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STATIC BRITTLE-FRACTURE INITIATION AT NET STRESS 40% OF YIELD

by

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December 29, 1958

Dear Sir:

As part of its research program related to the improvement of hull structures of ships, the Ship Structure Committee is sponsoring an investigation of Brittle Fracture Mechanics at Brown University. Herewith is a copy of the Third Progress Report, SSC-116, of the investigation entitled "Static Brittle-Fracture Initiation at Net Stress 40% of Yield," by C. Mylonas, D. C. Drucker and J. D. Brunton.

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-116

Third Progress Report
of
Project SR-130

to the

SHIP STRUCTURE COMMITTEE

on

STATIC BRITTLE-FRACTURE INITIATION AT NET STRESS 40% OF YIELD

by

C. Mylonas, D. C. Drucker and J. D. Brunton

Brown University
Providence, Rhode Island

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National Academy of Sciences-National Research Council
December 29, 1958

STATIC BRITTLE-FRACTURE INITIATION AT NET STRESS 40% OF YIELD

Brittle fracture of unwelded steel plate is initiated for the first time in the laboratory under controlled conditions at average net stresses well below yield level

BY C. MYLONAS, D. C. DRUCKER AND J. D. BRUNTON

ABSTRACT. Static fractures which are brittle from the start are evidence of lack of ductility at the point of crack initiation and occur at low average net stress. Past static tests, in failing generally to reproduce the phenomenon of brittle-fracture initiation, showed that undamaged steel plate under adverse notch conditions has sufficient ductility to allow general yielding before fracturing. Static initiation of brittle fracture can be achieved by an additional exhaustion of ductility. For this purpose, a steel of high transition temperature was subjected to various types of prestraining. The best results were achieved by precompressing $^3/_4$-in. thick 10-in. square plates with machined notches so as to produce large plastic strains at the notch roots.

When tested in central static tension at a temperature below the transition range, these plates fractured at average net stresses well below yield level. The lowest average stress at fracture was 36% of virgin yield. Thus, for the first time brittle fracture of unwelded steel plate has been initiated in the laboratory under controlled conditions at such low stress. The conditions at fracture indicate that energy theories are useless or inapplicable in the problem of fracture initiation. Finally, residual stresses are shown to be of little importance when ductility is ample. When embrittlement is excessive, they only hasten a fracture which would have occurred at low applied stress in the absence of residual stress.

Introduction

The problem of the brittle fracture of steels which, under the usual favorable circumstances, appear to have sufficient strength and ductility, is far from solved or even clearly understood. Several theories have been proposed on this subject, but all have serious limitations.* Thus, it has been found in practice and confirmed by theory that the severity of a notch enhances the occurrence of brittle fracture. It has also been shown that a statistical correlation exists between the temperature of steel at the time the fracture starts and the empirical standard of brittle transition temperature (especially as defined by energy absorption in the Charpy V-notch impact test). These results have helped select better steels and improve design and fabrication procedures so as to reduce significantly the occurrence of brittle fracture.[3, 4]

Nevertheless, several important points remain to be explained.[1–3] One of them is the equivocal behavior of steel with respect to the initiation of brittle fracture as distinct from its propagation. Experiments,[5–7] as well as actual fractures, have shown that a crack once started will, under suitable conditions, propagate at high speed at nominal stress levels considerably smaller than yield and lower than the nominal stresses present in many successfully operating structures.[1–6] However, contrary to all theories of the Griffith type, centrally loaded symmetrical plates of sound steel, having even the longest and sharpest cracks and temperatures below brittle transition, generally were not found to fracture before the average stress over the net section reached yield level[1–3, 11] and appreciable plastic deformation occurred,[1–3] unless an exceptionally severe impact was produced at the notch[5, 6] or an artificially highly embrittled area facilitated the initiation of cracking.[5, 7]

The conditions of initiation of actual in-service fractures were different, however. The over-all stresses clearly were well below yield in some instances[12] and the evidence is strong that they were low in many of the service failures. Furthermore, as a rule, there is little visible plastic deformation[1–3] in the region of fracture initiation.

The inability of notched plates of sound steel to fracture statically in the laboratory at net average stresses below yield has sometimes led to the opinion that high over-all stresses existed in all structures that failed. The low average net-stress fractures obtained in the tests described in the present paper under conditions not unlike those in actual structures, are sufficient proof that service fractures can and very likely often do start at low over-all stress levels.

The difficulty of initiation as compared to the case of propagation of fracture may be seen as a barrier: once this barrier is overcome, fracture may propagate easily. Fabrication and service conditions responsible for the lowering of this high initiation barrier are incompletely known. Thus, the existing theories can neither explain why brittle fracture had not been initiated at low static average stress nor indicate quantitatively the conditions which would make such initiation possible.

The difference between brittle initiations of fracture and those where general yielding first occurs can be explained easily in terms of the over-all stresses producing them.[1, 2,11] In a symmetrically loaded plate subjected to central static loading, the roots of sharp notches yield at low nominal stress, but the strain in their vicinity remains quite small because it is contained by surrounding material stressed elastically (i.e., with small strains). The neighborhood of the roots develops large strains (more than a few percent) only when the whole section yields. Consequently, fractures which are brittle at the point of origin indicate an inability of the steel at the notch roots to withstand the small plastic deformation demanded from it at low average stress. Conversely, the fracture which initiates when the average stress level is low involves small plastic strains and is of the brittle type from the start. Thus, in an experiment, a low average net stress at fracture, although it is not the cause of fracture, is an obvious criterion for the brittleness of fracture initia-

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* The literature on the subject of brittle fracture is too numerous to be mentioned in detail. General presentations and discussions of the theories are given in references 1 and 2. Reference 3 discusses most of the work presented up to 1954.

