STRESS CONCENTRATION FACTORS IN MAIN
MEMBERS DUE TO WELDED STIFFENERS

by

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A C K N O W L E D G E M E N T

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SUMMARY

The stress concentration factors in main members due to welded stiffeners are determined by the use of photoelastic methods. The effects of weld penetration and width of stiffener on the stress concentration factor are shown for various types of welded connections used in construction. Solid models were cut from Bakelite to represent the welded connections. The models were slit to show the effect of over and under weld penetration on the stress concentration factor. It was found necessary to make some basic assumptions. In this study it was assumed that there was perfect homogeneity between the parent metal and the weld metal, and that there was perfect fusion and uniform bond strength throughout with no initial stresses present. These assumptions are not wholly true in actual practice, but are justifiable in this experimental work.

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INTRODUCTION TO OBJECT

From time to time the Fundamental Research Division of The Engineering Foundation suggests to its researchers fundamental welding problems that seem to be of outstanding importance. The most recently suggested problem (1940) apparently is one whose solution might be most easily found by photoelastic methods.

The suggested problem is to determine the stress distribution and stress concentration factor (the ratio of the stress at a point to the average stress in the member) for a type of welded joint shown in Fig. 1a or Fig. 1c. The thick horizontal plate may represent the web of a plate girder that is loaded either in tension or compression, while the thin vertical plate is a stiffener and carries no load.

Joints of this type occur frequently in all kinds of welded or riveted construction. Probably some of the more recent usages of this type joint are stiffeners for the bulkheads of our newest all-welded ships, long steel columns or tension members with some type of stiffener to reduce vibrations or towers of all steel welded construction. With recent developments and improvements in the field of welded construction, the riveted joint is rapidly being outmoded. Hence, with this advance there comes, of course, much research on the problem of welded joints with the view to constant improvement of methods, procedure, and materials, as well as intensive study as to the strength of the weld and the stress distribution throughout the welded joint.

When a problem arises, or is suggested, the immediate question that must be answered is "What research has been conducted on joints of these types?" Very little. Type C was investigated by Coker.[3] His model was 5 inches long and cut from a plate about 0.1 inch thick. The angles were rounded to a radius of 1/16 inch. The stress at the angles was 79.7 per cent higher than the average stress in the main member. The investigation, however, was very limited. Type A has not been studied to the author's knowledge.

Hence, it was the purpose of this research to determine the stress distribution and the stress concentration factors for joints of type A and type B for various width stiffeners and various degrees of weld penetration.

APPARATUS AND PROCEDURE

The photoelastic polariscope used is shown in Fig. 3a. It is equipped with a 100-watt mercury vapor lamp, Wratten filters numbers B-58 and 77, Nicol prism polarizer and analyzer, and quarter wave plates. The resulting light is monochromatic (5461A line of mercury arc spectrum) and circularly polarized.

To determine the effects of width of stiffener and weld penetration on the stress concentration factor, 5 models were cut from Bakelite, type "BT-61-893 Water White," to the dimensions shown in Fig. 1. Model blanks were first cut from 1/4 inch sheets of Bakelite with a jig saw, then semipolished, dry, on a wood sander of the belt type. They were then laid out to the proper dimensions with a scratch awl. The holes were drilled in an accurate drill press almost through from

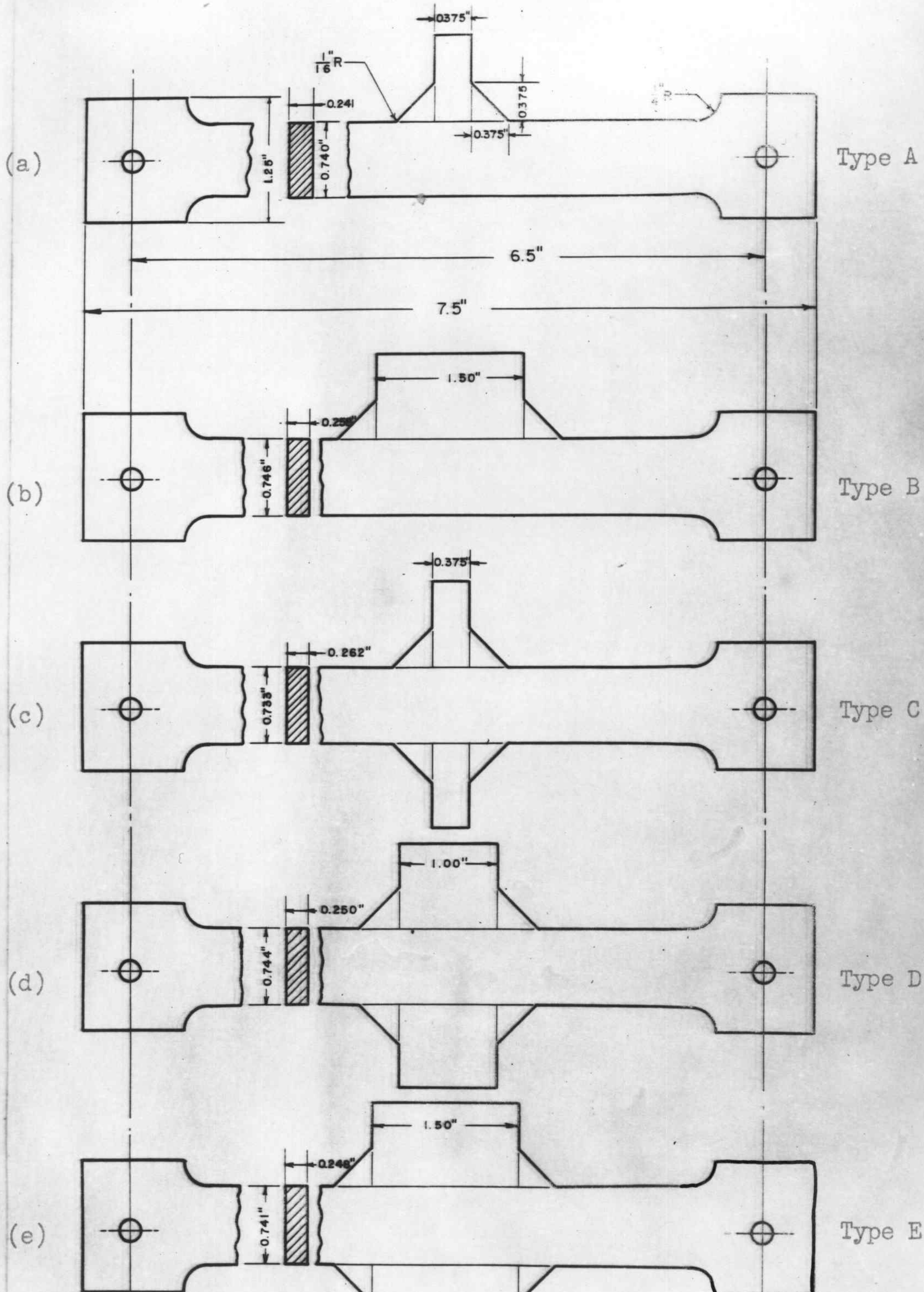


Fig. 1. Details of Bakelite Models.

one side, until the point of the drill came through, and the operation completed from the other side. This prevented chipping of the blanks. The blanks were then fastened to a wooden block and the block put in a compound-rest on the drill so the fillets could be drilled. After drilling the fillets, the models were cut out roughly with the jig saw, then remounted in the compound-rest on the drill press and cut to the exact dimensions with a high speed vertical milling tool. The models were then polished on a circular lap with a suspension of No. 600 carborundum in water and finished with a suspension of levigated Alumina in water. In order to cut the slits it was found necessary to drill first a small hole through the weld then use a very fine jeweler's saw in the jig saw. The weld terminology is shown in Fig. 3b.

