SSC-115

BRITTLE FRACTURE INITIATION TESTS

by

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and

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SHIP STRUCTURE COMMITTEE

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October 15, 1958

Dear Sir:

As part of its research program related to the improvement of hull structures of ships, the Ship Structure Committee is sponsoring and investigation of Brittle Fracture Mechanics at Brown University. Herewith is a copy of the Second Progress Report, SSC-115, of the investigation entitled "Brittle Fracture Initiation Tests," by C. Mylonas, D. C. Drucker and L. Isberg.

The project is being conducted with the advisory assistance of the Committee on Ship Structural Design of the National Academy of Sciences-National Research Council.

Comments concerning this report are solicited and should be addressed to the Secretary, Ship Structure Committee.

This report is being distributed to those individuals and agencies associated with and interested in the work of the Ship Structure Committee.

Yours sincerely,

E. H. Thiele
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

Serial No. SSC-115

Second Progress Report
of
Project SR-130

to the

SHIP STRUCTURE COMMITTEE

on

BRITTLE FRACTURE INITIATION TESTS

by

C. Mylonas, D. C. Drucker and L. Isberg

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Providence, Rhode Island

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Washington, D. C.
National Academy of Sciences-National Research Council
October 15, 1958

BRITTLE FRACTURE INITIATION TESTS

Exploratory tests have been successful in producing many typically brittle fractures at loads corresponding to an average stress smaller than virgin yield

BY C. MYLONAS, D. C. DRUCKER AND L. ISBERG

ABSTRACT. A running crack will propagate at nominal stresses of 10,000 psi in steel plate. Nevertheless, structures of such steel operate at higher nominal stress. Furthermore, laboratory tests generally fail to initiate brittle fracture at nominal stresses below yield except by extreme cooling or impact loading. A strong barrier to the static initiation of brittle fracture thus exists.

The object of the present investigation is to study the conditions under which this barrier is lowered. Until static laboratory tests reproduce fractures at the temperatures and nominal stresses encountered in service, brittle fracture will remain essentially unexplained.

Moderate success has been achieved so far. Welded and unwelded notched steel plates with various prestrains were pulled at various temperatures. Transversely prestrained plates with punched notches fractured consistently below yield under static loading. The fractures were as brittle as those found in service in the region of propagation and, far more important, also at the point of initiation.

Introduction

Observations on the brittle fracture of steel structures are not new, but relatively little is known about the phenomenon except among those concerned with its investigation. Many descriptions and surveys of such failures exist[1-5] and lead to the following general conclusions.

1. Brittle fracture can occur under completely static loading in steels which comply with conventional specifications on strength and ductility.
2. The nominal stress level before fracture may be low, as little as one half of yield or less.
3. The fractures originate at or near some discontinuity or defect due to design, fabrication or subsequent repair.
4. Once started the crack can propagate at high speed through regions of low stress.
5. The main body of the fracture is typically "brittle" as evidenced by the small lateral contraction at fracture (of the order of 1%), the virtual absence of shear lip and the cleavage appearance of the fractured surface.
6. Steels which fail exhibit some notch brittleness at the temperature of the failures. As would be expected more fractures occur in cold than in warm weather.
7. Fatigue does not appear to be a contributory factor in most instances.
8. Conditions of loading quite similar to those at fracture are often successfully sustained for some time prior to the failure.

The intensive research spurred by several catastrophic failures was of great value in design. It showed the deleterious effects of stress-raisers—corners, intersections, cutouts, cracks, imperfect welds, arc strikes etc.—and helped to reduce the occurrence of brittle failures by improving the design and the methods of fabrication. It also showed a correlation between susceptibility to brittle fracture and brittle transition temperature, and allowed the selection of better steels. However the basic problem of the mechanism of brittle fracture in steel plate was not solved. Most of the laboratory tests only showed that, in spite of severe elastic stress raisers and low temperatures, steel plate does not fail under central static loading before yielding occurs over the net section.[6-17,46] However once a fracture is started it will generally run across the plate through warmer regions of low stress[19,20] probably even below 10,000 psi for ordinary structural steel.[18]

The initiation of fracture at low stress generally has been achieved by impact or by a highly embrittled area or by both. Thus, Robertson[19,20] cooled with liquid nitrogen and struck a blow on a hollow knob at the edge of the test plate; Feely[18] and associates used a wedge blown by explosion into a prepared notch of a uniformly cooled plate; and Pellini[21,22] and associates, and Noren[23] used a brittle bead weld which broke first and transmitted its fracture to the test plate.

The difficulty in starting a crack, as compared to the ease of its propagation, indicates that a crack initiation barrier generally exists. The level of that barrier is not known, nor is it certain that a simple measure of it can be stated. It is the purpose of the study

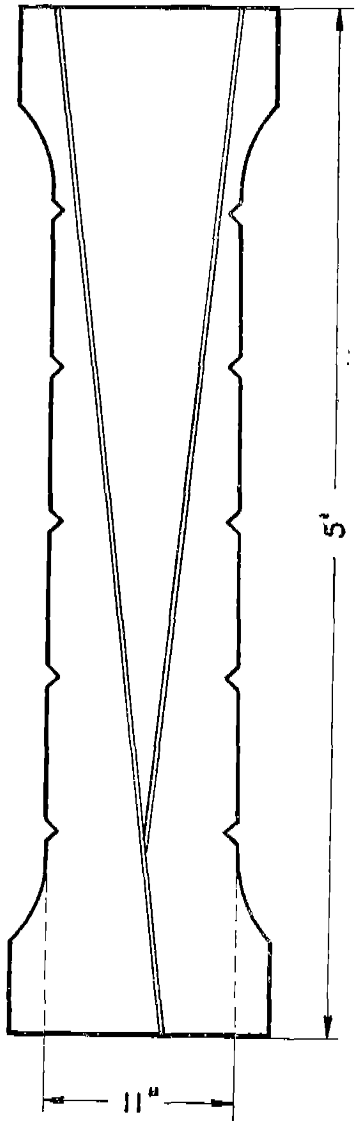

Fig. 1 Five-foot test plate with longitudinal welds. Net section ~$^3/_4$ x 8 in.