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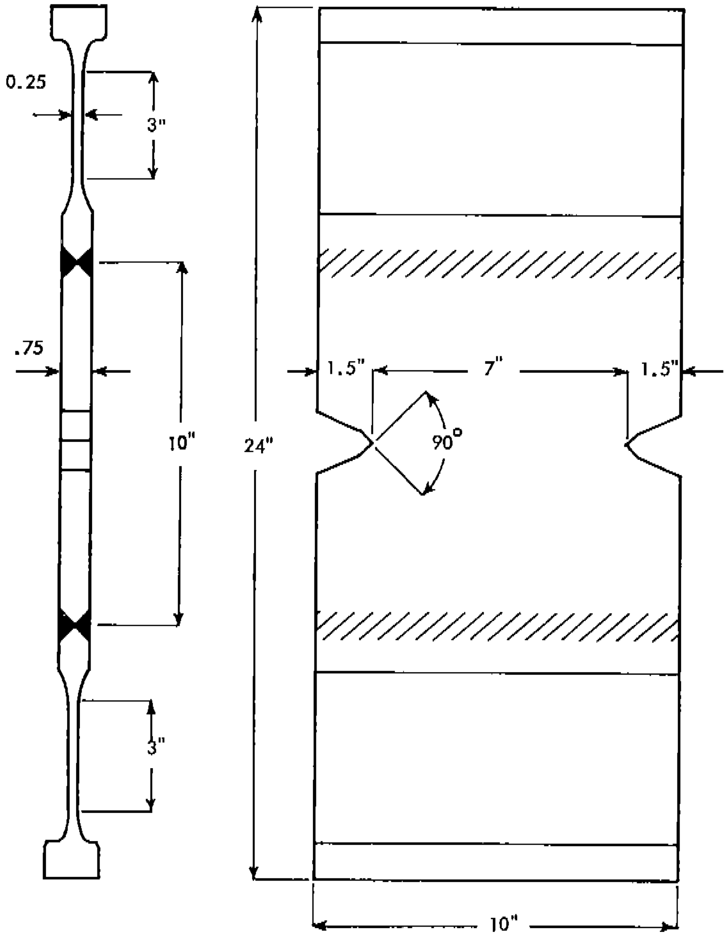

Fig. 1 10-in. test plate with plastic hinges

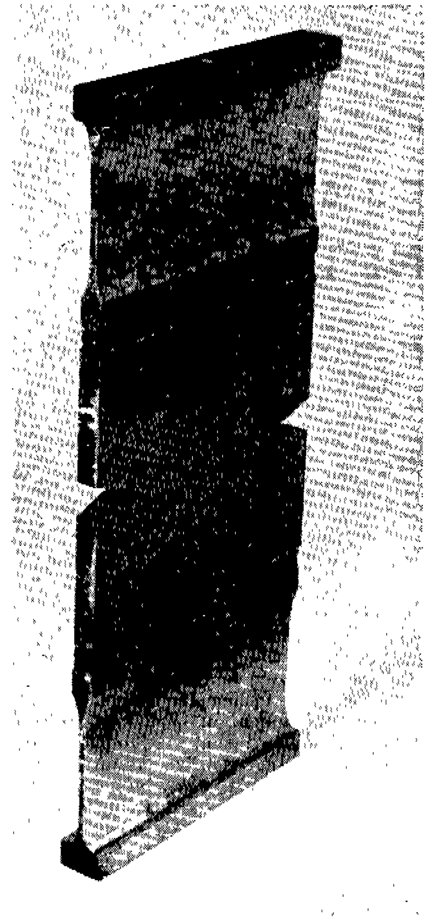

Fig. 2 Test plate showing plastic hinges

tion. Experiments where general yielding (i.e., net average stress of yield level) precedes fracture cannot help to explain or to understand the phenomenon of brittle-fracture initiation, because they do not correspond to the brittle in-service initiations of fracture they are supposed to simulate.

The object of the tests described in the present paper was to initiate fractures at low average static stress under controlled conditions and so permit study of the problem. According to the previous discussion, fracture initiation at low average static stress may be achieved with steel lacking the small amount of ductility required at the notch roots at low average stresses. But even poor but undamaged steels with the most severe stress raisers or constraints were found to exhibit sufficient ductility so as to break only at central static loads of yield level. It must be concluded that brittle-fracture initiation will be enhanced and the initiation barrier will be lowered under conditions which produce fracture at smaller strains, hence in general have the effect of a reduction or *"exhaustion" of ductility* in the region of fracture initiation.

