SSC-166

Reversed-Bend Tests of ABS-C Steel with AS-Rolled and Machined Surfaces

by

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SHIP STRUCTURE COMMITTEE

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SECRETARY
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April 1965

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 Third Progress Report, SSC-166, Reversed-Bend Tests of ABS-C Steel with As-Rolled and Machined Surfaces by K. Satoh and C. Mylonas.

The project is conducted under the advisory guidance of the Ship Hull Research Committee of the National Academy of Sciences-National Research Council.

Comments on this report would be welcomed and should be addressed to the Secretary, Ship Structure Committee.

Sincerely yours,

John B. Oren

John B. Oren
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

SSC-166

Third Progress Report
of
Project SR-158
"Macrofracture Fundamentals"

to the

Ship Structure Committee

REVERSED-BEND TESTS OF ABS-C STEEL WITH AS-ROLLED AND MACHINED SURFACES

by

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Brown University
Providence, Rhode Island

under

Department of the Navy
Bureau of Ships Contract NObs-88294

Washington, D. C.
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ABSTRACT

Comparative tests between bars with as-rolled and with machined surfaces show a small difference in the compressive prestrain needed to exhaust the original extensional ductility of the steel, as this is determined by the reversed bend test.[9,10] Machined bars show a higher exhaustion limit (prestrain) than as-rolled bars by 0.03 at 70 F and 0.06 at -16 F. Stress Calculations show that the most brittle fractures may occur at applied elastic macroscopic stresses as low as about 50 ksi at 70 F and about 30 ksi at -16 F. Highly ductile bars sustained a stress close to 90 ksi at both test temperatures.

CONTENTS

PURPOSE OF THE TESTS

The important influence of the history of strain and temperature on the ductility of structural steel and on the initiation of brittle fracture have been demonstrated and discussed in several earlier papers.[1-15] It was shown that precompressed notched mild steel plates tested in central static tension would develop arrested cracks or would fracture at an average net stress as low as 10% of the original yield point. Without prior compressive prestraining this steel, like all other mild steels tested in the laboratory, would not fracture before general yielding of the net section, in spite of the most severe notches and temperatures below Charpy transition. The reduction of the extensional ductility caused by cold or hot compression has been studied with axially compressed bars[5-7, 14-17] and with reversed-bend sheets[18-20] and bars.[9-15] A remarkable result of these tests was the sudden drop of the extensional ductility at a narrowly determined limit of the prestrain, henceforth called the exhaustion limit for the particular testing conditions. Prestrains lower than this limit had little effect on the extensional ductility. This behavior was particularly evident in the reversed bend test (Fig. 1, 2) in which the compressive prestrain at the interior of the bent bar was calculated after stages 1a and 1b from the radius of curvature and the bar thickness. The test load (as in Fig. 1c) of bars of an ABS-C steel is plotted in Fig. 3 against the prestrain for reversed-bending at 70 F (left) or -16 F (right). Bars prestrained by 0.59 or more and tested at 70 F (left) developed arrested cracks or fractured at loads smaller than 2000 lb and corresponding extensional strains of the order of 0.01, with hardly any opening of the U-shaped bar. Bars prestrained by less than 0.59 did not fracture even at a load of 5000 lb., at which the bent bars opened up by very large angles corresponding to strains considerably higher than 0.10. For bars tested by unbending at -16 F the exhaustion limit was 0.55 to 0.57 (compressive prestrain). The sudden transition of the ductility makes it unnecessary to measure exactly the strains at fracture. It is only required to know whether the strains are large or very small, and this is directly reflected in the magnitude of the load. Thus the reversed bend test is very simple, requiring only a measurement of the maximum applied load, and the exhaustion limit is a realistic measure of the quality of the steel since it measures its resistance to embrittlement by prestraining.

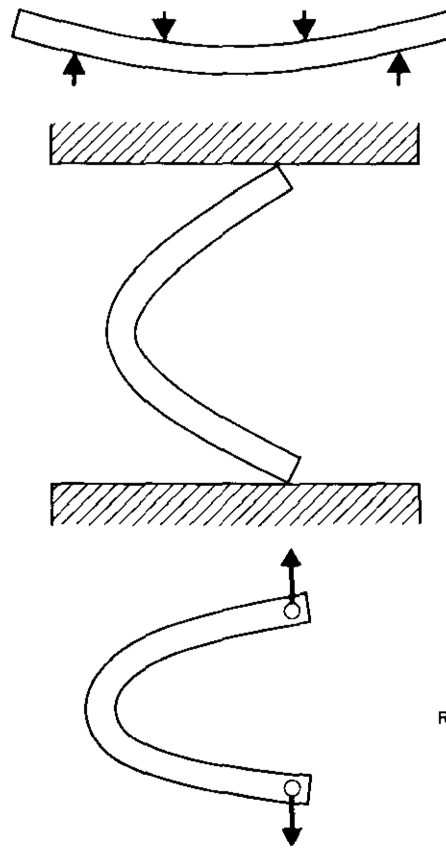

FIG. 1a
FIRST STAGE
OF BENDING

FIG. 1b
SECOND STAGE
OF BENDING

FIG. 1c
THIRD STAGE
REVERSED BENDING

FIG. 1. FIRST STAGE, SECOND STAGE, AND THIRD STAGE OF REVERSED BENDING.

Earlier tests[9] did not show any significant size effect for bars varying in thickness from 1/8 in. to 3/4 in., and in width from 1 in. to 4 in. A small number of tests had shown that bars with machined surfaces probably had a slightly higher exhaustion limit as compared with bars having surfaces in the as-rolled condition. The present tests were designed for a more systematic study of the effect of the surface condition and of size on the exhaustion limit determined by the method of reversed-bending.

MATERIAL

The material used was 1-1/4 in. thick plate of ABS-C steel (1956 classification) and belonged to the same heats as plates tested at the National Bureau of Standards. The details of plate preparation, composition, and properties are given in Table I (NBS data).