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reported here to determine likely means by which this barrier is overcome and fracture occurs at moderate stress levels. If some crack initiation barrier exists under all field conditions, its minimum could well be taken as the basis of design against brittle fracture. This would be helpful as it does not seem economically feasible at present to use steels with known high initiation barrier (very notch insensitive) everywhere in the structure, nor does it appear possible to design for a stress so low as to halt the propagation of a crack. Such a lower limit was indicated by the work of Robertson,[20] but in other tests[18] it does not appear to be clearly determined, and if it exists would be very low for most steels in common use today.

The phenomenon of crack spreading has been extensively studied by energy methods similar to the Griffith theory of fracture but including plastic work. Irwin,[24,26,28] Orowan,[25,27,29] Felbeck and Orowan,[13] Wells, [16,30,31] and others have contributed significant theoretical and experimental results. However these studies establish with certainty only the necessary condition for crack spreading, i.e., that the dissipated energy be less than the available energy, but are inconclusive as to the sufficient conditions.[17,44] That steel plate with unimpaired ductility will not fail without general yielding of the net section irrespective of the length and sharpness of original cracks is a clear indication that an additional requirement, perhaps a maximum stress, must be met in addition to the energy criterion.[17] It may be considered as equivalent to an energy barrier which must be overcome, as in the example of two reservoirs with different water levels joined by a syphon rising above them. The difference of the two water levels is a necessary condition for flow, but to start it some additional energy must first be provided in order to raise the water to the highest point of the syphon. Thus for the initiation of the flow the higher barrier of the syphon is the deciding factor, whereas for the continuation of the flow the difference of water levels is enough.

The crack propagation problem in its most simplified form is one of dynamic elastic-plastic wave propagation and is far beyond our present ability to obtain solutions. Adding the unjustified assumption of perfect elasticity provides great simplification, but the problem is still far from trivial. A steady state plane strain elastic solution by Yoffe[45] for a moving system of loads on the surface of a half plane is indicative of what can be expected, but the relevance of quantitative or even qualitative conclusions is by no means obvious. The main point in the spreading of a crack is that the distribution of stress is quite different from the static and that fracture is governed by the time history of stress, by strain history and by temperature. Almost nothing is known about the equivalent of the energy barrier either at low speeds or at the enormous rates of strain developed; that is, information is not available on the stresses developed and required.

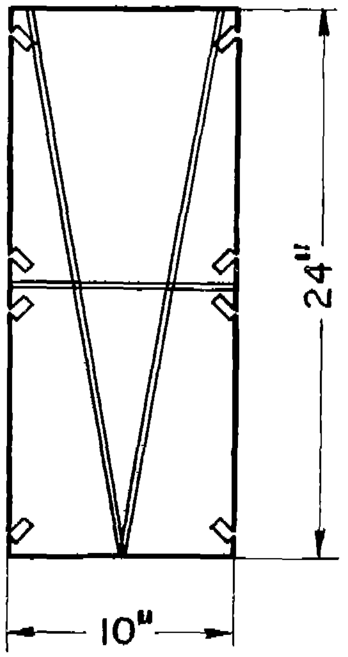


Fig. 2 Two-foot test plate with longitudinal and transverse welds. Net section $\sim^3/_4$ x 7 in.

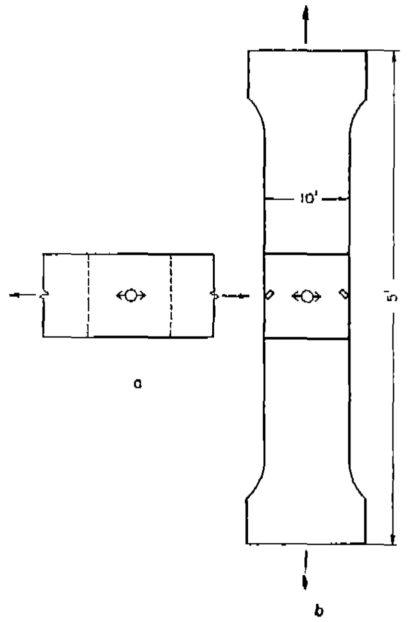


Fig. 3 Test plate with transverse prestrain. Net section $\sim^3/_4$ x 7 in.

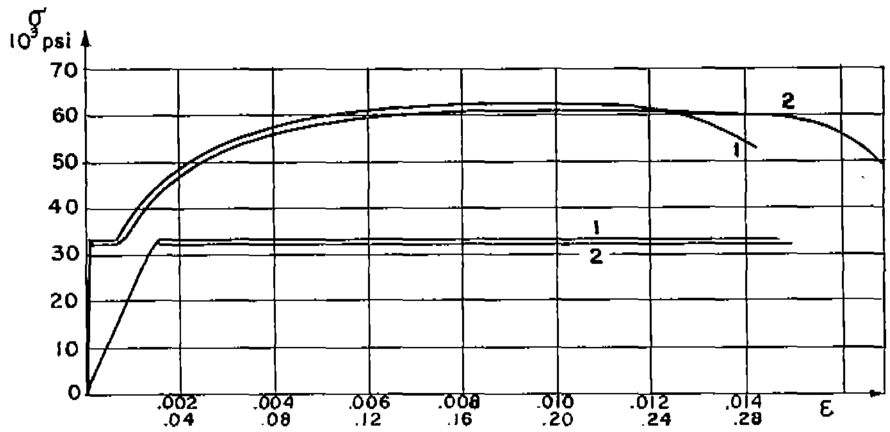


Fig. 4 Stress-strain curve of virgin plate 5E. *1*, Parallel to direction of rolling. *2*, Transverse to direction of rolling