Recent work of considerable importance has thrown new light on the problem of fracture. It shows the possibility that brittle-fracture initiation depends on the development of a critical stress several times larger than the static yield stress just below the root of a notch or crack, and that this may be achieved at very high stress rates in combination with low temperatures. This work is in full agreement with the opinion of the present and earlier papers,[1,2] that independently of the true cause of fracture, its "brittleness" or "ductility" can be judged by the average net stress criterion. However, this work does not seem to explain the cause of initiation of "brittle" fractures in plates under *static loading* and at moderately low temperatures, since even with the greater constraints of a round bar with a deep circumferential groove, fractures could not be produced at a temperature of −110° F with rates of nominal net stress application lower than about 3×10^6 psi/sec, and at a temperature of −25° F with even the highest applied stress rate of 1.5×10^7 psi/sec. To explain such fractures one must still consider conditions which will make possible the initiation of fracture at smaller overall strains.

The factors reducing the ductility have been extensively studied,[3,4] mainly by the amount they raise the empirical standard of brittle-transition temperature. None of them generally had been sufficient to initiate laboratory fractures at low net average stress, at least not when present in the amounts which are accepted as existing in actual structures and which have been found to raise the brittle-transition temperature well beyond the dangerous levels. Such factors are an originally high transition temperature of the virgin steel plate, welds, notches, sheared or punched edges,[17] prestrain and test temperatures below brittle transition. The effect of residual stresses is not certain, but as discussed later appears to be small. In particular, since no static test using undamaged steel had achieved low-stress fractures, it was felt that some factors acting during construction or service might produce sufficient additional embrittlement or reduction of ductility so as to permit low-stress fracture initiation. Welding, sheared edges, and the several possible types of prestraining were good possibilities. Prestraining seemed an important but insufficiently explored factor. It can greatly embrittle steel but follows unknown complicated path-dependent and temperature-dependent anisotropic laws of strain hardening. In the present tests, all these factors were used singly or in combination in an effort to achieve the greatest exhaustion of ductility but, in general, without severely exceeding the conditions encountered in past or present construction practice or service. Once success was achieved, the conditions were changed to correspond better to possible conditions in actual structures.

Table 1—Composition and Properties of "E" Stee.

C, %	0.29
Mn, %	0.39
P, %	0.017
S, %	0.035
Si, %	0.025
Lower yield point (according to parent plate), psi	33,000–30,000
Ultimate strength, psi	61,000
Elongation, over 2 in., %	36.5
Impact energy (Charpy V-notch), ft-lb	
−10° F	3
0° F	3.5
10° F	4.0
20° F	5.5
32° F	7.5

Description of the Tests

Steel

A $^3/_4$-in. pedigree rimmed project steel "E," of high brittle-transition range was used in all tests. Its typical composition and properties were as shown in Table 1.

The mechanical properties in the parallel and transverse directions to rolling did not differ significantly.

Plates with Compressive Prestrain

Most of the tests reported in this paper were made on $^3/_4$-in. thick, 10-in. square plates machine notched (except for the first 5 which were punch notched) on the sides parallel to the direction of rolling and welded to plastically yielding steel hinges for testing in tension (Figs. 1 and 2). Before welding, the notched plates were subjected to various amounts of prestrain in compression in the rolling direction. The compressive deformation was measured over a length 2 in. across the notch on the plate edge and over 1 in. at the notch root on the plate faces (Fig. 8). Buckling was prevented by two $1^1/_4$-in. thick plates supporting the compressed plate, one against each face. Friction was reduced by lubrication. Strain aging was minimized by keeping the plates at −25° F in a special freezer up to the time of testing, except for a period not exceeding a day needed for welding on the hinges and covering the test plate with 2-in. thick foam-plastic insulation. The test results of all plates with compressive prestrain are given in Table 2 (10-in. wide plates).

Testing

The insulated plates were taken directly from the freezer to the testing machine, and they were pulled some ten minutes later when the temperature had risen to about −5 to −10° F, which is below the lower end of the transition

Table 2 Brittle-Fracture Tests of 10-In. Wide Plates Prestrained in Compression after Notching