After cutting and polishing, the models were annealed in the electric oven, shown in Fig. 2, at 260° F for two hours then allowed to cool to room temperature at the rate of 15° F per hour. The stress optical coefficient of Bakelite, as determined in the laboratory, was 32.2 Brewsters. The models were first tested with 100 per cent weld penetration, then slit to represent various degrees of weld penetration as shown in Table I. The slits were 0.015 inch wide. Successive tests were made with the same model for various assumed penetrations of the weld.

For each model a constant tensile load of 416 lb. was applied as shown in Fig. 3, and the resulting fringes photographed as shown in Fig. 4, 5, 6, 7, and 8.

TABLE I

Test Number	Weld Penetration in Inches	Stress Concentration Factors Root	Stress Concentration Factors Neck
	Type A		
1	0.187	0.60	1.74
2	0.094	0.86	1.69
3	0.047	0.86	1.78
4	0.000	0.96	1.71
5	-0.020	0.96	1.69
6	-0.040	0.97	1.67
7	-0.080	1.14	1.64
8	-0.120	1.19	1.71
	Type B		
9	0.750	0.52	1.58
10	0.375	0.69	1.80
11	0.187	0.91	1.83
12	0.000	1.14	1.72
13	-0.020	1.19	1.62
14	-0.040	1.31	1.52
15	-0.080	1.45	1.76
16	-0.120	1.67	1.62
	Type C		
17	0.187	0.70	1.75
18	0.094	1.02	1.84
19	0.047	1.14	1.69
20	0.000	1.19	1.73
21	-0.020	1.21	1.75
22	-0.040	1.24	1.77
23	-0.080	1.38	1.67
24	-0.120	1.38	1.79
	Type D		
25	0.500	0.69	1.87
26	0.250	1.14	2.01
27	0.125	1.38	2.24
28	0.000	1.64	2.56
29	-0.020	1.58	2.24
30	-0.040	1.72	2.60
31	-0.080	1.79	2.49
32	-0.120	2.01	2.49
	Type E		
33	0.750	0.65	1.74
34	0.375	1.10	2.00
35	0.187	1.41	2.00
36	0.000	1.70	2.14
37	-0.020	1.70	2.32
38	-0.040	1.77	2.38
39	-0.080	1.88	2.54
40	-0.120	1.84	2.37

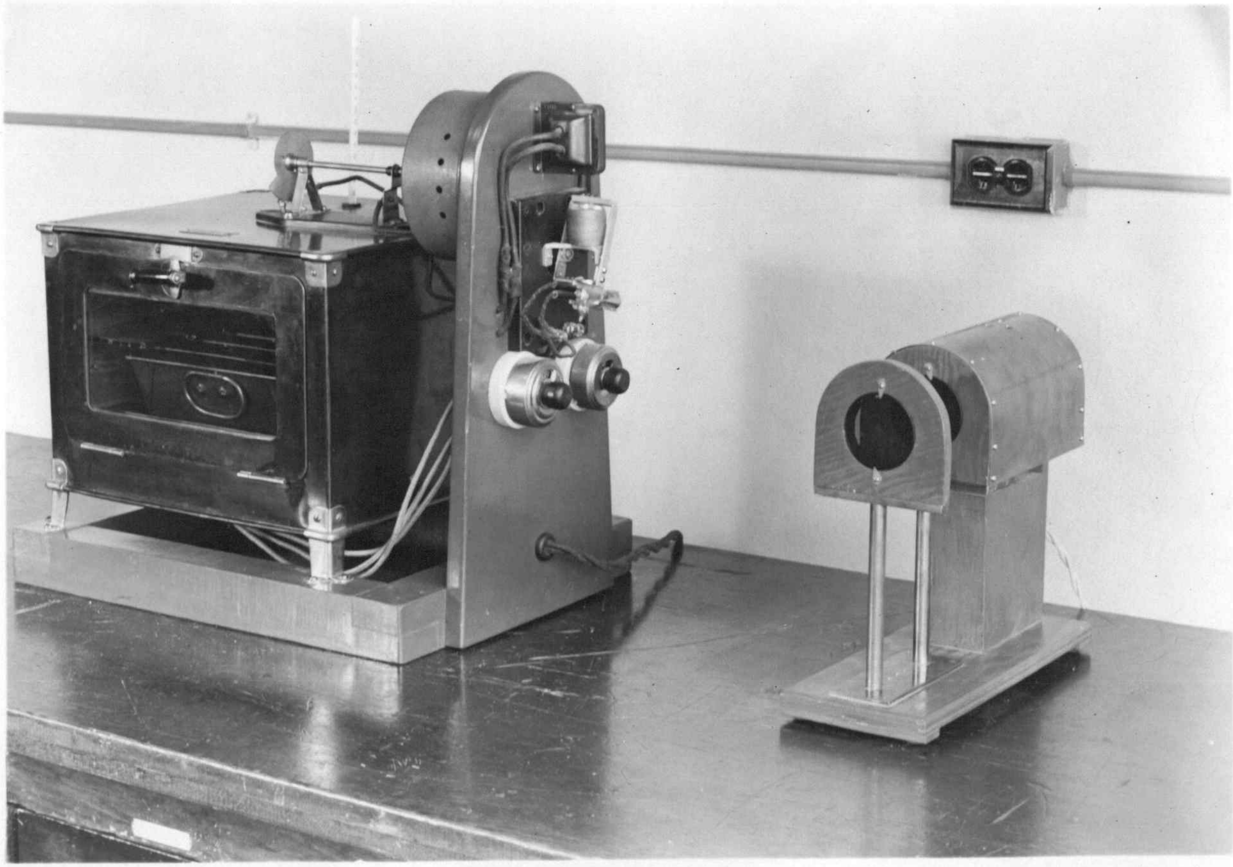
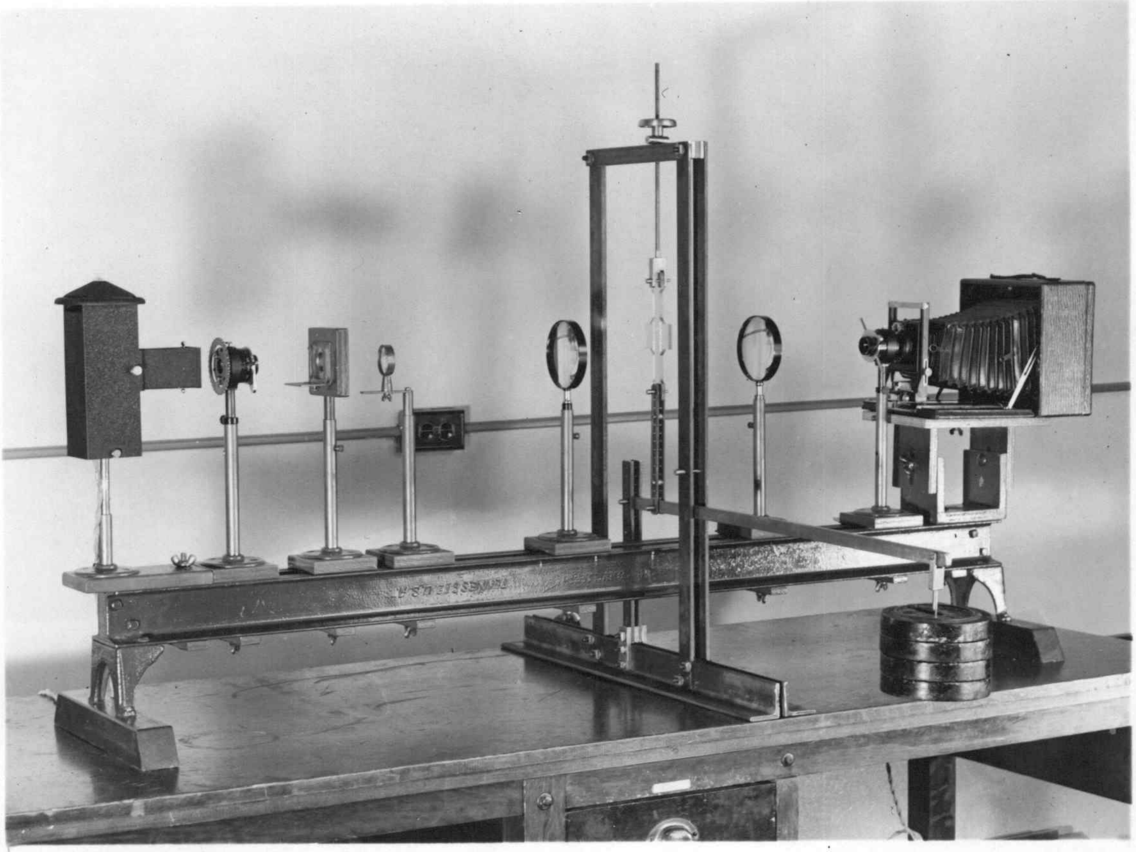
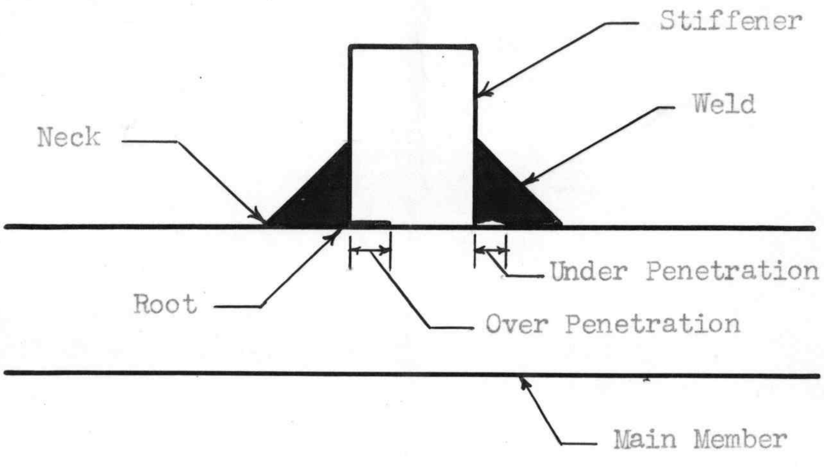


