5.451
1.3	2.594	3.234	3.744	2.332	3.417
1.5	2.623	3.151	3.264	2.255	2.887
2	2.703	3.066	3.020	2.158	2.411
3	2.825	3.020	2.992	2.080	2.155
5	2.927	3.004	2.997	2.033	2.049
8	2.970	3.001	2.999	2.014	2.018
∞	3.0	3.0	3.0	2.0	2.0

and ξ is related to θ, the polar angle from the center of the circle to the point under consideration, by:

$$\cos \xi = \frac{1 + \lambda \cos \theta}{\lambda + \cos \theta}$$

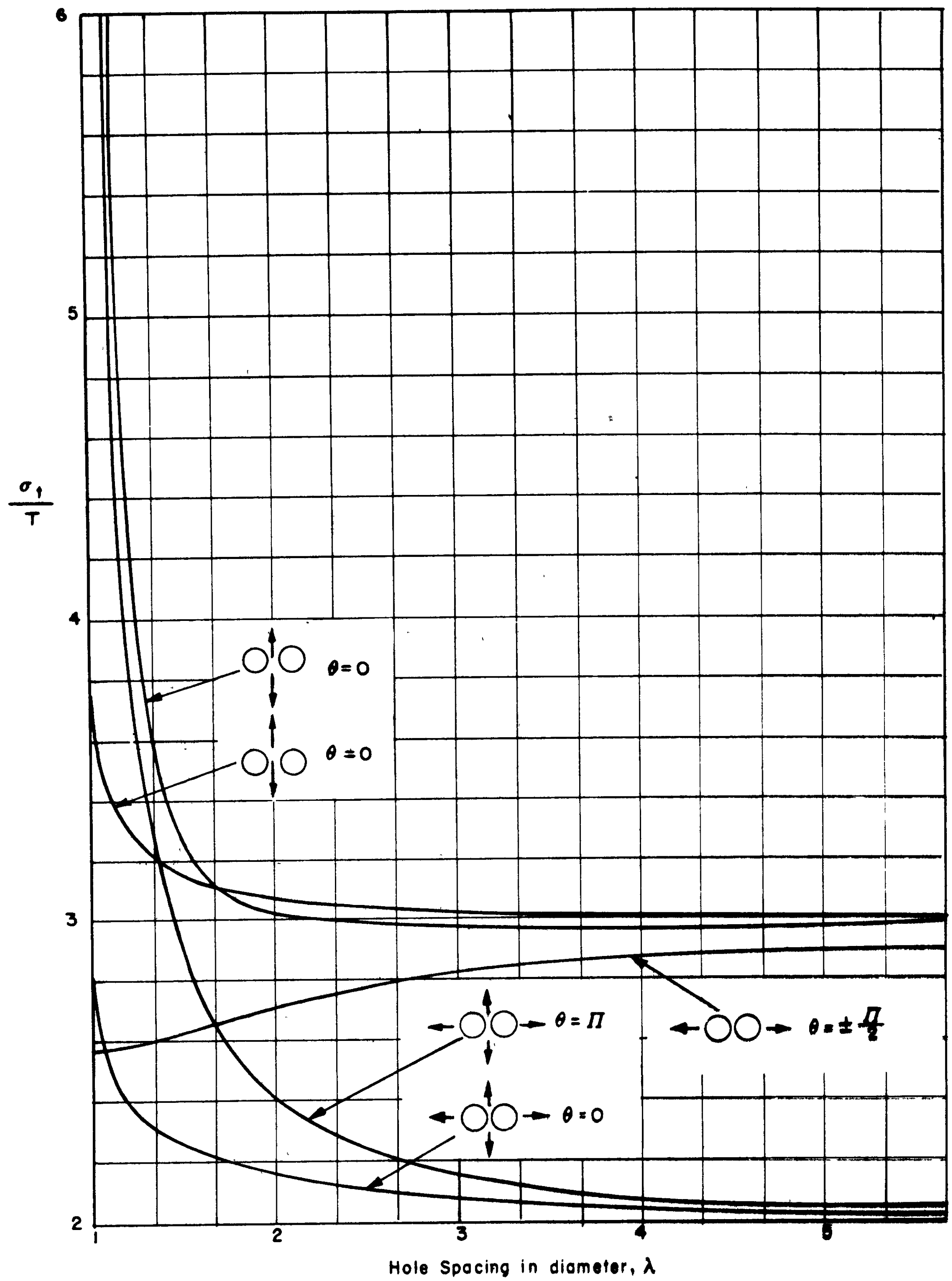


Figure 2 - Maximum Stress Concentration Factors versus Hole Spacing

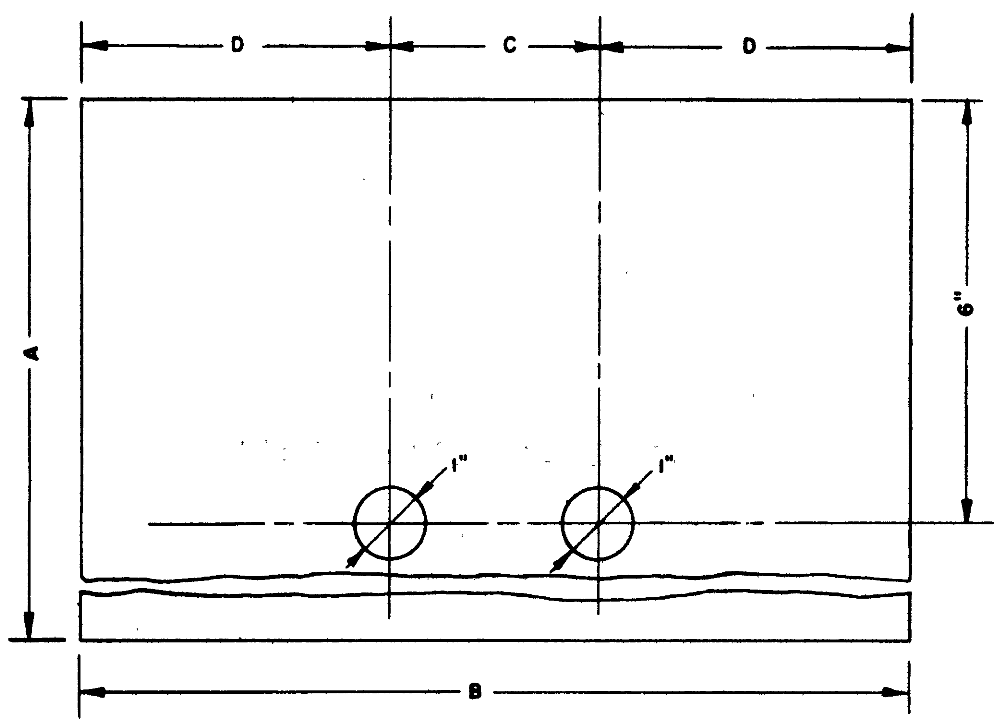
Calculated values of the stress concentration factor $(\sigma_t/T)_{max}$ for the three types of loading are summarized in Table 1 and plotted in Figure 2.

EXPERIMENTAL INVESTIGATION

Reference to Table 1 indicates that for $\lambda = 3$, there is no appreciable interaction of the effects of the two holes. Conversely, for $\lambda = 1.5$, the interaction is significant. Accordingly, the experimental investigation was designed to explore these two specific cases.

Two steel models were prepared having the dimensions shown in Figure 3. Both models were made from 3/8-in. nominal thickness plate and were essentially 12 in. square. The plates were ground to obtain parallel faces from which opposite edges were squared off and ground for parallelism within ± 0.0001 in. The surface finish for the edges of the plate and the insides of the holes was 63 μin.

