SSC-184

Exhaustion of Ductility in Compressed Bars with Holes

by

S. KABAYASHI and C. MYLONAS

SHIP STRUCTURE COMMITTEE

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June 1968

Dear Sir:

The Ship Structure Committee has been sponsoring a project on Macrofracture Fundamentals at Brown University to determine the effect of gross strain upon the metallurgical and mechanical properties of steel. Herewith is a techincal progress report covering one phase of this investigation by S. Kobayashi and C. Mylonas, entitled *Exhaustion of Ductility in Compressed Bars with Holes*.

This project is being conducted under the advisory guidance of the Ship Hull Research Committee 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,

D. B. Henderson
D. B. Henderson
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

SSC - 184

Sixth Progress Report

on

Project SR - 158

"Macrofracture Fundamentals"

to the

Ship Structure Committee

EXHAUSTION OF DUCTILITY IN COMPRESSED BARS WITH HOLES

by

S. Kobayashi and C. Mylonas

Brown University
Providence, R. I.

under

Department of the Navy
Naval Ship Engineering Center
Contract Nobs 88294

U. S. Coast Guard Headquarters
Washington, D. C.

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Abstract

The brittleness of mild steel subjected to tension after prior compressive prestraining has been in part attributed to the collapse of microscopic flaws or voids and to the resulting severe straining, work hardening, and sharpening of the flaw edges. A similar mechanism of embrittlement should operate also with artificial macroscopic flaws such as holes. This was checked with tests of axially compressed bars of ABS-B and of E-steel with transverse pre- or post-drilled single or double holes. The overall nominal compressive prestrain (exhaustion limit) causing brittleness in subsequent tension in bars with pre-drilled holes was about 1/4 the corresponding prestrain for solid bars of E-steel and about 1/2 for ABS-B steel. The possible causes of this difference and the modes of fracture initiation and propagation are discussed. The strong differentiation of steel quality achieved with these tests is very promising for the development of a related acceptance test.

CONTENTS

	Page
EMBRITTLEMENT BY PRESTRAINING	1
TESTS WITH FLATTENED HOLES	3
a. Bars with two transverse holes drilled before compression	3
b. Bars with 0.031 in. holes drilled after uniform compression	15
c. Bars with pre-drilled parallel or blind holes	16
CONCLUSION	20
ACKNOWLEDGMENT	21
REFERENCES	21

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Embrittlement by Prestraining

A reduction of the initial ductility of steel by suitable prior cold or hot straining has been shown in earlier papers to be an important cause of brittle fracture initiation under subsequent tension. In particular precompression of notched mild steel plates has resulted in fracture in subsequent static tension at loads as low as 10% of the load limit for general yielding [1-5]. Uniform axial prestraining of smooth bars by about 0.65 or more when cold (70°F) or about 0.52 when hot (600°F) caused a sudden drop of the reduction of area at fracture from 0.80 or more to about 0.02 [3,6,7]. Prestraining in compression by bending followed by tension in reversed bending [3,4,7-10] showed embrittlement after cold prestraining of about 0.50, or after hot prestraining of about 0.25. In all instances the ductility was reduced only when the prestrain reached a narrowly defined value, the exhaustion limit, but remained almost unimpaired at smaller prestrains. Lighter prestraining, however, can also cause brittle behavior when aggravated by notches. Bars with deep circumferential grooves machined after uniform prestraining showed a rapid reduction of fracture elongation at prestrains as low as 0.05 [6].

The importance of the phenomenon of exhaustion of ductility by suitable prestraining is made evident by numerous brittle fractures of structures in service, which have been found to start at stress concentrations within cold worked regions or close to welds where severe hot straining had occurred. In general the ductility of the steel was found to depend on the whole history of strain (including temperature) as well as on the conditions at fracture (stress, strain rate, temperature, etc.). Few types of controlled prestrain history have been tried because of considerable experimental difficulties. Of those tested, precompression seems to be the most embrittling in a subsequent reversal to tension in the same direction, but not in a transverse tension [11]. One explanation has been suggested at past meetings of the Ship Hull Research Committee [12]. Precompression flattens pre-existing flaws or voids, sharpening the notches with axis perpendicular to the direction of precompression and blunting those with axis parallel. The sharper notches are also work-hardened in compression, and they are at right angles to the applied tension parallel to the precompression, hence give rise to very high local stresses. On the contrary, the sharpened notch axes are parallel and the blunted edges perpendicular to an applied transverse tension, hence both are relatively inoffensive. In a study of the possible explanations of macroscopic properties based on a continuum approach, D. C. Drucker [4] discusses the mechanism of flaw sharpening by precompression. He shows that the resulting straining and hardening does explain the observed behavior. He also explains why prestraining in torsion causes less embrittlement than ir compression. It is interesting to note that initially oblate flaws with their large dimension normal to the precompression may close up and avoid further local work-hardening. Conversely oblong flaws compressed along their length may never get to be too sharp, and starting with a small factor of stress concentration, may never cause much work hardening, except at extremely large prestrains. The shape of the worse flaw will lie between the two extremes and will cause the worse combination of high straining and notch sharpening.

All the above may be extended to the case of a flaw within the strained region of a larger flaw with only a substitution of the strain at the large flaw for the overall macroscopic strain. It may be necessary to consider also the size of the strained region and of the highly stressed region, and their distribution density when several exist. The size effect in brittle fracture has been disputed [13], but the problem is somewhat beclouded by the difference between initiation and propagation of fracture [2,5,14].

Tests with Flattened Holes

The explanation of embrittlement by precompression as due to the flattening of holes was checked by tests of specimens containing controlled known flaws or cavities. A general study with various cavity shapes and sizes did not appear possible, but meaningful limited tests could be done with drilled cylindrical holes. The round hole, though probably not the "worst" shape, is intermediate to the oblong and oblate, and the cylindrical form ensures the constraint severity of plate strain for the local straining. Even if the holes are not the most damaging cavities, they do cause much larger local compressive straining and work hardening than the average in the specimen and give rise to high stress concentration in tension, hence they should intensify the damage and cause brittleness at lower overall strains.

