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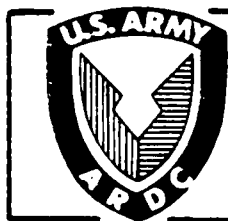
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TECHNICAL REPORT ARLCB-TR-84037

**STRESS CONCENTRATION DUE TO
AXIAL TENSION OF LOADED
NONSYMMETRIC-SHAPED GROOVES**

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NOVEMBER 1984



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20. ABSTRACT (CONT'D)

describes a photoelastic study on stress concentration in plates due to axial tension of loaded nonsymmetric-shaped grooves. Groove geometries as well as loading conditions are given. Maximum groove stresses were found and stress concentration factors were calculated. Also, parametric curves of stress concentration were obtained. A comparison was made between experimental results and those calculated by means of Heywood's equation.

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INTRODUCTION

Lug and groove connections are frequently found in structures where two components meet and loads are transmitted. These grooves usually have a nonsymmetric shape, i.e., the flank angle at the loaded face is different from that at the free face. While numerous data on stress concentrations for symmetric-shaped grooves (for example, U- or V-shaped) are available (ref 1), very little information exists for nonsymmetric-shaped grooves. This report describes a photoelastic study on stress concentration in plates due to axial tension of loaded nonsymmetric-shaped grooves. Three loading conditions were investigated: remote load, concentrated flank load, and distributed flank load. The objectives were (1) to find how the magnitude and position of the maximum groove stresses vary with the groove geometry, the type of load, and the point of application of the load, and (2) to construct parametric curves of stress concentration factors for design use. In addition, the models were modified to resemble loaded projections and tested under concentrated flank load. The results were compared with those calculated by means of Heywood's equation (ref 2).

MODELS AND LOADING

Figures 1(a), (b), and (c) show sketches of models for investigations in remote load, flank load, and loaded projections, respectively. The grooves had a British standard buttress profile with a primary flank angle α of 7

¹Peterson, R. E., Stress Concentration Factors, John Wiley & Sons, 1974.

²Heywood, R. B., "Tensile Stresses in Loaded Projections," Proceedings of the Institute of Mechanical Engineers, Vol. 159, pp. 384-391, 1948.

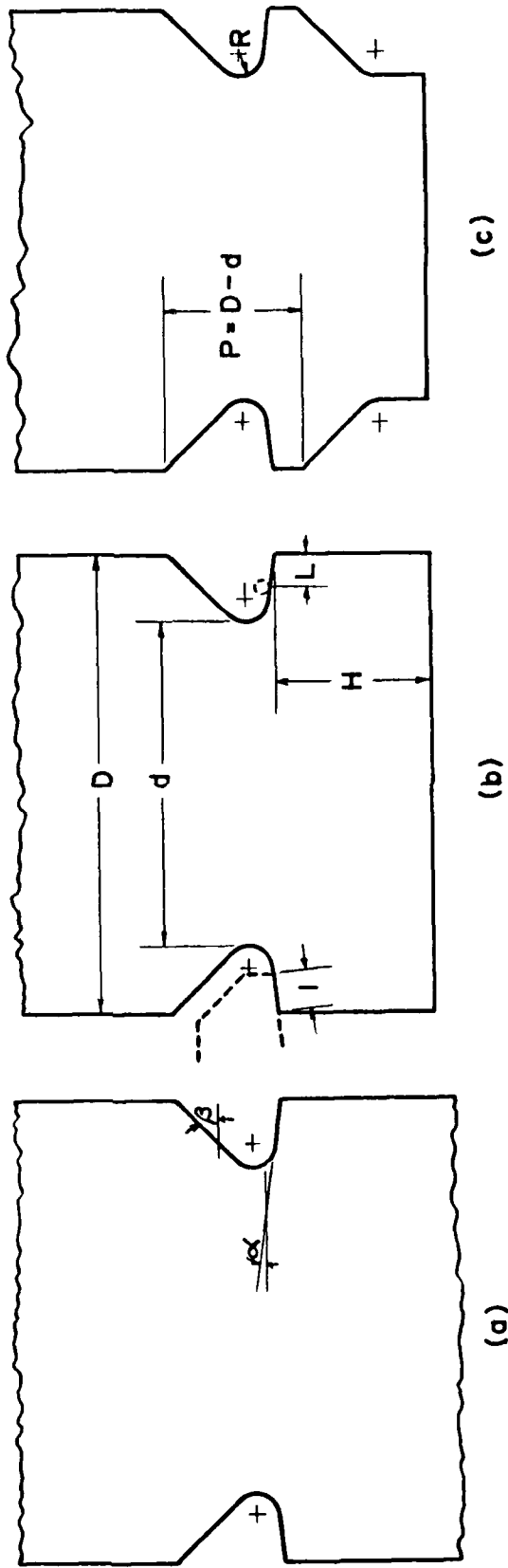


Fig. 1 Sketch of models

degrees at the loaded face and a secondary flank angle β of 45 degrees. The models had a gross width D of 90 mm and a net width d of 63 mm at the narrowest transverse section. They were made of photoelastic model material type PSM-1, supplied by Measurement Group, Raleigh, NC. The material had a fringe value of 252 kPa per fringe per inch. Four combinations of model thickness and groove radius were studied. They are shown in Table I.

TABLE I. MODEL THICKNESS AND GROOVE RADIUS

Model	A	B	C	D
Thickness, t , mm	3.18	6.35	6.35	6.35
Radius, R , mm	3.18	6.35	9.53	12.7

Remote loads were applied through pins at both ends of the model, Figure 1(a). After tests in remote load were completed, the lower end containing primary flank was shortened and models for flank load with $H = 0.5d$ were obtained, Figure 1(b). An aluminum fixture having two mating 7 degree inclined faces, Figure 2, was used to apply distributed loads to both flanks. Concentrated loads were applied via 3.2 mm diameter steel pins as shown by dotted lines in the figure. The length, ℓ , Figure 1(b), of loaded face in distributed load varied from 2.18 mm to 10.2 mm. The transverse distance L , Figure 1(b), from the edge of the model to the point of application of concentrated load varied from 2.34 mm to 10.7 mm. These results are shown in Tables III and IV in the following section.

