SERIAL NO. **SSC-98**

ENERGY RELEASE RATES DURING FRACTURING OF PERFORATED PLATES

by

M. W. BROSSMAN
J. A. KIES

Mechanics Division
Naval Research Laboratory

Distributed by

SHIP STRUCTURE COMMITTEE

Convened by
The Secretary of the Treasury

Member Agencies—Ship Structure Committee

Bureau of Ships, Dept. of Navy
Military Sea Transportation Service, Dept. of Navy
United States Coast Guard, Treasury Dept.
Maritime Administration, Dept. of Commerce
American Bureau of Shipping

Address Correspondence To:

Secretary
Ship Structure Committee
U. S. Coast Guard Headquarters
Washington 25, D. C.

SERIAL NO. **SSC-98**

APRIL 22, 1955

SHIP STRUCTURE COMMITTEE

MEMBER AGENCIES:

BUREAU OF SHIPS, DEPT. OF NAVY
MILITARY SEA TRANSPORTATION SERVICE, DEPT. OF NAVY
UNITED STATES COAST GUARD, TREASURY DEPT.
MARITIME ADMINISTRATION, DEPT. OF COMMERCE
AMERICAN BUREAU OF SHIPPING

ADDRESS CORRESPONDENCE TO:

SECRETARY
SHIP STRUCTURE COMMITTEE
U. S. COAST GUARD HEADQUARTERS
WASHINGTON 25, D. C.

April 22, 1955

Dear Sir:

As a result of discussions at the Conference to Evaluate the Current Knowledge of the Mechanics of Brittle Fracture held at Massachusetts Institute of Technology on October 15 and 16, 1953 (Proceedings distributed as Ship Structure Committee Report Serial No. SSC-69), investigators from the Mechanics Division of the Naval Research Laboratory performed preliminary experiments designed to resolve several of the points raised. These experiments are described in Naval Research Laboratory Memorandum Report 370, "Energy Release Rates During Fracturing of Perforated Plates" by M. W. Brossman and J. A. Kies, which has been reprinted by the Ship Structure Committee and is forwarded herewith as SSC-98.

This report is being distributed for the information of persons interested in the mechanics of brittle fracture and for the particular attention of those who attended the Conference at M.I.T. in 1953.

Permission of the Naval Research Laboratory to reprint this material is gratefully acknowledged.

Very truly yours,

K. K. Cowart

K. K. COWART
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

TABLE OF CONTENTS

LIST OF FIGURES

PREFACE

The work described in this report was stimulated by a timely and searching question raised by Mr. E. M. MacCutcheon, Jr., during a conference on Fracture Mechanics held at Massachusetts Institute of Technology in October 1953. If brittle fracture instability depends on a critical release rate of elastic energy, how is that release rate influenced by the presence of a large opening such as a hatch from the boundary of which a crack may spread? The primary purpose of this report is to answer that question. In doing this, no attempt has been made to treat the general case when considerable ductility may be exhibited.

A more general expression for the conditions of fast fracturing developed by Irwin includes a term giving the work expended in producing permanent set. The Griffith-like term only has been used here, and this represents not the available energy release rate but rather a minimum value for the energy release rate which is exact only when the permanent set is negligible.

Studies of fast fracturing are continuing at the Naval Research Laboratory.

ENERGY RELEASE RATES DURING FRACTURING OF PERFORATED PLATES

By

M. W. Brossman
J. A. Kies

Mechanics Division
Naval Research Laboratory

(NRL Memorandum Report No. 370)

Distributed by

SHIP STRUCTURE COMMITTEE

ENERGY RELEASE RATES DURING FRACTURING OF PERFORATED PLATES

ABSTRACT

A preliminary study of energy release rates in simple structures has been made.

These simple structures consisted of 75ST specimens 6-in. wide, 12-in. long, and .032-in. thick. The specimens contained holes of various geometric shapes: circles, ellipses, squares, and slots. Symmetrical slots which serve as crack simulators of increasing length were introduced at the extremities of the holes.

Energy release rates of the specimens with slots up to 2/3 the plate width were measured and compared with rates for a plate containing a simple slot alone. The energy release rates for the plates containing a hole-slot combination were quite similar to the rates for plates containing simple slots. Thus the instability stress for a plate containing a hole from which a crack has started should be approximately equal to the instability stress for a plate containing a crack of length equal to the hole-crack combination.

Comparisons of test results with theoretical values show good agreement with a function of the Griffith type for the full range of slot lengths evaluated. Agreement of test results with the modified Greenspan relation was satisfactory

up to ratios of slot width to plate width of 1/4. Beyond this range the experimental rate was considerably less than the calculated rate.

A calculation is included in the Appendix based on the Griffith function for the case of a Liberty ship with a deck width of 60 ft. and a hatch opening of 20 ft. from which a crack has started. Using a typical energy release rate of 200 in-lb per sq. in. for brittle fracture of steel, the instability stress calculated is 3980 lb. per sq. in. This figure corresponds remarkably with calculated nominal (still water) stress in Liberty ships which failed in a catastrophic manner.

The numerical example is purely illustrative, since extensive studies of the effect of residual stress, structural constraint, load redistributions, and so forth, are required to completely predict instability behavior of cracks in complex structural systems such as ships.

PROBLEM STATUS

This is an interim report. Work on this problem is continuing.

AUTHORIZATION

NRL PROBLEM F01-03

NR No. 631-030

INTRODUCTION

The purpose of this investigation is to obtain information relating to the effect of cracks on the fracture strength of simple structures.

In the past few years the Mechanics Division of NRL has made a theoretical and experimental study of the role of stored elastic energy in the fracture phenomenon. A theory has been developed based upon the strain energy release rate method for calculating the sudden collapse by fracturing of a centrally notched plate in tension[1,2,3]. The theory development shows[4] a relationship between the energy available in the fracture system and specimen geometry, modulus, and load. The equation appears in the following form:

$$-\left(\frac{\partial E_s}{\partial A}\right)_\delta = \frac{1}{2}\,\frac{\pi P^2}{BEt^2 r}\left(\frac{\partial \frac{1}{K}}{\partial y}\right)_\delta \qquad [1]$$

and at instability $-\frac{\partial E_s}{\partial A} = \frac{\partial W}{\partial A}$

where δ = extension of specimen

$-\frac{\partial E_s}{\partial A}$ = energy available/unit area

$\frac{\partial W}{\partial A}$ = energy consumed/unit area

P = load

E = Young's modulus

L = length of specimen

$r = \frac{\pi B}{L}$

t = thickness of specimen

B = width of specimen

$K = \frac{k}{k_o}$ = ratio of spring constant of perforated specimen to unperforated specimen

x = dimension of perforation normal to load

$y = \frac{x}{B}$

The function $\frac{\frac{1}{K}}{y}$ in the above relation can be evaluated experimentally or determined analytically using solutions of Greenspan[5] for the rigidity of a rectangular plate containing a centrally located elliptical hole*. Kies[4] has extended this solution, representing a crack as an ellipse whose minor axis is zero and whose major axis equals the crack length. Then

$$K = \frac{2 - y^2 - y^4}{2 + (r - 1)y^2 - y^4} \qquad [2]$$

and

$$\frac{\partial \frac{1}{K}}{\partial y} = \frac{2ry(2 + y^4)}{(2 - y^2 - y^4)^2} \qquad [3]$$

---

*Greenspan[5] has illustrated the limitations in the application of his solution for the case of a thin rectangular plate with a circular hole. The values computed are in error when the diameter of the hole is large compared to the plate width and/or plate length.