Plate	Group	Average compression* across notch (10^{-3} in.): 2 in. on edge	Average compression* across notch (10^{-3} in.): 1 in. on face	Average net compressive stress, psi	Test temperature, ° F	Average net tension, Max. applied§: Psi	Average net tension, Max. applied§: % of virgin yield	Virgin yield	Average net tension, At significant crack, % of virgin yield: 1st	Average net tension, At significant crack, % of virgin yield: 2nd	Obvious thumbnail
A10	Punched	None	...	...	−9	23,100	77		...	...	...
B10		None	...	...	−7	25,800	87		...	...	...
E10		30	...	34,800	−8	19,100	64		...	...	...
F10		40	...	36,800	−7	16,500	55		...	...	...
G10		40	...	35,700	−9	17,700	58		...	...	...
H10	Machined notches	70, over 4"	...	36,000	−9	22,700	76		...	...	...
I10		Buckled	...	30,000	−7	>33,000	>110		...	...	...
J10		70, over 4"	...	36,400	−11	31,200	104		...	...	...
C10		None	...	...	−7	>33,000	>110	Virgin yield 30,000 psi	...	...	...
D10		None	...	...	−9	>33,000	>110		...	...	...
13A		50–67	31–35	35,600	−12	17,400	58		...	...	...
13B		61–50	33–34	36,500	−1	21,000	70		45	...	...
13C		11-8	15–13	31,600	−8	>32,100	>107		...	...	...
13D		24-6	19–9	34,800	−6	31,200	104		...	...	...
13E		38–27	22–17	36,100	−10	18,900	63		39†	...	...
13F		33–26	23–21	35,200	−10	17,400	58		...	...	...
13G		13–8	13–8	33,400	−8	>31,200	>104		...	...	...
13H		35–30	21–19	35,600	−9	26,400	88		38	...	$^3/_4$
13I		51–44	17–17	35,600	−8	>31,200	>104		48	...	...
13J		40–38	14–13	35,400	−5	30,600	102		...	...	...
13K		35–36	9–11	35,400	−11	27,600	92		...	...	...
13L		35–33	11–9	35,400	−11	>31,200	>104		...	...	...
14A		30–26	19–19	35,600	−10	>31,200	>95		36	...	...
14B		30–36	20–20	35,600	−13	15,300	46		...	...	...
14C		28–26	21–21	36,200	−7	31,200	95		...	....	...
14D		27–29	22–21	36,200	−10	26,400	80	33,000 psi	22†	..	$1^1/_4$
14E		14–13	8–8	34,300	−10	>31,200	>95		...	...	...
14F		52–48	30–28	38,000	−4	30,300	92		15	29†	...
14G		33–34	19–20	35,200	−8	20,000	61		15	29†	$2^1/_2$
14H		61–61	32–36	38,100	−4	12,000	36		14	...	...
14I		35–36	21–22	36,000	−2	27,900	85		14	...	1
14J		52–50	32–34	38,100	−3	18,600	56		15	...	...
14K		Welded at notch roots			−11	>31,800	>96		...	...	...
14L		Welded at notch roots			−10	>31,800	>96		...	...	...
14M		73–60	39–36	38,100	−9	14,400	44		12	39†	$3^1/_4$

* First number for side of crack initiation.
† Louder noise.
§ Stress at fracture unless preceded by >, signifying that no fracture occurred.