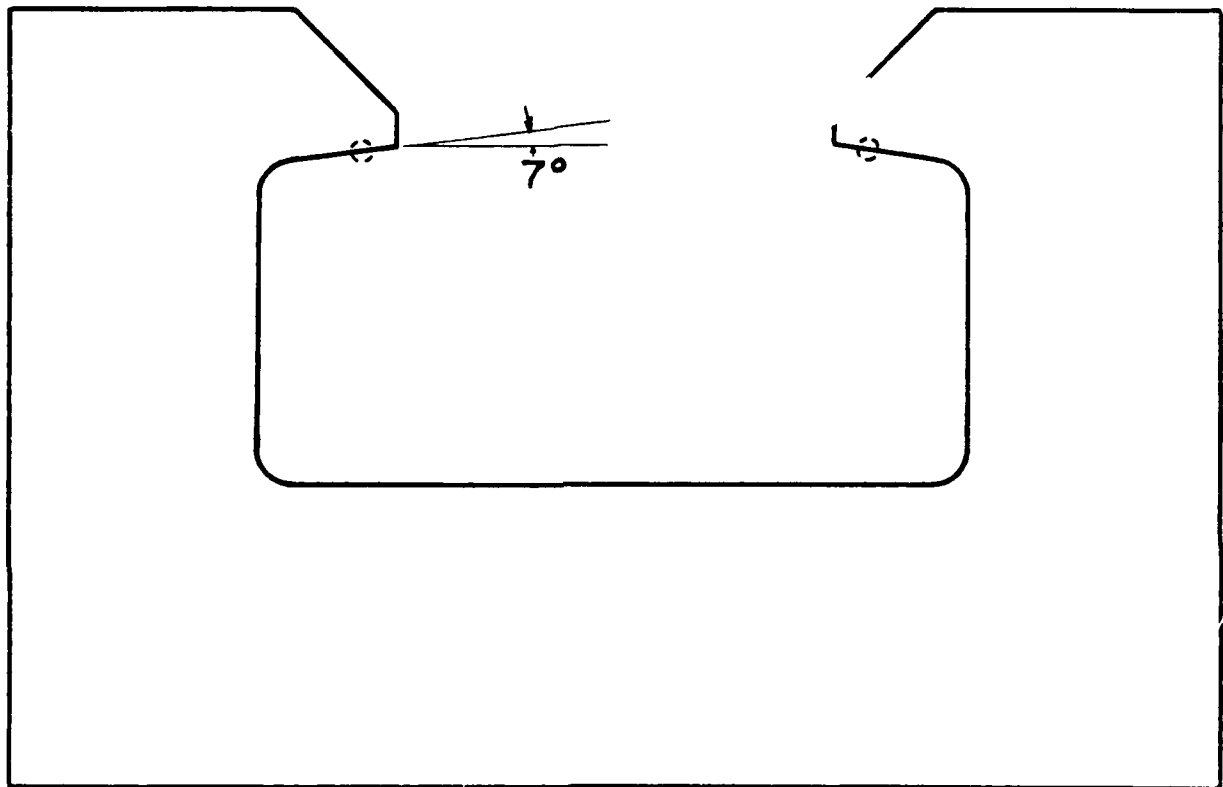


Fig. 2 Sketch of flank loading fixture

After tests in the flank load were completed, the models were again modified to resemble loaded projections, Figure 1(c). Model and loading geometries for this series of tests are shown in Table V in the following section.

All loads were applied in steps by means of a dead weight loading machine. Precautions were taken to ensure symmetry of loading. Also, maximum groove stress was kept within linear range of the model material.

APPARATUS AND EXPERIMENTAL TECHNIQUES

A lens-type transmission polariscope with collimated monochromatic light of 5461 Å was used. Photographs of isochromatic fringe patterns were taken in both bright and dark field after each step of loading. Maximum fringe order and its position were determined from 7-magnification of photographs.

On the free boundary one of the principal stresses was identically zero and the remaining principal stress tangent to the boundary was directly given by the fringe order. Stress concentration factor, K , was defined as the ratio of the maximum groove stress, σ_{\max} , to the nominal stress, σ_{nom} , at the narrowest section. Thus

$$K = \sigma_{\max} / \sigma_{\text{nom}} = (d)(t)(\sigma_{\max}) / W \quad (1)$$

where W is the load. Using the difference method, Eq. (1) was rewritten as

$$K = (d)(t)(\Delta\sigma_{\max}) / (\Delta W) \quad (2)$$

where Δ denotes increments between steps. Equation (2) was used to calculate K throughout this investigation.

RESULTS AND DISCUSSION

Remote Loading

Figure 3 shows a typical boundary fringe distribution of nonsymmetric-shaped grooves under remote tensile load. It can be seen that the maximum fringe order, hence, the maximum groove stress, σ_{max} , does not occur at the narrowest section. It is displaced toward the 7 degree face. Angular displacement varies from 1 degree for $R/d = 0.2$ to 5 degrees for $R/d = 0.05$. Results are shown in Table II and Figure 4. Stress concentration factor for U-grooves, K_u , is included for comparison (ref 1).

TABLE II. STRESS CONCENTRATION FACTOR K FOR NONSYMMETRIC-SHAPED GROOVES UNDER REMOTE TENSION, $d/D = 0.7$

Test	R/d	K	Angular Displacement, Degrees	K_u	Reduction, $\frac{K_u - K}{K_u} \times 100\%$
A	0.05	3.25	5.0	3.47	6.34
B	0.10	2.75	3.2	2.87	4.18
C	0.15	2.38	2.0	2.43	2.05
D	0.20	2.15	1.0	2.18	1.37

It is known that most materials in straight sides of U-grooves are idle and do not carry any load. In comparison with U-grooves, materials in nonsymmetric-shaped grooves are better utilized, stresses are redistributed, and maximum groove stress and stress concentration are reduced. The degree of reduction, based on K_u , varies from 1.4 percent for $R/d = 0.20$ to 6.3 percent

¹Peterson, R. E., Stress Concentration Factors, John Wiley & Sons, 1974.