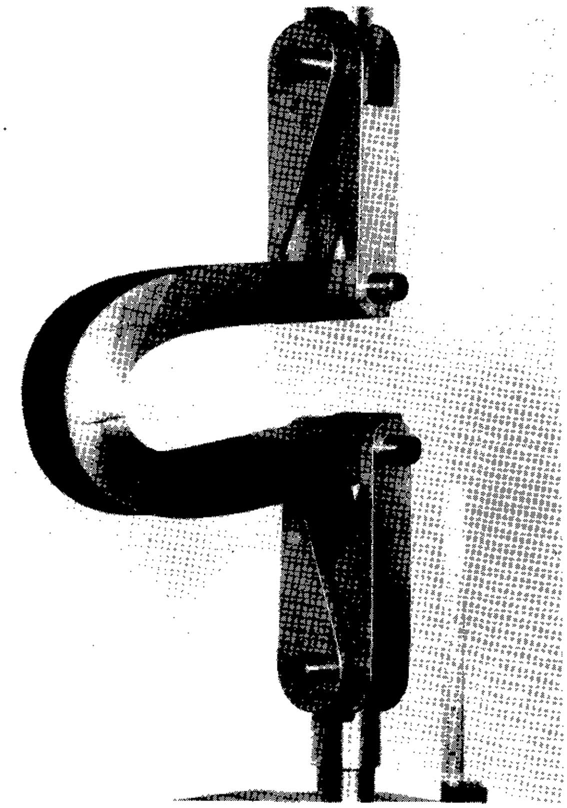

FIG. 2. SHACKLES FOR TESTING PRE-BENT BARS IN REVERSED BENDING.

TESTS FOR THE EFFECT OF SURFACE CONDITION

Plates 242, 243, 245, and 246 of heats C-4 and C-5 were used (Table I) as their finishing temperatures, yield and tensile strength, elongation, and NDT temperature were almost identical. Fifty-eight 1.00 in. wide bars were cut in the direction of rolling, and their thickness was reduced by one-sided machining from 1.25 in. to 0.75 in. The bars were bent to various radii (Fig. 1a, b) half of them with the as-rolled face and the other half with the machined surface at the interior of the bend. The final test in reverse bending was done either at 70 F or at -16 F, in a tension machine equipped with specially constructed sets of shackles for 0.75 in. thick bars, and also for the 1.25 in. thick bars (Fig. 2) used in the tests for size effect. The test results are given in Tables II and III, and in the graphs of Fig. 3 and 4. Machining of the surface raised the exhaustion limit from about 0.59 to about 0.66 for final testing at 70 F, and from about 0.56 to about 0.59 for final testing at -16 F. The final results are summarized in Table V, where they are also compared with the exhaustion limits of other steel previously tested in reversed bending.

TESTS FOR SIZE EFFECT

Comparative tests of bars of full plate thickness (1.25 in.) and of reduced thickness (0.75 in.) by one-sided machining were also made. ABS-C steel heat C-7 was used (Table I), and all tests were performed with the same as-rolled face on the interior of the bend. The test results are given in Table IV and Fig. 5, and the corresponding exhaustion limits are indicated on the last two lines of Table V. The exhaustion limit is slightly different for heat C-7 than for C-4 or C-5, but does not change with the thickness.

STRESS AT FRACTURE

An attempt was made to calculate the macroscopic fracture stress at the inner surface of the bent bars, on the assumption of a smooth bar surface. The bending moment at fracture was calculated from the load and the moment arm, which were measured in each test. But the stress-distribution depends also on the exact stress-strain relations of the prestrained steel, and these were not known. The exact bending stress just before fracture can be found only when the stresses are elastic, i.e. for fractures at very low loads. It can also be estimated for fractures at large loads and deformations, when considerable strain hardening has occurred and the slope of the stress-strain curve is substantially reduced, so that the stress distribution will approach the fully plastic bending stress distribution with a yield stress equal to the fracture stress. In intermediate situations the stress cannot be found exactly from the existing data, but it will certainly lie between the extreme values of stress calculated for an elastic and for a perfectly plastic stress distribution. These two extremes were calculated for all fractures. The upper limit of stress (elastic) is likely to be correct for fractures at the lowest loads, and the lower limit of stress (fully plastic) for fractures at the highest loads.

The deformation of the cross-section due to the large bending strains was also taken into consideration. The true shape of the deformed cross-section is curvilinear (Fig. 6, inset) and was approximated by a trapezoid. It was also assumed that the line parallel to the bases and