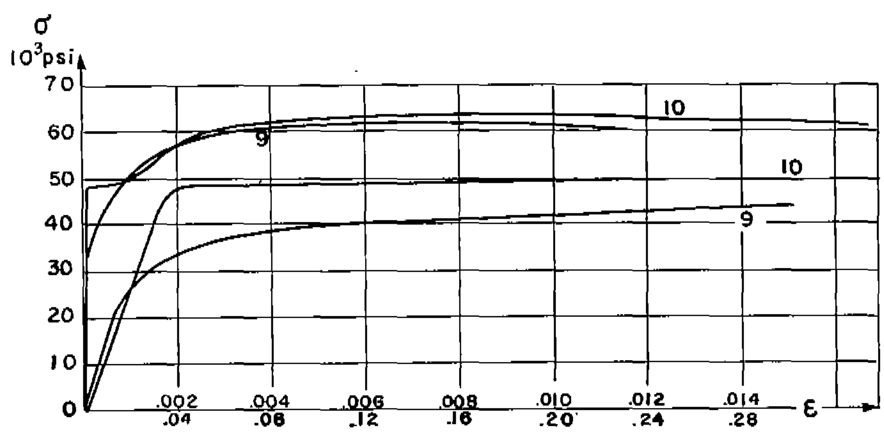


Fig. 5 Stress-strain curves after 2.4% prestrain in direction of rolling. *9*, Transverse to prestrain. *10*, Parallel to prestrain

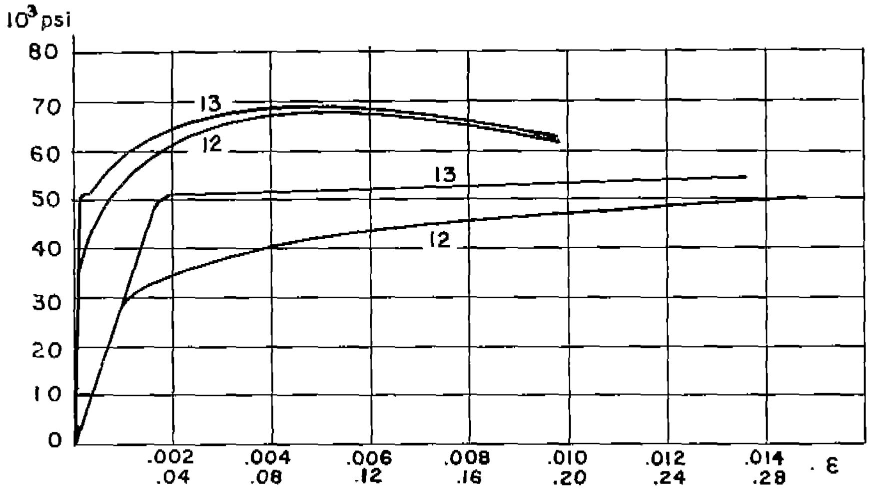


Fig. 6 Stress-strain curves after 2.6% prestrain in direction of rolling. *12*, Transverse to prestrain. *13*, Parallel to prestrain

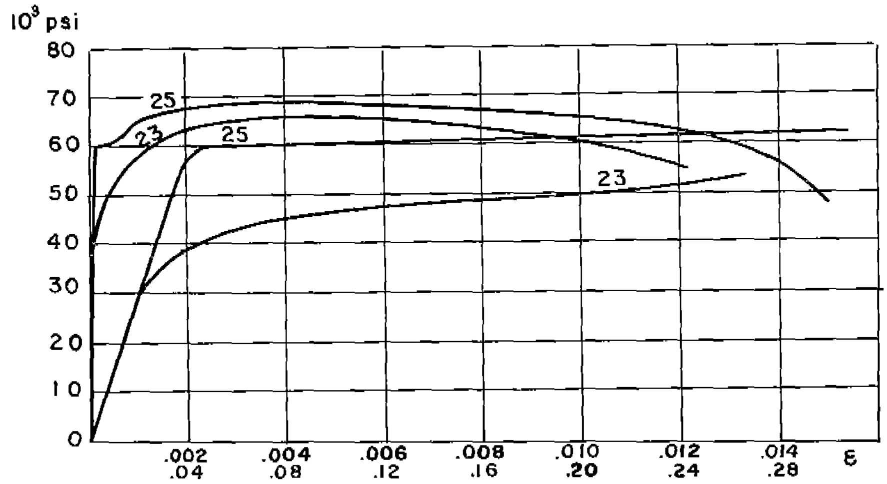


Fig. 7 Stress-strain curves after 6.0% prestrain in direction of rolling. *23*, Transverse to prestrain. *25*, Parallel to prestrain