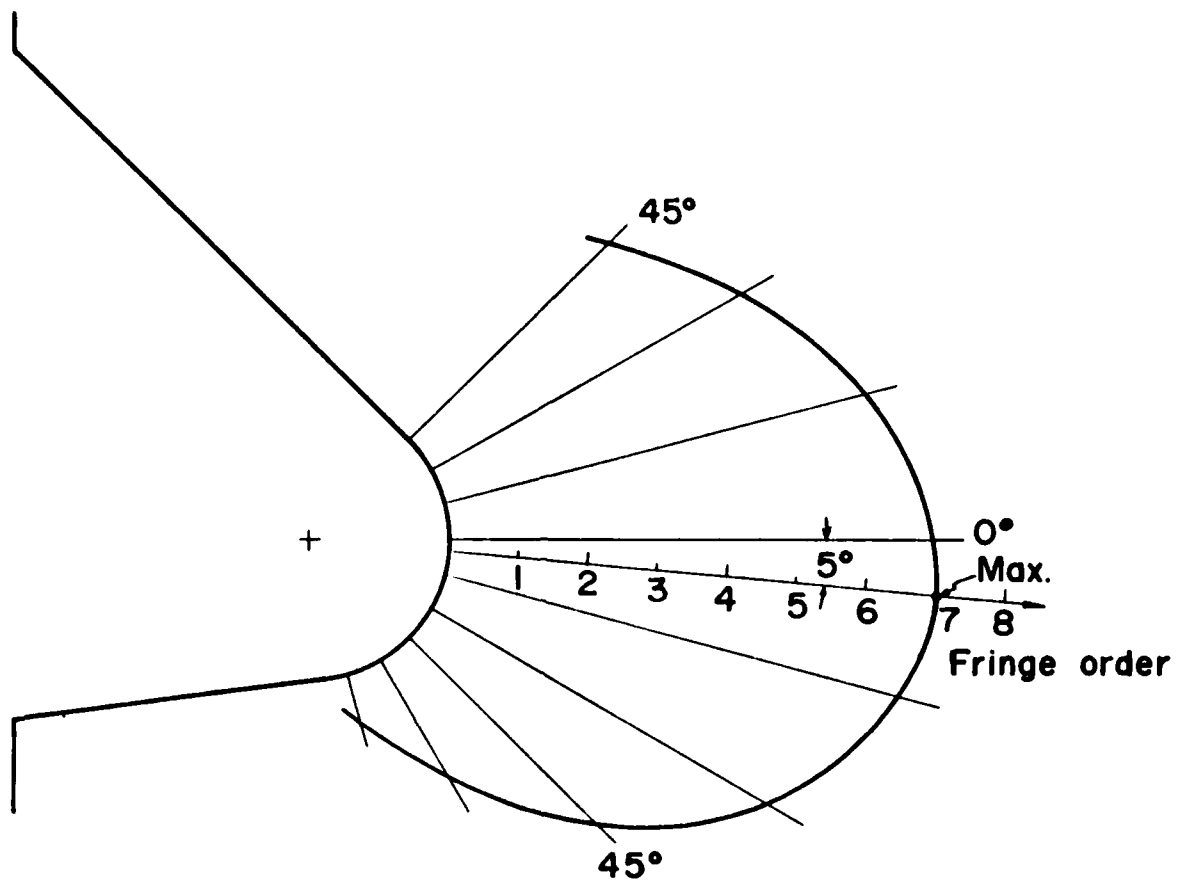


Fig. 3 Boundary fringe distribution of nonsymmetric-shaped grooves under remote tension
 $R=t=6.35\text{mm}$, $W=267\text{newton}$, Material: PSM-1

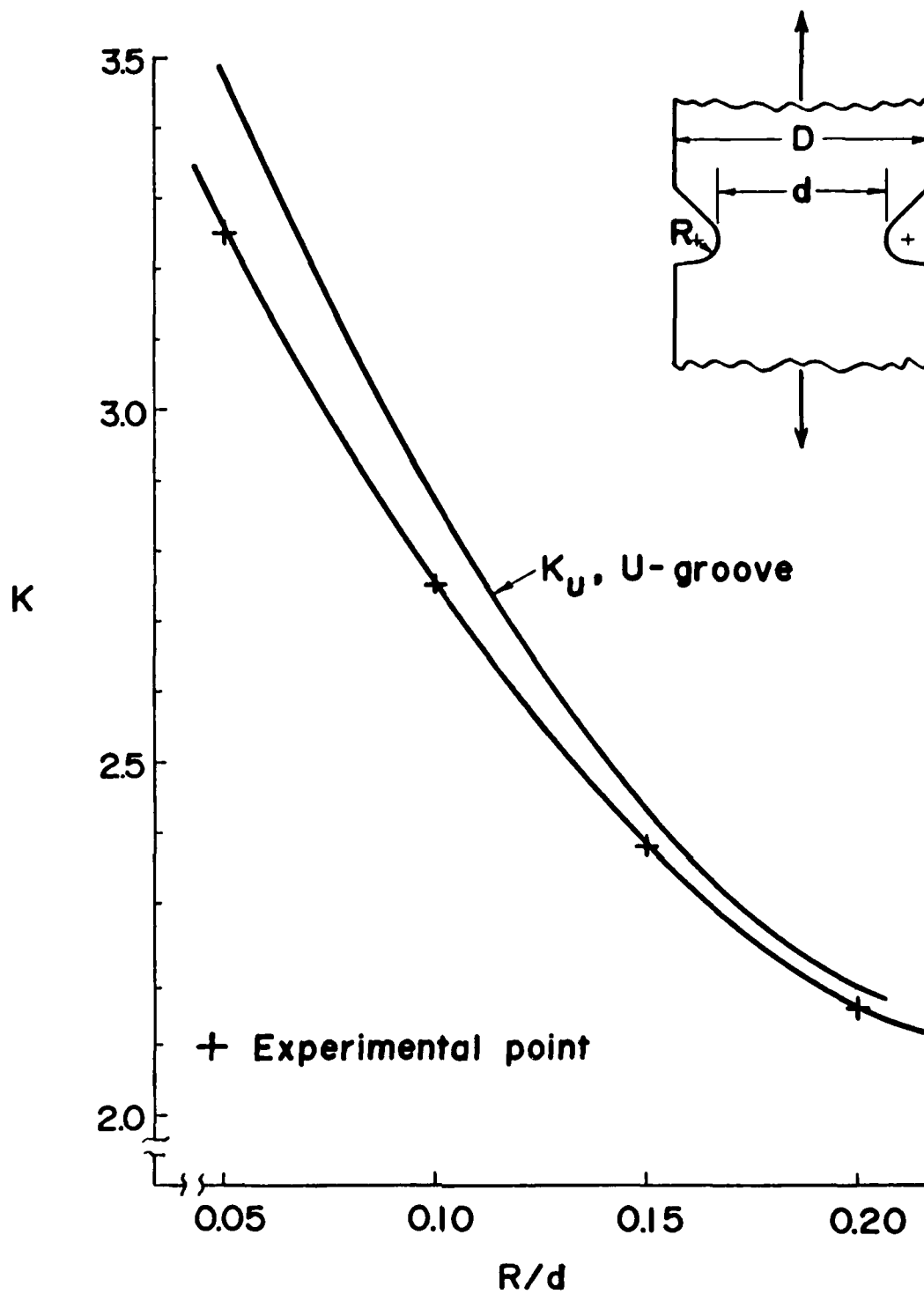


Fig. 4 Stress concentration factor K versus R/d in plates with nonsymmetric-shaped grooves under remote tension, $d/D=0.7$

for $R/D = 0.05$.

Distributed Flank Loading

Table III shows that the angular displacement in distributed flank loading has a larger value than that under remote loading. The maximum groove stress is displaced farther toward the 7 degree loaded face. Angular displacement varies directly with groove radius R and inversely with the length of loaded face l .

