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SIZE EFFECT IN BRITTLE FRACTURE OF NOTCHED STEEL PLATES IN TENSION

by

J. H. Ludley and D. C. Drucker

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November 24, 1961

Dear Sir:

In order to study the effect of gross strain upon the mechanical and metallurgical properties of steel and to relate these variables to steel embrittlement, the Ship Structure Committee is sponsoring a project at Brown University entitled "Macrofracture Fundamentals." Herewith is a copy of the First Progress Report, SSC-135, Size Effect in Brittle Fracture of Notched Steel Plates in Tension by J. H. Ludley and D. C. Drucker.

This project is being conducted under the advisory guidance of the Committee on Ship Structural Design of the National Academy of Sciences-National Research Council.

This report is being distributed to individuals and groups associated with or interested in the work of the Ship Structure Committee. Comments concerning this report are solicited.

Sincerely yours,

J. A. Alger, Jr.
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

Serial No. SSC-135

First Progress Report
of
Project SR-158

to the

SHIP STRUCTURE COMMITTEE

on

SIZE EFFECT IN BRITTLE FRACTURE OF NOTCHED STEEL PLATES IN TENSION

by

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Providence, Rhode Island

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ABSTRACT

Direct experimental evidence is presented here to support the hypothesis that a Griffith-type theory is not the critical condition for the initiation of brittle fracture in steel plates. The data indicate almost complete size independence for notched, compressively prestrained, Project E steel specimens of 6 2/3 in., 10 in., and 20 in. widths, which had geometrically similar dimensions in the plane of the plate but were of the same thickness.

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INTRODUCTION

There appears to be general agreement in the literature that geometrically similar sharp-notched bars or plates in tension and beams in bending become increasingly less ductile or more brittle in behavior as the size of the specimen increases. Also, the nominal stress required for fracture tends to decrease with increasing size. The situation is not quite as clear for plate specimens of the same thickness that have geometrically similar dimensions in the plane of the plate. However, the same trend is to be expected on simple statistical grounds based upon any reasonable variation of mechanical properties of any given material.

The concept employed by Griffith[1] to explain the tensile fracture strength of a brittle material such as glass leads to a very marked size effect. Essentially, crack growth is viewed as an equilibrium process quite similar to bubble growth in a liquid under decreasing pressure. Energy needed to maintain additional crack surface is equated to the accompanying release of the potential energy of strain and of the loading system. The result is that the nominal or average fracture stress varies inversely with the square root of the crack length.

A modified Griffith hypothesis has been advanced for the brittle fracture of notched plates of normally ductile steel.[2,3] The word "brittle" is to be understood as indicating that the change in thickness of the plate is at most a few per cent everywhere, especially at the root of the notch where the fracture initiates. The surface energy is taken as the energy needed to produce the fracture surface and so is primarily the energy dissipated in the highly localized plastic deformation accompanying "brittle" fracture. Once again, of course, the result is that the nominal fracture stress for a specimen 64 ft in width is but 1/8 that of a geometrically similar specimen 1 ft in width. The implication for ships or for large storage or pressure vessels with openings is most alarming.

However, the validity of the Griffith-type reasoning as the critical condition for the initiation and propagation of brittle fracture in steel seems highly doubtful.[4] Certainly a crack cannot increase in length unless the energy needed is available. The availability of energy, however, does not require the crack to grow. In other words, the Griffith-type theory gives a necessary condition for the extension of a crack, not a sufficient one. There is an auxiliary requirement to be met, perhaps maximum stress, which may be thought of as an energy barrier. The fracture of glass and the growth of bubbles, along with many other problems in physics, can be treated properly by the simple energy-balance concept because thermal or other fluctuations are large enough to overcome any small energy barrier that may be present. The tremendous barrier against initiation of brittle fracture in structural steel is evident from the very low nominal stress at which a crack in as-received material will continue to propagate once it has been initiated at a much higher nominal stress.[5]

An investigation of size effect in brittle fracture obviously must begin with a steel specimen that will fracture consistently in a brittle fashion. If the test series is to be meaningful to design practice, the fractures must occur under conditions reasonably comparable to those that might arise in actual structures.

The 10-in. wide, 10-in. long, 3/4-in. thick edge-notched plate of Project E-steel welded to special pull heads (Fig. 1) is the type of specimen on which most of the previous work of this investigation has been done.[6-9] A simple and relevant test procedure was evolved after considerable experimental study. An average axial precompression of at most a few per cent on the net section is employed to embrittle or exhaust the ductility of the steel at, and in the vicinity of, the root of the notch. Subsequent tension at below-zero temperatures consistently initiates brittle fracture at a nominal stress well below the original yield stress.