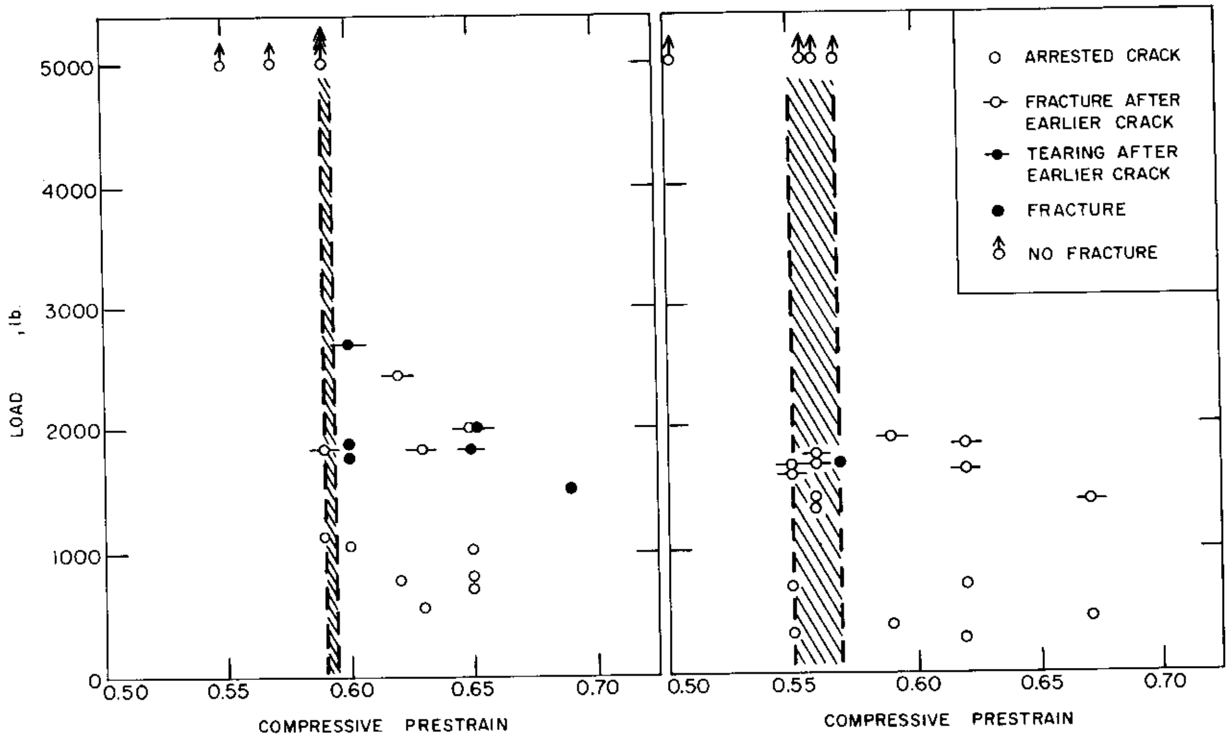

FIG. 3. EXHAUSTION LIMITS OF ABS-C (1956) STEEL TESTED ON AS-ROLLED SURFACE THICKNESS 0.75 IN. MACHINED FROM 1.25 IN. TESTS AT 70 F (LEFT) AND -16 F (RIGHT)

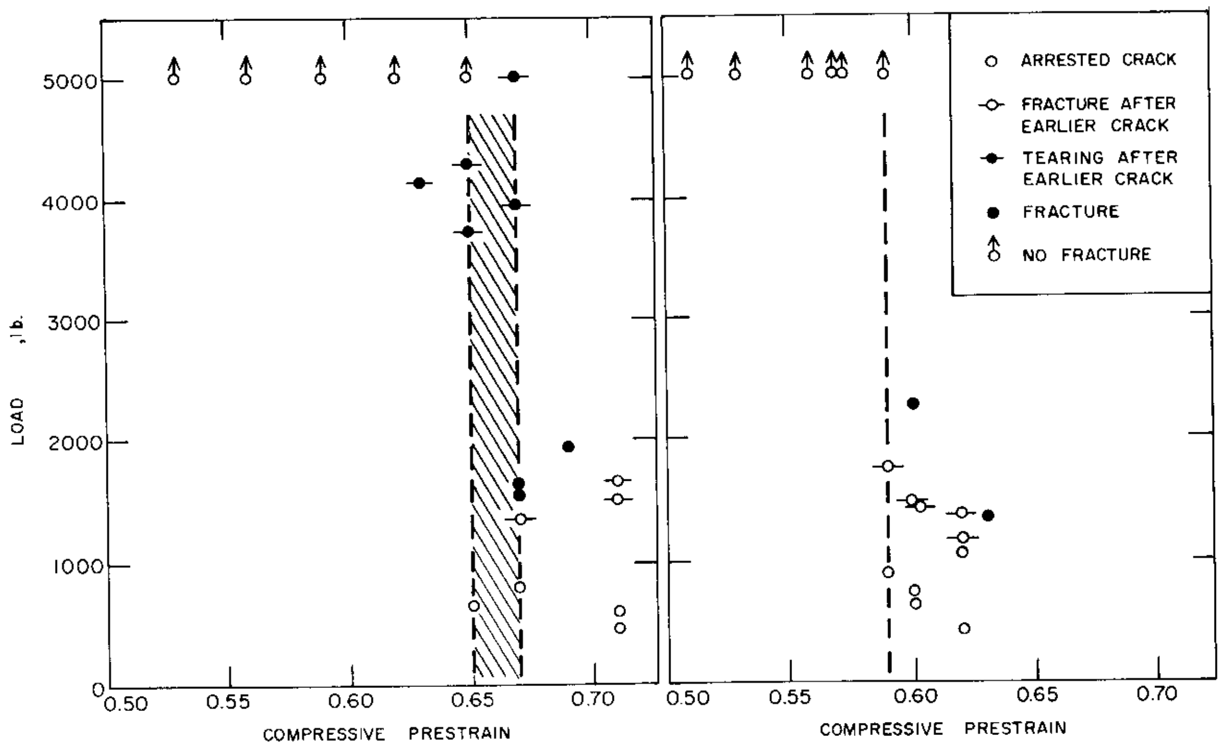

FIG. 4. EXHAUSTION LIMITS OF ABS-C (1956) STEEL TESTED ON MACHINED SURFACE THICKNESS 0.75 IN. MACHINED FROM 1.25 IN. TESTS AT 70 F (LEFT) AND -16 F (RIGHT).

TABLE I. PROPERTIES OF 1-1/4 IN. THICK ABS-C STEELS (1956)*

STEEL		TESTS FOR SURFACE EFFECTS				SIZE EFFECT
Heat Code		C-4	C-4	C-5	C-5	C-7
Plate No.		242	243	245	246	252
Plate Position		Top	Center	Top	Center	Center
Ingot Location		Next to Last	Next to Last	Next to Last	Next to Last	Last
Yield Point, (ksi)		32.2	32.9	32.3	32.0	36.7
Tensile Strength (ksi)		62.3	61.8	61.3	61.3	65.0
Elongation (8") (%)		32.5	32.0	33.0	31.0	30.5
Transition Temp. $^{\circ}F$	T_{v10}	-6	-18	-7	-6	-24
	T_{v15}	-1	-10	+7	0	-10
	T_{v25}	+10	+12	+19	+18	+17
	50% Fibrous	+58	+54	+52	+57	+77
	10% Fibrous	-7	-11	+5	-3	-13
NDT ($^{\circ}F$)	Edge	+20	+20	+30	+10	0
	Center	+20	+20	+10	+10	-10
Finishing Temp. ($^{\circ}F$)		1,840	1,890	2,000	1,950	1,500
Ferrite Grain Size		7.6	7.1	7.5	7.2	7.2
Chemical Composition (%)	C	0.16	0.16	0.16	0.15	0.15
	Mn	0.73	0.73	0.68	0.68	0.74
	Si	0.23	0.22	0.22	0.23	0.25
	P	0.011	0.011	0.011	0.010	0.008
	S	0.032	0.031	0.028	0.027	0.035

*NBS test data.