TABLE III. STRESS CONCENTRATION FACTOR K FOR NONSYMMETRIC-SHAPED GROOVES UNDER DISTRIBUTED FLANK LOADING, $d/D = 0.7$

Test	R/d	l , mm	K	Angular Displacement, Degree	$2l\cos 7^\circ / (D-d)$
A11	0.05	10.2	8.01	30.0	0.76
A12	0.05	7.01	8.55	35.0	0.52
A13	0.05	4.98	8.81	38.0	0.37
A14	0.05	2.18	8.60	40.0	0.16
B11	0.10	7.01	6.43	37.5	0.52
B12	0.10	4.98	7.33	39.0	0.37
B13	0.10	2.18	6.97	43.0	0.16
C11	0.15	4.98	5.77	40.0	0.37
C12	0.15	2.18	6.33	46.0	0.16
D11	0.20	2.18	6.23	75.0	0.16

Figure 5 shows values of K versus R/d . Stress concentration under remote tension was included. A curve was drawn passing through points of $l = 2.18$ mm. The results indicate that (1) K varies inversely with groove radius R, and (2) under distributed flank load K is about 2.5 to 3 times as high as that under remote tension.

Figure 6 shows values of K versus $2l\cos 7^\circ/(D-d)$, a ratio of transverse projection of the length of loaded face, $l\cos 7^\circ$, to the groove depth, $(D-d)/2$. A curve was drawn through points of $R/d = 0.05$. The results indicate that, at least for values of $R/d < 0.1$, K increases as the length of loading l is reduced, reaches a maximum at approximately $2l\cos 7^\circ/(D-d) = 0.3$, and then starts to decrease as l is further reduced.

Concentrated Flank Loading

The tests made under concentrated flank loading and their results are shown in Table IV. Within the ranges of geometries and load points, the angular displacement of maximum groove stress varies from 22.5 degrees to 38.5 degrees, considerably less than that under distributed flank loading. Same as under distributed loading, the angular displacement varies directly with groove radius R and inversely with the distance L.

Figure 7 shows that K decreases as groove radius R is increased. It also shows that under concentrated flank loading K is considerably higher than that under remote tension. A comparison between Figures 5 and 7 reveals that, in general, for small values of R, K is higher under concentrated flank load than that under distributed flank load, and conversely for larger values of R.

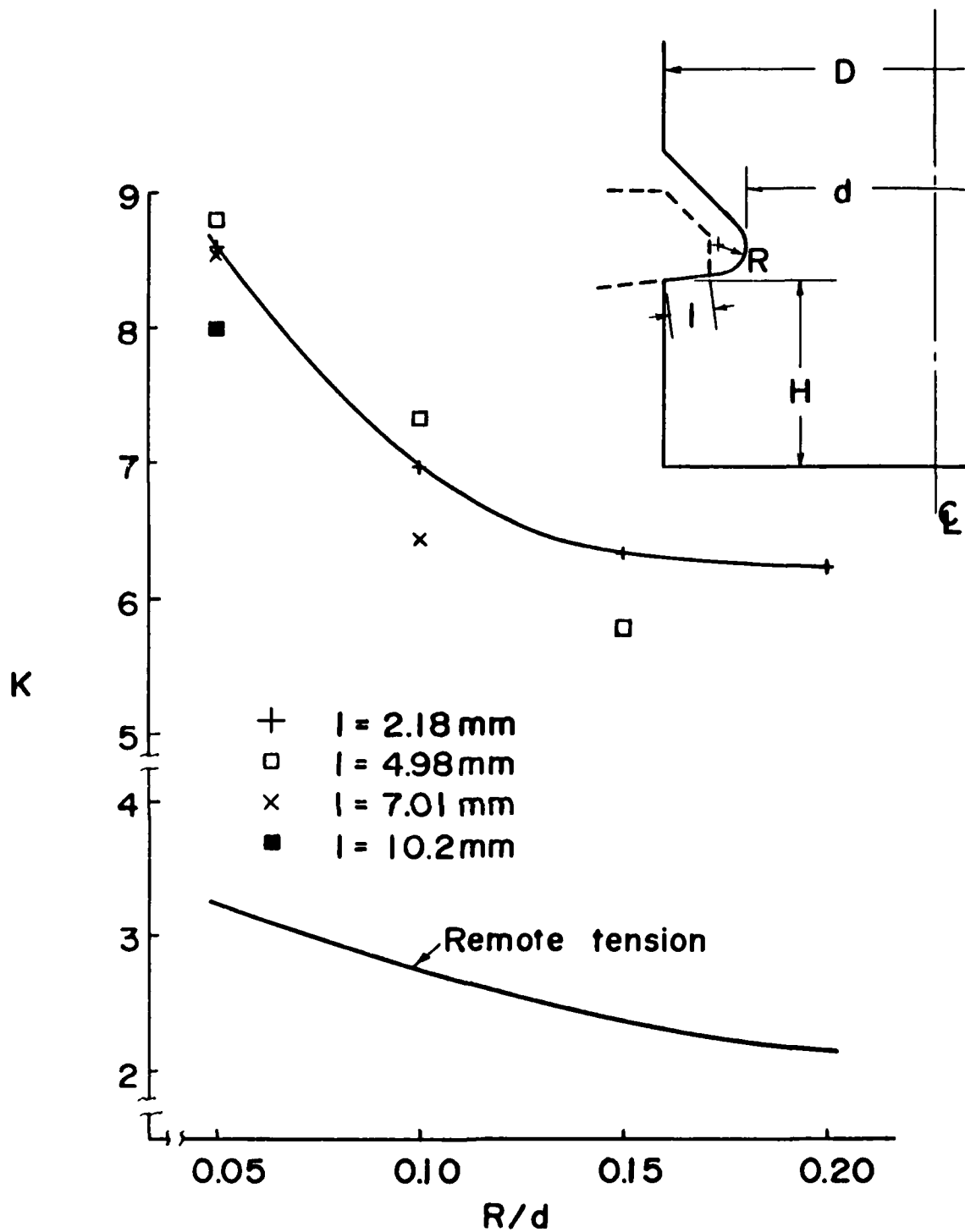


Fig. 5 Stress concentration factor K versus R/d in plates with nonsymmetric-shaped grooves under distributed flank loading