Substituting in Equation [1], we have

$$-\left(\frac{\partial E_s}{\partial A}\right)_\delta = \frac{\pi P^2}{BEt^2} \; \frac{y(2 + y^4)}{(2 - y^2 - y^4)^2} \qquad [4]$$

If one neglects the higher powers of y in Equation [3],

$$\frac{\partial \frac{1}{K}}{\partial y} = ry \qquad [5]$$

Substituting in Equation [1], we have

$$-\frac{\partial E_s}{\partial A} = \frac{1}{2} \; \frac{\pi P^2 ry}{BEt^2 r} = \frac{\pi P^2 x}{2B^2 Et^2}$$

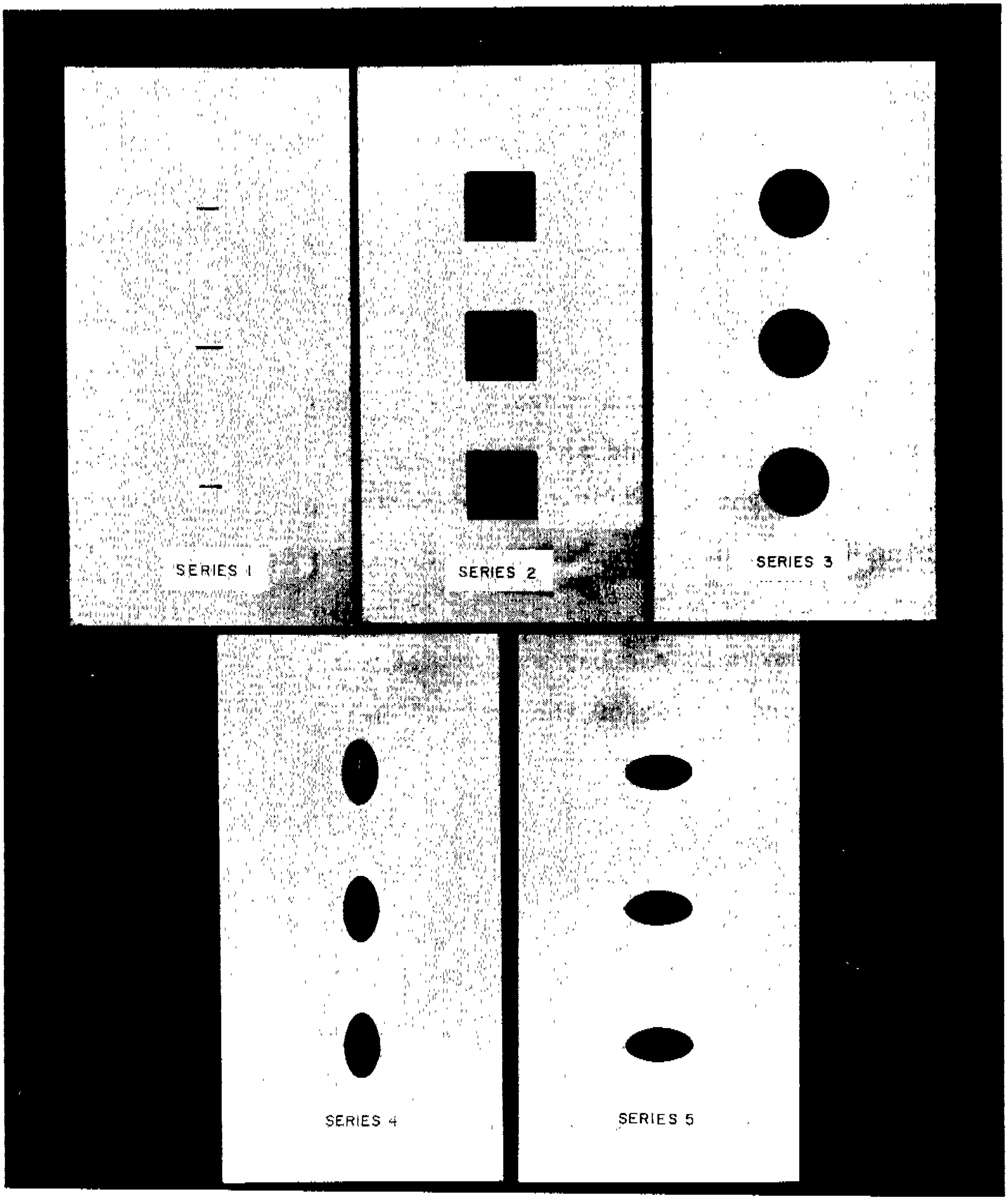
$$= \frac{\pi \sigma^2 x}{2E} = \frac{\partial W}{\partial A} \text{ at instability} \qquad [6]$$

Equation [6] is the well known Griffith formula. Experimental work at this laboratory on acrylic sheet materials with a central notch has lent supporting evidence to the stored elastic energy fracture theory. However, studies have not been made to evaluate the limits of application of the modified Greenspan calculation used in Equation [4].

Furthermore, the case of the centrally notched plate is but one of the many cases of interest. The plate material is fabricated into a structure containing various discontinuities such as holes and stiffeners, i.e., airplane skins, ship plate, and so forth. In order to gain some information on the mechanics of fracture in more complex structural systems containing notches, a program of study has been initiated in which perforated plates containing slots are subjected to tensile loads. The behavior of these more complex slot systems and the limitations of application of the modified Greenspan solution and the Griffith formula will be evaluated for the specimens used in these tests. A narrow machined slot was used instead of a true crack to facilitate preparation of specimens and to insure reproducibility.