TABLE II. REVERSED-BEND TESTS. EFFECT OF SURFACE CONDITION 0.75 IN. THICK BARS PRESTRAINED AND TESTED AT 70 F. ABS-C STEEL (1956)

STEEL	BAR	PRE-STRAIN	TEST LOAD (lb) Arr. Crack	TEST LOAD (lb) Fracture	FRACTURE STRESS $4M/bd^2$ ksi Arr. Crack	FRACTURE STRESS $4M/bd^2$ ksi Fracture	
C-4	2	0.55	-	5 000+	-	87.3+	As-Rolled Surface
C-4	6	0.57	-	5 000+	-	87.3+	
C-4	5	0.59	-	5 000+	-	83.8+	
C-4	7	0.59	-	5 000+	-	87.3+	
C-5	51	0.59	-	5 000+	-	89.0+	
C-4	8	0.59	1 110	1 820	28.0	-	
C-4	4	0.60	1 860	1 860	48.0	-	
C-5	33	0.60	1 780	1 780	45.0	-	
C-5	37	0.60	1 080	2 700	27.2	-	
C-5	38	0.62	780	2 430	20.0	-	
C-5	36	0.63	560	1 820	14.5	-	
C-4	1	0.65	800	2 000	18.8	-	
C-5	34	0.65	1 020	1 820	26.2	-	
C-5	35	0.65	760	2 000	19.2	-	
C-4	3	0.69	1 490	1 490	35.6	-	
C-4	9	0.53	-	5 000+	-	89.3+	Machined Surface
C-4	10	0.56	-	5 000+	-	89.0+	
C-4	11	0.59	-	5 000+	-	89.0+	
C-4	13	0.62	-	5 000+	-	87.3+	
C-4	31	0.63	-	4 130	-	78.0	
C-4	16	0.65	-	5 000+	-	90.8+	
C-4	15	0.65	-	4 300	-	64.0	
C-4	12	0.65	640	3 720	16.8	-	
C-4	30	0.67		4 990	-	88.9	
C-4	14	0.67	800	1 340	21.3	-	
C-5	44	0.67		3 980	-	78.0	
C-5	39	0.67	1 600	1 600	42.6	-	
C-5	59	0.67	1 580	1 580	42.2	-	
C-5	43	0.69	1 920	1 930	50.5	-	
C-5	56	0.71	450	1 490	12.0	-	
C-5	55	0.71	590	1 650	15.6	-	

+ The loading was stopped at 5000 lb.

TABLE III. REVERSED-BEND TESTS. EFFECT OF SURFACE CONDITION 0.75 IN. THICK BARS PRESTRAINED AT 70 F AND TESTED AT -16 F. ABS-C STEEL (1956)

STEEL	BAR	PRE-STRAIN	TEST LOAD (lb)		FRACTURE STRESS $4M/bd^2$ ksi		
			Arr. Crack	Fracture	Arr. Crack	Fracture	
C-4	17	0.50	-	5 000+	-	90.8+	As-Rolled Surface
C-4	23	0.55	700	1 640	17.9	-	
C-5	52	0.55	310	1 600	7.7	-	
C-4	18	0.56	-	5 000+	-	90.0+	
C-4	22	0.56	1 320	1 740	33.3	-	
C-4	24	0.56	1 400	1 710	35.8		
C-5	50	0.56	-	5 000+	-	94.5+	
C-4	21	0.57	-	5 000+	-	90.8+	
C-5	49	0.57	1 680	1 680	42.5	-	
C-5	48	0.59	380	1 900	9.6	-	
C-4	19	0.62	700	1 620	17.9	-	
C-5	47	0.62	270	1 840	6.8	-	
C-4	20	0.67	430	1 380	11.0	-	
C-4	25	0.51	-	5 000+	-	90.0+	Machined Surface
C-4	26	0.53	-	5 000+	-	89.0+	
C-4	27	0.56	-	5 000+	-	92.5+	
C-5	45	0.57	-	5 000+	-	90.8+	
C-5	46	0.57	-	5 000+	-	89.3+	
C-4	28	0.59	-	5 000+	-	92.5+	
C-5	41	0.59	900	1 760	23.3	-	
C-5	42	0.59	1 790	1 790	46.5	-	
C-5	54	0.60	650	1 460	17.1	-	
C-5	57	0.60	2 280	2 280	59.2	-	
C-5	58	0.60	740	1 450	19.2	-	
C-4	29	0.62	420	1 170	10.9	-	
C-5	40	0.62	1 070	1 370	28.2	-	
C-4	32	0.63	1 340	1 340	35.3	-	

+ The loading was stopped at 5000 lb.

TABLE IV. REVERSED-BEND TESTS. EFFECT OF BAR THICKNESS 0.75 and 1.25 IN. THICK BARS PRESTRAINED AT 70 F AND TESTED AT -16 F. ABS-C STEEL (1956)

STEEL	BAR	PRE-STRAIN	TEST LOAD (lb)		FRACTURE STRESS $4M/bd^2$ ksi		
			Arr. Crack	Fracture	Arr. Crack	Fracture	
C-7	8	0.45	-	4 000+	-	87.2+	0.75 thick × 0.75 wide × 9" long
C-7	10	0.48	-	4 000+	-	87.2+	
C-7	15	0.50	-	4 000+	-	89.1+	
C-7	19	0.50	-	4 000+	-	87.2+	
C-7	20	0.50	-	4 000+	-	85.4+	
C-7	14	0.51	-	4 000+	-	87.2+	
C-7	5	0.51	630	1 180	20.8		
C-7	12	0.51	1 960	1 960	63.2		
C-7	11	0.52	-	4 000+	-	87.2+	
C-7	16	0.52	-	4 000+	-	89.1+	
C-7	18	0.52	-	4 000+	-	87.2+	
C-7	17	0.52	480	1 290	15.7	-	
C-7	6	0.53	490	1 150	16.5	-	
C-7	9	0.53	1 300	1 300	42.5	-	
C-7	7	0.56	1 030	1 320	34.7	-	
C-7	1	0.57	1 130	1 130	38.1	-	
C-7	2	0.59	370	1 410	12.4	-	
C-7	3	0.62	560	1 330	19.2	-	
C-7	4	0.65	640	1 180	22.2	-	
C-7	1	0.48	-	7 500+	-	85.2+	1.25 thick × 1.67 wide × 18" long
C-7	4	0.50	-	7 500+	-	88.6+	
C-7	10	0.50	-	7 500+	-	84.7+	
C-7	8	0.50	2 060	4 200	24.2	-	
C-7	3	0.51	1 180	3 030	14.0	-	
C-7	5	0.51	4 000	4 000	47.3	-	
C-7	9	0.51	1 860	3 890	22.0	-	
C-7	14	0.51	2 430	3 680	28.6	-	
C-7	15	0.51	5 710	5 710	66.3	-	
C-7	7	0.52	-	7 500+	-	85.8+	
C-7	13	0.52	1 540	4 060	18.2		
C-7	2	0.53	380	3 390	4.5		
C-7	6	0.53	930	3 230	11.0	38.4	
C-7	12	0.53	2 400	3 330	28.6	39.6	
C-7	11	0.57	380	2 690	4.6	32.3	

+ The loading was stopped at 4000 lb. (0.75 0.75 in. bars) or 7500 lb. (1.25 1.67 in. bars).