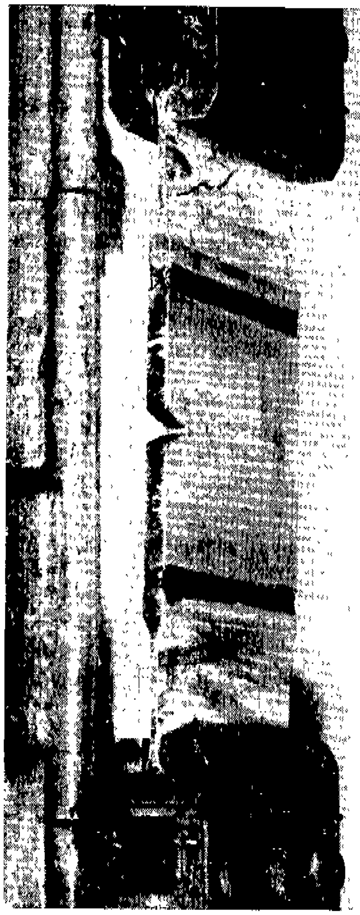

Fig. 3 Plate in testing machine showing plastic hinges and dovetailing T-heads

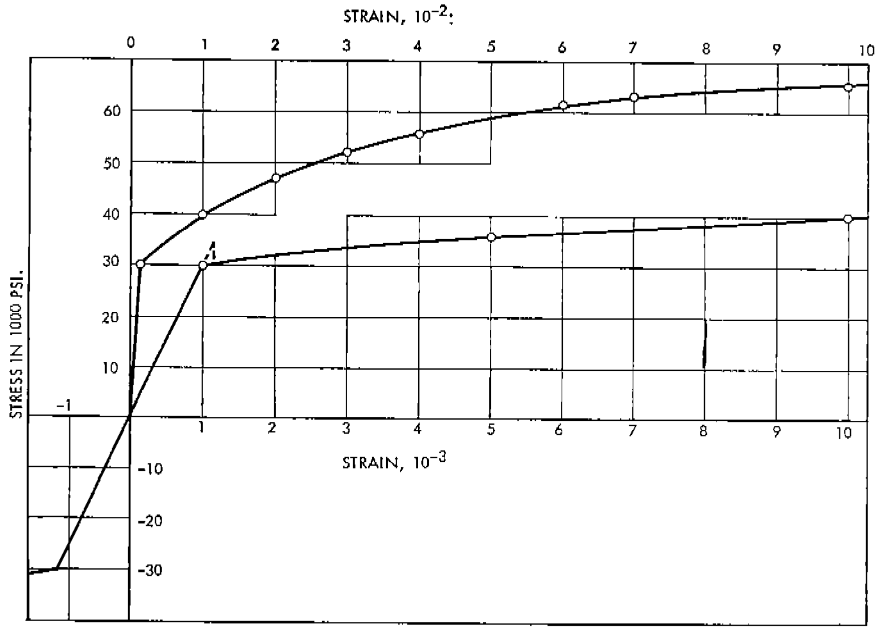

Fig. 4 Stress-strain diagram of hinge steel

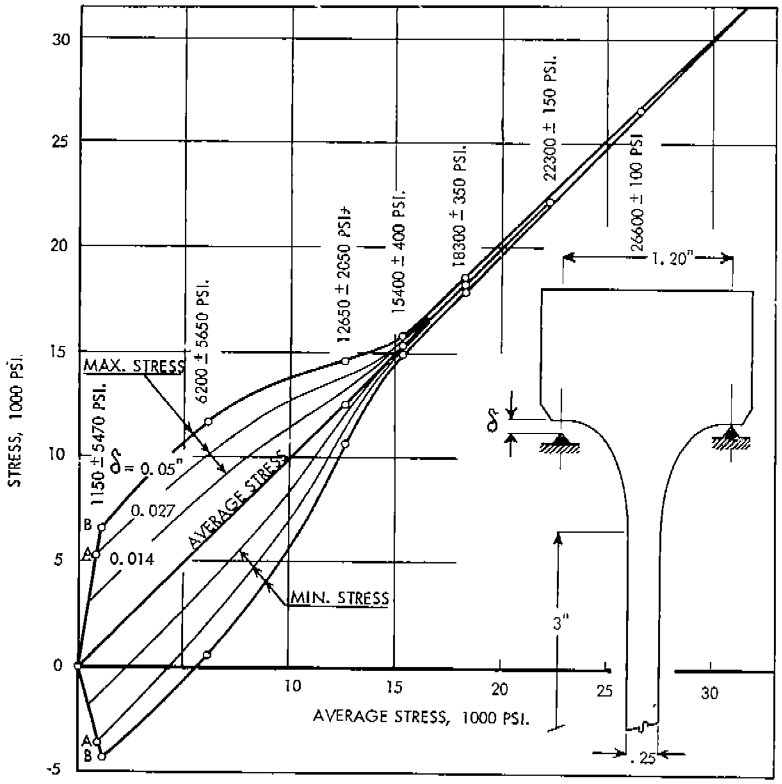

Fig. 5 Extreme vs. average stress in test plate showing the plastic hinge action

range (Table 1). The temperature was checked to differ by not more than 1° F over the significant test area. The loading was continuous at a speed of about 50,000 lb/minute, so that general yield was reached in about 3 minutes if the plate did not fail earlier.

Plastic Hinges

The T-heads of the plastic hinges dovetailed into special pulling heads (Fig. 3) which were held in the jaws of a 400,000-lb testing machine. The upper pulling head was put in place first, and the lower pulling head was clamped in the machine jaws as it was hanging in place from the test plate and upper pulling head. This helped minimize the in-plane eccentricity of loading. The out-of-plane eccentricity was reduced and gradually eliminated with increasing load by the yielding of the hinges. These were made of a steel (0.16-0.26 C; 0.60–1.00 Mn; max. 0.04 P; max 0.05 S; 0.15–0.30 Si; made to fine grain specifications), with a continuously sloping yield curve (no flat yield) and an ultimate strength about twice the lower yield point, so that the "hinge" worked over the greatest possible range of loads. The stress-strain curve is given in Fig. 4. The calculated effectiveness of the plastic hinges in centering the load is shown in the graphs (Fig. 5) of the extreme stresses over the net section of the test plate (without considering the stress concentration due to the notches) plotted against the average net stress. The graphs were calculated for the T-head initially touching on the one side (Fig. 5) and tilted so as to leave a gap of $^1/_{20}$ of an inch on the other side, which is several times more than actually observed. The calculations only involve the determination of the stresses in an eccentrically loaded wide beam subjected to prescribed strains and made of a material strain-hardening according to the curve of Fig. 4. The region *OA* corresponds to loads producing only elastic bending in the hinges; *AB* to plastic bending of the hinges up to the moment when both sides of the T-head are touching; and from *B* onward to increasing extension of the hinge without additional bending. It may be seen that the eccentricity existing at low loads is quickly wiped out as the hinges yield. At about 40% of average net yield the extreme stresses differ by

Table 3—Brittle-Fracture Tests of Plates Prestrained in Tension Transversely to the Direction of Testing

	Plate	Prestrain, %	Prestrain, Direction relative to rolling	Temperature, ° F	Max. applied net average tension: Direction relative to rolling	Max. applied net average tension: Psi	Max. applied net average tension: % of Virgin yield	Type of notch	Impacts at fracture load	
Welded to pulling heads (W)	A2	2.4	‖	−9	⊥	33,000	103 (Virgin yield 33,000psi)	Punched notches	None	6-lb hammer blows at various loads
	B2	2.4	‖	−9	⊥	23,600	72		One	
	A3	2.6	‖	−11	⊥	31,900	97		None	
	B3			−3	⊥	34,100	103		One	
	C3			−3	⊥	32,000	97		Two	
	D3			−8	⊥	30,400	92		None	
Plastic hinges welded to pulling heads (HW)	A4	4.0	⊥	−12	‖	30,000	94 (Virgin yield 32,000 psi)		No hammer blows at any load	
	B4			−7	‖	30,000	94			
	C4			−8	‖	29,000	91			
	D4			−5	‖	>34,500	>108	Saw cuts		
	E4			−3	‖	>33,400	>104	Saw cuts		
	A5	6.0	⊥	−6	‖	29,700	93	Punched notches		
	B5			−8	‖	29,700	93			
HD	C5			−5	‖	22,400	70			
HD	D5			−6	‖	29,200	91			
	E5			−9	‖	25,700	80			
HW	A6	None		−7	‖	29,500	92			
HW	B6			−5	‖	29,100	91			
HW	E6			−7	⊥	27,600	86			
Plastic hinges dovetailing in pulling heads (HD)	F6			−8	⊥	30,500	95			
	G6			−4	⊥	33,600	105			
	C6			−9	‖	>37,000	>116	Machined		Cold worked at notch roots
	I6			−6	⊥	>32,000	>100	Machined		
	D6			−8	‖	>35,200	>110	Sawed		
	H6			−7	⊥	>32,000	>100	Saw cuts		
	A7	1.0	⊥		‖	29,000	91	Punched notches		
	B7				‖	24,200	76			
	C7				‖	27,600	86			