Three types of tests were made with bars of 0.75 in. square cross-section and 9 in. length cut in the direction of rolling of 0.75 in. thick plates of ABS-B and of E-steel (composition and properties in Table I).

a. Bars with two transverse holes drilled before compression. One hole was perpendicular, the other parallel to the as-rolled surfaces and far enough not to affect the first (Fig. 3, inset). both of 0.031 in. dia. The

TABLE I. TYPICAL COMPOSITION AND PROPERTIES OF STEELS.

Steel	Element, per cent									Yield Strength psi	Ultimate Tensile Strength psi	Elongation per cent		Charpy Impact	
	C	Mn	P	S	Si	Cn	Ni	Cr	Mo			In 8 in.	In 2 in.	ft-lb	Temp. deg. Fahr.
E	0.20	0.33	0.013	0.020	0.01	0.18	0.15	0.09	0.02	32 000	65 000	36	30	15 to 3.3	55 to -11
ABS-B	0.14	1.04	0.011	0.018	0.056	0.083	0.023	0.031		33 800	58 400	33		20 to 10	18 to -5
	0.15	0.94	0.009	0.027	0.046	0.094	0.040	0.023		35 700	59 800	32		20 to 10	11 to -11

bars were prestrained axially in compression at about 70°F in a machine described in an earlier paper [3], were artificially aged for 90 minutes at 300°F and machined into standard 0.505 in. dia. tension specimens, and were then tested in tension at -16°F. The results are given in Table II and Figure 1 for ABS-B steel and in Table III and Figure 2 for E-steel.

Nominal prestrains up to 0.60 (length compressed by 60%: natural strain -0.92) were applied to ABS-B and up to 0.30 (natural strain -0.36) to E-steel bars. The strain non-uniformity around the holes was checked with measurements of the deformation of scribed 1/4 in. squares centered on the holes (Fig. 3, inset) and with microphotographs of the flattening of the holes. The change of hole diameter along the bar was much greater but proportional with the applied nominal prestrain up to about 0.18-0.20, when the holes closed up (upper two curves of Fig. 3). The curves of transverse diameter expansion showed a gradual change of slope at the same prestrain of about 0.20 and increased rapidly at prestrains of about 0.45 to 0.60. The curves of lateral expansion over the 1/4 in. grids, parallel and across the initial plate thickness (two lower curves in Fig. 3) matched reasonably well the overall expansion curves of ABS-B bars without holes given in an earlier report [6], except

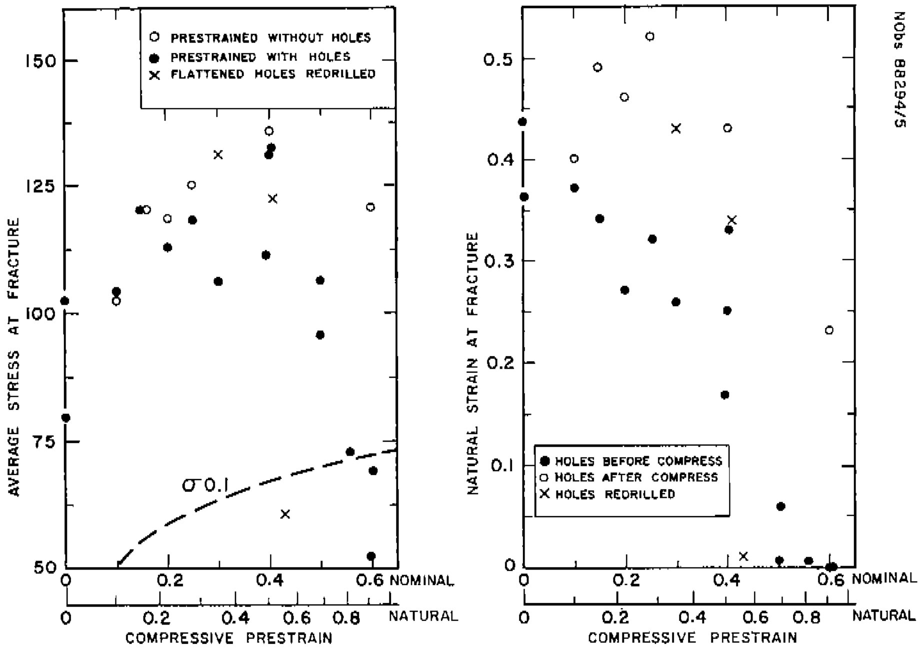


Fig. 1. ABS-B Steel Bars With Holes Compressed and Aged Tested In Tension At -16°F.

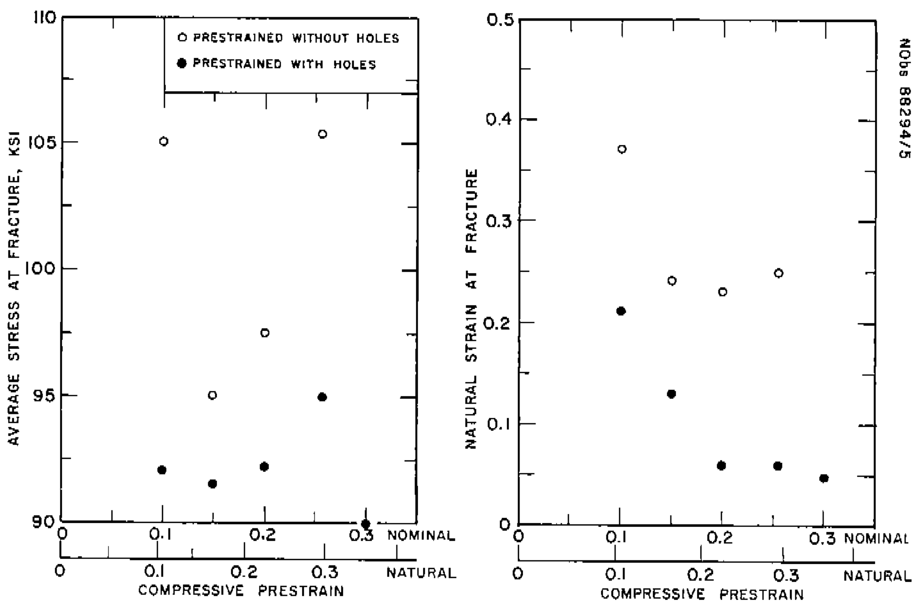


Fig. 2. Project E-Steel Bars With Holes Compressed And Aged Tested In Tension At -16°F.