METHOD OF TESTING

The tests discussed in this report were carried out in substantially the same way as the previous tests. An attempt was made to keep constant the prestrain, test temperature, and testing procedure, so that any variation in results would be due solely to size effects. The notches were machined by using a 6-in. milling cutter for the 20-in. plates, and a 4-in. cutter for

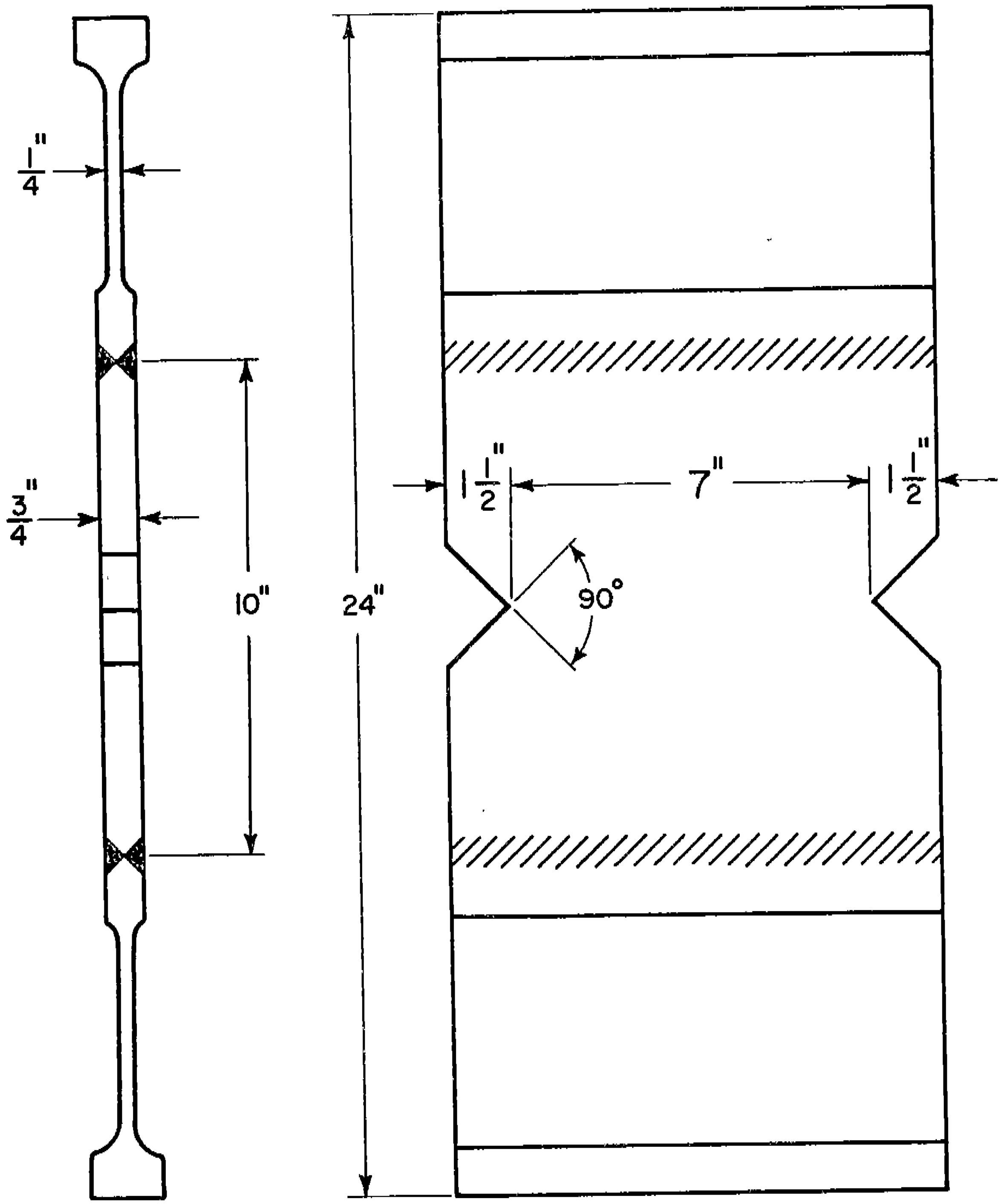

FIG. 1 A TYPICAL NOTCHED TEST PLATE WITH PLASTIC HINGE, PULL HEADS

the other plates. The same cutters were used throughout to provide the only control in the notching process.

The specimens were beveled along the top and bottom edges. As they were longitudinally prestrained in compression between two parallel surfaces, these thin edges yielded first, thereby allowing the compressive stress to attain a fairly uniform value across the width of the plate. During the slow, constant-rate, prestraining operation, the specimens were sandwiched between greased steel plates 1 1/2-in. thick to prevent lateral buckling. The sandwich was held together by initially finger-tight bolts. The bolts were slackened and retightened in turn to their original tension, so that any frictional forces which may have been generated by the small movements of the plate surface during the general yield deformation were relaxed.