±16% (±6.4% of yield) from the average stress, and at about 50% of yield by ±2.5% (±1.25% of yield). When the initial tilt of the T-head is smaller, the stress differential practically vanishes at even smaller average stress. Curves are given for a mismatch δ of 0.05, 0.027 and 0.014 in.

Plates with Transverse Tensile Prestrain

An earlier series of tests, partially described in Reference 2, was extended and completed. It contains plates prestrained in tension as in Fig. 6a and then cut up in 10-in. squares, notched on the sides perpendicular to the direction of prestrain, and welded to pulling heads as in Fig. 6b so as to be tested transversely to the prestrain. Early in the series, plastic hinges were welded between plate and pulling heads, and later the hinges were made as in Figs. 1 and 2, dovetailing in the pulling heads. Some plates were prestrained in the direction of rolling, others at right angles to it.* The notches were punched, machined or sawed. In some of the tests, the plates were hit with a 6-lb hammer at various loads. However, this practice obscured the results of these tests without reducing the fracture load and was discontinued.

Standard tension specimens and Charpy V-notch specimens were made of plate material prestrained in tension. The tension tests showed[2] that the yield point is raised considerably in the direction of the prestrain, and that the yield strength is not lowered in the transverse direction. In fact, generally the 0.0005, 0.001 and 0.002 offset values are all equal or higher than virgin yield. The effect of prestrain on the Charpy V-notch brittle-transition temperature is shown in Fig. 7. The whole transition range is seen to be raised some 15° F by 1% prestrain and 25° F by 2% prestrain in tension. The direction of the specimen relative to the prestrain did not appear to be significant. These results agree with earlier tests on similar steels.[4]

Test Results

The results of the precompressed plates described in Section 2b are given in Table 2 and in the corresponding graphs of Fig. 8. As may be seen, the prestraining of notched plates in compression does embrittle them, since most fracture at an average stress over the net section considerably lower than virgin yield. Actually, failures have been recorded down to 36% of virgin yield. But even more than that, significant cracking noises have been heard much before complete fracture, at loads down to 12% of yield, and, in about half the cases, a thumbnail appeared on the fracture surface at depths between 1 and $3^1/_4$ in. from the notch root. Similar plate tests showed arrested cracks which developed at about 10 to 40% of virgin yield, but the plates themselves did not fail when loaded up to 90–95% of virgin yield. Thus, not only have brittle fractures been initiated at very low average net stress, but it is obvious that the cause of fracture lay in the prestrained region which was unable to yield by the small amount demanded by the elastically strained areas of relatively small stress surrounding the notch region. The concept of want or exhaustion of ductility is clearly exemplified. This is particularly well shown by the

* C. E. Turner of the Imperial College, London, pointed out a discrepancy in Reference 2 which led the authors to scrutinize the experimental data and to find that in Table 3 of that paper plates A-4 to D-6 should have been reported as prestrained in the direction of rolling and tested transversely to it. Plates A-2 to B-3 were correctly reported. The complete series of these tests, including the new results, is given in Table 3 of the present paper.