PROCEDURE AND TESTS

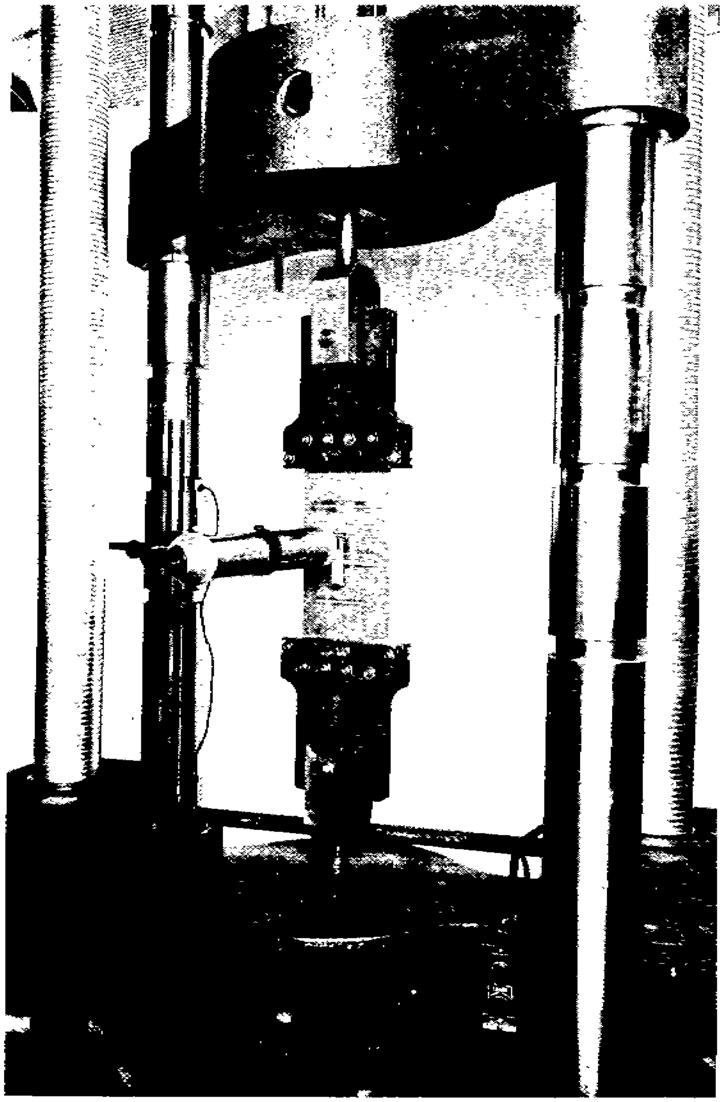
Specimens of 75ST 6-in. wide by 12-in. long by .032-in. thick were prepared with 3 holes spaced on 3-in. centers and are subsequently referred to as 3-bay members. The specimens are shown in Fig. 1. A 3-bay member was chosen to aid in eliminating the effect of grip restraint and to insure that the ends of the bay remain plane. Series 1 specimens contained a 1/16-in. slot with a 1/16-in. diameter curvature at the root of the slot. Series 2 specimens contained square holes 1 1/2-in. by 1 1/2-in. with corner filets of 1/8-in. diameter. Series 3 specimens contained circular holes of 1 1/2-in. diameter. Series 4 specimens contained elliptical holes of 1.45-in. major axis and 0.775-in. minor axis with the major axis parallel to the load. Series 5 specimens contained elliptical holes of 1.45-in. major axis and 0.775-in. minor axis with the minor axis parallel to the direction of the load.



Basic 3-Bay Test Specimens

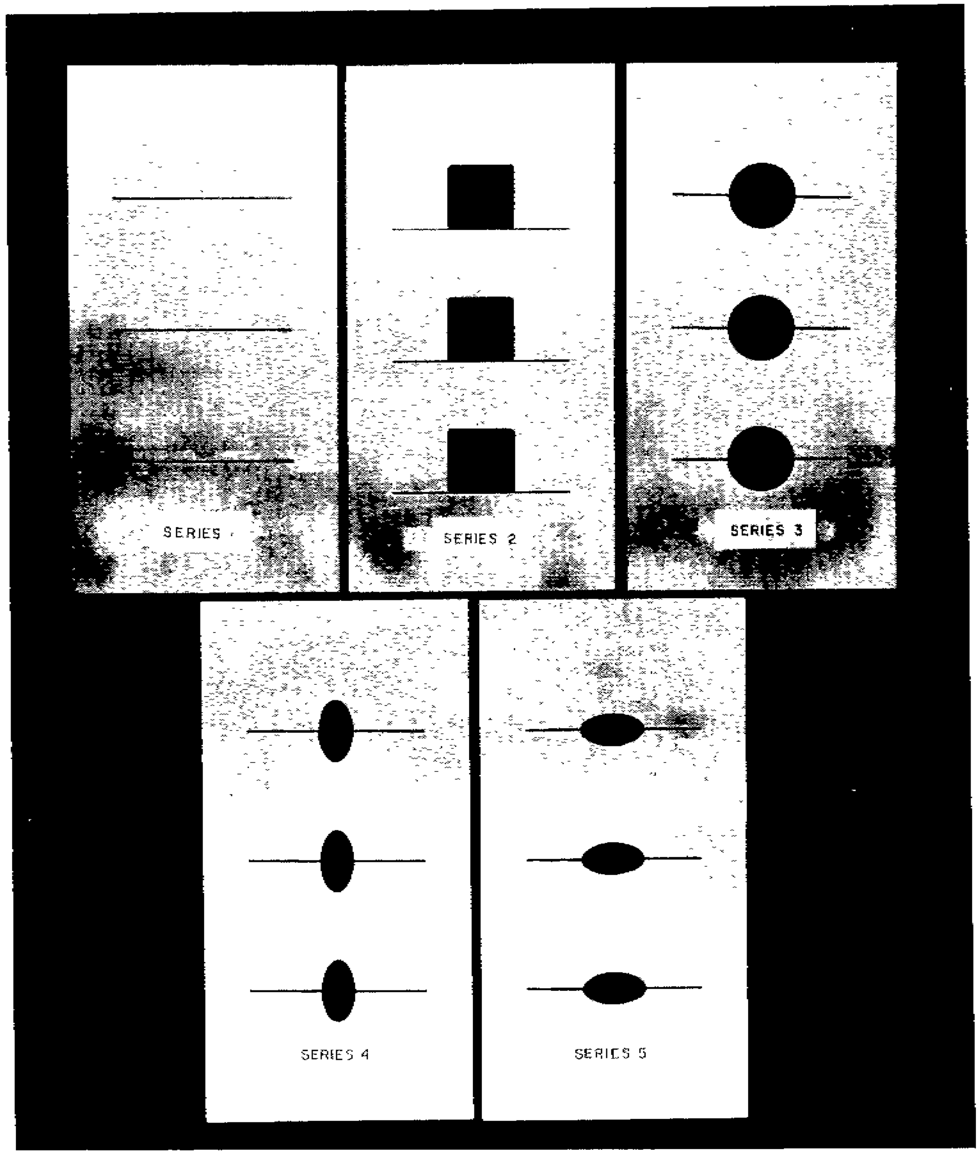
Fig. 1

Each specimen was instrumented with Tuckerman optical strain gages of 3-in. gage length applied at mid-width to opposite faces of the central bay. The strain was readable to .000008 in. or .0000027 in. per inch. Tensile loads were applied to the specimen through spherically seated wide-plate grips which gripped the specimens their full width for 1-in. length. The test set-up is shown in Fig. 2. The test specimens were loaded well within their elastic ranges, and strain-load measurements were made during the load and unload cycle. Symmetrical slots of 1/16-in. height and 1/32-in. end radius and systematically increasing lengths were then introduced in the Series 2, 3, 4, and 5 specimens as shown in Fig. 3. In order to evaluate the effectiveness of the multiple bay system, strain measurements were made at the edges and center of the central 3-in. bay members. No differences were found between the strains measured at the edges and those measured at the centers for the specimens from 1/2-in. to 4-in. slot length so instrumented. Strain-load measurements were again made well within the elastic range for each slot length in intervals of approximately 1/2 in. up to a total slot length of 4 in. Figs. 4--8 show the spring constants vs. crack length for the Series 1 to 5 specimens. Crack length is defined as the total length of the slot. The spring constants obtained from the load-unload measurements are shown individually. An average line is drawn through these points since the loads are purely elastic and the scatter of values appear to be