TABLE II. ABS-B STEEL BARS WITH HOLES, AXIALLY PRECOMPRESSED AT 72°F AGED 2 HRS. AT 330°F, TESTED IN TENSION AT -16°F.

TABLE II

ABS-B STEEL

BARS WITH HOLES, AXIALLY PRECOMPRESSED AT 72°F
AGED 2 hrs. AT 330°F, TESTED IN TENSION AT -16°F

BAR	NOM. COMPR.	BAR DIA., in.		HOLE DIA., 10^{-3} in.			FRACTURE		Direction[f] and Fract. Type
		Orig.	Fract.[a]	Orig.	Compr.[b]	Fract.[c]	ksi[d]	Strain[e]	
B-272	0	0.501	P 0.432 N 0.374	30	30	20	103	0.43	shear
B-273	0	0.501	P 0.435 N 0.394	31	31	20	79	0.36	shear
B-227	0.10	0.505	P 0.465 N 0.387	32	T 35 L 18	28	104	0.37	PF, shear
B-228	0.15	0.504	P 0.473 N 0.391	32	T 36 L 8	34	120	0.34	NF, shear
B-229	0.20	0.500	P 0.479 N 0.410	33	T 40 L 0	40	113	0.27	PF, shear
B-230	0.25	0.504	P 0.484 N 0.392	32	T 43 L 0	43	118	0.32	NF, shear
B-270	0.30	0.504	P 0.470 N 0.425	31	T + L 0	41	106	0.26	55% sh.
B-237[g]	0.30	0.507	P 0.440 N 0.393		T 41 L 0	41	131	0.43	shear
B-249	0.40	0.504	P 0.491 N 0.441	31	T + L 0	45	111	0.17	shear
B-246	0.40	0.498	P 0.450 N 0.436	32	T 50 L 0	48	131	0.25	25% sh.
B-231	0.41	0.510	P 0.465 N 0.410	32	T 50 L 0	45	132	0.33	NF, shear
B-239[h]	0.41	0.501	P 0.460 N 0.403		T 50 L 0	49	122	0.34	PF, shear
B-238[i]	0.43	0.504	P 0.502 N 0.502		T 52 L 0	52	61	0.01	NF, cleav.
B-271	0.50	0.504	P 0.502 N 0.501	31	T + L 0	49	95	0.005	cleav.
B-245	0.50	0.496	P 0.488 N 0.477	31	T + L 0	55	106	0.06	3% sh.
B-232	0.56	0.499	P 0.499 N 0.498	32	T + L 0	55	73	0.005	cleav.

TABLE II. (continued) ABS-B STEEL BARS WITH HOLES, AXIALLY PRECOMPRESSED AT 72°F AGED 2 HRS. AT 330°F, TESTED IN TENSION AT -16°F.

BAR	NOM.	BAR DIA., in.		HOLE DIA., 10^{-3} in.			FRACTURE		Direction[f] and
	COMPR.	Orig.	Fract.[a]	Orig.	Compr.[b]	Fract.[c]	ksi[d]	Strain[e]	Fract. Type
B-248	0.60	0.502	P 0.502 N 0.502	34	T + L 0	59	52	0.002	cleav.
B-247	0.60	0.503	P 0.503 N 0.502	33	T + L 0	58	69	0.003	cleav.
B-235	0.10	0.496	P 0.430 N 0.380	32	Holes made after com- pres- sion	22	103	0.40	NF, shear
B-236	0.15	0.512	P 0.420 N 0.375	32		23	120	0.49	PF, shear
B-234	0.20	0.502	P 0.420 N 0.375	32		24	118	0.46	PF, shear
B-235	0.25	0.510	P 0.430 N 0.360	32		24	125	0.52	NF, shear
B-243	0.40	0.502	P 0.416 N 0.383	32		17	136	0.43	PF, shear
B-244	0.60	0.498	P 0.445 N 0.424	32		16	121	0.23	NF, shear

a. Bar diameter parallel (P) or normal (N) to axis of hole

b. Hole diameter transverse (T) or longitudinal (L) to length of bar

c. Transverse diameter of hole after fracture

d. Average fracture stress based on net area at fracture

e. Natural strain based on change of net area at fracture

f. Each bar had two holes, one parallel (PF) and one normal (NF) to the original face of the parent plate. The fracture initiating hole is indicated.

g. Holes redrilled at 18% nominal strain. Hole diameter was 0.038 in.

h. Holes redrilled at 18% and 31% nominal strain. Hole diameters were 0.038 in. and 0.046 in., respectively.

i. Holes redrilled at 18% and 33% nominal strain. Hole diameters were 0.038 in. and 0.046 in., respectively.

\+ Closed-up hole could not be seen.