Fig. 2. Electric Annealing Oven and
Small Polariscope



(a) Photoelastic Polariscope



(b) Weld Terminology

Fig. 3.

DISCUSSION

No satisfactory theoretical solution has yet been developed that gives a clear picture of the stress distribution in the welds or parent metal of any of the common types of welded connections used in construction. Numerous mechanical tests have been made but mostly for the purpose of determining the ultimate strength of the joint as a whole, under various conditions of loading. However, in the last few years the photoelastic method has been used extensively for the study of stress concentrations in fillet-welds of all kinds.

Photoelastic analysis is a comparatively recent adaptation of a physical phenomena discovered in 1816 by David Brewster[1]. It is a visual means of measuring quantitatively or comparatively the shear and flexural stresses induced in an isotropic material by a desired loading condition. As the principles and method involved in photoelastic stress analysis are too lengthy to be included in this discussion, it will be assumed that the reader has a working knowledge of photoelasticity and its terminology. A satisfactory discussion on the subject is given by Coker and Filon[2].

From a preliminary investigation the author found that it was necessary to make some basic assumptions. In this study it was assumed that there was perfect homogeniety between the parent metal and the weld metal, and that there was perfect fusion and uniform bond strength throughout with no initial stresses present. Of course, these assumptions are not wholly true in actual practice, but for experimental purposes it makes it possible to cut models from a solid plate rather than using a built-up model of elements cemented together. It has been shown by Solakian[4] that stress fringes were continuous across the cemented joints of a built-up model and were identical with those obtained in a similar solid model.

In order to take into consideration as many typical factors as possible, the models were assumed to have varying degrees of weld penetration, as would be the case in actual practice. Hence slits were cut in the models to represent the faying surface exposed by varying degrees of penetration. Also the effect of width of stiffener was found by varying the stiffener width and keeping other conditions constant.

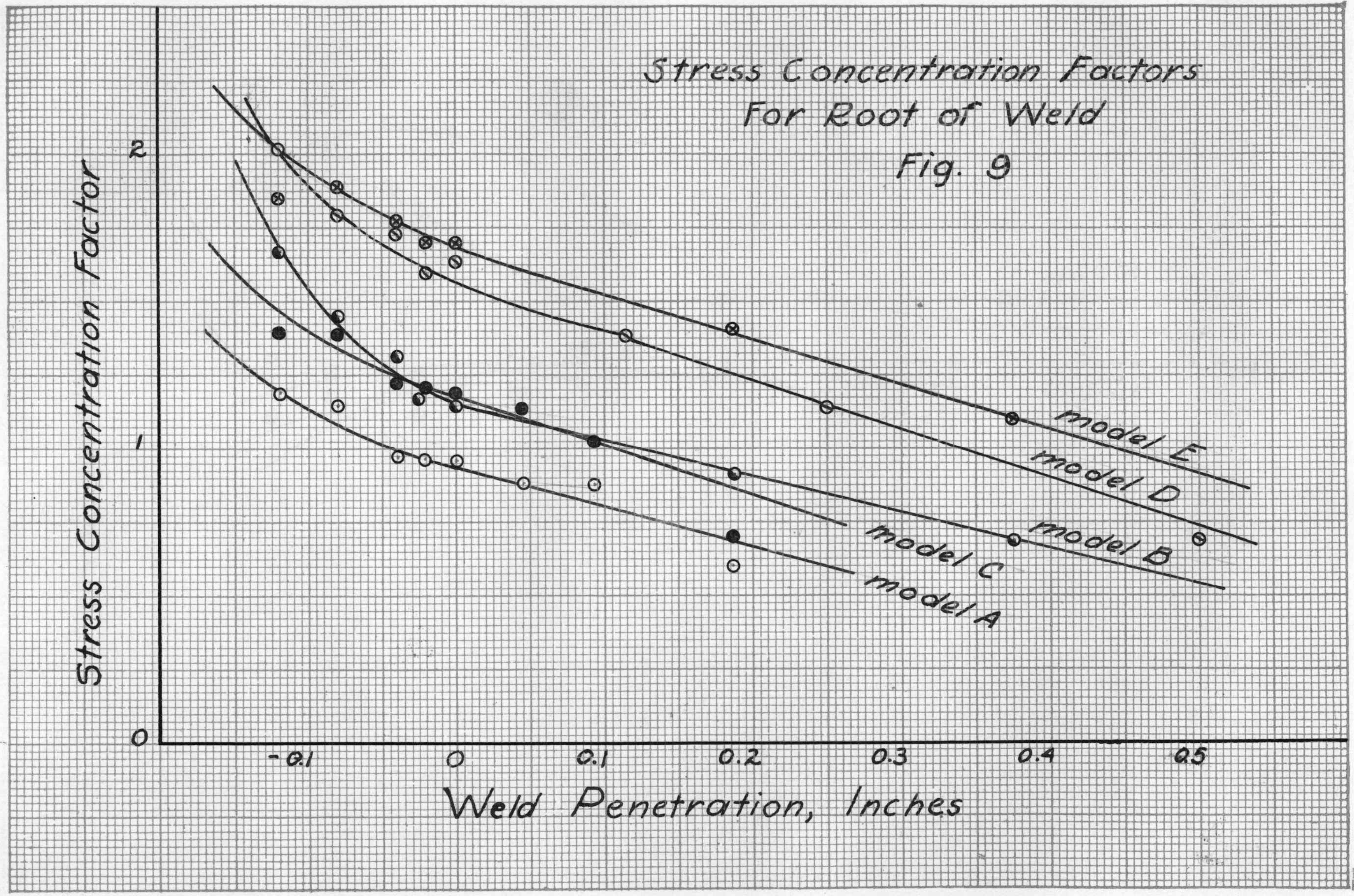
It should be pointed out at this time that the stress concentration factor, K, depends upon the type of discontinuity of the boundary (size and shape of slit, notch, or hole) and the length of the stressed area. But since the dimensions of the slit (size and shape) are constant, any change in K is due to the length of the slit, or more specifically the amount of weld penetration. Also K depends upon the shape and size of fillet as tests by Solakian[4] suggested. But if the size and shape of the fillets are kept constant, values of K obtained must be correct qualitatively and if the models are made fairly accurate, good quantitative results can be expected.