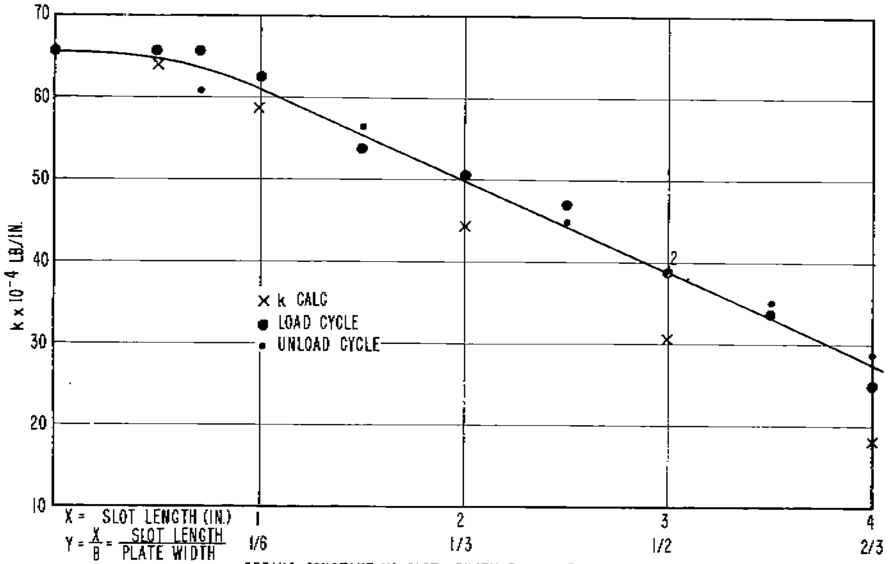
Test Set-up Showing Tuckerman Optical Strain Gage

Fig. 2



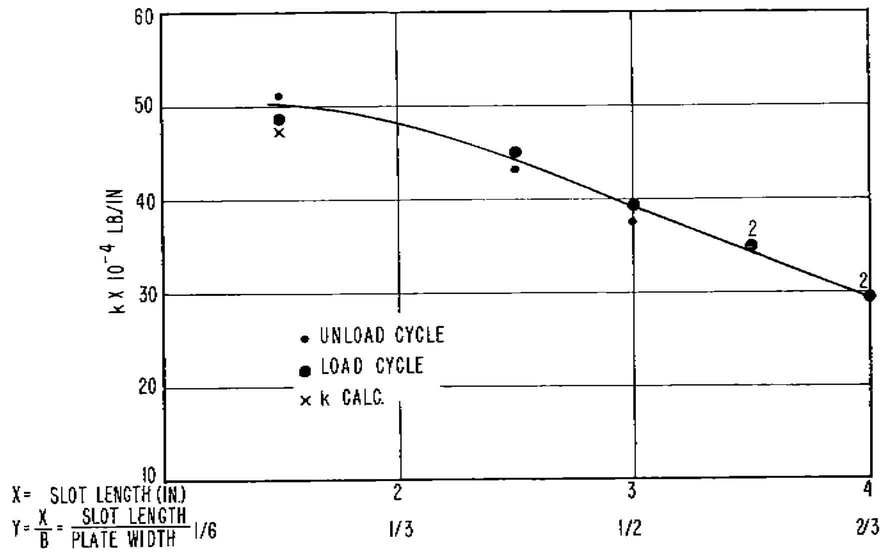
Test Specimens after Slotting

Fig. 3



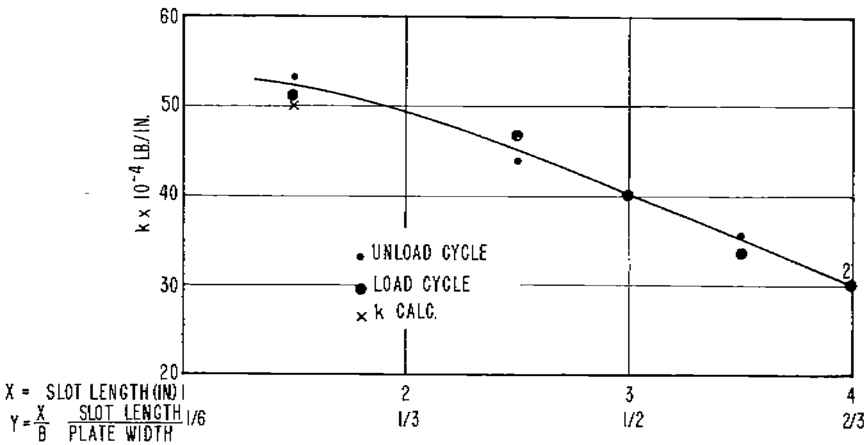
SPRING CONSTANT VS. SLOT LENGTH FOR 1/16" WIDTH SLOT

Fig. 4



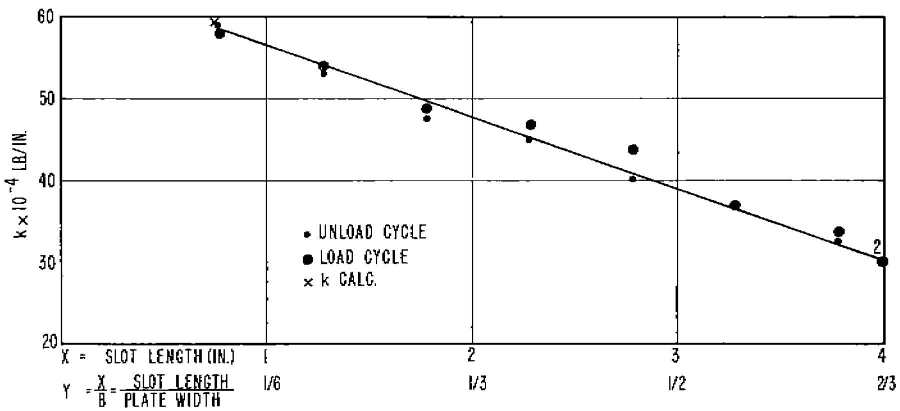
SPRING CONSTANT VS. SLOT LENGTH FOR 1 1/2" X 1 1/2" SQUARE PERFORATION WITH 1/16" WIDTH SLOT