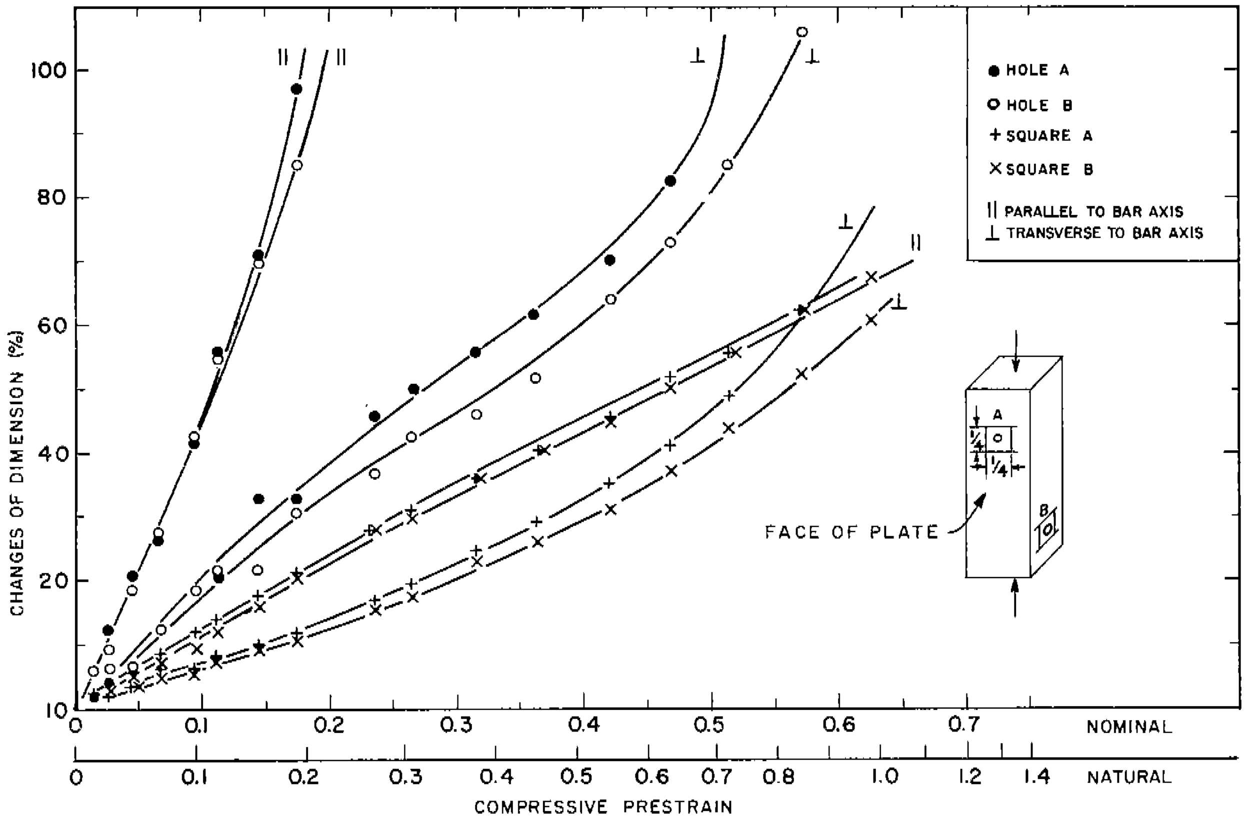


Fig. 3 Dimension Changes Of ABS-B Steel Bar With Holes During Compression.

at compression ratios of 0.60 or more, when the lateral expansion around hole B (lowest curve +, ||) increased faster, and around hole A (curve x) slower than the expansion in the absence of holes. The grid contraction parallel to the bar axis (curves + and x, ||) was almost exactly linear but slightly faster than the applied prestrain up to 0.20, when the holes closed. At prestrains above 0.20 the longitudinal grid contraction matched exactly the nominal bar compression. It appears, therefore, that all the strain concentration caused by the hole occurred within the region of the 1/4 in. squares and maybe within an even smaller region, as indicated by microphotographs of the etched surfaces.

The strain concentration around a flattened hole is also indicated by the surface deformation as in Figure 4 for a 0.03 in. hole after a nominal prestrain of 0.18, and in Fig. 5 after re-drilling to a 0.041 in. dia. at a prestrain of 0.18 and then continuing the axial prestraining up to 0.31 (nominal total). At the upper left of each figure is a photograph of the free surface showing shadows caused by the ridges of lateral expansion at the sharp corners and along the shear zones emanating from them. The lower left corner shows a polished section along the longitudinal mid-plane, and the upper right the same area after heating to 400°F and etching by repeated immersion in a solution of 6 gr. each of cupric and ferric chloride and 10 ml. hydrochloric acid in 100 ml. of ethyl alcohol. The deformation of the banded structure indicates the more highly strained regions and the shear zones emanating from the sharp corners. Completely flattened holes after prestrains of 0.32 and 0.60 are shown in Figure 6 (not re-drilled).

The results of main interest in Tables II and III are the fracture strain and stress at each prestrain shown in the 2nd and 3rd columns before the last and in Figures 1 and 2. At prestrains between 0 and 0.41 the fracture strains of ABS-B bars (Fig. 1, right) show a lot of scatter but generally decrease from about 0.40 ± 0.03 to about 0.25 ± 0.08. This is about a half to a third of the fracture strain of solid bars [6] but still large enough to qualify the behavior as ductile. A reduction of the fracture strain to about 0.01 (with an exception of 0.05) was found to occur at nominal prestrains between 0.41 and 0.50 or about 2/3 of the exhaustion limit for solid bars (0.75). The difference is actually much bigger, as shown by

TABLE III E-STEEL BARS WITH HOLES, AXIALLY PRECOMPRESSED AND AGED, TESTED IN TENSION AT -16°F

BAR	NOM. COMPR.	BAR DIA., in. Orig.	BAR DIA., in. Fract.[a]	HOLE DIA., 10^{-3} in. Orig.	HOLE DIA., 10^{-3} in. Compr.[b]	HOLE DIA., 10^{-3} in. Fract.[c]	FRACTURE ksi[d]	FRACTURE Strain[e]	Direction[f] and Fract. Type
E-318	0.10	0.504	P 0.474 N 0.428	33	T 36 L 18	30	94	0.21	PF, 50% sh.
E-319	0.15	0.504	P 0.480 N 0.467	32	T 36 L 10	35	92	0.13	NF, cleav.
E-320	0.20	0.495	P 0.482 N 0.478	33	T 37 L 0	37	92	0.06	NF, cleav.
E-321	0.25	0.505	P 0.495 N 0.483	32	T 40 L 0	40	95	0.06	PF, cleav.
E-322	0.30	0.500	P 0.491 N 0.483	32	T 44 L 0	44	90	0.05	PF, cleav.
E-326	0.10	0.491	P 0.420 N 0.392	32	Holes made after com- pres- sion	26	105	0.37	NF, shear
E-327	0.15	0.502	P 0.450 N 0.440	32		30	95	0.24	NF, 15% sh.
E-324	0.20	0.510	P 0.460 N 0.450	32		31	98	0.23	PF, 15% sh.
E-325	0.25	0.512	P 0.460 N 0.455	32		31	105	0.25	PF, 10% sh.

a. Bar diameter parallel (P) or normal (N) to axis of hole
b. Hole diameter transverse (T) or longitudinal (L) to length of bar
c. Transverse diameter of hole after fracture
d. Average fracture stress based on net area at fracture
e. Natural strain based on change of net area at fracture
f. Each bar had two holes, one parallel (PF) and one normal (NF) to the original face of the parent plate. The fracture initiating hole is indicated.