Two groups of SR-4 strain gages were installed. Group I, those identified by letters in Figure 4, were installed on the faces of the plates, back to back, to determine the stress



Model	λ	A in.	B in.	C in.	D in.	Thickness in.
1	3	12.01	12.01	3.0	4.505	0.3736
2	1.5	12.0	12.0	1.50	5.25	0.3283

Figure 3 - Dimensions of Steel Models

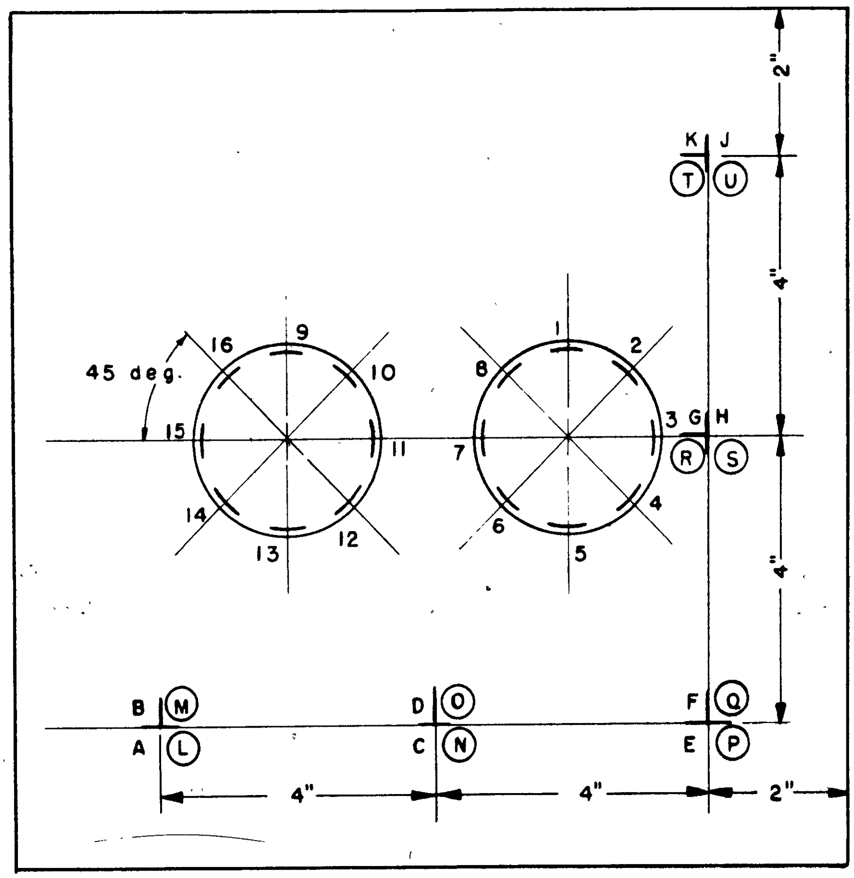


Figure 4 - Location of Strain Gages

Numbers indicate A-8 gages. Letters indicate A-1 gages.
Circled letters indicate gages on opposite face.