Fig. 5



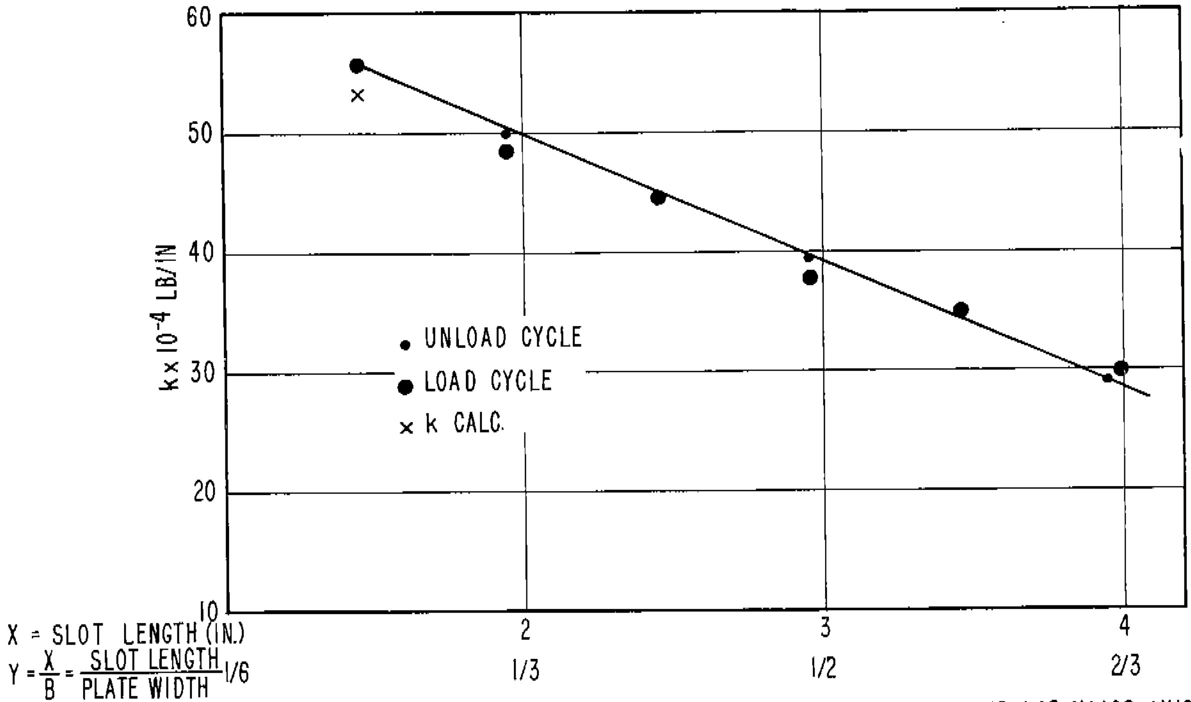
SPRING CONSTANT VS SLOT LENGTH FOR 1 1/2" DIAMETER PERFORATION WITH 1/16" WIDTH SLOT

Fig. 6



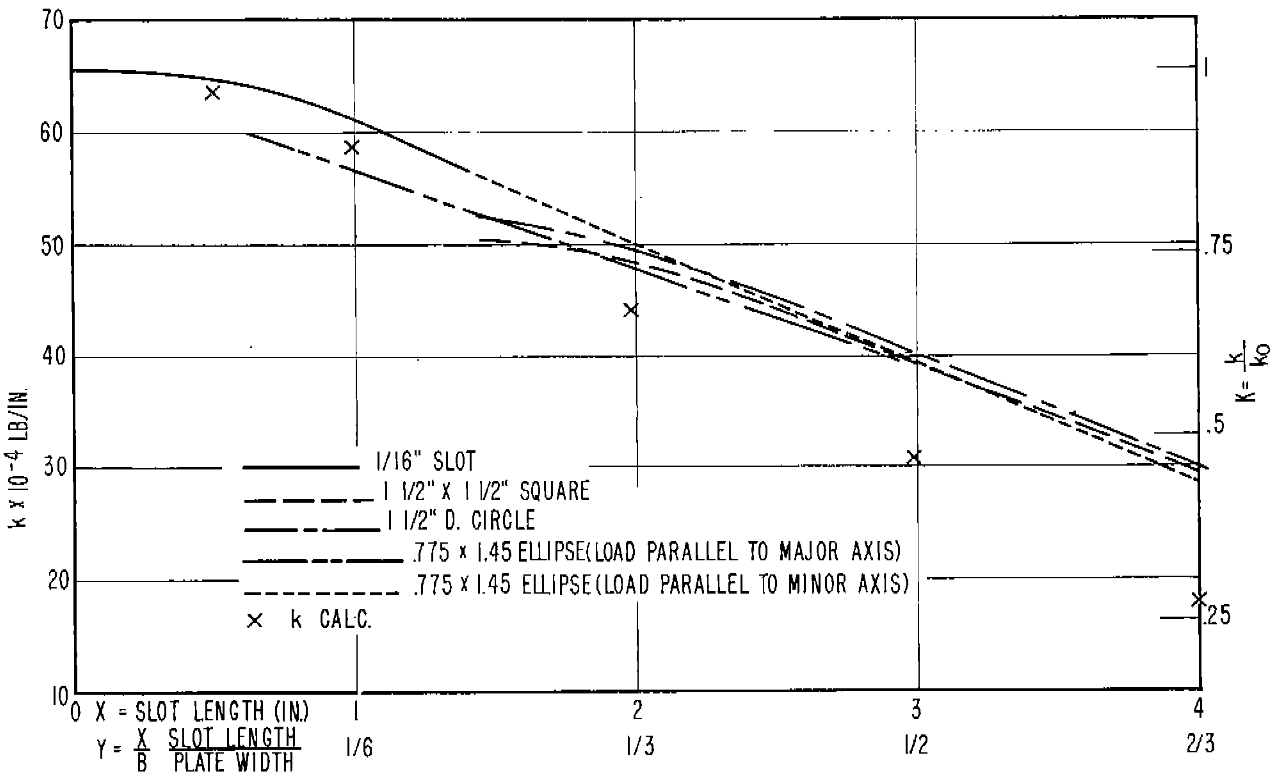
SPRING CONSTANT VS. SLOT LENGTH FOR ELLIPSE OF .775 MINOR AXIS AND 1.45 MAJOR AXIS. LOAD APPLIED PARALLEL TO DIRECTION OF MAJOR AXIS

Fig. 7



SPRING CONSTANT VS. SLOT LENGTH FOR ELLIPSE OF .775 MINOR AXIS AND 1.45 MAJOR AXIS
LOAD APPLIED PARALLEL TO DIRECTION OF MINOR AXIS

Fig. 8



SPRING CONSTANTS VS. SLOT LENGTH FOR SLOTTED SPECIMENS

Fig. 9

random. Fig. 9 shows a superposition of these curves on a common plot. Also shown in Fig. 9 are the values computed from the modified Greenspan relation.