Upper left:
Surface

Right:
Etched
mid-plane

Lower left:
Mid-plane

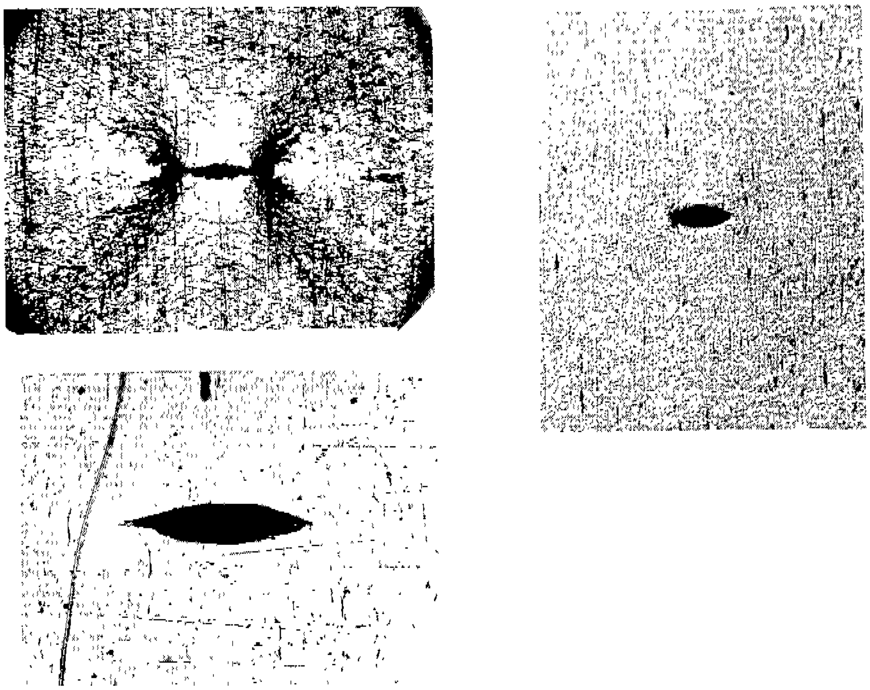


Fig. 4 Deformation of 0.031 in. Dia. Hole During Compression By 0.18.

Upper left:
Surface

Right:
Etched
mid-plane

Lower left:
Mid-plane

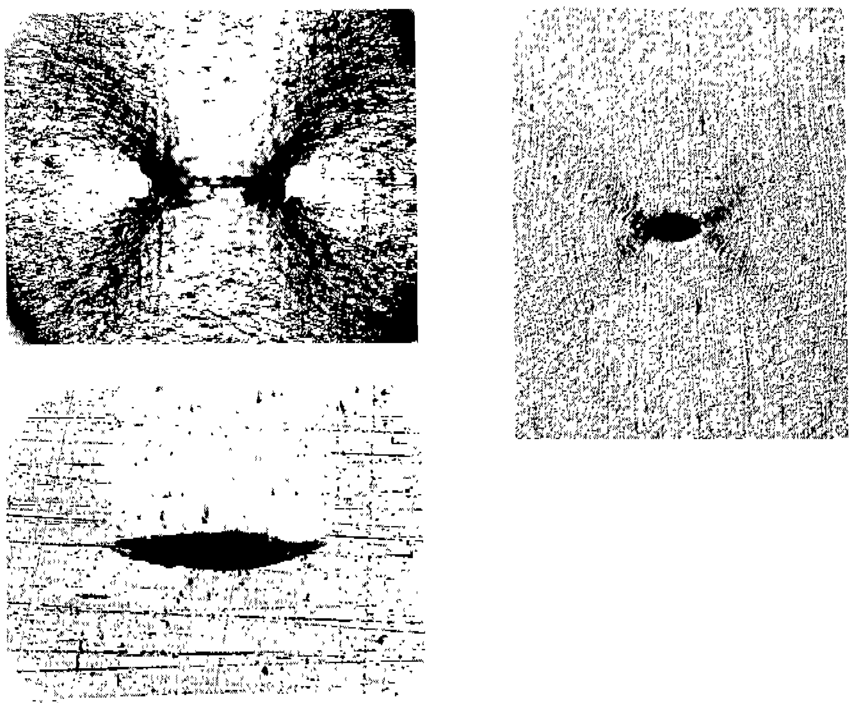
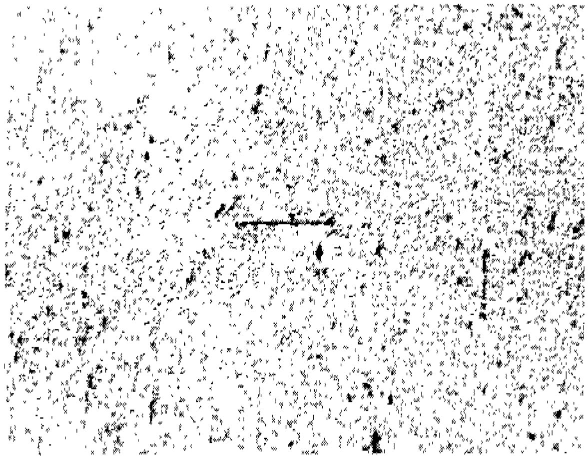
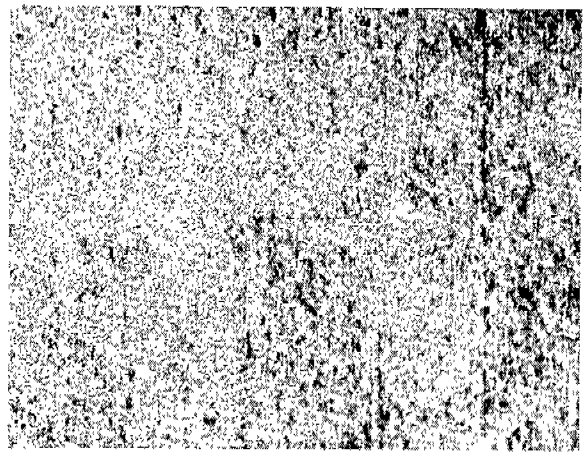


Fig.5 Deformation of 0.031 in. Dia. Hole After Compression By 0.18 Redrilling To 0.041 in. Dia. And Compressing To 0.31.