The relation between the stress concentration factor, the amount of weld penetration, and width of stiffener is shown graphically in Fig. 9 for the root of the weld, and Fig. 10 for the neck of the weld. These curves were plotted directly from Table I.

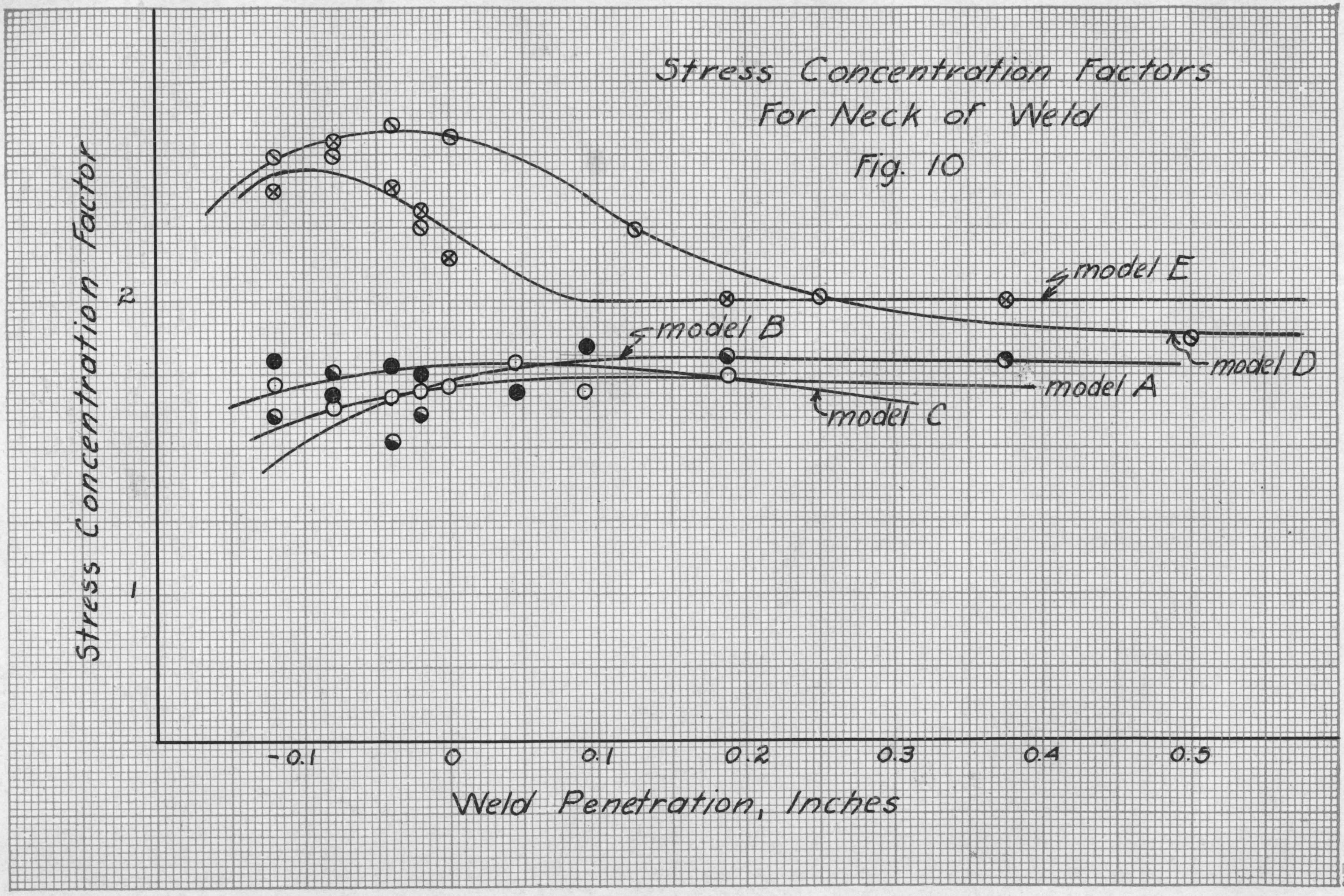
The fringe patterns shown in Fig. 4, 5, 6, 7, and 8, or more specifically each fringe line, represents a constant value of $(\sigma_1 - \sigma_2)$ stress, depending upon the fringe order, where σ_1 and σ_2 are the maximum and minimum principal stresses acting at a point in the plane of the model. Also it is shown in a study of photoelasticity[2] that one-half of $(\sigma_1 - \sigma_2)$ is equal to the maximum shearing stress at that point. At the boundary or on an axis of symmetry, the fringes represent tensile or compressive stresses, since one of the principal stresses must be zero. Hence Table I is obtained directly from the fringe pattern. The order of the fringes are marked on the photograph.

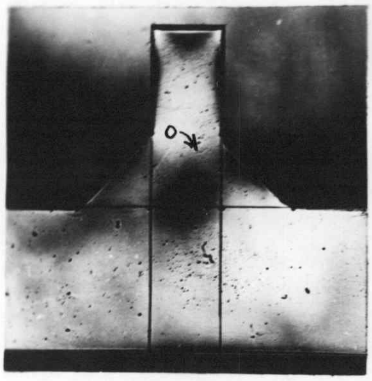
It is very evident from a study of Fig. 9 that the greater the weld penetration the lower the value of K, at the root of the weld, for all types of joints studied. However, K increases very slowly from 100 per cent weld penetration to zero weld penetration, and very rapidly as the weld penetration becomes negative or an under-penetration exists. This serves to emphasize the injurious nature of an under-penetration of the weld.