Before testing, the specimens were welded to the thin steel pull-heads (Fig. 1). During testing, these heads yielded plastically, thereby helping to even out the stress both through the plate thickness and across the width.[7]

All the notched plates were tested at temperatures below -12 F in an attempt to achieve better consistency of data than in the earlier tests. The temperatures were measured using copper-constant on thermocouples located in small holes drilled near the notched sections of the plates. During testing, the loads were applied at the reasonably slow, initial rate of between 40,000—60,000 lb/min.

All the specimens tested were of Project E-steel, 3/4-in. thick and 10-in. long. Four different plate widths were used. 3 1/3 in., 6 2/3 in., 10 in., and 20 in. The notch depth on each side was always 15 per cent of the gross plate width. Five plates of each width were tested; the results are shown in Table 1.

The average face compressive strains were measured across the notches with gages of lengths of 1 in. and of 1/10 plate width. The two values of strain given for each specimen and for each gage length in Table 1

TABLE I. Summary of brittle-fracture tests on 3/4-in. thick, notched, E-steel plates of various widths. The plates were compressively prestrained longitudinally after machine notching before testing in tension.

Yield stress of the virgin metal was 33,000 psi.

Plate width (in.)	Average face compressive strain at notch root: On 1 in. gage length	Average face compressive strain at notch root: On gage length of 1/10 x plate width	Average prestraining stress across notched section (psi)	Temp. (F)	Tension Test: Average stress across notched section (psi): At 1st crack	Tension Test: Average stress across notched section (psi): At fracture
	.077-.080	.050-.052	38,000	-12	15,200	23,800
	.074-.085	.047-.052	38,000	-21	8,250	20,500
20	.040-.062	.025-.040	34,000	-16	9,250	17,500
	.040-.050	.025-.033	34,000	-24	8,250	24,000
	.047-.054	.029-.035	38,000	-19	10,200	17,150
	.035-.035	.035-.035	38,000	-18	4,780	18,650
	.075-.089	.075-.089	38,000	-16	9,580	28,500
10	.030-.045	.030-.045	38,000	-19	3,300	29,100
	.040-.042	.040-.042	38,000	-22	2,640	18,500
	.040-.041	.040-.041	38,000	-21	6,930	20,300
	.024-.030	.035-.039	38,200	-18	11,550	25,400
	.027-.029	.037-.039	38,500	-20	--	16,350
6 2/3	.029-.033	.032-.042	38,500	-20	--	17,650
	.033-.035	.033-.037	39,000	-20	--	13,550
	.027-.034	-----	38,800	-20	5,600	19,800
	.042-.044	.050-.069	40,000	-16	No cracks	
	.028-.030	.036-.046	38,300	-18		
3 1/3	.029-.030	.025-.066	38,300	-20	or fractures	
	.025-.033	.040-.042	38,300	-20		
	.035-.036	.041-.057	38,300	-22	up to yield.	

represent the maximum and minimum of four gages, one on each side of the plate at each notch. Much higher strains than these averages do occur, of course, in the vicinity of the root of the notch. This accounts for the variation of the average readings with the size of plate despite the almost constant average stress imposed. If, for example, the pattern of strain were geometrically similar in the plane of the plate for all sizes of plate, the 1/10 readings would be the same for all. The 1 in. gage length readings, however, would increase with the increase in the size of plate because the region of high local strain in the vicinity of the root of the notch would occupy a larger and larger proportion of the gage length. Evidence of this trend is clear in the data. On the other hand, if the pattern of strain were purely local to the notch and independent of the size of the plate, the 1 in. strain readings would remain constant while the 1/10 readings would decrease with increasing plate size. A little of this latter trend is discernable but it is far less marked than the geometric effect of increasing size on the 1 in. readings.

Figure 2 is a graph showing the nominal stresses at which cracking was heard (open circles) and the nominal fracture stresses (dark circles).

CONCLUSION

The data are in complete contradiction with the critical values predicted by a Griffith-type theory. A three-to-one ratio of size would correspond to a 1.73 ratio of nominal fracture stress. Dividing the fracture stresses for the 6 2/3-in. plates by 1.73 gives a set of numbers each of which is below the full range of values for the 20-in. plates. In fact, the data indicate almost complete size independence for 6 2/3-in., 10-in., and 20-in. plates.