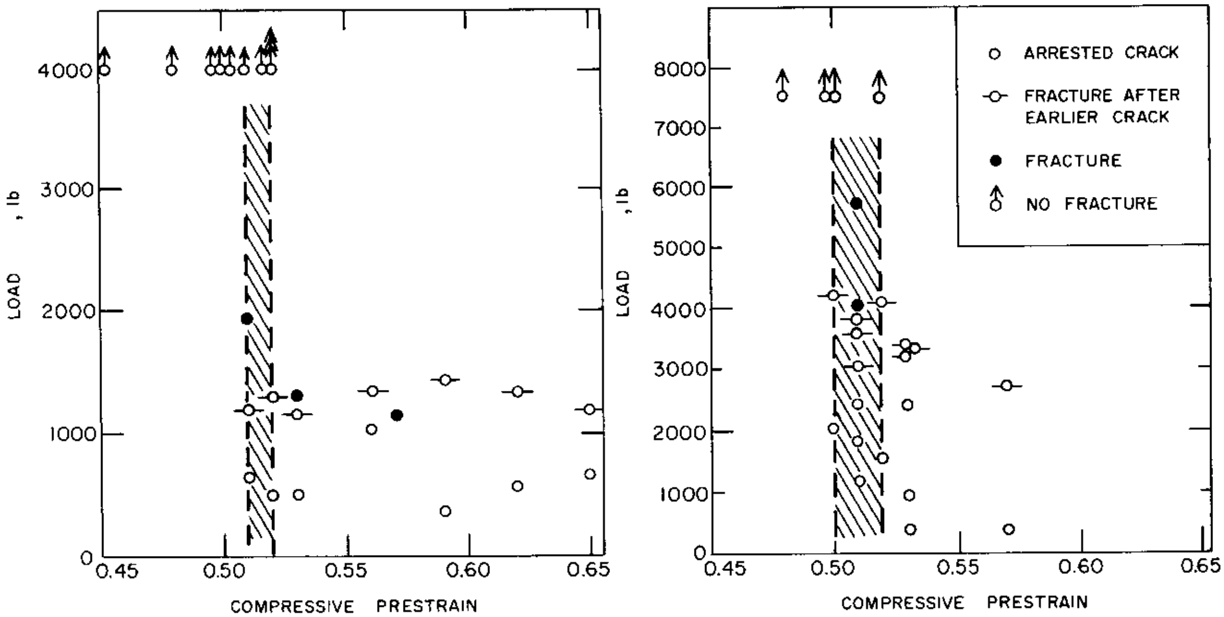

FIG. 5. EXHAUSTION LIMITS OF ABS-C (1956) STEEL TESTED ON AS-ROLLED SURFACE AT -16 F. 9 x 0.75 x 0.75 in. THICK BARS (LEFT); 18 x 1.67 x 1.25 in. THICK BARS (RIGHT)

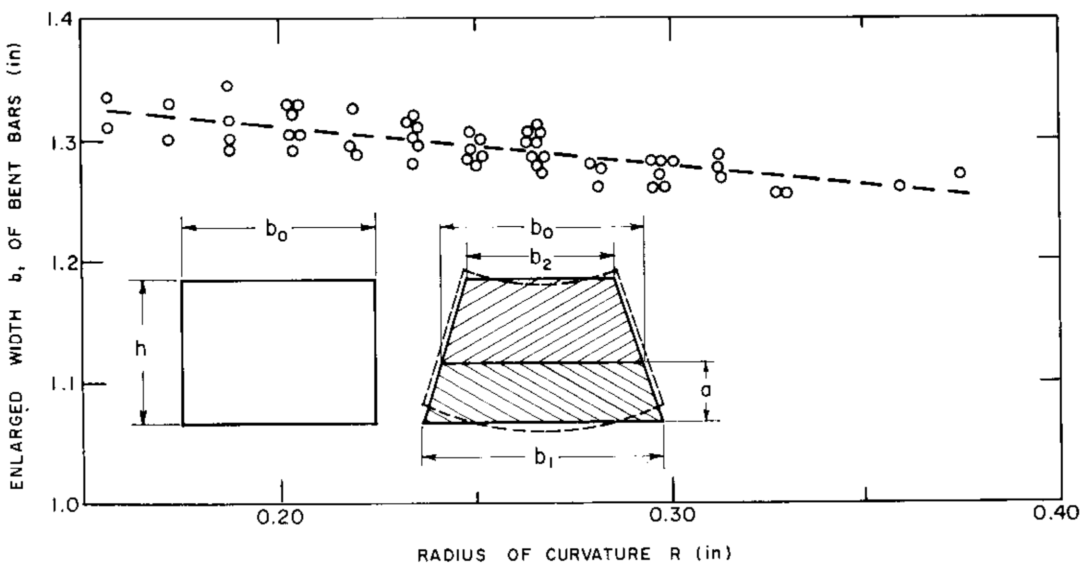

FIG. 6. ENLARGED WIDTH VS. RADIUS OF CURVATURE OF 0.75 IN. BARS

dividing the cross-section in two equal areas retained its original width b_0. As the height did not change appreciably during bending, a single measurement of the largest base b_1 was sufficient for the determination of the trapezoid. The width b_1 after various amounts of bending of 0.75 x 1.00 in. bars was plotted against the radius of curvature at the intrados (Fig. 6). The approximate linear relationship found experimentally (Eq. 7 of Appendix) was used in all calculations.