The effect of width of stiffener is also shown in Fig. 9. The wider the stiffener the greater K becomes regardless of the type of joint. Also joint type A, Fig. 1a, has a lower K than type C, yet both have the same width stiffener. The same can be said of type B and type E. Hence the effect of welding two stiffeners opposite each other on a main member is to raise the stress concentration factor, and as the width of the stiffener increases, the stress concentration


Stress Concentration Factors
For Root of Weld
Fig. 9
Stress Concentration Factor
2
1
0
-0.1
0
0.1
0.2
0.3
0.4
0.5
Weld Penetration, Inches
model E
model D
model B
model C
model A

11


Stress Concentration Factors
For Neck of Weld
Fig. 10
Stress Concentration Factor
2
1
model E
model B
model D
model A
model C
-0.1
0
0.1
0.2
0.3
0.4
0.5
Weld Penetration, Inches



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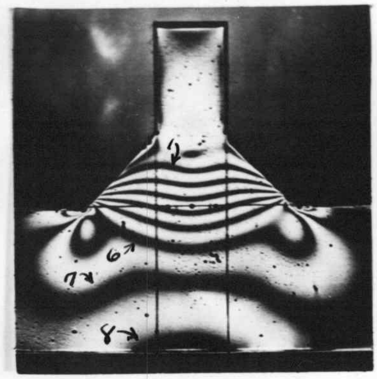
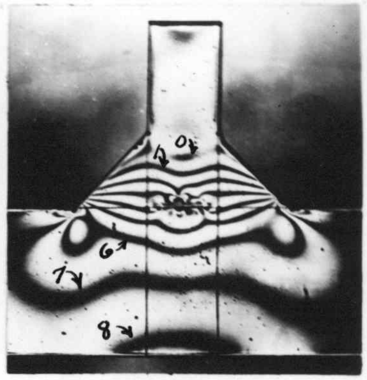
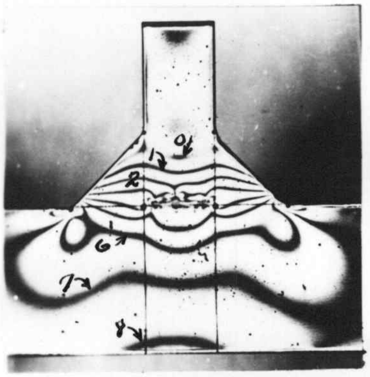


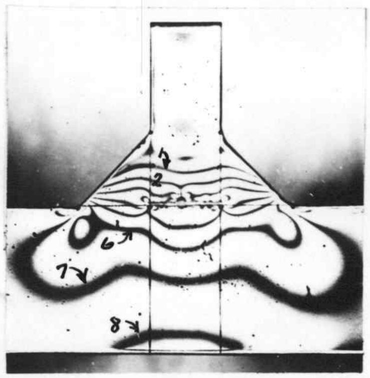
100% Penet.



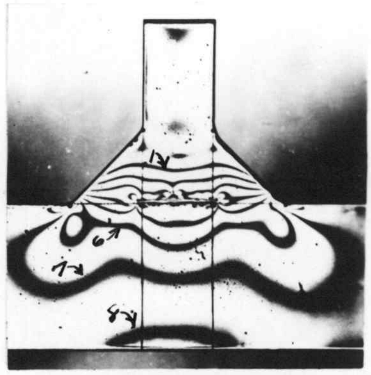
0.094 Penet.



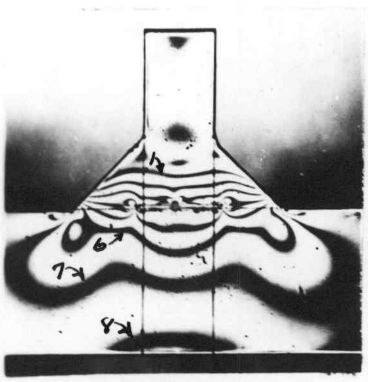
0.047 Penet.



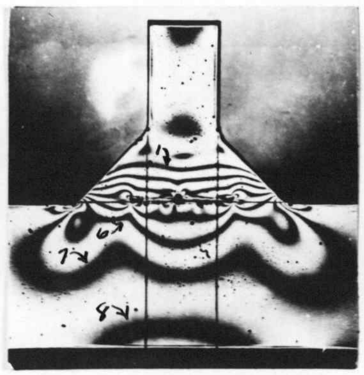
0.000 Penet.



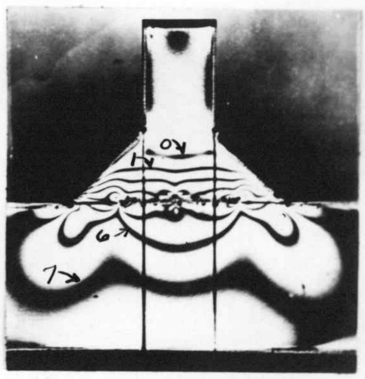
-0.020 Penet.



-0.040 Penet.

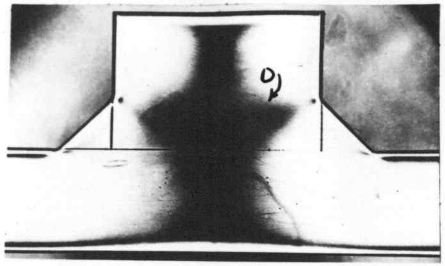


-0.080 Penet.



-0.120 Penet.

Fig. 4. Isochromatic Pattern of Type A.
Tensile Load of 416 lb.



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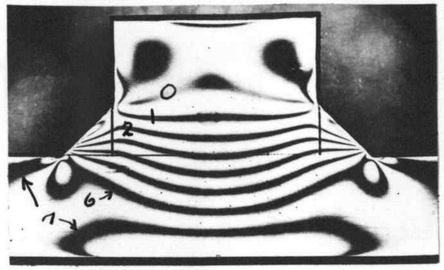
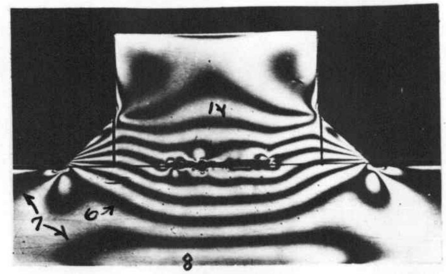
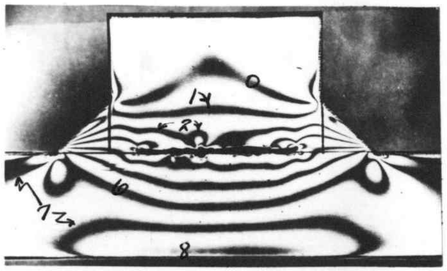


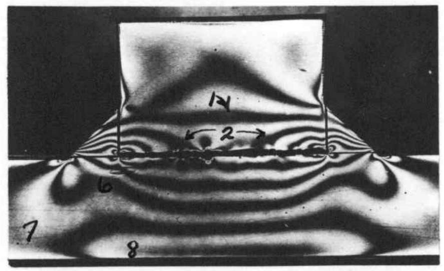
100% Penet.



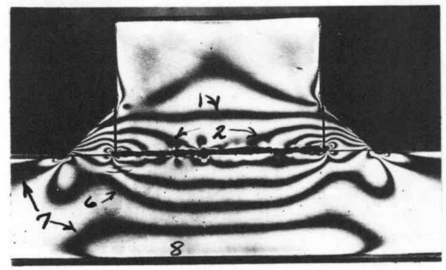
0.375 Penet.