B-004 INIT. DIA. 0.032 in. $\epsilon_0 = 0.32$



B-005 INIT. DIA. 0.032 $\epsilon_0 = 0.60$

Fig. 6 Completely Flattened Holes

the corresponding natural strains: -0.51 to -0.64 vs. -1.30 for solid bars. The net fracture stress exceeded 100 ksi (with one exception) at prestrains up to 0.50. This is well above the 0.1% offset yield strength of solid bars which rises gradually from about 36 ksi at 0 prestrain to about 70 ksi at 0.50 prestrain [6], but less than their corresponding fracture stress (about 150 ksi). At prestrains of 0.56 and 0.60 the fracture stress was between 73 and 52 ksi, which is about equal with the corresponding 0.1% offset value (about 71 ksi) and much smaller than the fracture stress (about 160 ksi) of solid bars.

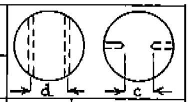
With E-steel the fracture strain was 0.21 at a prestrain of 0.10 (Fig. 2, right), which is a quarter or fifth of the fracture strain of solid bars [3,5]. and was reduced to about 0.05 at prestrains of 0.20 or more. The drop in ductility occurred at the low prestrains of about 0.15 to 0.20 (natural prestrains -0.15 to -0.21), much less than with solid bars (nominal -0.60, natural -0.85). The reduced ductility of 0.05, though higher than with solid bars (about 0.02). is low enough to qualify the bars as brittle.

The reduction of the exhaustion limit in E-steel to 1/3 or 1/4 its value for solid bars appears as a reasonable consequence of the local straining, work hardening, and stress concentration of collapsing holes. The corresponding reduction to 2/3 of the nominal or 1/2 of the natural prestrain in ABS-B steel could be attributed to an early closing of the holes which stops further strain concentration and hardening. Enlargement or re-drilling of the holes before continuing the prestraining would then permit additional straining and hardening. Accordingly at a compressive prestrain of 0.18, the holes of bar B-237 were re-drilled to a 0.038 in. diameter, slightly smaller than the width of the collapsed hole and prestraining was continued. Bars B-239 and B-238 (Table II and Fig. 1) were re-drilled twice, at a nominal prestrain of 0.18 (new diameter 0.038 in.) and at about 0.32 (new diameter 0.046 in.), when they appeared to have closed again. The re-drilling did not reduce the ductility of bars B-237 (prestrain 0.30) or B-239 (prestrain 0.41). Their fracture strains were about the same or slightly larger than bars of equal prestrain but no re-drilling. Bar B-238 (prestrain 0.43) did fracture with the small strain of 0.01, but its prestrain was in the region between 0.41-0.50 where ductility was found to drop even without re-drilling, hence the brittle fracture cannot be attributed mainly to re-drilling. Apparently re-drilling and re-compressing did not cause fracture at smaller prestrains than without re-drilling. The results of these few tests, if confirmed, are not incompatible with the discussed concept of embrittlement by the collapse of voids. The local work hardening may be so high as to produce arrested cracks at very low loads as in earlier tests of notched precompressed plates [2,5] and in tests of plates containing welds running over notches [15-20], occasionally even "spontaneous cracks" without any external loading. Such an arrested cleavage crack followed by a rougher jagged fracture surface could be seen in bar B-239. In all these cases the arrest is the result of a low crack velocity at the end of the small damaged region, insufficient for propagation in the sound region at low stress. Re-initiation of fracture in the sound region is not easy when the triggering effect of the damaged region is used up. In fact, fracture was then found to occur only when the load was increased to the level of general yielding. Early arrested cracks can have the peculiar result of strengthening a structure. This would explain the existence of many arrested cracks in welded regions of stress concentration observed in ships [21]. If such arrested cracks do occur in the compressed bars with re-drilled holes, the final fracture should depend on the brittleness or ductility of the region beyond the highly work-hardened edges of the flattened re-drilled holes where fracture must re-initiate. Indeed this seems to be the case since all bars of one steel, whether re-drilled or not, became embrittled at the same overall prestrain.

It would then seem that the process of embrittlement requires not just sufficient local work hardening and stress concentration to start a crack, but also conditions which will ensure propagation in the region beyond the local damage. The necessary condition must combine suitable degrees of work hardening and stress concentration and a sufficient size of the embrittled region. Such an explanation of the size effect was advanced in earlier papers [14]. Exact similarity is possible between specimens of different sizes under static loading. The stress and strain distributions can be exactly similar and their peaks equal, so that the size effect cannot be explained on a basis of stress magnitude. Similarity breaks down in the dynamic case of an advancing crack, as velocities and strain rate or inertia effects cannot be similar, hence will cause a size effect. This is clearly a dynamic size effect indirectly related with the static stress distribution or with the singularity at the crack tip.

b. Bars with 0.031 in. holes drilled after uniform compression. Another check on the effect of local work hardening and stress concentration was made with uniformly prestrained bars drilled transversely after compression. Six bars of ABS-B were tested, five prestrained by 0.10 to 0.40 (end of Table II and Fig. 1) giving fracture strains between 0.40 and 0.52 and one prestrained by 0.60 giving a fracture strain of 0.23. Four bars of E-steel were also tested (end of Table III and Fig. 2), one prestrained by 0.10 which fractured with a strain of 0.37, and three prestrained by 0.15 to 0.25 which fractured at strains of about 0.25. No bar was considered brittle, even at the highest prestrains. They all exhibited appreciably higher ductility than bars with pre-drilled holes, but much lower than solid bars.