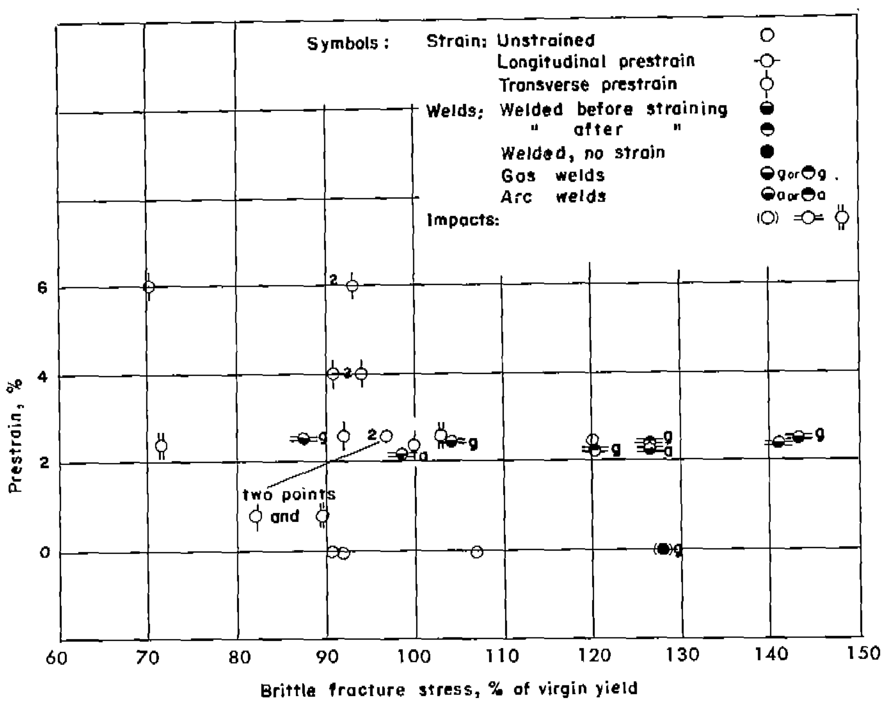


Fig. 8 Summary of test results

Nevertheless, the evidence does seem conclusive that in structural steel the barrier is enormous and that the energy balance is so highly unstable that a Griffith type theory can be misleading if applied to structures. A guess[17] as to the probable state of stress ahead of the crack and of the work of fracture as functions of crack velocity, indicates that there is an instability caused by the reduction of work of crack formation as the velocity increases. However some plastic deformation takes place even in the most brittle fractures[10,14,32] and such studies cannot yet be made quantitative. Little can be said about the state prior to the initiation of fracture because the plastic deformation may be quite large.

As was noted, static laboratory tests on centrally loaded notched plates with unimpaired ductility fail to initiate a fracture before general yielding of the net section. Nevertheless, conditions of fracture initiation at low stress obviously exist. It appears worth while, therefore, to review and compare the laboratory and the service fractures in an effort to assess the plausible causes of the unsuccessful attempts to reproduce the service initiations of brittle fracture. One conclusion is that in all static tests the material had sufficient ductility to yield even in the most constraining shapes of models. The reason the section flow limit* was always reached and general yielding occurred is simple and has already been given by Wells.[16] It is that before the flow limit is reached under symmetrical over-all loading only small plastic deformation may occur at the root of the notch. Some general yielding must take place before the plastic deformation and the strain hardening at the root of the notch are sufficient to cause failure.

On the other hand, many indications exist that brittle fracture may occur at low nominal stress when the ductility at the root of the notch is exhausted. The cold working of steel raises the transition temperature, as is discussed by Lankford.[35] In the experiments of Greene[36] and Wells,[30] who initiated fractures at low stress, yielding occurred at the root of notches from the shrinkage of long welds in wide plates. In addition there may have been a concurrence of the detrimental metal-

* By "flow limit" is meant the nominal stress at which large plastic strains occur over all the cross section. For plates with internal notches this limit coincides with yield stress over the net section (neglecting strain hardening). For plates or bars with external notches[17, 33] the limit is higher than the yield point, depending on the angle and sharpness of the notch and the ratio of thickness to width of the plate.[34] For very thick plates or for round bars notched circumferentially the flow limit may be considerably higher than the yield stress. When factors of 2.5 to 2.8 are reached, fracture may occur prior to over-all yielding. For the notched plates of most tests, including the present tests, the flow limit should exceed the yield stress over the net section by a very small amount and for practical purposes will not be differentiated from it.

Table 1—Tensile Specimens

Specimens 1–7 with 0.75 in. section; 9–25 standard 0.505 in. diam

Source	*Prestrain*	*Specimen*	*Direction* relative to rolling*	*Direction* relative to prestrain*	*Yield point, kips*	*Offset yield strength, in. 0.0005*	*0.001*	*0.002*	*Ultimate strength, kips*
Pl. 5E	None	1	‖	..	32.8	..	..	..	61.6
	None	2	⊥	..	32.0	..	..	..	60.5
Pl. 6E	None	3	‖	..	33.0	..	..	..	60.9
	None	4	⊥	..	33.0	..	..	..	59.1
Test plate No. 2 containing A-2, B-2, C-3 and D-3	None	7	⊥	..	31.5	..	..	..	61.5
	2.4%	9	‖	⊥	..	31	34.2	37.2	61.8
	2.4%	10	⊥	‖	48.5	..	48.5	48.5	63.5
Test plate No. 3 containing A-3 and B-3	2.6%	12	‖	⊥	..	33.0	36.0	39.0	67.5
	2.6%	13	⊥	‖	51.0	51.2	51.2	51.5	68.6
Test plate No. 4 from Pl. nE	None	16	⊥	..	32.0	..	..	..	60.8
	4.0%	19	‖	⊥	..	34.0	38.0	40.8	63.1
Test plate No. 5 from Pl. nE	None	21	⊥	..	32.5	..	..	..	63.9
	None	22	⊥	..	32.0	..	..	..	62.4
	6.0%	23	‖	⊥	..	36.0	41.7	44.5	66.5
	6.0%	25	⊥	‖	60.5	60.5	60.5	60.8	69.0

* Parallel (‖), or transverse (⊥).

lurgical effects in the vicinity of the weld as shown by the raised transition temperature in a zone along the weld of virgin plate[37] and of prestrained plate.[38] The residual stresses arising from welding may be very high[39,40,42] and, together with the other causes mentioned, account for the spontaneous fractures produced by Weck.[42] The initiation of fracture at low stress from a notched plate subjected to fatigue achieved by Schaub[43] may be open to a similar interpretation, namely that the ductility at the tip of a fatigue crack was exhausted by the repeated loadings. This experiment also shows that welds are not indispensable in the initiation of brittle fracture, but rather the exhaustion of ductility whether achieved by the shrinkage of welds or by other methods.

Accordingly in the present attempts to lower the initiation barrier and produce fractures at low average stress levels, the guiding principle has been to exhaust the ductility of the material, but only by methods corresponding to or not much beyond the most severe service conditions.

Description of the Tests

A number of factors are known or are thought to contribute to the danger of brittle fracture through local or over-all decrease in ductility. Those that were felt to represent a reasonable approach to possible conditions of past or present construction practice were used singly or in combination. Thus a steel of high transition temperature was chosen; the test plates were cooled well below the transition range: various test plates were prestrained by different amounts; some contained welds; they all had stress-raising notches; and they were sheared or punched. The significant properties and procedures of preparation and testing follow.