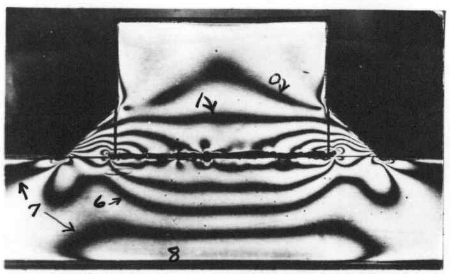
0.187 Penet.



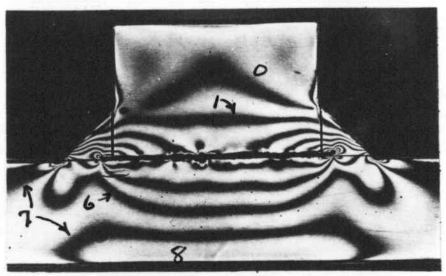
0.000 Penet.



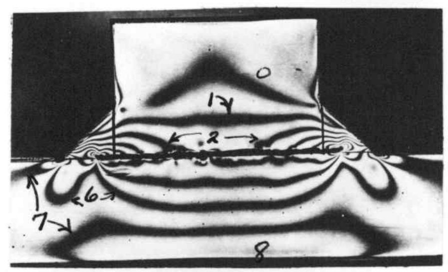
-0.020 Penet.



-0.040 Penet.

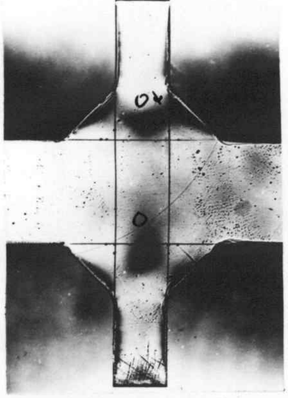


-0.080 Penet.



-0.120 Penet.

Fig. 5. Isochromatic Pattern of Type B.
Tensile Load of 416.1 lb.



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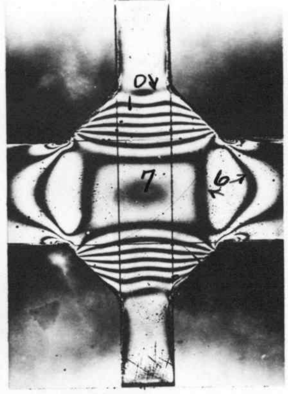

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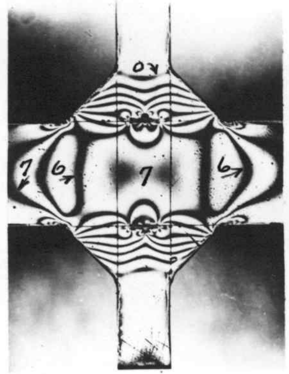
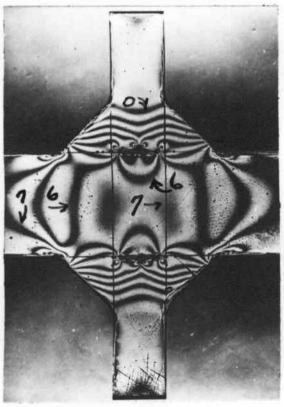
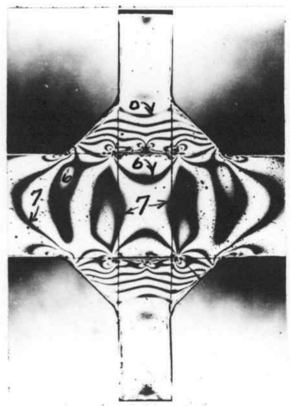


0.094 Penet.

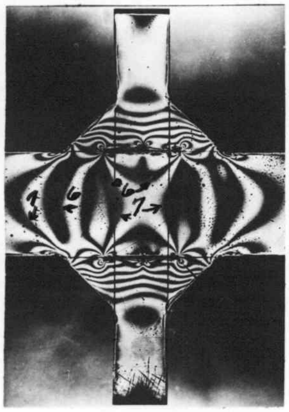


0.047 Penet.

0.000 Penet.

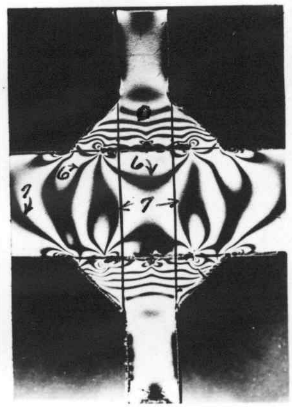


-0.020 Penet.



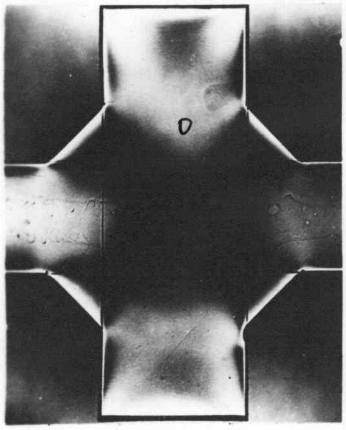
-0.040 Penet.

-0.080 Penet.



-0.120 Penet.

Fig. 6. Isochromatic Pattern of Type C.
Tensile Load of 416 lb.



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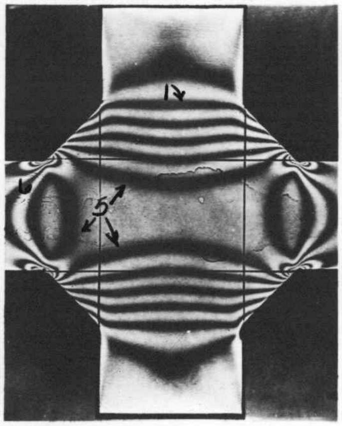

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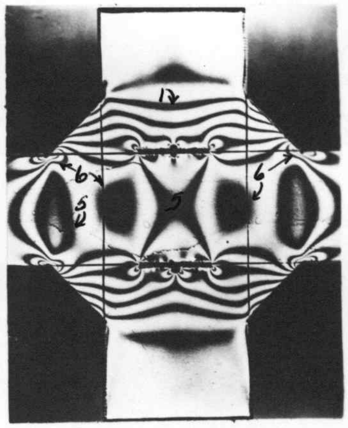
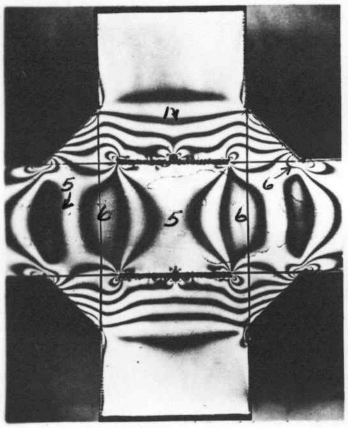
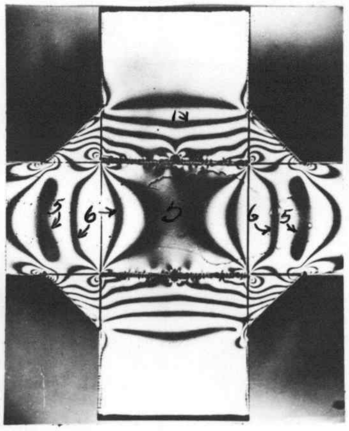


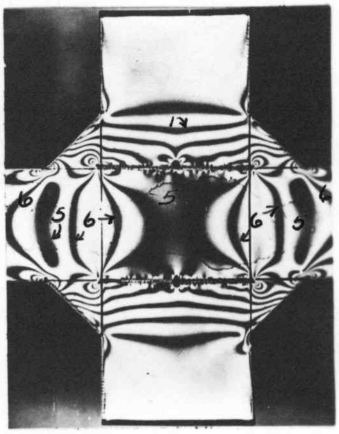
0.250 Penet.