Calculations were made according to straight and to curved beam theory for elastic[20] and for fully plastic behavior[21-23] according to the formulas given in the Appendix. Stress from axial loading was added to the bending stress only in elastic behavior. In fully plastic action the small axial force of the present tests (about 10% of the yield load in pure tension corresponding to the raised yield strength) causes a negligible reduction of the plastic bending capacity, as can be easily seen from the interaction curve

TABLE V. SUMMARIZED RESULTS OF REVERSED BEND TESTS

Steel	Tested at -16°F		Tested at 75°F	
	Aged Exhaustion Limit	Unaged Exhaustion Limit	Aged Exhaustion Limit	Unaged Exhaustion Limit
E	0.40 to 0.44	0.50 to 0.55	0.50 to 0.55	0.57 to 0.59
ABS-C*	0.50 to 0.52	0.57 to 0.57	0.52 to 0.56	0.60 to 0.62
HY-80	0.59 to 0.63	0.60 to 0.63	0.61 to 0.65	0.65 to 0.69
A-7	0.46 to 0.48	0.52 to 0.55	0.52 to 0.55	0.61 to 0.62
T-1	0.49 to 0.52	0.52 to 0.53	0.56 to 0.59	0.60 to 0.64
ABS-C-4 ABS-C-5				
As-rolled Surface		0.55 to 0.57		0.59 to 0.60
Machined Surface		0.59 to 0.60		0.65 to 0.67
ABS-C-7 As-rolled				
0.75" square		0.50 to 0.52		
1.67 x 1.25 thick		0.51 to 0.52		

*Tests of 1960.

for combined bending and tension.[21-23]

The results are tabulated in Tables VI and VII. The stresses calculated by straight and curved elastic beam formulas differ substantially, but those for rectangular and trapezoidal cross-sections are surprisingly close. The trapezoidal section gives elastic stresses only 6 to 7% smaller than the rectangular, and fully plastic stresses only 8 to 10% larger. In view of the approximations introduced by the finite bending and by the assumption of the trapezoidal shape, and of the uncertainty of the stress-strain law, these small differences do not justify the laborious calculations for trapezoidal sections. Rectangular curved beam formulas give a sufficiently good approximation.

The fracture stresses calculated by rectangular curved beam theory for the extreme instances of purely elastic and of fully plastic behavior (Tables VI and VII, Columns 4 and 6) have been plotted against prestrain in Fig. 7 and 8. A vertical line joins the points corresponding to the elastic stress (higher) and the fully plastic stress (lower) for the same test. As already discussed, it appears reasonable to accept the stress based on a fully plastic distribution for bars which sustained high loads and deformations (lower end of vertical lines on upper part of graphs), and the elastic curved-beam stress for bars which fractured at low loads and deformations (upper end of vertical lines in lowest part of the graphs). It is quite interesting to find that several brittle bars fractured at a calculated elastic stress of about 50 ksi at 70 F, and even down to 30 ksi or less at -16 F. These stresses are very close to the expected 0.1% offset tensile yield strength, which from analogy with earlier tests with E-Steel[14] and with recent unpublished tests of bars of ABS-B steel compressed axially by 0.50 but unaged, should be about 40 to 50 ksi. The low nominal stress fractures are probably caused by stress concentrations from surface irregularities or from flaws, and to a certain extent by residual stresses, but they indicate an extreme brittleness, i.e. an inability of the steel to yield locally so as to reduce the stress concentrations and wipe out the residual stresses.[12] The calculated yield stress based on an assumed fully plastic distribution was equal to about 90 ± 3 ksi for all the bars which withstood large deformations, irrespective of surface condition and test temperature.

CONCLUSIONS

a. Bars of ABS-C steel with machined surfaces have a slightly higher exhaustion limit than bars with as-rolled surfaces, as found by the reversed-bend test. The difference is equal

TABLE VI. STRESS AT FIRST CRACK OR MAXIMUM LOAD FOR ELASTIC OR FULLY PLASTIC DISTRIBUTION. TESTS AT 70 F. ABS-C STEEL (1956)

BAR	PRE-STRAIN	MAXIMUM ELASTIC STRESS ksi.			YIELD STRESS ksi. FOR FULLY PLASTIC STRESS DISTRIBUTION		
		Rectang. Straight	Rectang. Curved	Trapez. Curved	Rectang.	Trapez.	
2	0.55	137.6+	217.7+	204.0+	87.3+	95.5+	As Rolled
6	0.57	137.6+	222.7+	208.6+	87.3+	96.4+	
5	0.59	134.2+	270.2+	206.6+	83.8+	93.3+	
7	"	137.6+	229.2+	212.6+	87.3+	97.2+	
51	"	140.2+	233.7+	218.9+	89.0+	99.3+	
8	0.59	43.5	72.9	68.3	28.0	31.2	
4	0.60	74.5	126.3	118.7	48.0	53.5	
33	"	69.8	117.8	111.5	45.0	50.2	
37	"	42.2	71.5	67.2	27.2	30.4	
38	0.62	31.1	54.2	51.0	20.0	22.4	
36	0.63	22.5	41.0	37.4	14.5	15.3	
1	0.65	29.3	53.7	50.4	18.8	21.3	
34	"	40.8	74.7	69.8	26.2	29.7	
35	"	29.8	54.6	51.3	19.2	21.7	
3	0.69	55.4	109.4	101.7	35.6	40.8	
9	0.53	140.7+	217.7+	203.5+	89.3+	97.0+	Machined
10	0.56	140.2+	224.7+	210.9+	89.0+	97.8+	
11	0.59	140.2+	233.7+	218.8+	89.0+	98.0+	
13	0.62	137.7+	238.7+	224.6+	87.3+	98.2+	
31	0.63	122.5	216.2	204.6	78.0	87.8	
16	0.65	142.9+	259.9+	244.7+	90.8+	102.7+	
15	"	101.7	184.2	173.3	64.0	72.5	
12	"	26.1	47.8	44.9	16.8	19.0	
30	0.67	140.2	260.5	248.4	88.9	101.2	
14	"	33.1	62.9	58.7	21.3	24.2	
44	"	122.3	231.3	217.2	78.0	88.7	
39	"	66.0	125.3	117.9	42.6	48.5	
59	"	65.3	123.9	116.8	42.2	48.0	
43	0.69	78.4	154.8	144.8	50.5	57.8	
56	0.71	18.6	38.1	35.8	12.0	13.8	
55	0.71	24.2	49.5	46.6	15.6	17.9	

+ stress corresponding to an applied load of 5000 lb. at which no fracture occurred.