(*a*) *Plate Material.* A pedigree rimmed project steel "E," $^3/_4$ in. thick was used as it is known to be very prone to brittle fracture. Typical compositions and properties are as follows:

	Plate 5E	*Plate 6E*	*Plate nE*
C	0.29	0.28	..
Mn	0.39	0.40	..
P	0.015	0.022	..
S	0.028	0.043	..
Si	0.03	0.02	..
Lower yield point, psi	33,000	33,000	32,000
Ultimate strength, psi	61,600	60,900	60,800
Elongation, % in:			
8 in.	28.4	31.2	..
2 in.	..	..	36.5
Charpy V-notch impact, ft-lb at −11° F: 3.3 (avg)			

The yield point, tensile strength, elongation and Charpy V-notch impact strength parallel to and transverse to rolling did not differ significantly. The Charpy V-notch transition range from brittle to ductile fracture determined by earlier investigations was between 0 and 80° F.

(*b*) *Test Plates.* Plates $^3/_4$ in. thick and approximately 10 in. wide were used in all tests. Some were 5 ft long (Fig. 1) and were welded to special pulling heads, some were 2 ft long, and others were 10 in. long welded to intermediate plates to make up the same 5-ft length (Figs. 2 and 3*b*). In all cases the final testing was in the direction of rolling. The surfaces of the plates were left in the as-rolled condition. The plates were prestrained before or after being cut up and rewelded. The notches were made last and never existed during the prestraining.

(*c*) *Prestrain.* The present series of tests, which are exploratory for a more systematic investigation, included prestrain by tension in six consecutive loadings of increasing intensity up to about 2.5% permanent elongation in the direction of final testing for the 5- and 2-ft plates, and between 2.5 and 6% transversely to the direction of testing for the 10-in. plate. The latter was achieved by prestraining longitudinally a 10- x 60-in. plate, sectioning it in 10-in. square plates and welding each square into a longer composite plate (Fig. 3*a*, *b*). All prestraining was carried out at room temperature. The aging of the specimens varied from 2 to 200 days at room temperature, with one plate heated to 220° F for one-half hour.

Tension specimens were taken from the virgin and the prestrained plates in the logitudinal and transverse directions. Typical curves are shown in Figs. 4–7 and the characteristic values in Table 1. It may be seen that, in the direction of prestrain, the yield *point* is raised considerably, and the yield *strength* is not lowered in the transverse direction. The curve for the transverse direction is very gradual without a definite yield point, but the 0.0005 offset and, much more, the 0.001 and 0.002 offset values are all above virgin yield (with the exception of the 0.0005 offset of Specimen 9 which is only 1.5% less than virgin yield).

(*d*) *Welds.* A survey of the available data of both service fractures and tests indicates that cracks seldom extend along or parallel to welds. They may start near the weld but tend to turn away from it, and when propagating they cross the welds almost perpendicularly. Accordingly it was thought best to make welds in the direction of testing so that the longitudinal stresses from welding would be superimposed on those of loading. The plates were sheared and rewelded along the legs of a very elongated V symmetric to the axis of the plate (Figs. 1 and 2), so that the welds passed at various distances from a row of notches of constant depth, with each pair of notches leaving approximately the same net section. Thus the effect of the notches would be exerted at various distances from the weld centerline, varying from zero to 3 in. Arc welding with ASTM-AWS E6013 $^5/_{32}$-in. electrode and gas welding in one pass with No. 1 MnSi welding rod were used. A mediocre welder was purposely employed.

(*e*) *Notches.* As explained earlier, plates with external notches have a somewhat higher flow limit than plates with internal notches. Their pattern of deformation is actually closer to that of prototype structures and the slightly higher stress level before general yielding is one of the conditions which may enhance fracture. As sheared edges facilitate the initiation of brittle fractures,[46] the notches were made by punching. A rectangular punch was driven through the thickness of the plate and into a suitable die supporting the plate on the opposite side. A complete rectangular hole was punched slightly inside the edge (Figs. 2 and 3*b*) so as to avoid a severe side thrust on the punch, and the continuity of the edge next to the hole was cut by a handsaw. The sides of the notches were at angles of 45 degrees to the edge. The punching did not produce any obvious deformation in the plane of the plate, whose faces were left in the as-rolled condition. In some plates similar notches were machined, and in a few of the laterally prestrained plates the punched notches were deepened by $^1/_2$ and 1 in. by sawing.

(*f*) *Cooling During the Tests.* During testing the plates were covered with a wooden jacket insulated with foam plastic 2 in. thick. The whole jacket was filled with crushed ice mixed with over 30% kitchen salt packed against the plates. Thermocouples were used to record the temperature at various points of the plate, two near the notches and one half-way between them, all 1 in. away from the line of the net section. The temperature over the plate was constant to within 1° F, but from test to test varied from −3 to −12° F.