0.125 Penet.



0.000 Penet.



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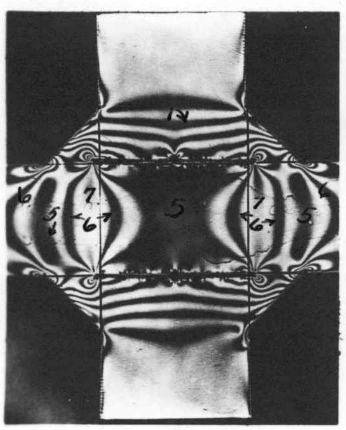
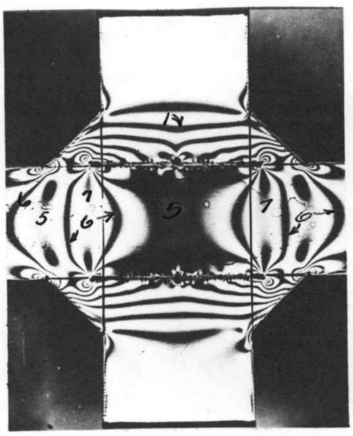
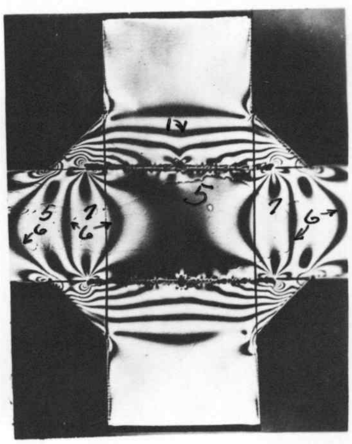


-0.040 Penet.

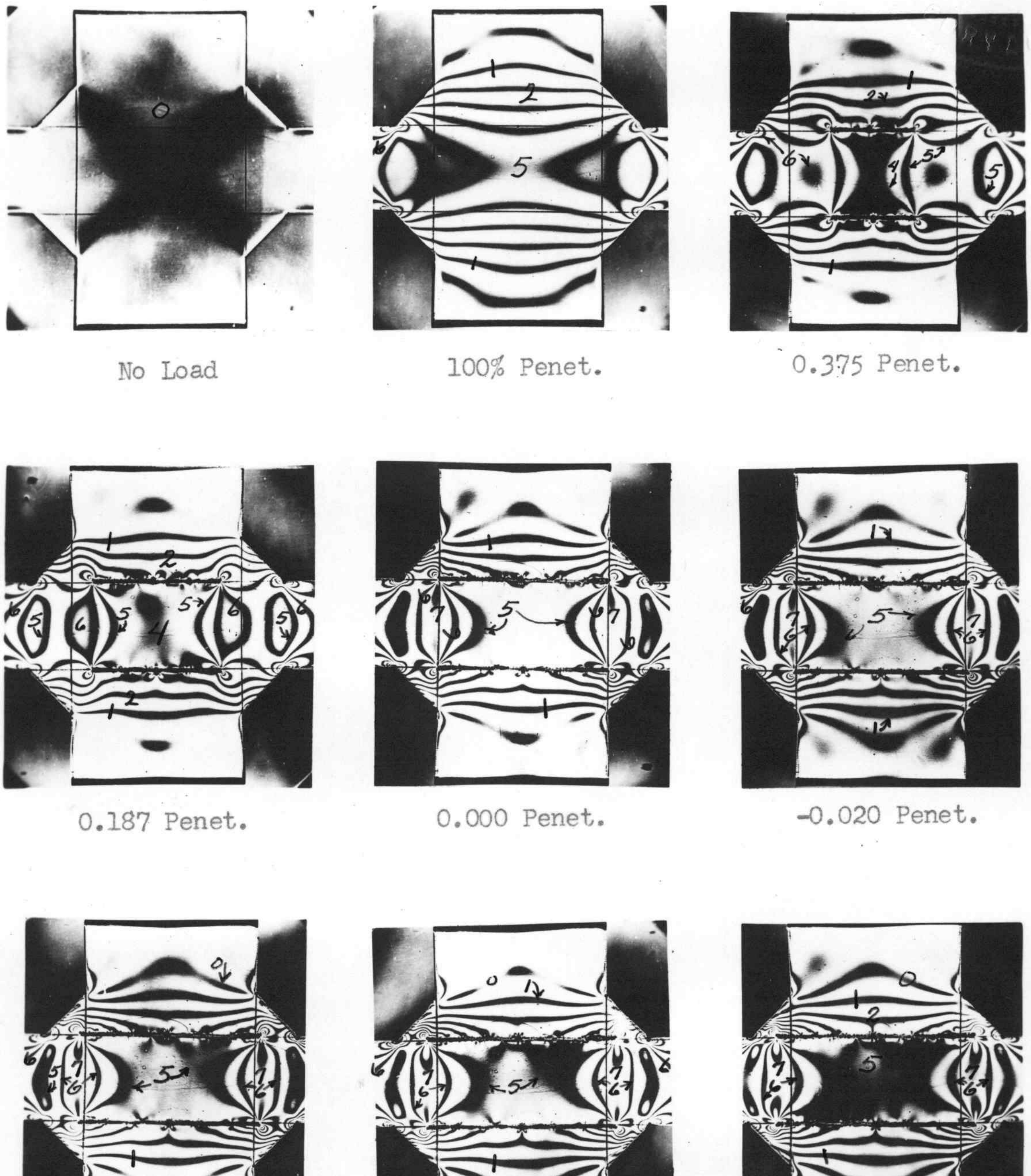


-0.080 Penet.



-0.120 Penet.

Fig. 7. Isochromatic Pattern of Type D.
Tensile Load of 416 lb.



No Load — 100% Penet. — 0.375 Penet.

0.187 Penet. — 0.000 Penet. — -0.020 Penet.

-0.040 Penet. — -0.080 Penet. — -0.120 Penet.

Fig. 8. Isochromatic Pattern of Type E.
Tensile Load of 416 lb.

factor increases; that is, K increases more rapidly between type B and E than between type A and C.

From Fig. 10 it is evident that the stress concentration factor for the neck of the weld is almost constant for any degree of weld penetration and varies slightly with width of stiffener. This, however, is what should be expected since the shape and size of the neck of the weld is constant. Fig. 10 also shows that K is approximately constant for types A and B joints, and varies considerably for types C and D. This can be explained on the basis of the elastic restraint offered to the main member by the various type stiffeners, however, types A and B should be discussed separately from types C, D, and E.

In types A and B, since the strain of the model is retarded by the presence of weld and stiffener and the free boundary is unrestrained to deformation, there must necessarily be an unequal distribution of stress or a moment caused in the main member. This stress concentration factor at the outer boundary of the main member opposite the stiffener is of the order of 1.2 maximum for both types A and B, and does not depend on the width of stiffener.

In types C, D, and E the strain of the model is retarded equally on both sides of the main member, and hence, no moment exists. Evidently the welds in restraining the elasticity of the main member, are subjecting themselves to a part of the main member load, and the wider the welds and stiffeners the more of the main member load they carry and the less the main member carries in the region of the weld. This is evident from a study of Fig. 6, 7, and 8. It will be noticed that for zero weld penetration for types C, D, and E, the fringe order at the center of the main member and opposite the stiffeners are 6.5, 5, and 4.5 respectively. Hence the increase in K at the neck of the weld for types C, D, and E is due directly to the width of stiffener.