TABLE VII. STRESS AT FIRST CRACK OR MAXIMUM LOAD FOR ELASTIC OR FULLY PLASTIC DISTRIBUTION. TESTS AT -16 F. ABS-C STEEL (1956)

BAR	PRE-STRAIN	MAXIMUM ELASTIC STRESS ksi.			YIELD STRESS ksi. FOR FULLY PLASTIC STRESS DISTRIBUTION		
		Rectang. Straight	Rectang. Curved	Trapez. Curved	Rectang.	Trapez.	
17	0.50	142.9+	213.7+	200.5+	90.8+	97.5+	As Rolled
23	0.55	27.8	44.2	43.7	17.9	19.6	
52	"	11.9	18.9	17.8	7.7	8.5	
18	0.56	141.7+	226.7+	213.0+	90.0+	98.8+	
22	"	56.8	91.5	78.1	36.7	36.6	
24	0.56	55.6	89.4	83.9	35.8	39.4	
50	"	147.9+	238.7+	223.6+	94.5+	103.8+	
21	0.57	142.9+	231.7+	216.6+	90.8+	100.5+	
49	"	65.9	107.2	100.2	42.5	46.9	
48	0.59	14.9	25.0	23.3	9.6	10.7	
19	0.62	27.8	48.5	45.6	17.9	20.1	
47	"	10.6	18.5	17.4	6.8	7.7	
20	0.67	17.1	32.5	30.4	11.0	12.5	
25	0.51	141.7+	214.2+	200.5+	90.0+	97.0+	Machined
26	0.53	140.2+	217.5+	213.0+	89.0+	96.8+	
27	0.56	145.4+	232.7+	218.9+	92.5+	101.5+	
45	0.57	142.9+	231.2+	217.1+	90.8+	101.0+	
46	"	140.7+	227.7+	213.6+	89.3+	98.6+	
28	0.59	145.4+	242.7+	227.1+	92.5+	102.6+	
41	"	36.2	60.7	56.7	23.3	25.9	
42	"	72.1	120.6	113.0	46.5	51.6	
54	0.60	26.5	45.0	42.4	17.1	19.0	
57	"	91.1	155.3	145.5	59.2	66.0	
58	0.60	29.8	50.6	47.5	19.2	21.4	
29	0.62	17.0	29.7	27.7	10.9	12.2	
40	"	43.9	76.7	71.7	28.2	31.6	
32	0.63	54.8	97.3	91.1	35.3	39.8	

+ stress corresponding to an applied load of 5000 lb. at which no fracture occurred.

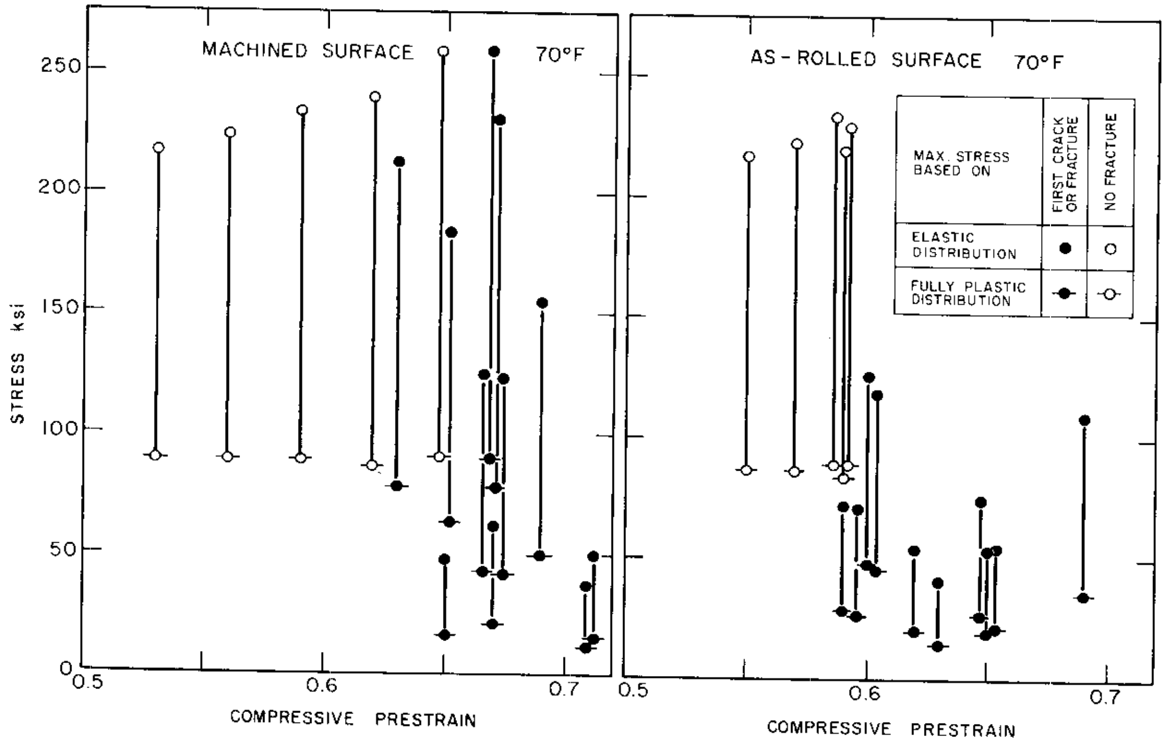

FIG. 7. CALCULATED STRESS AT FIRST CRACK FOR PURELY ELASTIC AND FOR FULLY PLASTIC BEHAVIOR. 0.75 IN. THICK BARS TESTED AT 70 F.