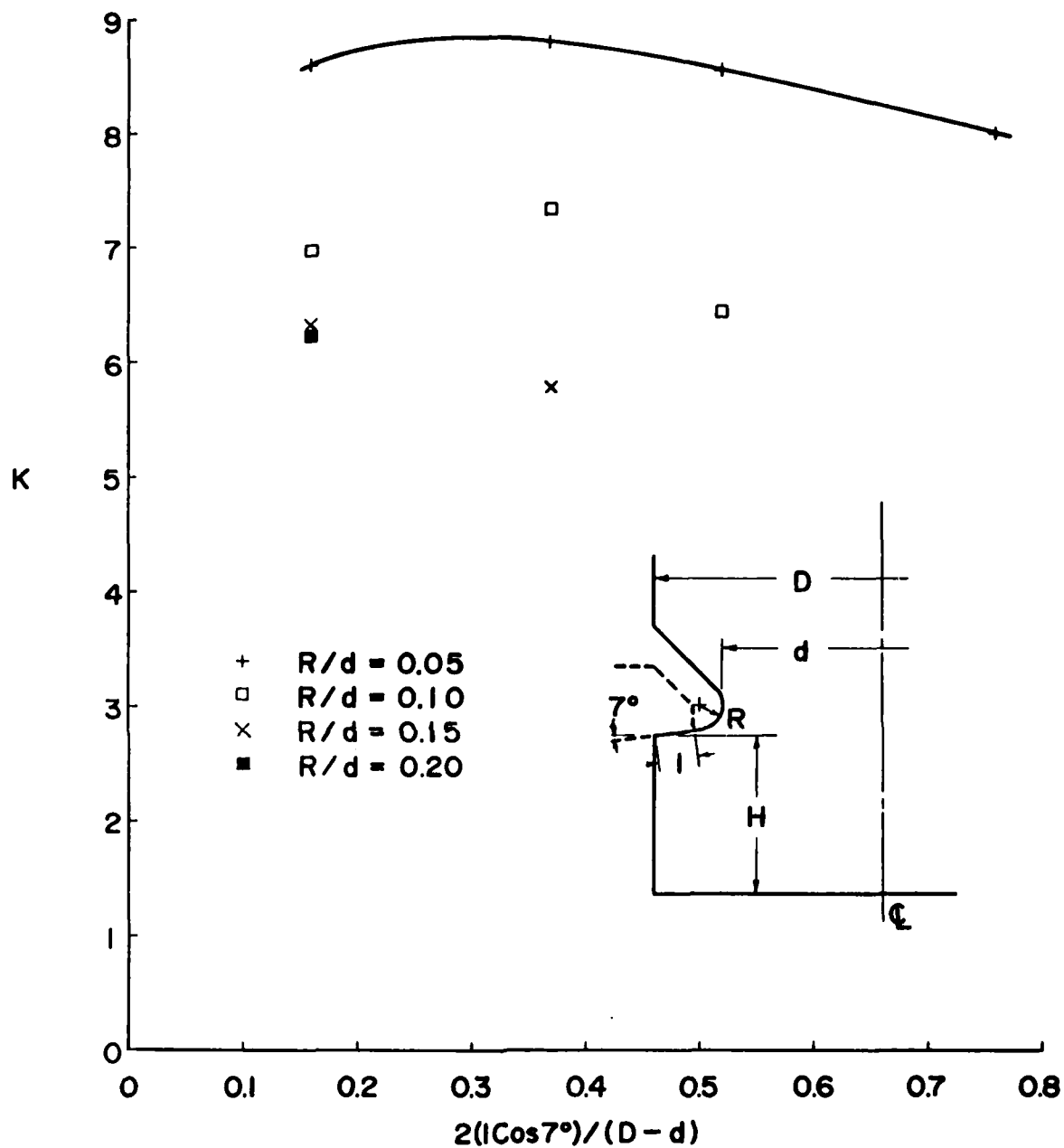


Fig. 6 Stress concentration factor K versus $2(l\cos 7^\circ)/(D-d)$ in plates with nonsymmetric-shaped grooves under distributed flank loading

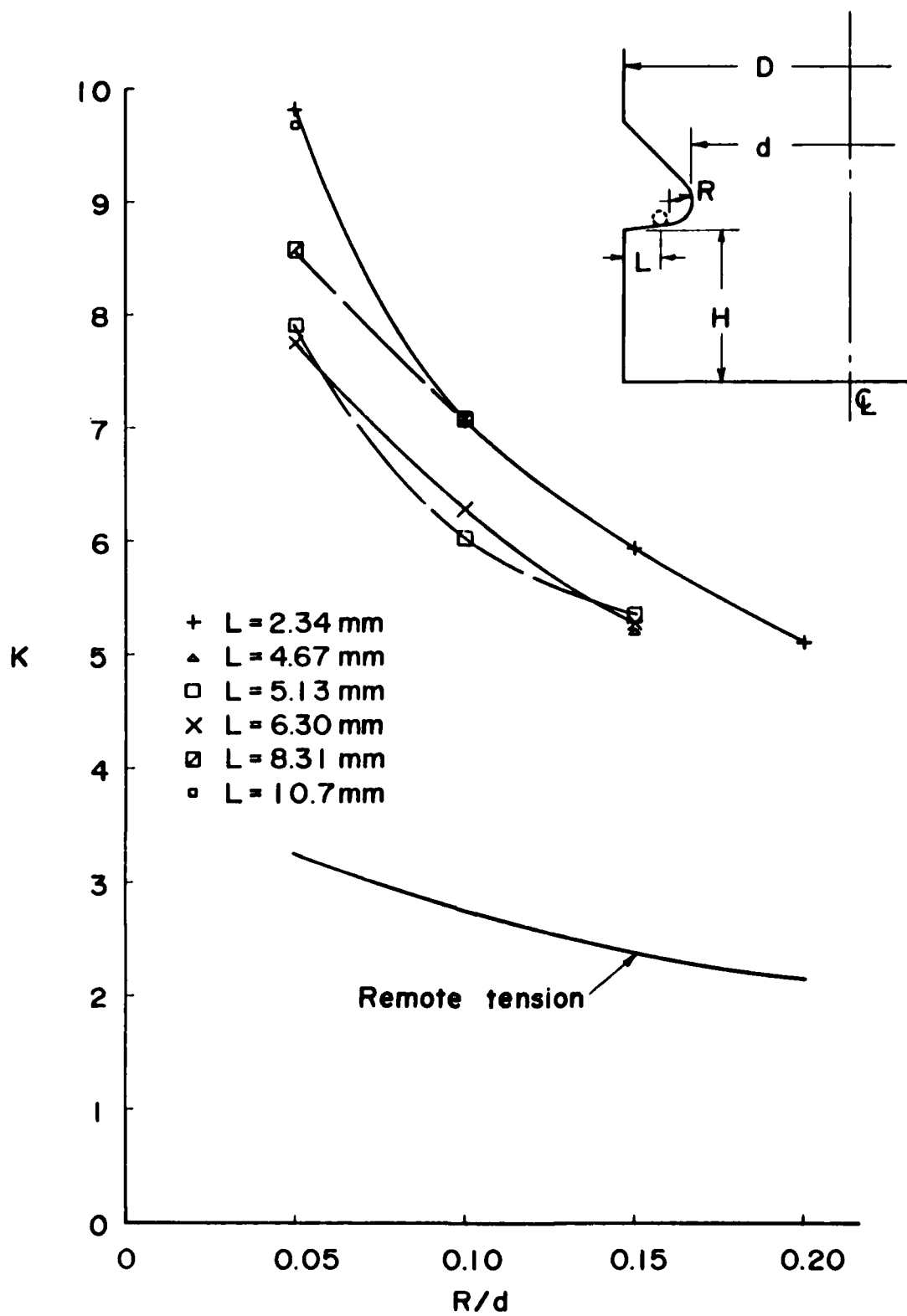


Fig. 7 Stress concentration factor K versus R/d in plates with nonsymmetric-shaped grooves under concentrated flank loading