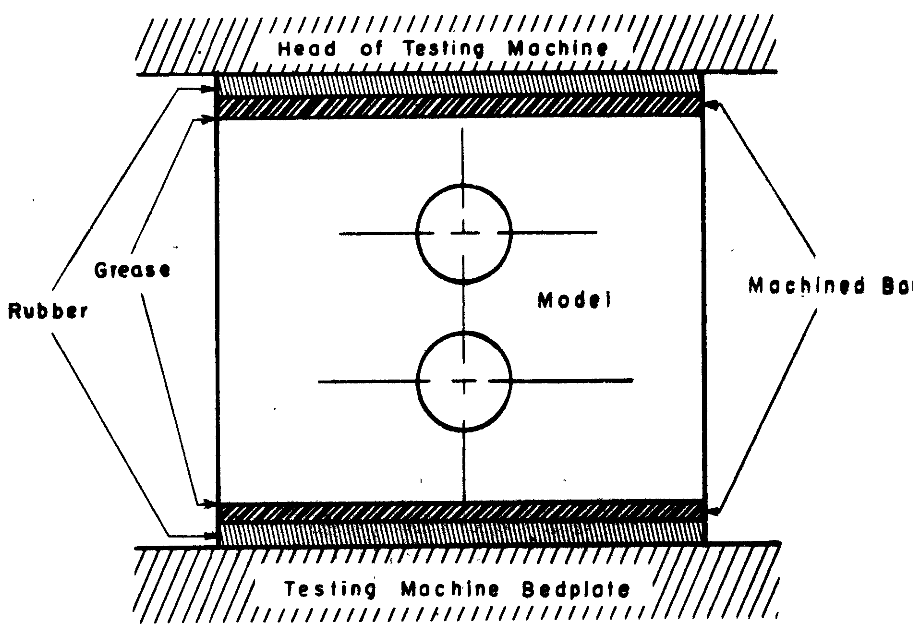


Figure 5 - Schematic Loading Arrangement

distribution in the plate remote from the openings. Group I gages were installed normal and parallel to the direction of applied loads. Group II, those identified by numbers in Figure 3, were installed inside the holes to determine the stress distribution along these boundaries.

The models were compressed in the 600-kip testing machine first longitudinally, then transversely. To assure uniform loading, the edges of the plates were coated with grease and centered top and bottom on machined bars, 12 by 1 by 1/2 in. A 1/8-in. strip of rubber was placed between each machined bar and loading plate of the testing machine. Figure 5 shows the loading arrangement schematically.

Load was applied in increments of 5000 lb up to maximum load. The maximum load was 35,000 lb longitudinally and 30,000 lb transversely. At each increment of load, all gages were read.

TEST RESULTS

Modulus of elasticity E and Poisson's ratio ν were determined experimentally for each model and for each condition of loading. The average strain values remote from the openings were calculated from these average values. Data for longitudinal loading are summarized in Table 2 and for transverse loading in Table 3.

TABLE 2

Experimental Data for Longitudinal Loading

Gages	Average Strain μin/in.		Calculated Stress psi		Young's Modulus $E \times 10^{-6}$ psi		Poisson's Ratio ν	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
B,M	−279.0	−305.0	−7800	−8880	27.94	29.12		
D,O	−279.0	−312.5	−7800	−8880	27.94	28.44		
F,Q	−274.0	−305.0	−7800	−8880	28.45	29.12		
H,S	−269.0	−305.0	−7800	−8880	28.98	29.12		
J,U	−264.0	−332.5	−7800	−8880	29.52	Negl.		
A,L	+ 76.1	+ 95.0	−7800	−8880			0.279	0.310
C,N	+ 76.1	+ 97.0	−7800	−8880			0.279	0.316
E,P	+ 76.1	+ 92.0	−7800	−8880			0.279	0.30
G,R	+ 66.0	+ 89.0	−7800	−8880			Negl.	0.290
K,T	+ 76.1	+ 95.0	−7800	−8880			0.279	0.310
Average	−273.0 + 76.1	−306.5 + 93.6	−7800	−8880	28.57	28.95	0.279	0.305

TABLE 3

Experimental Data for Transverse Loading

Gages	Average Strain μin/in.		Calculated Stress psi		Young's Modulus $E \times 10^{-6}$ psi		Poisson's Ratio ν	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
A,L	−229.0	−317.5	−6690	−8880	29.21	27.96		
C,N	−223.0	−302.5	−6690	−8880	29.99	29.34		
E,P	−239.0	−315.0	−6690	−8880	27.98	28.18		
G,R	−229.0	−307.5	−6690	−8880	29.21	28.89		
K,T	−223.0	−322.5	−6690	−8880	29.99	27.52		
B,M	+ 69.0	+ 95.0	−6690	−8880			0.304	0.304
D,O	+ 61.0	+ 87.6	−6690	−8880			0.267	0.280
F,Q	+ 71.0	+ 95.1	−6690	−8880			0.311	0.304
H,S	+ 66.0	+ 90.2	−6690	−8880			0.289	0.288
J,U	+ 66.0	+ 95.2	−6690	−8880			0.289	0.304
Average	−228.3 + 66.7	−312.9 + 92.6	−6690	−8880	29.28	28.38	0.292	0.296