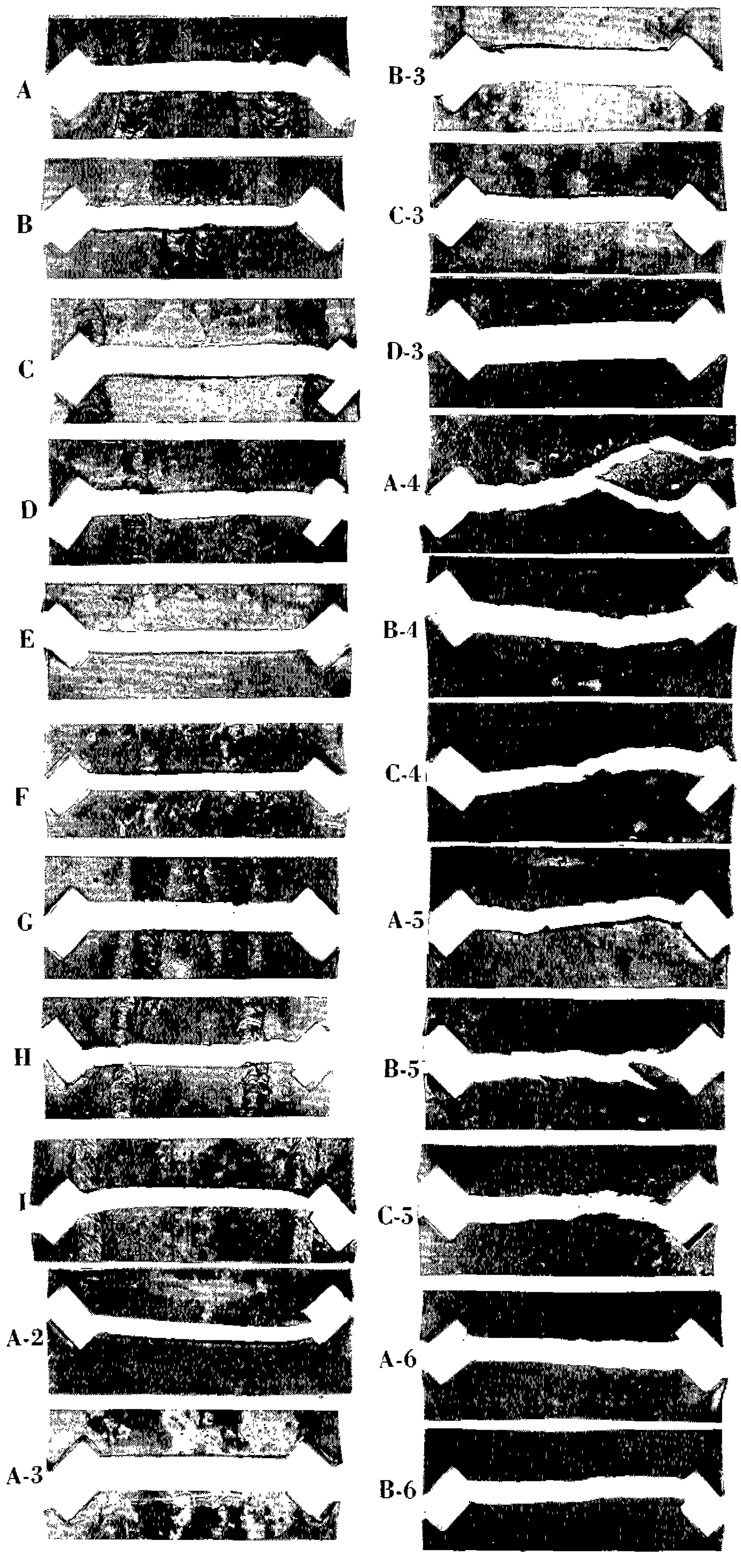


Fig. 9 Fracture profiles. Fractures in general initiate at left end

Table 2—Plates with Longitudinal Prestrain Tested in Direction of Rolling

Virgin yield: ~33,000 psi

Specimen	Prestrain, %	Raised yield point, psi	Nominal stress at failure: Psi	Nominal stress at failure: % of virgin yield	Nominal stress at failure: % of raised yield	°F	Remarks
AA, arc welds	2.3% after welding	46,000	41,800	126.5	91	−10	Struck on edge. Broke in three.
D, gas welds	2.45% after welding	44,000	34,400	104	78	−9	Load held 3–5 min. at each increment.
C, gas welds	2.50% after welding	43,500	28,900	87.5	66.5	−9	
B, gas welds	2.40% before welding	42,100	41,800	126.5	100	−8.5	
A, gas welds	2.45% before welding	42,400	39,600	120	93.5	−9	
E, no welds	0	33,000	35,400	107	..	−11	Failed during load increase without blow.
F, no welds	2.3%	42,400	39,600	120	93.5	−8.5	
G, gas welds	0	33,000	42,300	128	..	−10.5	
H, gas welds	2.5% after welding	43,500	47,000	143	108	−8	
I, arc welds	2.2% after welding	50,700	32,500	98.5	64	−11	
J, gas welds	2.2% after welding	46,000	No failure at 157%			−10	First test unnotched. Retested twice, once after notching and again after cycling 20 times to 52,000 psi.
A-1, arc welds	2.3% before welding	44,000	No failure at 116%			−9	Specimen E-1 after first test was warmed to room temperature and cycled 10 times to 116% of virgin yield and then was retested cold at 110% virgin yield without failure. It was rewarmed and cycled 16 times to 135% of virgin yield and then retested cold at 110% of virgin yield without failure.
B-1, arc welds	2.8% after welding	53,000	No failure at 110%			−9	
D-1, arc welds	2.4% after welding	52,000	46,000	141	88	−10	
C-1, arc welds	2.6% before welding	44,000	No failure at 110%			−12	
E-1, arc welds	2.8% before welding	45,000	No failure at 110%			−9	
F-1, arc welds	2.4% after welding	53,000	No failure at 110%			−9	

NOTE: Plates AA to J as in Fig. 1 with a net section of ~3/4 x 8 in. Plates A-1 to F-1 as in Fig. 2 with a net section of ~3/4 x 7 in. All plates except AA were struck with a 6-lb hammer on middle of face; plate AA was struck on edge. The loading was in increments of 20 kips (~3000 psi) at low loads and 10 kips (~1500 psi) at high loads, except for a few tests with continuous increase of load.

(g) *Loading.* The loading procedure was not always the same. However continuous or incremental loading with longer or shorter pauses or with unloading between increments did not appear to affect the results significantly. The first test plates were hit by a 6-lb hammer normally to their plane a little above their middle to simulate cargo dropping on the deck of a ship. Three blows were given at each load increment but this did not seem to accelerate the fracture. Irrespective of the magnitude of the failure load some plates failed upon impact, others while the load was being increased. The later tests were without any impact, except when the plate did not fail prior to reaching 110% of the yield load.