TABLE IV. STRESS CONCENTRATION FACTOR K FOR NONSYMMETRIC-SHAPED GROOVES UNDER CONCENTRATED FLANK LOADING, $d/D = 0.7$

Test	R/d	L, mm	K	Angular Displacement, Degrees	$2L/(D-d)$
A21	0.05	10.7	9.67	22.5	0.80
A22	0.05	8.31	8.57	22.0	0.62
A23	0.05	6.30	7.75	30.0	0.47
A24	0.05	5.13	7.89	30.0	0.39
A25	0.05	2.34	9.81	34.5	0.18
B21	0.10	8.31	7.07	35.0	0.62
B22	0.10	6.30	6.28	31.5	0.47
B23	0.10	5.13	6.02	35.0	0.39
B24	0.10	2.34	7.05	36.5	0.18
C21	0.15	6.30	5.27	30.0	0.47
C22	0.15	5.13	5.34	33.0	0.39
C23	0.15	4.67	5.21	37.5	0.35
C24	0.15	2.34	5.93	38.5	0.18
D21	0.20	2.34	5.11	38.0	0.18

Figure 8 shows values of K versus $2L/(D-d)$, a ratio of transverse direction, L, to the groove depth $(D-d)/2$. The results indicate that K decreases as the load is moved out from the groove, reaches a minimum, and then starts to increase as the load is moved out farther.

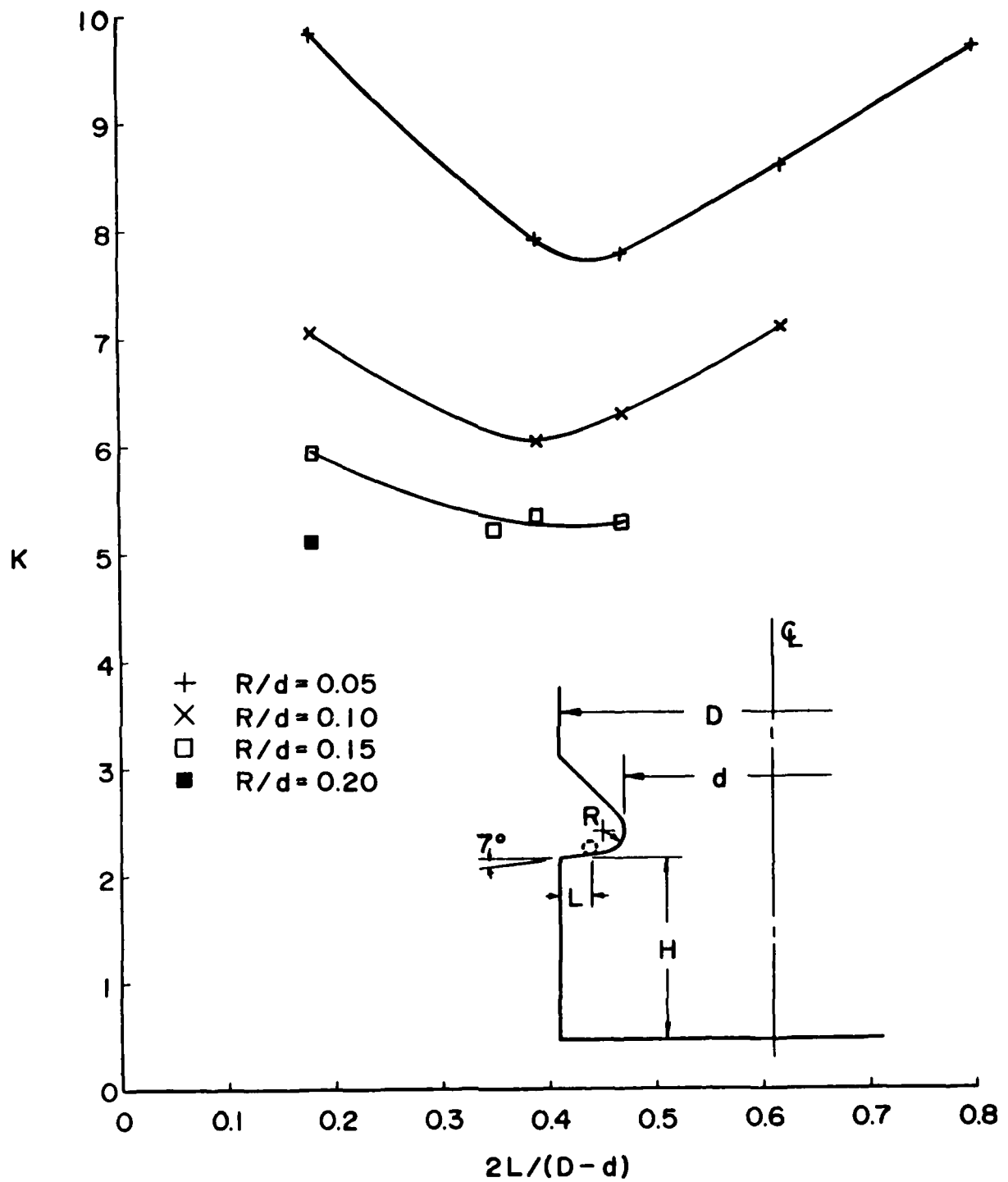


Fig. 8 Stress concentration factor K versus $2L/(D-d)$ in plates with nonsymmetric-shaped grooves under concentrated flank loading

A comparison between Figures 6 and 8 further reveals that K reaches a maximum between extremes of l under distributed load, but a minimum between extremes of L under concentrated load.

Loaded Projection

It can be seen in Table V that the angular displacement of maximum groove stress has the same trend found in flank loading, i.e., it varies directly with R and inversely with L. However, the displaced magnitude is larger in loaded projection than that in concentrated flank loading.

TABLE V. STRESS CONCENTRATION FACTOR K IN CONCENTRATEDLY LOADED PROJECTIONS

Test	R/d	L, mm	K	Angular Displacement, Degrees	2L/(D-d)
A31	0.05	10.7	10.9	26.0	0.80
A32	0.05	8.31	9.17	26.0	0.62
A33	0.05	6.30	9.55	29.0	0.47
A34	0.05	5.13	10.5	32.5	0.39
A35	0.05	2.34	11.9	38.0	0.18
B31	0.10	8.31	7.05	37.0	0.62
B32	0.10	6.30	6.63	37.0	0.47
B33	0.10	5.13	6.90	38.0	0.39
B34	0.10	2.34	8.40	50.0	0.18

Figure 9 shows curves of K versus $2L/(D-d)$. Results from concentrated flank load are included for comparison. It can be seen that stress concentrations under loaded projection are higher than those under concentrated flank loading. Moreover, K has the same trend found in concentrated flank loading, i.e., it decreases as the load is moved away from the groove, reaches a minimum, and then starts to increase as the load is moved farther away.