Nondimensional stress representations (σ_t/T) were calculated by dividing measured strains by the average strains remote from the openings. For the latter, values taken from Tables 2 and 3 were used. For the case of all-around loading, the nondimensional stress representations were obtained by superposition. The data are summarized in Table 4.

[Editor's Note: The geometrical symmetry about an axis normal to the line of centers would permit detailed study of a single hole. The stress distributions around the holes are mirror images. The symmetry of the loading, about the axis formed by the line of centers, similarly, would permit the detailed study of one half of one hole. Circles of only 1 in. in diameter did not permit gages any closer than 45 deg; larger diameter holes would have permitted gages every 15 deg. If symmetry had been used to best advantage, larger specimens with larger holes should have been employed to determine the stress distribution more closely and with fewer gages.

The data from Table 4 can, therefore, be compressed into a smaller table by taking advantage of the inherent symmetry. Table 5 is the result of this reduction obtained by averaging the values measured at corresponding points. In addition, the maximum theoretical values, taken from Table 1, are supplied for comparison purposes.]

TABLE 4

Summary of Experimental Nondimensional Stress Data

Gage	Nondimensional Stress									
	Longitudinal Loading				Transverse Loading				All-Around Loading	
	Model 1		Model 2		Model 1		Model 2		Model 1	Model 2
	ϵ	$\frac{\sigma_t}{T}$	ϵ	$\frac{\sigma_t}{T}$	ϵ	$\frac{\sigma_t}{T}$	ϵ	$\frac{\sigma_t}{T}$	$\frac{\sigma_t}{T}$	$\frac{\sigma_t}{T}$
1	−760.0	+2.783	−787.8	+2.570	+265.0	−1.160	+ 320.0	−1.024	+1.623	+1.546
2	+221.0	+0.810	−221.6	+0.723	−215.0	+0.942	− 346.9	+1.109	+1.752	+1.832
3	+300.8	−1.102	+356.2	−1.162	−710.0	+3.107	−1065.0	+3.403	+2.005	+2.241
4	−220.2	+0.807	−215.4	+0.703	−217.4	+0.952	− 343.2	+1.097	+1.759	+1.800
5	−768.7	+2.817	−790.0	+2.578	+262.0	−1.147	+ 329.3	−1.053	+1.670	+1.525
6	−219.1	+0.803	−216.3	+0.706	−215.8	+0.945	− 340.5	+1.089	+1.748	+1.795
7	+299.7	−1.098	+163.0	−0.532	−706.6	+3.093	−1031.0	+3.296	+1.995	+2.764
8	−222.2	+0.814	−221.9	+0.724	−214.2	+0.938	− 351.0	+ 1.122	+1.752	+1.846
9	−764.2	+2.80	−798.0	+2.602	+263.0	−1.151	+ 324.0	−1.036	+1.649	+1.566
10	−219.4	+0.804	−220.6	+0.720	−214.0	+0.937	− 345.7	+1.105	+1.741	+1.825
11	+298.2	−1.092	−165.2	−0.539	−712.4	+3.120	−1052.0	+3.362	+2.028	+2.823
12	−223.0	+0.817	−220.0	+0.718	−216.0	+0.946	− 348.2	+1.114	+1.763	+1.832
13	−768.0	+2.812	−800.0	+2.610	+267.7	−1.172	+ 332.0	−1.061	+1.640	+1.549
14	−223.2	+0.818	−218.8	+0.714	−213.3	+0.934	− 349.7	+1.118	+1.752	+1.832
15	+303.9	−1.114	+362.0	−1.181	−704.0	+3.082	−1085.0	+3.468	+1.968	+2.287
16	−223.6	+0.819	−219.4	+0.716	−214.0	+0.937	− 352.3	+1.126	+1.756	+1.842