Referring to Equation [1],

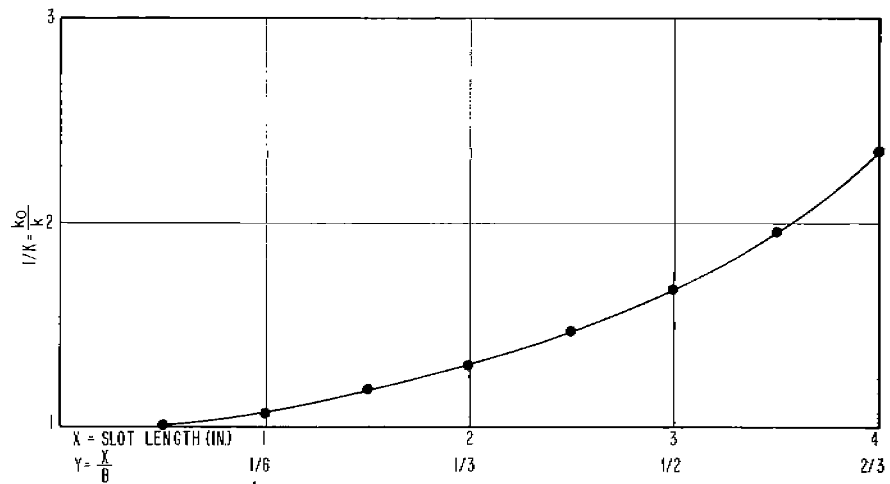
$$-\left(\frac{\partial E_s}{\partial A}\right)_\delta = \frac{1}{2}\ \frac{\pi P^2}{BEt^2 r}\left(\frac{\partial \frac{1}{K}}{\partial y}\right)_\delta$$

it will be noted that $\left(\frac{\partial \frac{1}{K}}{\partial y}\right)_\delta$ is an important factor in the energy release rate function. Accordingly, the reciprocal of K has been plotted with respect to y in Figs. 10--15. Slopes taken from these plots have been plotted vs. y in Fig. 16.

DISCUSSION

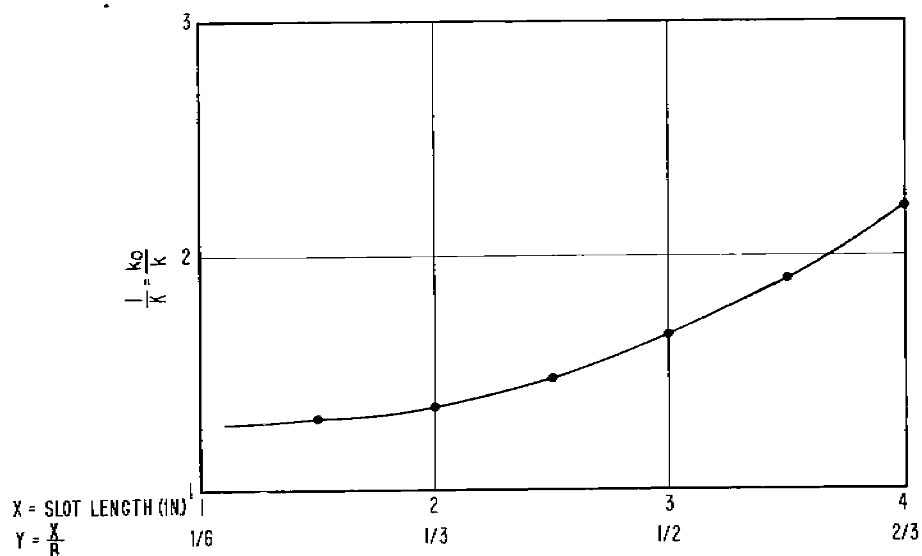
Reference to Fig. 9 shows good agreement between the calculated values of spring constant based on the modified Greenspan relation and the experimental values up to a slot length of approximately 1.5 in. or y = 1/4. For specimens containing slot lengths greater than 1.5 in., the experimental values lie considerably above the calculated values. Reference to Fig. 16 illustrates the change of $\frac{1}{K}$ with respect to y. Although the specimens containing the slot alone show $\frac{\partial \frac{1}{K}}{\partial y}$ values greater than any of the hole and slot combination specimens, the values are quite similarr

Thus the instability load for a plate containing a hole and slot should be approximately equal to the instability load



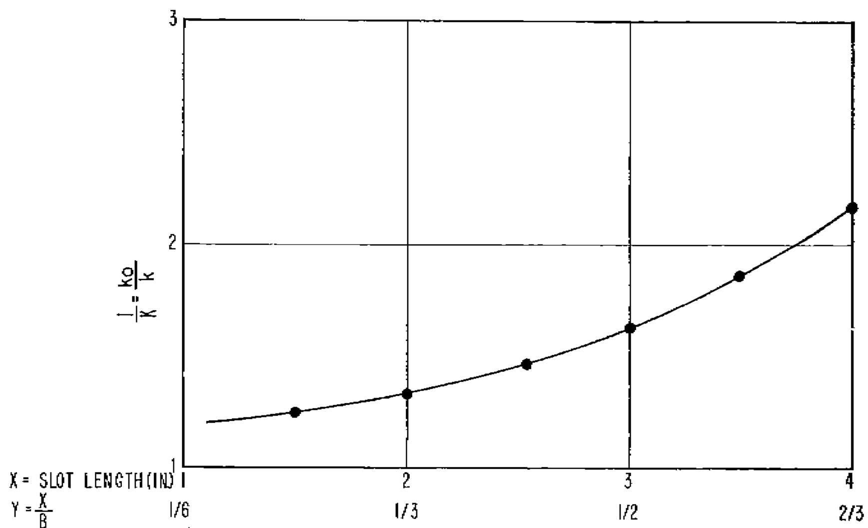
$\frac{1}{K}$ VS. SLOT LENGTH FOR 1/16" SLOTTED SPECIMEN

Fig. 10



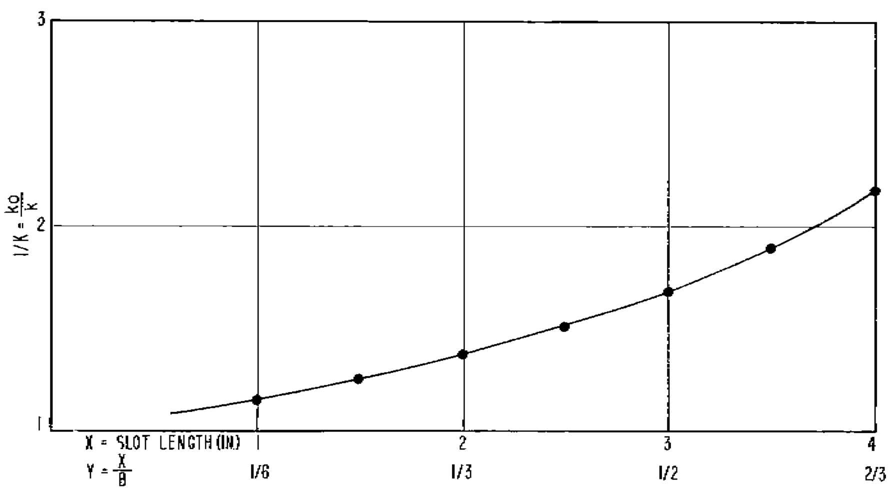
$\frac{1}{K}$ VS. SLOT LENGTH FOR SPECIMEN WITH 1 1/2" X 1 1/2" SQUARE HOLE AND SLOT