Heywood's Empirical Equation

In 1948, Heywood (ref 2) suggested an empirical equation of the following form:

$$\sigma_{\max} = [1 + 0.26(e/R)^{0.7}][[(1.5 a/e^2) + (0.36/be)^{1/2}(1+0.25\sin\gamma)](W/t) \quad (3)$$

for calculating the maximum groove stress σ_{\max} in loaded projection, Figure 10. In this equation, it was assumed that σ_{\max} falls at point A, 30 degrees from the point of tangency on the groove, and the dimensions a, b, and e, and the angle γ are as shown in the figure. Recently, Allison and Hearn (ref 3) reported the movement of maximum groove stress position in a range of angle from 30 degrees to 70 degrees as load point is varied. Our results shown in this report as well as previous results (ref 4) are well within this range.

Following Eq. (3), stress concentration factor can be expressed as

$$(\sigma_f)_{\max} \cdot d/(2W/t) = [1+0.26(e/R)^{0.7}][[(1.5a/e^2) + (0.36/be)^{1/2}(1+0.25\sin\gamma)](d/2) \quad (4)$$

²Heywood, R. B., "Tensile Stresses in Loaded Projections," Proceedings of the Institute of Mechanical Engineers, Vol. 159, 1948, pp. 384-391.

³Allison, I. M. and Hearn, E. J., "A New Look at the Bending Strength of Gear Teeth," Experimental Mechanics, V. 20, No. 7, July 1980, pp. 217-225.

⁴Cheng, Y. F., "A Photoelastic Investigation of Stresses and Load Distributions in Lug-Groove Joints," Proceedings of the Army Symposium on Solid Mechanics, 1982, pp. 454-470.

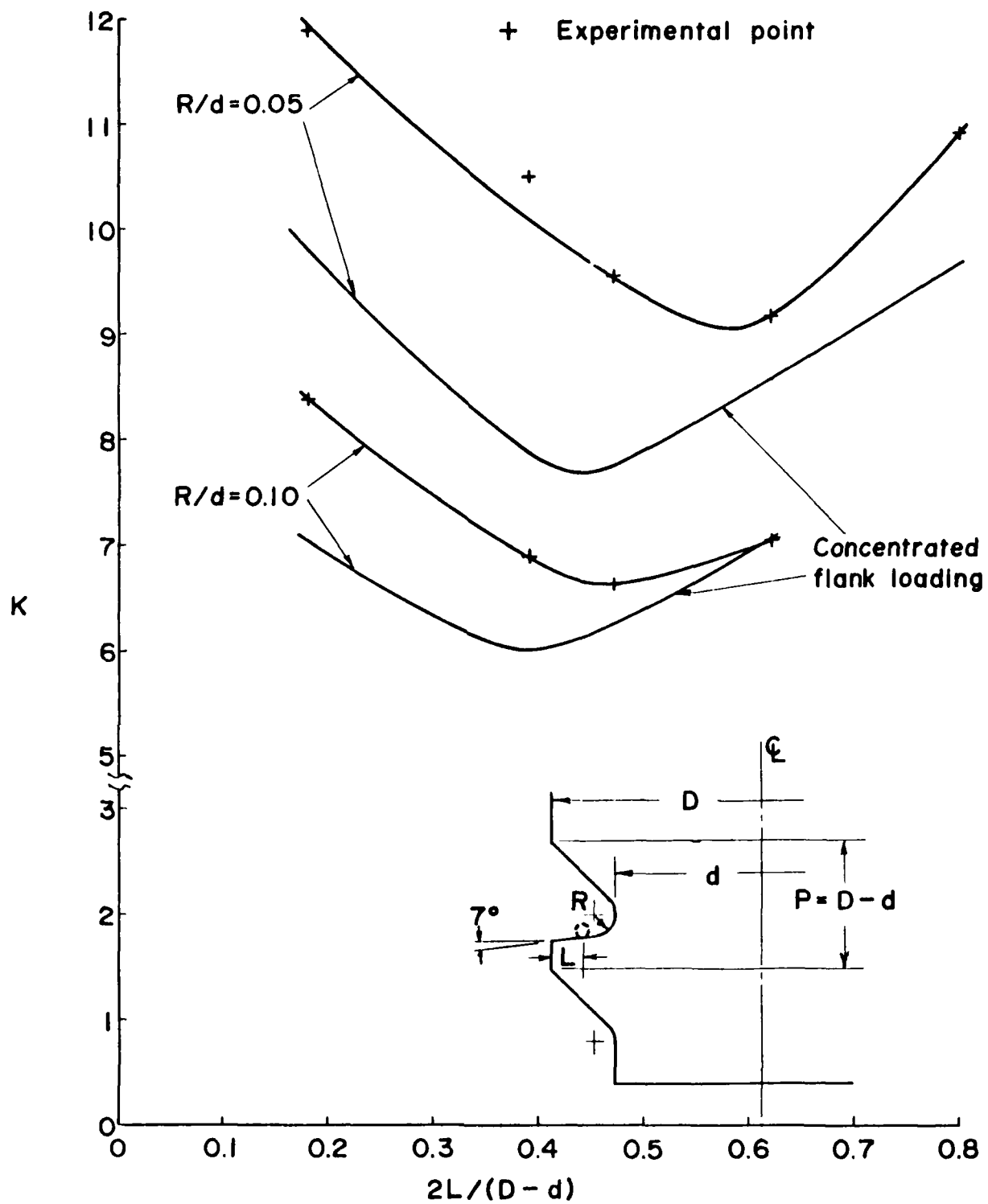


Fig. 9 Stress concentration factor K versus $2L/(D-d)$ in loaded projections

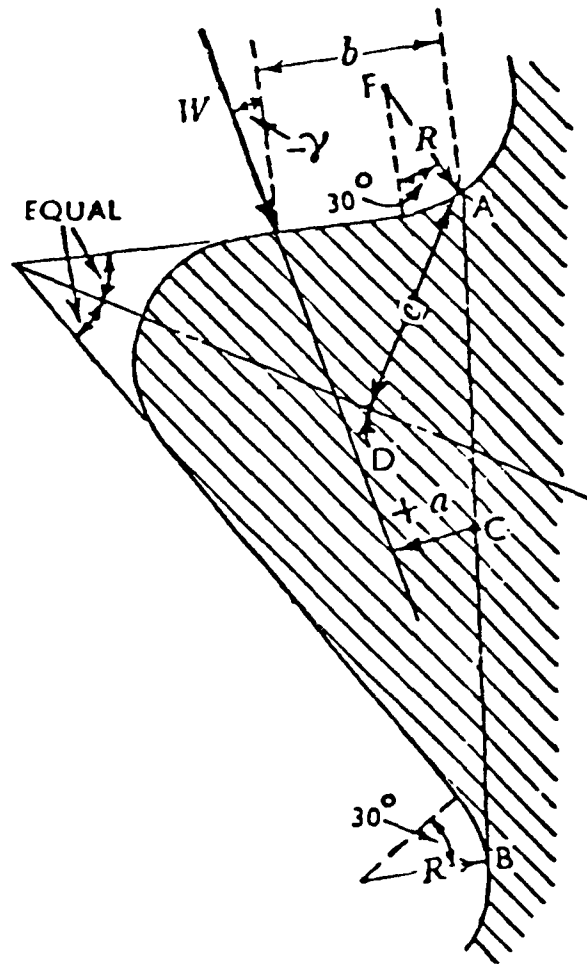


Fig. 10. Dimensions used for calculating maximum groove stress by Heywood.