It should also be noticed that the stress concentration factor is, in general, greater for the neck of the weld than for the root of the weld.

CONCLUSIONS

The stress concentration factor, K, for the root of the weld, in general, has the following properties:

1. Minimum for 100 per cent weld penetration and increases toward a maximum as the weld penetration decreases.
2. Minimum for type A joint and maximum for type C. Showing that the width of stiffener causes an increase in K, the actual value depending on the width of stiffener.
3. Joints of type A give a lower value of K than type C, yet both have the same width stiffener.

The stress concentration factor, K, for the neck of the weld, in general, has the following properties:

1. For joints of type A, K is approximately constant, showing that K does not depend on weld penetration or width of stiffener.
2. For joints of type C, K is approximately constant for any one width of stiffener, but increases as the width of stiffener increases, the actual value depending upon the width of stiffener.
3. The stress concentration factor for the neck of the weld is higher than for the root of the weld.

Since the value of K is directly proportional to the fringe order, an error of one fringe induces an error of about 7.5% in K. However, it is probable that the data are less than 1 fringe in error.

SUGGESTIONS FOR FUTURE STUDY

It is recognized by the author that the problem is by no means fully solved, but such a solution is beyond the scope of this research.

It would be worth while for an investigator to determine the effect on the stress distribution and stress concentration factor of staggering the stiffener along the main member. This is sometimes desirable for theoretical reasons and to distribute distortion and heat effect more evenly. Also the effect of various types of welds and sizes would be worth knowing. However, Solakian[4] has studied the effect of different welds for a welded butt joint by photoelastic methods. One would expect a similar set of results for this type of joint. It often happens that the stiffeners are required to carry loads. It would be very desirable to know what effect a stiffener load would have upon the stress distribution and concentration factor.

Of course, a series of pure mechanical tests would serve to give a correlation between the photoelastic results obtained and results obtained in actual practice.

DATA - GENERAL

Lamp--Mercury vapor

Filters--Wratten No. 77 and No. B58

Material--Bakelite BT 61-893 Water White

Loading frame ratio--10 to 1

Load on hanger--40 lb. constant

Tare converted to load on hanger--1.61 lb.

Tensile load on models--416.1 lb.

DIMENSIONS OF FINISHED MODELS

Model No.	Thickness In.	Width of Main Member In.	Width of Stiffener In.	Area $In.^2$	Average Stress Psi
A	0.241	0.740	0.375	0.178	2340
B	0.258	0.746	1.500	0.192	2165
C	0.262	0.733	0.375	0.192	2165
D	0.250	0.744	1.000	0.186	2240
E	0.248	0.741	1.500	0.184	2260

+AVERAGE FRINGE ORDER

Penetration	Type A		Type B		Type C		Type D		Type E	
of Weld	Root	Neck	Root	Neck	Root	Neck	Root	Neck	Root	Neck
100%	3.5	10.2	3.0	8.9	4.5	10.3	4.0	10.8	3.8	10.1
50%	5.0	9.9	4.0	10.4	6.0	10.8	6.6	11.6	6.4	11.6
25%	5.0	10.4	5.3	10.6	6.7	9.9	8.0	13.2	8.2	11.6
0.0	5.6	10.0	6.6	10.0	7.0	10.2	9.5	14.8	9.9	12.4
-0.020 in.	5.6	9.9	6.9	9.4	7.1	10.3	9.1	13.0	9.9	13.5
-0.040 in.	5.7	9.8	7.6	8.8	7.3	10.4	9.9	15.0	10.3	13.8
-0.080 in.	6.7	9.6	8.4	10.2	8.1	9.8	10.3	14.4	10.9	14.8
-0.120 in.	7.0	10.0	9.7	9.4	8.1	10.5	11.6	14.4	10.7	13.7

+The fringes were determined for each root or neck and the average value taken.

STRESS CALCULATIONS

$$(\sigma_1 - \sigma_2) = \frac{\lambda N}{1.752 \text{ h C}} = \frac{5461 \text{ N}}{1.752 \times 32.2 \text{ h}}$$

where $_1$ = stress, tension or compression

$_2$ = 0 at boundary

λ = wave length of light, 5461 ä

N = fringe order

h = thickness of model in inches

C = stress optical coefficient, Brewster

Hence the fringe value for

Model A = 401 N

Model B = 374 N

Model C = 369 N

Model D = 388 N

Model E = 389 N.

STRESS CONCENTRATION FACTORS, K

Weld Penetration Inches	Fringe Order Root	Fringe Order Neck	Actual Stress Psi Root	Actual Stress Psi Neck	K Root	K Neck
			Type A			
0.187	3.5	10.2	1400	4080	0.6	1.74
0.094	5.0	9.9	2000	3960	0.86	1.69
0.047	5.0	10.4	2000	4165	0.86	1.78
0.000	5.6	10.0	2240	4010	0.96	1.71
-0.020	5.6	9.9	2240	3960	0.96	1.69
-0.040	5.7	9.8	2280	3920	0.97	1.67
-0.080	6.7	9.6	2680	3840	1.14	1.64
-0.120	7.0	10.0	2800	4010	1.19	1.71
			Type B			
0.750	3.0	8.9	1120	3430	0.52	1.58
0.375	4.0	10.4	1495	3890	0.69	1.80
0.187	5.3	10.6	1980	3960	0.91	1.83
0.000	6.6	10.0	2470	3740	1.14	1.72
-0.020	6.9	9.4	2580	3520	1.19	1.62
-0.040	7.6	8.8	2840	3290	1.31	1.52
-0.080	8.4	10.2	3140	3820	1.45	1.76
-0.120	9.7	9.4	3630	3520	1.67	1.62
			Type C			
0.187	4.5	10.3	1660	3800	0.70	1.75
0.094	6.0	10.8	2215	3980	1.02	1.84
0.047	6.7	9.9	2470	3650	1.14	1.68
0.000	7.0	10.2	2580	3760	1.19	1.73
-0.020	7.1	10.3	2620	3800	1.21	1.75
-0.040	7.3	10.4	2690	3840	1.24	1.77
-0.080	8.1	9.8	2990	3620	1.38	1.67
-0.120	8.1	10.5	2990	3875	1.38	1.79
			Type D			
0.500	4.0	10.8	1550	4190	0.69	1.87
0.250	6.6	11.6	2560	4500	1.14	2.01

(Type D)

0.125	8.0	13.2	3100	5120	1.38	2.24
0.000	9.5	14.8	3685	5745	1.64	2.56
-0.020	9.1	13.0	3530	5040	1.58	2.24
-0.040	9.9	15.0	3840	5820	1.72	2.6
-0.080	10.3	14.4	4000	5590	1.79	2.49
-0.120	11.6	14.4	4500	5590	2.01	2.49
		Type E				
0.750	3.8	10.1	1480	3930	0.65	1.74
0.375	6.4	11.6	2490	4510	1.10	2.00
0.187	8.2	11.6	3190	4510	1.41	2.00
0.000	9.9	12.4	3850	4825	1.70	2.14
-0.020	9.9	13.5	3850	5250	1.70	2.32
-0.040	10.3	13.8	4000	5370	1.77	2.38
-0.080	10.9	14.8	4240	5750	1.88	2.54
-0.120	10.7	13.9	4160	5330	1.84	2.37

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