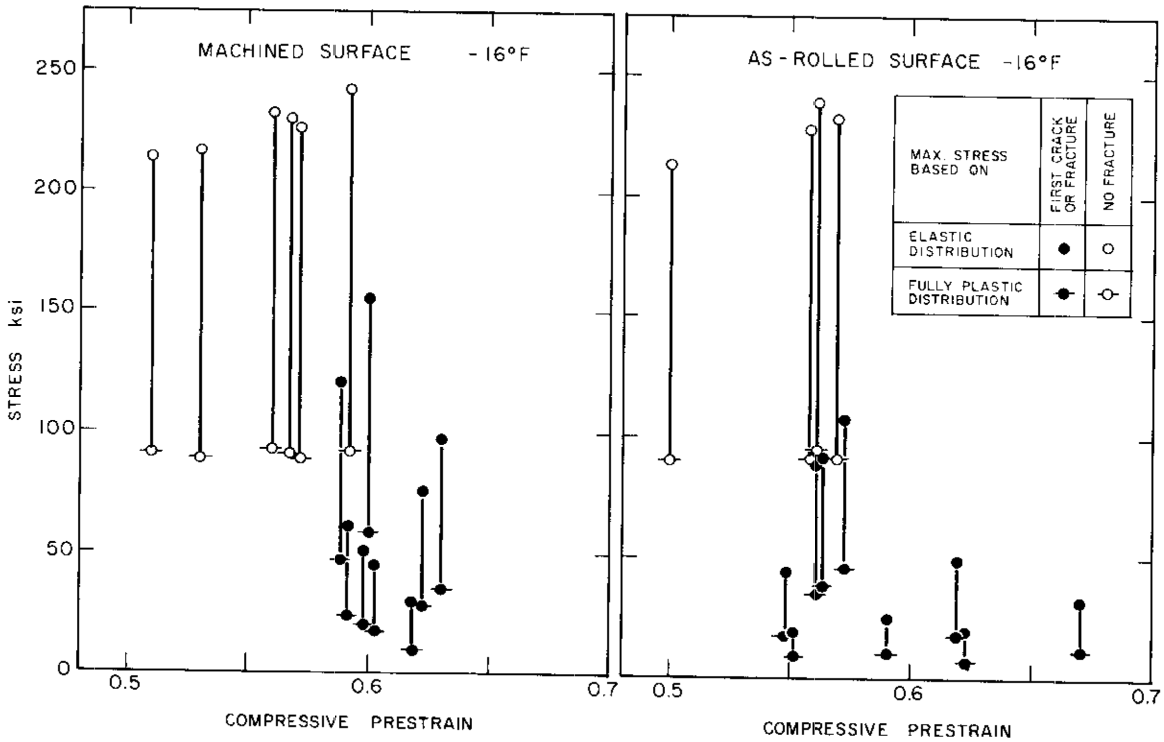

FIG. 8. CALCULATED STRESS AT FIRST CRACK FOR PURELY ELASTIC AND FOR FULLY PLASTIC BEHAVIOR. 0.75 IN. THICK BARS TESTED AT -16 F.

to about 0.03 for tests at 70 F and 0.06 at -16 F.

b. No size effect was reflected in the exhaustion limit when the thickness of the test bars was increased from 0.75 to 1.25 in.

c. The calculated stress on the assumption of an elastic stress distribution for the most brittle of the bars prestrained beyond the exhaustion limit was close to, and sometimes lower than the 0.1% offset strength after compression. The calculated stress on the assumption of fully plastic stress distribution for bars prestrained below the exhaustion limit (ductile) was close to 90 ksi with few exceptions.

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APPENDIX

CALCULATION OF FRACTURE STRESS FOR RECTANGULAR AND FOR TRAPEZOIDAL CROSS-SECTIONS, FOR STRAIGHT AND CURVED BEAMS, AND FOR PURELY ELASTIC AND FOR FULLY PLASTIC BEHAVIOR

I. Rectangular Cross-Section

a. Straight elastic beam $\sigma^r_{s,e} = 6M/b_o h^2 + P/A$ (1)

b. Straight fully plastic $\sigma^r_{s,p} = 4M/b_o h^2 \qquad (\frac{P}{A} << \sigma^r_{s,p})$ (2)

c. Curved elastic $\sigma^r_{c,e} = M\left[\frac{h}{2I} + \frac{1}{b_o h}\left(\frac{1}{R} + \frac{1}{R+\frac{1}{2}h}\right)\right] + \frac{P}{A}$ (3)

d. Curved fully plastic $\sigma^r_{c,p} = \sigma^r_{s,p} = 4M/b_o h^2$ (2)

II. Trapezoidal Cross-Section

Assumption: The line dividing the cross-section in two equal areas (Fig. 6, inset) retains the initial width b_o. Then

$$b_2 = \sqrt{2b_o^2 - b_1^2} \tag{4}$$

$$a = h(b_1 - b_o)/(b_1 - b_2) \tag{5}$$

Distance of centroid from lower base b_1

$$c = \tfrac{1}{3}h(b_1 + b_2)/(b_1 + 2b_2) \tag{6}$$

From experiment: $b_1 = 1.38 - \frac{R}{3} = 1.38 - \frac{1}{8}(\frac{1}{\epsilon} - 1)$ (7)

a. Straight elastic beam: $\sigma^{tr.}_{s,e} = \frac{12M}{h^2}(b_1+2b_2)/(b_1^2+4b_1b_2+b_2^2) + \frac{P}{A}$ (8)

b. Straight fully plastic: $\sigma^{tr.}_{s,p} = 6M/(A \times L)$ (9)

$$L = \frac{h}{b_1 - b_2}\left[\frac{b_o + 2b_2}{b_o + b_2}(b_o - b_2) + \frac{b_o + 2b_1}{b_o + b_1}(b_1 - b_o)\right] \qquad (10)$$

c. Curved elastic: $\sigma^{tr}_{c,p} = M\left[\frac{c}{I} + \frac{1}{2b_1 c}\left(\frac{1}{R} + \frac{1}{R + c}\right)\right] + \frac{P}{A}$ (11)

d. Curved fully plastic: $\sigma^{tr}_{c,p} = \sigma^{tr}_{s,p} = 6M/(A \times L)$ (9)

M: applied bending moment

P: applied force

A: area of cross-section

I: moment of inertia about centroid

R: radius of curvature at intrados of curved beam

ϵ: nominal compressive prestrain at intrados

NONE

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Comparative tests between bars with as-rolled and with machined surfaces show a small difference in the compressive prestrain needed to exhaust the original extensional ductility of the steel, as this is determined by the reversed bent test.[9,10] Machined bars show a higher exhaustion limit (prestrain) than as-rolled bars by 0.03 at 70 F and 0.06 at -16 F. Stress calculations show that the most brittle fractures may occur at applied elastic macroscopic stresses as low as about 50 ksi at 70 F and about 30 ksi at -16 F. Highly ductile bars sustained a stress close to 90 ksi at both test temperatures.

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