TABLE 5

Comparison of Experimental and Theoretical Nondimensional Stress Relations

Polar Angle θ, rad.	Nondimensional Stress											
	Longitudinal Loading				Transverse Loading				All-Around Loading			
	$\lambda = 1.5$		$\lambda = 3$		$\lambda = 1.5$		$\lambda = 3$		$\lambda = 1.5$		$\lambda = 3$	
	Exp.	Theory	Exp.	Theory	Exp.	Theory	Exp.	Theory	Exp.	Theory	Exp.	Theory
$0, 2\pi$	−1.171		−1.108		+3.436	+3.151	+3.095	+3.020	+2.264	+2.255	+1.987	+2.080
$\pm \frac{\pi}{4}$	+0.714		+0.814		+1.112		+0.941		+1.827		+1.755	
$\pm \frac{\pi}{2}$	+2.590	+2.623	+2.803	+2.825	−1.044		−1.158		+1.547		+1.646	
$\pm \frac{3\pi}{4}$	+0.717		+0.810		+1.108		+0.941		+1.825		+1.751	
π	−0.536		−1.095		+3.329	+3.264	+3.107	+2.992	+2.794	+2.887	+2.012	+2.155
$\frac{\text{Exp.}}{\text{Theory}}$	0.987		0.993		1.09 1.019		1.024 1.037		1.004 0.969		0.956 0.934	

DISCUSSION OF RESULTS

The discrepancies between experiment and theory range from −6.5 to +9.0 percent as shown in Table 5. This constitutes essential agreement between the two.

The usual possible sources of experimental error apply:

1. A variation of ± 2 percent of the strain gages.
2. A variation of ± 4 percent caused by integration of strain over the gage length of 1/8 in.
3. A variation of ± 0.5 percent in the auxiliary equipment for strain gages.
4. A variation of ± 0.5 percent in the load-measuring device of the testing machine.

If a combination of extreme variations should occur, the total experimental error could vary from − 6.8 to + 7.2 percent. In addition, there is always the possibility of slight misalignment of gages. Inasmuch as the experimental variations lie in the band normally expected, it is considered that essential agreement exists between theory and experiment.

CONCLUSIONS

1. The experimental data reported herein confirm Ling's theory. Equation [1] is a satisfactory prediction of maximum stress.

2. For engineering purposes, the maximum stress values listed in Table 1 can be used with confidence. Figure 2 will, however, usually be more useful.

3. For transverse loading with hole spacings equal to or greater than two diameters ($\lambda \geq 2$), there is less than 5-percent increase over the stress values predicted for a single hole. For all-around loading with hole spacings equal to or greater than three and a half diameters ($\lambda \geq 3.5$), there is a corresponding increase over the stress values predicted for a single hole of only 5-percent. For longitudinal loading regardless of the hole spacing, the stress is always less than that predicted for a single hole.

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2. Plates – Elasticity
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MAXIMUM STRESS CONCENTRATION FACTORS CAUSED BY TWO EQUAL CIRCULAR HOLES IN A PLATE SUBJECTED TO UNIFORM AXIAL LOADING, by Matthew F. Borg. Edited by S.R. Heller. Sep 1957. ii, 13p. tables, graphs, diagrs., refs. (Structural Mechanics Laboratory Research and Development Report)
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Two specimens, designed to explore significant and insignificant interaction of the effects of two circular holes, were tested under uniform axial compression. The experimental data verify the maximum stress concentration factors obtained theoretically by Ling. The verified theoretical values are presented both in tabular form and in a chart suitable for engineering purposes.

1. Plates – Stresses
2. Plates – Elasticity
I. Borg, Matthew P.
II. Title: Stress concentration
III. NS 731-037