Fig. 11



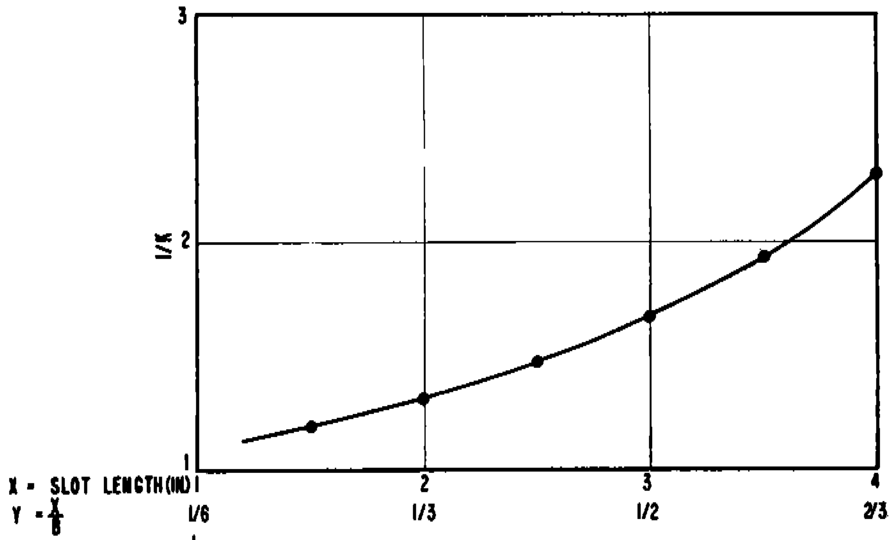
$\frac{1}{K}$ VS. SLOT LENGTH FOR SPECIMEN WITH 1 1/2" DIAMETER HOLE AND SLOT

Fig. 12



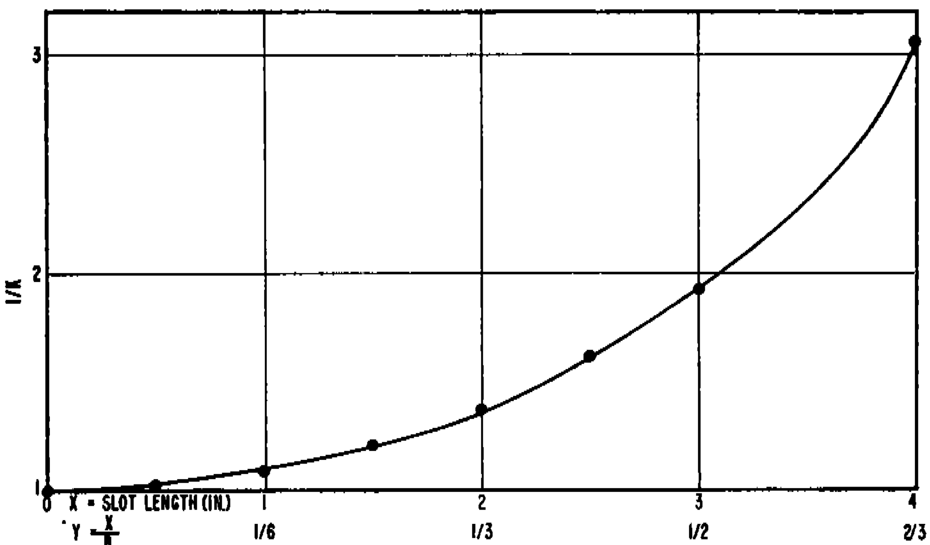
$\frac{1}{K}$ VS. SLOT LENGTH FOR SPECIMEN WITH ELLIPTICAL HOLE .775 MINOR AXIS AND 1.45 MAJOR AXIS.
LOAD PARALLEL TO MAJOR AXIS.

Fig. 13



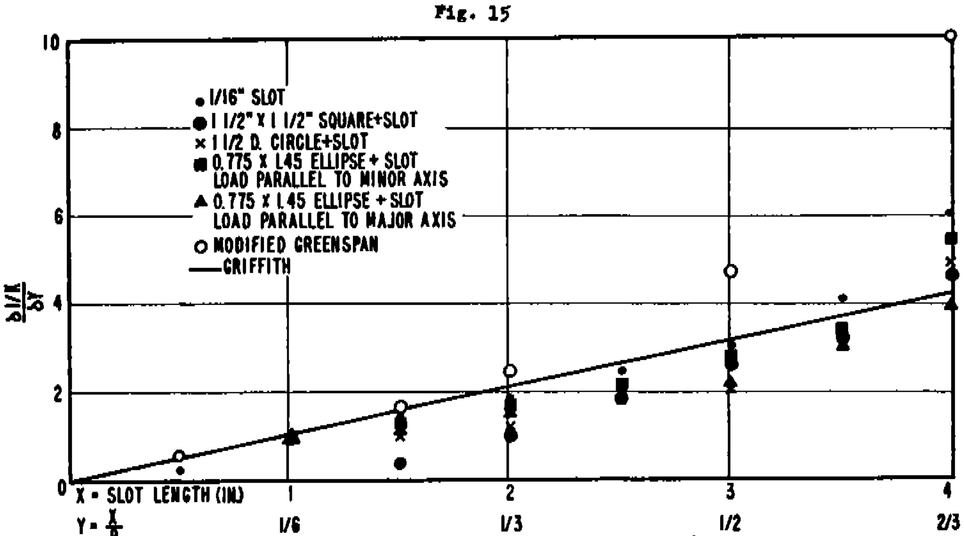
$\frac{1}{K}$ VS. SLOT LENGTH FOR ELLIPSE OF .775 MINOR AXIS AND 1.45 MAJOR AXIS. LOAD PARALLEL TO MINOR AXIS

Fig. 14



$\frac{1}{K}$ VS. SLOT LENGTH CALCULATED FROM MODIFIED GREENSPAN RELATION

Fig. 15



δ 1/K/δY VS. SLOT LENGTH FOR SLOTTED SPECIMENS

Fig. 16

for a plate containing a simple slot of equal total length. Obviously, this has serious implications with respect to the failure stresses in ships containing large hatch openings from which short cracks have started. A calculation illustrating the importance of the result in predicting ship failures is included in the Appendix.