They were calculated for tests A31-A35 and B31-B34 and shown in Table VI.

TABLE VI. COMPARISON BETWEEN STRESS CONCENTRATION FACTOR OBTAINED EXPERIMENTALLY AND FROM HEYWOOD'S EQUATION

Test	R, mm	L, mm	K	$(\sigma_f)_{\max} \cdot d / (2W/t)$
A31	3.18	10.7	10.9	10.0
A32	3.18	8.31	9.17	9.38
A33	3.18	6.30	9.55	10.4
A34	3.18	5.13	10.5	11.2
A35	3.18	2.34	11.9	13.3
B31	6.35	8.31	7.05	8.59
B32	6.35	6.30	6.63	9.06
B33	6.35	5.13	6.90	9.65
B34	6.35	2.34	8.40	11.4

It can be seen from Table VI and Figure 11 that Heywood's values are high. Perhaps this equation is not applicable to lug-groove or screw-thread connections since sectional dimensions are not included.

CONCLUSIONS

The following conclusions are made for stress concentration in plates due to axial tension of loaded nonsymmetric-shaped grooves.

1. Stress concentration factor K varies inversely with groove radius R under all loading conditions (remote tension, distributed flank load, concentrated flank load, and loaded projections).

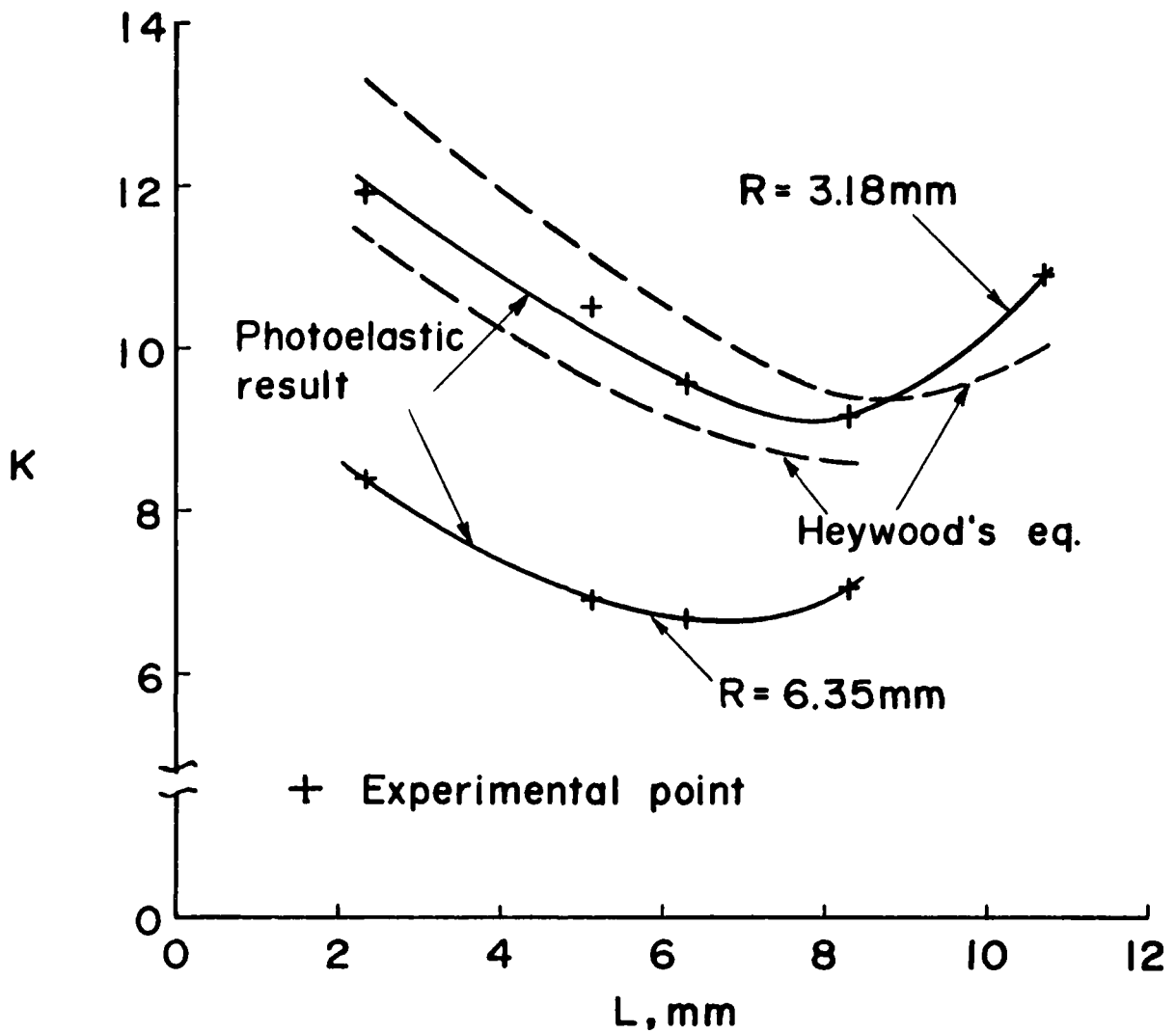


Fig. 11 Comparison between stress concentration factors obtained experimentally and from Heywood's equation

2. Stress concentration factor K in loaded projections is higher than that in concentrated flank load.

3. Stress concentration factor K in flank load (distributed and concentrated) is higher than that in remote tension.

4. For shorter groove radius, K is higher under concentrated flank load than under distributed flank load, and conversely for longer groove radius.

5. K has a maximum between extremes of ℓ under distributed flank load, but a minimum between extremes of L under concentrated flank load and loaded projections.

6. The position of maximum groove stress is displaced toward the loaded flank under all flank loading (distributed, concentrated, and loaded projections) and is displaced toward the flank with small flank angle under remote tension. In general, angular displacement varies directly with R and inversely with ℓ or L .

7. Heywood's values are high. Perhaps, Heywood's equation should not be applied in lug-groove or screw-thread connections since sectional dimensions are not included.

8. Under remote tension, a nonsymmetric-shaped groove has lower stress concentration than a symmetric-shaped U-groove.

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