Test Results

The results obtained from the tension specimens parallel and transverse to straining are given in Table 1. The results of the plate tests are given in Table 2 for longitudinally and in Table 3 for transversely prestrained plates along with details of the test conditions. The fracture profiles are shown in Fig. 9 and the fracture surfaces in Fig. 10. The results of all the tests are plotted in the diagram of Fig. 8.

It is seen that in almost every case the welded plates, whether prestrained initially or finally or not at all, failed at loads well above the flow limit for virgin yield. In addition portions of the fracture surfaces showed substantial plastic deformation as evidenced by some thumbnail and shear lip. With some exceptions the fractures originated at the root of the notch in the welded plates.

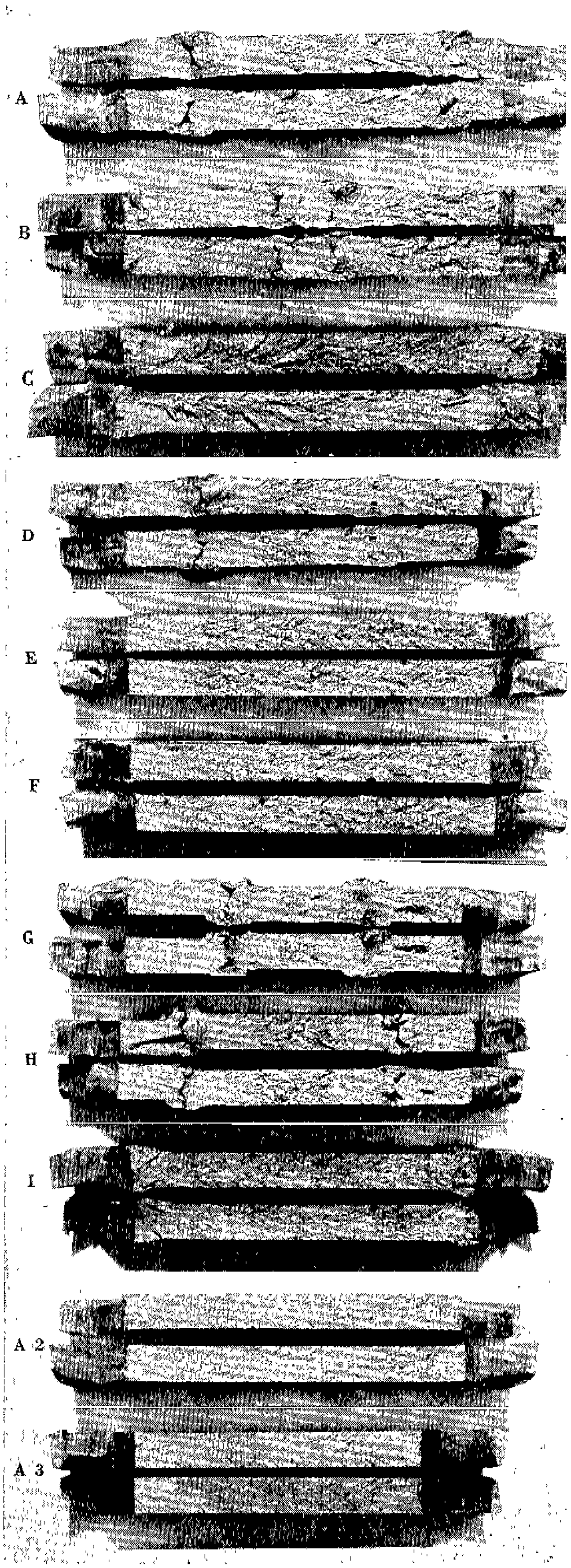
It is noteworthy that in the series of tests shown in Table 2 the nominal failure stress of the unstrained plates was above virgin yield, but of the longitudinally prestrained plates it was generally below the raised yield point, in some instances about two-thirds of that value. Although inconclusive this may raise a question as to the safety of basing the design stress of prestrained metal on the raised yield point.

On the contrary the transversely prestrained plates with punched notches but without welds generally failed at or a little below the load corresponding to virgin yield over the net section. One of the specimens failed at 71.5% and one at 70.2% of average virgin yield, the first at a very moderate blow, the second without any impact at that or any previous load increment. The fractures always started at the root of a notch, and did not have any thumbnail or shear lip.

The transversely prestrained plates with sawcuts at the root of the punched notches did not fail at loads well above the general yield level for virgin yield, not even after hammer blows at this high load. On the other hand, plates without prestrain but with punched notches failed at loads just below virgin yield in the same manner as those with prestrain and punched notches. This raises the question of the relative importance of transverse prestrain and punching, but the number of tests available is not considered sufficient for a clear conclusion. However the important point is that both prestrain and punching result in plastic deformation at the critical area.

Conclusion

The exploratory tests described have been successful in producing many typically brittle fractures at loads corresponding to an average stress smaller than virgin yield. In two cases plates failed at little more than 70% of yield. Not only were the loads lower than yield, but the fractures were also characterized by the absence of visible evidence of appreciable plastic deformation, i.e., of shear lip and thumbnail. They seem to be of the same type as encountered in the catastrophic failure of storage tanks and ships. It is hoped that the more extended program of testing presently under way will furnish conclusions of greater