TABLE IV ABS-B STEEL BARS WITH PARALLEL AND WITH BLIND HOLES AXIALLY COMPRESSED AGED AND TESTED AT -16°F.

BAR	NOM. COMPR.	ORIG. DIA. in.	AREA, in^2 ORIG.[a] / FRACT.	LOAD kp MAX. / FRACT.	FRACTURE ksi[b]	FRACTURE Strain[c]		
1P	0.20	0.5065	0.16[illegible]5 / 0.1486	15.6 / 15.0	100.9	0.10	PARALLEL HOLES	d = 0.089"
2P	0.20	0.5050	0.1653 / 0.1316	15.7 / 14.0	106.2	0.23		d = 0.181"
3P	0.20	0.5055	0.1722 / 0.1453	16.2 / 15.5	106.7	0.17		d = 0.285"
4P	0.20	0.5055	0.1820 / 0.1418	16.0 / 13.0	91.7	0.25		d = 0.386"
1B	0.20	0.5045	0.1853 / 0.1332	15.9 / 13.2	99.1	0.33	BLIND HOLES	c = 0.140"
2B	0.20	0.5045	0.1889 / 0.1246	15.9 / 12.0	96.3	0.42		c = 0.214"
3B	0.20	0.5055	0.1933 / 0.1010	16.2 / 11.8	116.8	0.65		c = 0.319"
4B	0.20	0.5045	0.1961 / 0.0791	16.2 / 11.2	141.6	0.91		c = 0.405"

a. Net original area and at fracture after subtraction of holes.
b. Average fracture stress based on net area.
c. Natural strain at fracture based on change of net area, or natural logarithm of ratio of initial to fracture area.

c. Bars with pre-drilled parallel or blind holes. Attempts were also made to find more damaging configurations with double holes in bars of ABS-B steel. Two transverse symmetrical 0.032 in. dia. holes with axes lying in a cross-section were drilled before compression (inset in Table IV, top right). Four tests were made with a distance d between parallel holes changing from 0.089 in. to 0.386 in., all with the same compressive prestrain of 0.20. The closest hole spacing gave the lowest fracture strain of 0.10. The other three gave fracture strains between 0.17 and 0.25, the highest for the widest spacing. Four more tests were made with aligned double blind holes, drilled from diametrically opposite points of a cross-section so as to leave an undrilled solid central length c . Tests were made with values of c from 0.140 in. to 0.405 in., all with prestrains of 0.20. All four gave appreciable fracture strains, increasing with the length c from 0.33 to 0.91, equal or larger than bars of the same prestrain and a single through hole.

The worse effect was achieved with parallel holes of the closest spacing which gave the lowest fracture strain of 0.10, much less than with a single hole at the same prestrain, and small enough to border on the brittle. Probably the region between holes gets damaged more and fractures more easily.

Several fractured bars are shown in Figures 7-9. Symmetric inclined yield zones emanating from the flattened edges were visible in all but the

B-231 $\epsilon_0 = 0.41$ $\epsilon_f = 0.33$ B-228 $\epsilon_0 = 0.15$ $\epsilon_f = 0.34$

Fig. 7 Beginning Of Yielding And Fracture Of Bars With Holes Drilled Before Prestraining.

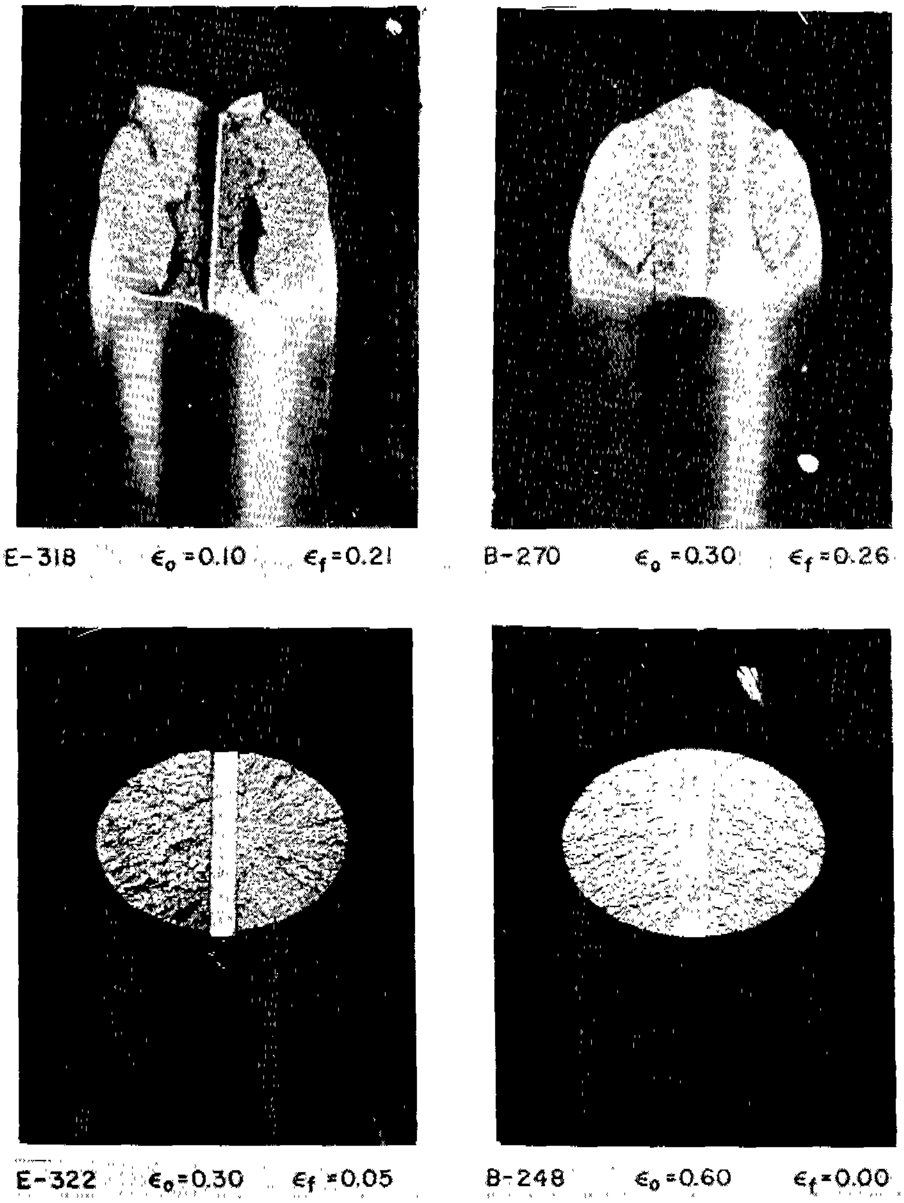
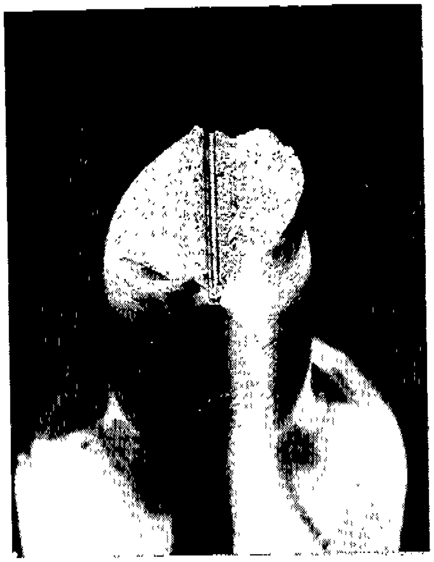
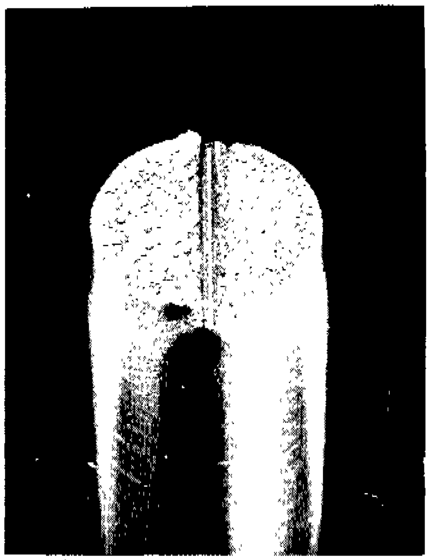