On the other hand, the 3 1/3-in. plates did not fracture at all at nominal stresses up to yield. A Griffith-type theory alone would not predict this result from the data for the 6 2/3-in. plate tests either. However, this latter evidence suggests the existence of a lower size limit for brittle fracture under the testing conditions of this series. In earlier work by Mylonas[8] on 2-in. and 4-in. wide specimens it was reported that only one of each of these narrow notched plates

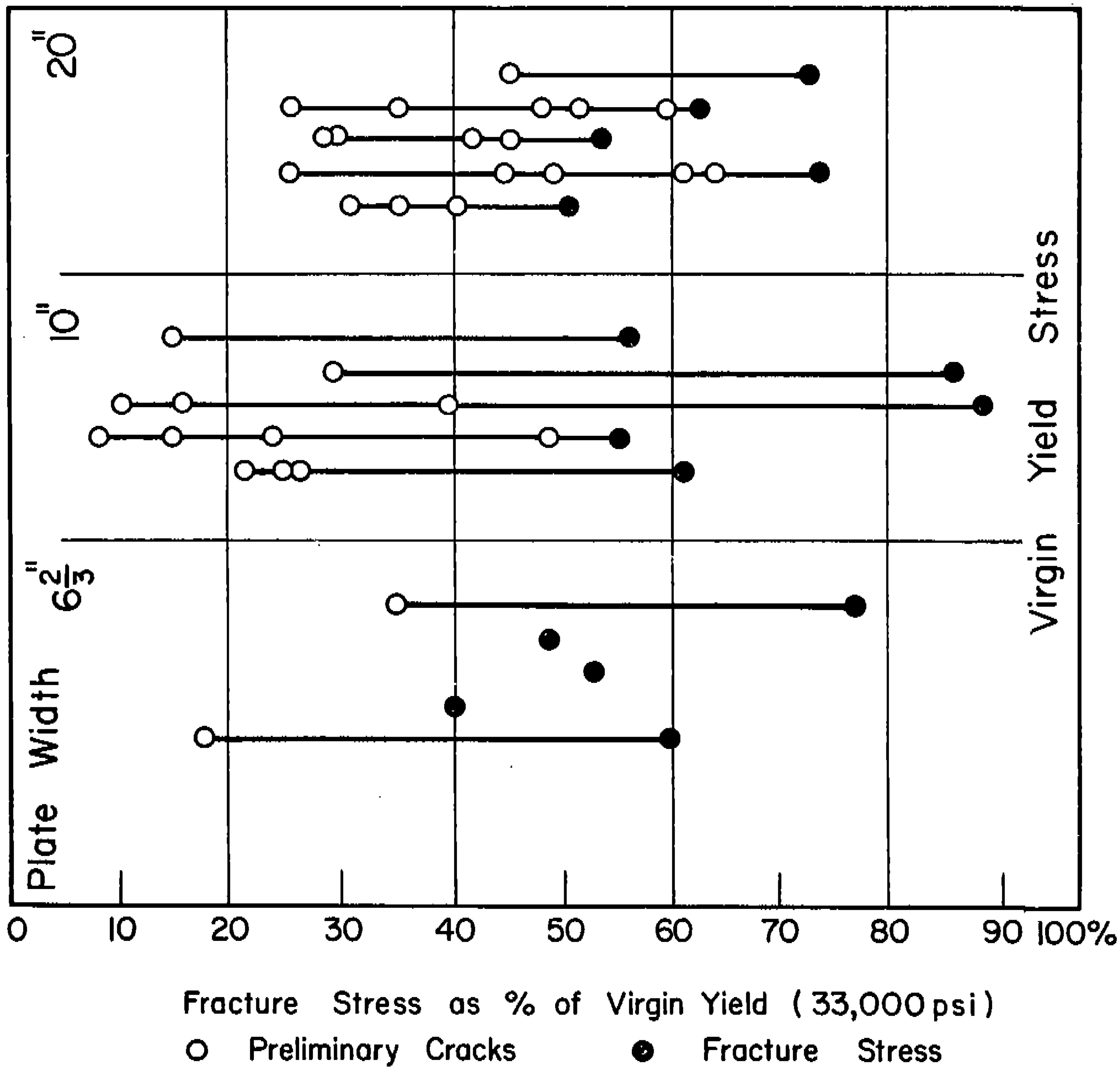

FIG. 2 RESULTS OF TESTS OF LONGITUDINALLY PRESTRAINED PLATES

fractured in a brittle manner. Nevertheless, even one fracture in a 2-in. specimen does raise the suspicion that, with more clever experimental technique, the threshold size for brittle fracture could be brought down considerably.

It would be of much greater interest, however, to test a 5-ft wide plate with 9-in. deep notches to check the conclusion that a Griffith-type energy condition is not critical. Such a test also would serve to determine experimentally the small size effect that is to be expected on statistical grounds from a variation of material properties.

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