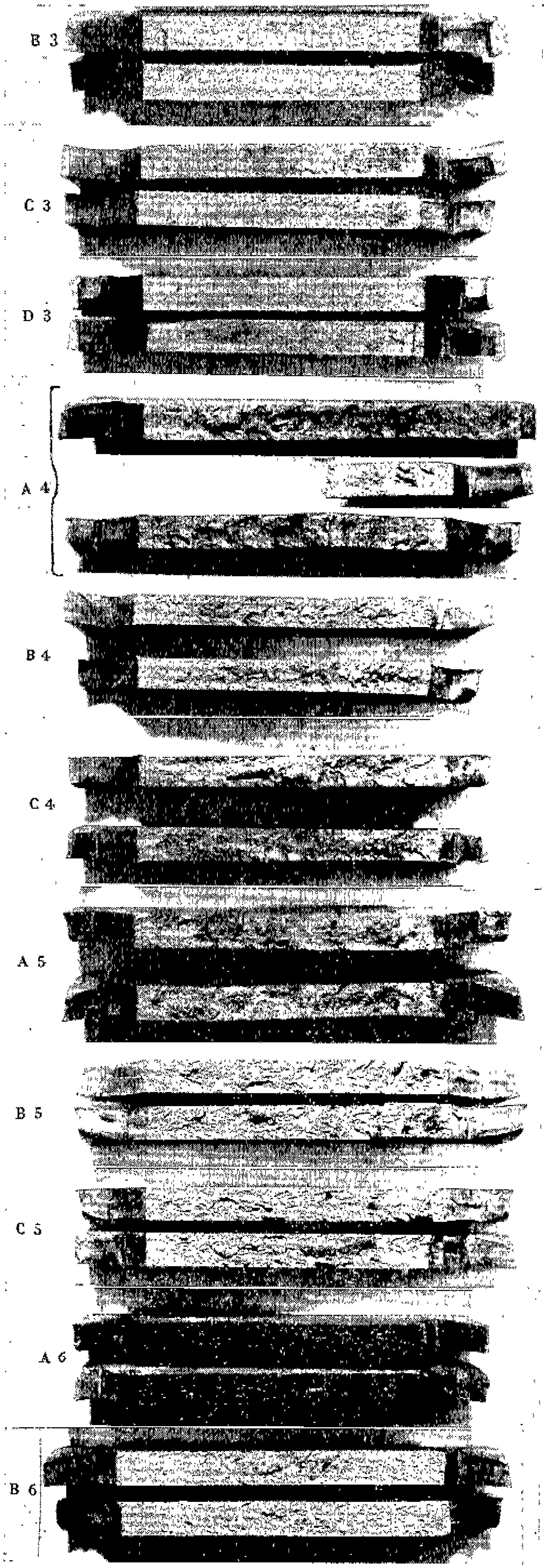


Fig. 10 Fracture surfaces. Fractures in general initiate at left end

Table 3—Plates with Transverse Prestrain Tested in Direction of Rolling (Fig. 3)

Virgin yield ~32,000 psi

Specimen	Transverse prestrain, %	Aging, days	Loading, kips	Stress at failure: Kips	Stress at failure: % of virgin yield	Temperature, °F	Remarks
A-2	2.4	53	100–140, ΔP = 20 150–170, ΔP = 10	33.0	100	−9	A-2 failed without impact.
B-2	2.4	57	100, 120	23.6	71.5	−9	B-2 failed at first blow at failing load.
BB-2	2.4	Rewelded	80–180, ΔP = 10	No failure at 114%		−9	B-2 rewelded
A-3	2.6	2	100–140, ΔP = 10	31.9	96.5	−11	No impact.
D-3	2.6	1/2 hr, at 220° F	100–140, ΔP = 10	30.4	92	−8	No impact.
B-3	2.6	105	80–160 in 7 cycles	34.1	103	−3	B-3 failed at first blow at failing load.
C-3	2.6	107	80–150 in 5 cycles	32.0	97	−3	C-3 failed at second blow.
A-4	4.0	94	1–80, ΔP = 20 80–155, ΔP = 5	30.0	93.9	−12	Punched notches
B-4	4.0	100	4–80, ΔP = 20 80–155, ΔP = 5	30.0	93.9	−7	Punched notches.
C-4	4.0	110	5–80, ΔP = 20 80–150, ΔP = 5	29.1	91	−8	Punched notches.
D-4	4.0	180	(a) 5–80, ΔP = 20 80–155, ΔP = 5 (b) 120–170, ΔP = 5	No failure at	(a) 108% (b) 118%	−5	1/2-in. saw-cuts at bottom of notches. Net section 3/4 x 6 in.
D-4	4.0	187	(a) 5–70, ΔP = 20 80–120, ΔP = 5 (b) 70–100, ΔP = 10 100–140, ΔP = 5	No failure at	(a) 100% (b) 116%	−3	Repeat of spec. D-4. Deepened saw-cuts to 1 in. Net section 3/4 x 5 in.
E-4	4.0	205	(a) 6–70, ΔP = 20 100–125, ΔP = 5 (b) 90–130, ΔP = 5	No failure at	(a) 104% (b) 108%	−3	1-in. saw-cuts at bottom of notch. Net section 3/4 x 5 in.
A-5	6.0	182	20–80, ΔP = 20 80–155, ΔP = 5	29.7	93	−6	Punched notches.
B-5	6.0	189	20–80, ΔP = 20 90–155, ΔP = 5	29.7	93	−8	Punched notches.
C-5	6.0	203	5–80, ΔP = 20 90–118, ΔP = 5	22.4	70.2	−5	Punched notches.
A-6	None	...	5–80, ΔP = 20 90–155, ΔP = 5	29.5	91.9	−7	Punched notches.
B-6	None		5–80, ΔP = 20 90–155, ΔP = 5	29.1	90.7	−5	Punched notches.
D-6	None		5–80, ΔP = 20 then ΔP = 5	No failure at 110% or during retest at 117%		−8	Sawed notches.

NOTE: All plates prepared and notched as in Fig. 3*b*. Net section 0.75 x 7 in. unless otherwise stated. The loading was by increments as shown in the fourth column.

Plates A-2 to C-3 were struck after each load increment. The remark "no impact" refers to the last increment.

The plates with 4% and 6% prestrain and those without prestrain were tested without impact. Impact was used only during the second loading of plates which had not failed under a static load above general yield.

certainty. The present results, however, do seem to confirm the opinion that the concept of exhaustion of ductility at the root of a notch provides the key to an understanding of the initiation of brittle fracture.

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