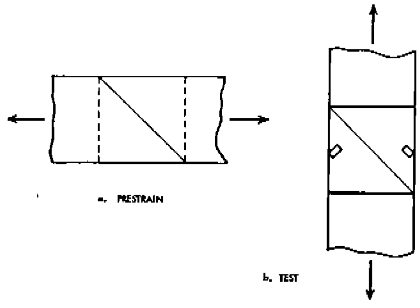

Fig. 6 Welded plates with prestrain transverse to the direction of testing

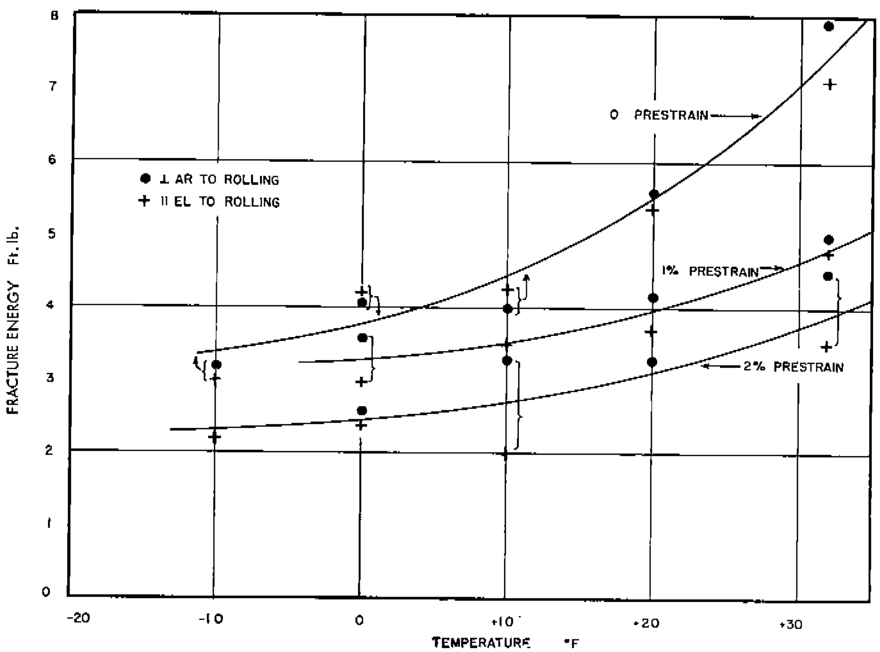

Fig. 7 Charpy-notch impact tests of steel prestrained in tension

cracks which were initiated at very low stress and were arrested at some distance from the highly prestrained tip, and by the inability of the remaining unstrained net section to fracture at loads producing general yielding. This low-stress fracture at a small depth of notch and the inability to fracture at high stress at the greater depth of notch plus arrested crack, and even more the arrest of a running crack of the highest possible sharpness at a length greater than when it started, raise serious questions as to the usefulness and perhaps even the applicability of energy theories of fracture in the problem of fracture initiation. It will be recalled that they predict an average fracture stress inversely proportional to the square root of the notch length.

The plates prestrained transversely to the direction of testing and then punch-notched failed systematically at average net stress below virgin yield but not as low as the precompressed plates. The lowest value was 70% of virgin yield (Fig. 9). The punching was chosen as a very severe punishment of the steel, known to induce fractures at average stress of yield level.[17] However, punching is not the sole cause of low-stress fractures. This is indicated by the plates with punched notches but no prestrain which always failed at higher average stress than the plates with prestrain. In addition, all the longitudinally prestrained plates described in Reference 2 failed well above virgin yield (but well below the raised yield) in spite of having punched notches. The influence of the combination of transverse prestrain and punching is clear.

Residual Stresses

The compressive prestrain of already notched plates produces yielding at the notch roots, and upon removal of the load obviously leaves the region of fracture initiation with appreciable residual stresses. These stresses are often considered to add to the externally applied stresses to produce early fracture. A discussion of their effect seems appropriate. Earlier investigators[3] have concluded that the residual stresses in the vicinity of a weld in a plate do not have a significant influence on brittle fracture, and also that they can be reduced considerably by low-temperature stress-relief procedures. However, other tests of wide plates of high transition-temperature steel with long welds and with notches made before welding and extending into the regions affected by the heat of welding, produced low-average-stress fractures, and even some spontaneous cracking over short distances beyond the notch roots.[8, 9, 10, 12] Several stress-relieving methods were recently tried on similar plates.[13] Low-temperature tests in tension parallel to the weld showed that the unrelieved plates fractured at low stress, but plates annealed above the transformation temperature, or stretched in the direction of the weld at a temperature above brittle transition, or (with slightly less success) plates stress relieved at low temperature, fractured only when the average net stress reached yield values. Since brittle fractures occurred in the presence of initial tensile stresses, but not after their removal, these tests were presented as proof of the importance of initial stresses in brittle fracture. However, earlier tests indicate that the conditions governing brittle fracture may be more complicated. Thus, tests[14] of a nature similar to those just described but with the notch made after welding did not lead to low-stress fractures, although the plates must have had high residual welding stresses, reaching and perhaps exceeding yield point at the notch roots. These tests were considered as proof of the unimportance of residual stresses in brittle fracture. The explanation of the low-stress fractures of the prenotched welded plates is that a very high straining[15] occurs at the roots of the notches during the cooling of the weld. In effect, the heat-affected zones without notches are strained by something of the order of 1%. In the presence of notches, extremely high local strains will occur and will exhaust the ductility at the most dangerous areas. On the contrary, the cooling of the unnotched weld area produces a uniform permanent strain but with residual stresses of yield level. Upon notching at room temperature, the plastic deformation of the notch roots will be much less than with prenotched plates, although residual stresses of yield level will remain at the notch area. The efficacy of the stress relief at a temperature above transformation is not surprising since it restores the ductility of prestrained steel. The results obtained by prestraining in tension at temperatures above transition indicate the importance of the strain history of the material. Similar results were obtained earlier by prestraining notched plates.[16] In the tests described in Reference 2 tensile prestrain was similarly found to increase the fracture stress even above general virgin yield, but not above the raised yield strength.