Fig. 8 Fracture Of Bars With Holes Drilled Before Compression.

most brittle bars. Figure 7 left, shows the beginning of yielding along symmetric planes intersecting along the hole and inclined by about 45° to the bar axis. Figure 7, B-231, shows how such intense cross-yielding forms a neck by lateral contraction mostly across the hole axis, and leads to a shear fracture along the inclined planes. This mechanism of yielding and



B-244 $\epsilon_0 = 0.60$ $\epsilon_f = 0.23$



E-325 $\epsilon_0 = 0.25$ $\epsilon_f = 0.25$

Fig. 9 Fracture Of Bars With Holes Drilled After Prestraining.

fracture was evident in all ductile bars. The fracture surface, however, was seldom as uniform as in bar B-231 (Fig. 7, center). Instead, the fracture appeared to occur along changing inclined planes, so as to form the familiar shape known as "dog's ears" (Bars B-228 and B-229, Fig. 7).

At higher prestrains fracture again started in shear along the inclined planes of cross yielding and changed into a fracture perpendicular to the bar axis (Bar B-270, Fig. 8, top right) but not with a typically cleavage appearance. As the prestrain increased the inclined shear fracture was confined to an ever narrower zone parallel to the hole axis, until with brittle bars it vanished completely (Bar B-248, Fig. 8), though traces of inclined yield zones were occasionally visible on the cylindrical bar surface very close to the hole. The behavior of bars of E-steel was in general similar, but the changes from oblique to normal fracture occurred at lower prestrains (E-318, E-322, Fig. 8). The oblique fracture is called a "shear" fracture and the normal "cleavage," and the percentage of shear failure is indicated in the last columns of Tables II and III.

The oblique yielding and initiation of fracture by shear at the hole edges was evident also when the holes were drilled after uniform prestraining. All ABS-B bars had 100% "shear" (oblique) failures (B-244, Fig. 9). In bars of E-steel prestrained by 0.15 or more, the fracture changed from oblique to normal a short distance away from the hole even though the total ductility was relatively high (0.25).

Conclusion

The existence of holes reduced the amount of compressive prestrain causing brittleness to 1/3 or 1/4 the amount needed in solid bars of E-steel and to 2/3 or 1/2 of ABS-B steel. The results with E-steel are in agreement with the notion of compressive embrittlement by the collapse of voids or flaws, less so the results with ABS-B steel. The large difference observed between E and ABS-B steels indicates that these tests could be quite suitable for distinguishing steels as to their resistance to embrittlement and fracture.

The geometry of the specimens appears to facilitate cross yielding by shear along inclined planes containing the axis of the hole, during both prestraining (Figs. 4-6) and final testing. Such reversed shearing deformation is less severe than compression reversed to tension [4] and may be the cause of the observed relatively high ductility. Containment of plastic deformation would then lead to a more brittle behavior. Such a constraint of extreme severity develops in bars with deep circumferential grooves machined after uniform straining and causes extreme brittleness at prestrains as low as 0.05 [6]. A further check could be obtained with tests of bars prestrained after notching. Such tests were included in the initial plans but were not completed.

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The brittleness of mild steel subjected to tension after prior compressive prestraining has been in part attributed to the collapse of microscopic flaws or voids and to the resulting severe straining, work hardening, and sharpening of the flaw edges. A similar mechanism of embrittlement should operate also with artificial macroscopic flaws such as holes. This was checked with tests of axially compressed bars of ABS-B and of E-steel with transverse pre- or post-drilled single or double holes. The overall nominal compressive prestrain (exhaustion limit) causing brittleness in subsequent tesnion in bars with pre-drilled holes was about 1/4 the corresponding prestrain for solid bars of E-steel and about 1/2 for ABS-B steel. The possible causes of this difference and the modes of fracture initiation and propagation are discussed. The strong differentiation of steel quality achieved with these tests is very promising for the development of a related acceptance test.

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