Fig. 16 also shows the function $\frac{\partial \frac{1}{K}}{\partial y}$ as calculated from Equation [3] based on the Greenspan solution. It will be noted that the calculated values show good agreement with the experimental values for the simple notch up to a notch length of 1 1/2 in. or $\frac{x}{B} = \frac{1}{4}$. Beyond this point the experimental value is less than the calculated value. At a slot length of 3 in., $\frac{x}{B} = \frac{1}{2}$; the experimental value is 33% less than the calculated value. At this laboratory the work value $\frac{\partial W}{\partial A}$ defined by Equation [3] is used as a basis of rating the fracture resistance of materials, a high value denoting good fracture resistance. In the case of the specimen studied here, a work value computed on the basis of Equation [3] with $\frac{\partial \frac{1}{K}}{\partial y}$ evaluated from the modified Greenspan relation would be 150% of its true value for $\frac{x}{B} = \frac{1}{2}$. The solid line in Fig. 16 illustrates the function $\frac{\partial \frac{1}{K}}{\partial y}$ as calculated for the case of small values of y from Equation [5]. As shown in Equation [6], this relation reduces Equation [3] to the well-known Griffith formula. The Griffith function $\frac{\partial \frac{1}{K}}{\partial y}$ as defined by Equation [5] shows good agreement with the experimental values within the range evaluated $\frac{x}{B} = 0$ to $\frac{x}{B} = \frac{2}{3}$. The applicability of the Griffith function to such large values of crack length is rather surprising. It must be emphasized, however, that the results discussed here apply to the particular specimen studied. The extent of application of these results to specimens of different geometry and different end constraints is not known. It is clear, however, from these studies that a thorough evaluation of the effect of specimen geometry and constraint on the function $\frac{\partial \frac{1}{K}}{\partial y}$ should be made. Furthermore, the effect of cracks in other structural systems, especially reinforced holes, should be studied in order that results of studies of cracks in simple plates can be applied to more complex systems. Results of studies using other specimen geometry and structures will be forthcoming. One special case of great interest will be that in which appreciable plastic flow occurs in the vicinity of the slot or crack. In such a case the functional relations found here between strain energy release factor and crack length could be materially altered.

SUMMARY

1. Tests conducted on plates with hole and slot combinations show energy release rates similar to those for plates containing simple slots equal in length to the hole-slot combination. These tests extended to specimens with slot widths

up to 2/3 the plate width.

2. Comparisons of test results with theoretical values show good agreement with a function of the Griffith type for the full range of slot lengths evaluated. Agreement of test results with the modified Greenspan relation was satisfactory up to ratios of slot width to plate width of 1/4. Beyond this range the experimental rate was considerably less than the calculated rate.

3. Calculations based on the test results showed excellent agreement with calculations of nominal (still water) stresses existing in Liberty ships which failed in a catastrophic manner.

4. Extensive studies of more complex model systems are required to understand the effect of residual stresses, structural discontinuities, and so forth, on instability behavior of cracks in such systems.

ACKNOWLEDGMENT

The valuable assistance of Mr. Robert McVicker in conducting these tests is gratefully acknowledged.

REFERENCES

1. Irwin, G. R. "Fracture Dynamics," Trans. A. S. M., vol. 40A, 1948.

2. Irwin, G. R., and Kies, J. A. "Fracturing and Fracture Dynamics," THE WELDING JOURNAL, Res. Suppl., February 1952, pp. 95-s--100-s.

3. Irwin, G. R., and Kies, J. A. "Critical Energy Rate Analysis of Fracture Strength," THE WELDING JOURNAL, Res. Suppl., April 1954, pp. 193-s--198-s.

4. Kies, J. A. "A Method of Evaluating the Shatter Resistance of Aircraft Canopy Materials," NRL Memorandum Report No. 237.

5. Greenspan, M. "Axial Rigidity of Perforated Structural Members," JOURNAL OF RESEARCH, National Bureau of Standards, 31-1943.

6. THE DESIGN AND METHODS OF CONSTRUCTION OF WELDED STEEL MERCHANT VESSELS. Washington, D. C.: Government Printing Office, July 15, 1946. P. 45, Fig. 29.

7. Wilson, W. M., Hechtman, R. A., and Bruckner, W. H. "Cleavage Fracture of Ship Plates." University of Illinois Bulletin, vol. 48, no. 50, March 1951.

8. Robertson, T. S. "Propagation of Brittle Fracture in Steel," JOURNAL of the IRON AND STEEL INSTITUTE, December 1953.

9. Feely, F. J. (Jr.), Hrtko, D., Kleppe, S. R., and Northup, M. S. "Report on Brittle Fracture Studies." Conference on Brittle Fracture Mechanics, Massachusetts Institute of Technology, October 15, 1953.

APPENDIX

The perforated specimens containing slots studied in this report serve as simplified models of a variety of openings in the plate material of ships and aircraft from which cracks can start. The instability behavior of a crack in these complex structural systems may be quite different from the behavior of a crack originating from a hole in a plate under simple tensile stress, however. Extensive studies of the effect of residual stress, structural constraint, load redistributions, and so forth, are required to completely predict instability behavior of cracks in these systems. However, sample calculations of instability stress levels based upon the results of the simple model studied in this report can illustrate the importance of understanding instability concepts in designing structures. The present calculations show the limitations of design based upon fracture strength considerations alone. Example No. 1.

A typical Liberty ship has a deck width of 60 ft. and a hatch opening of 20 ft. Considering the deck as a simple perforated plate, we shall calculate the instability stress for a crack starting at a hatch corner. Referring to Equation [6] we have $\frac{\partial W}{\partial A} = \frac{\pi \sigma^2 x}{2E}$. Tests have shown $\frac{\partial W}{\partial A}$ values of 200 in-lb per sq. in. and less for brittle fracture of ship steel*.

*Values of $\frac{\partial W}{\partial A}$ as high as 5000 in-lb per sq. in. have been obtained in modified Navy tear tests for ship steel but correspond to extremely ductile fracture.

With $\frac{\partial W}{\partial A}$ = 200 in-lb per sq. in., X = 20 ft., and E = 30×10^6 lb. per sq. in., we find σ = 3980 lb. per sq. in. This calculated value of the instability stress corresponds remarkably with calculations(6) of the nominal (still water) tensile stress in Liberty ships which failed in a catastrophic manner. The calculated stress levels in these ships at failure range from 3800 lb. per sq. in. to 6800 lb. per sq. in.

Many wide plate tests(7) have generally shown that regardless of the temperature or type of fracture the average nominal stress at failure was very close to the yield strength of the steel. It should be remembered that these tests were not made under conditions completely representative of service conditions. Many of the severe failures in ships started from weld defects or arc strikes. Such crack starters apparently had the role of suddenly introducing a brittle crack moving rapidly into the surrounding steel. The work of Pellini and others at NRL shows that such crack starters in specimens of full plate thickness can produce fractures with negligible plastic deformation in the drop-weight test. Specimens without crack starters tested in the same way retained great ductility. In addition the work of Robertson(8) and of Feely(9) tends to show that brittle crack propagation can be sustained at stresses far below yield. The results of Robertson and of Feely are perhaps not final because the dynamic stresses have not been fully measured or analyzed.

Ample evidence exists, however, for doubting that in service a nominal stress as high as that corresponding to general yield must exist during brittle fracturing. Example No. 2.

A typical transport aircraft contains a number of window and hatch openings in the aircraft skin. Consider a crack originating at the edge of a 2-ft. opening. Calculating the limiting stress for instability from Equation [6] with a value of $\frac{\partial W}{\partial A}$ = 300 in-lb per sq. in. for the 75ST6 Alclad skin, we have σ= 9750 lb. per sq. in. This instability stress level is dangerously near the design nominal tensile stress in the fuselage of 7500 lb. per sq. in. Larger openings could materially reduce the instability stress to values considerably below the design stress. Both of the above examples serve to exhibit the dangerous consequences of design based on standard tensile properties alone.