Since some amount of yielding usually precedes brittle fracture and, in essence, wipes out any pre-existing residual stresses, these cannot in general have an important influence in brittle fracture. Thus, one may assume a plate of those failing at low average stresses, say 50% of virgin yield, with high residual tensile stresses at the notches. At 30 or 40% of virgin yield the plate is still unbroken, but yielding has certainly occurred at the notch roots since the elastic factor of stress concentration is very high. If at this point the loading is stopped and reduced to a small value, the residual tension at the notch roots will be found to have disappeared and perhaps even be changed into a small amount of compression. If the unloading does not produce yielding in compression (and a load may be left on to ensure this), it does not in any way affect the plate which, upon reloading, should fail at the same low load as if the loading had been continuous. Yet, the plate of interrupted loading may be free of initial stresses or even have residual stress of reversed sign. The only effect of the initial residual tension is to increase slightly the plastic deformation preceding fracture at the root of the notch, but this strain must be a little larger yet still of the order of the elastic strain at the limit of elasticity. Usually, the plastic strains preceding brittle fracture are many times larger, so that the small importance of residual stresses is obvious. However, the residual stress may have an influence when the ductility at the notch roots is so highly exhausted and the material is so brittle that it cannot withstand plastic strains of the order of 0.001 in. Then even "spontaneous" fractures could be expected over regions with residual tension of yield intensity. This is what probably happened in the tests mentioned earlier. It is obvious, however, that the real cause of fracture is the very low steel ductility at the test temperature and not the residual stresses, since, even if free of residual stresses, these plates should have fractured at very low loads (such as the arrested cracks at about 10% of virgin yield mentioned in Paragraph 3). In fact, fracture should occur at an average stress which, multiplied by the very high elastic factor of stress concentration, would give yield stress at the notch. However, the visible signs of small amounts of plasticity in actual brittle failures seem to indicate that such high exhaustion of ductility is not usual. It thus appears that in the usual circumstances the residual stresses should be of small importance, but even when they have an influence this is only to hasten a fracture initiation which should anyway happen at a low load. The importance of the *small average net applied-stress criterion* of brittleness of fracture remains valid even in the presence of initial stresses.

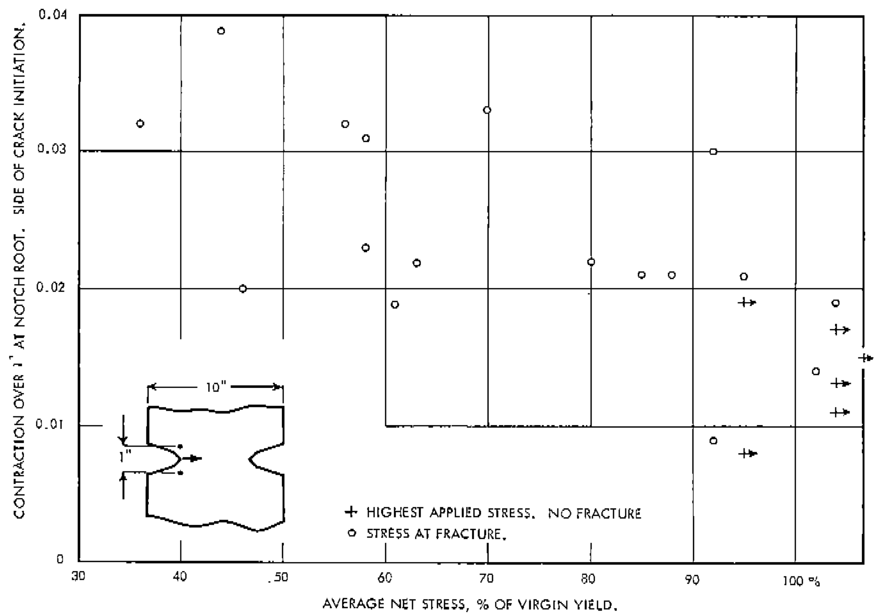

Fig. 8 Brittle-fracture results of longitudinally precompressed plates

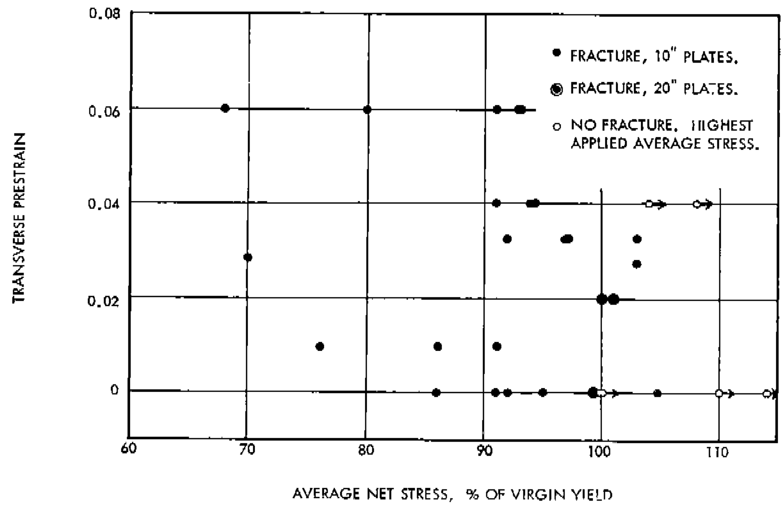

Fig. 9 Brittle-fracture results of transversely prestrained plates

Conclusion

Static initiation of brittle fracture at low average net stress requires a great reduction of the usual ductility of steel. The criterion of brittleness of fracture initiation, whether with or without residual stresses, is a low average net stress at fracture. Such exhaustion of ductility is easily achieved by compressive prestrain. In this way, typically brittle fractures have been achieved at static average net stress even smaller than 40% of virgin yield and arrested cracks at 10%. A discussion of the plastic strains at the notch roots shows that the residual stresses should not be of great importance. The strain history at the notches appears as a factor of great significance.

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