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Crack Initiation in Flat Plate Tests and its Dependence on Structural Size and Tensile Properties

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SUMMARY

This paper presents experimental fracture data obtained on test plates, with through thickness transverse cracks, subjected to uniformly distributed applied loads. The test plates, which were all 25mm thick, ranged in size from 790 mm x 813mm to 790mm x 2030mm. The materials tested were 0.2%C, 0.36%C steels and type 316 stainless steel. Tests on this latter steel were carried out in the as-received and stress-relieved condition.

Considering planes drawn from a crack tip to a plate boundary because of this particular loading technique, it is possible to calculate the average value of the shear stresses that act along such a plane. For a particular plane the average value of the shear stress will have a maximum value, and it is shown that, for these test plates, crack initiation occurs when this maximum average value of shear stress becomes equal to $\sigma_y/\sqrt{3}$, the von Mises yield criterion.

INTRODUCTION

In a previous paper the three modes by which a through thickness defect, located in a flat plate subject to a monotonically applied load acting perpendicularly to the direction of the defect, can propagate were discussed.(1) These modes are, fast propagation, slow stable growth characterised by the requirement that an increasing load is required for continued crack propagation, and a "pop-in" mode in which the defect increases in length in a series of discreet jumps, again under increasing load. It was suggested(2) that the latter two modes would be influenced by the method by which the load was applied to the test plate, and also by deformation-induced bending moments which would either reduce or augment the σ_{yy} stresses acting normally at the crack tip.

The supporting experimental work, most of which provided strain gauge derived stresses in flat plates subject to uniformly distributed applied loading, has been extended to cover differing plate sizes and materials. This additional test data has enabled an investigation to be made into the parameters that control crack initiation, that is, the onset of slow stable crack growth.

EXPERIMENTAL METHOD

The test plate assembly and loading method used for this series of tests is shown schematically in Fig 1 and is described in Ref 3. It will be noted that the vertical slots which divide the loading flanges into sections ensure that no horizontal loads are applied to test plate as would be the case if the loading flanges were thick and continuous. In this latter loading method the vertical stresses in the test plate would be greater than the vertical stresses in the much thicker loading flange. Thus an incompatibility would arise between the Poisson contraction requirements of the plate and flange, with the result that a horizontal force would be applied by the flange to the plate. The slots also ensure that by removal of the flange rigidity, the application of an applied load is achieved even in the presence of a large defect.

Slow stable crack growth has been investigated on several materials with various plate and crack sizes, the experimental data being given in Table I where it will be seen that plate sizes ranged from 790 mm high x 813 mm wide to 790 mm high x 2030 mm wide. All plates, with the exception of the edge cracked plate, were 25 mm thick, the edge cracked plate being 21 mm thick.

The materials used were 0.2%C steel, 0.36%C steel, and type 316 stainless steel. Test plates of this latter material included, for comparison, as-received and stress relieved plates, as received and plain plates containing transverse welds, one plate with a "T" weld, that is a transverse weld with a vertical weld abutting it, and one plate with a simulated major weld repair, this test series being reported in Ref 4.

All the test plates had a through thickness central crack with the exception of plate MSTP1 which had a through thickness edge crack.

In all the tests, except the two carbon steel test plates, the crack tip was prepared using a 0.15 mm thick jeweller's saw. For the two carbon steel plates, spark erosion using a 0.10 mm wire was employed to produce a 0.15 mm wide slit at the crack tip.

In the earlier tests crack initiation was observed visually through TV monitors, on crack initiation being observed, the load was reduced to zero, this action producing a chevron mark on the crack surface for post test confirmation of the crack size at which visual initiation was detected. For the later stainless steel tests an electric potential drop technique was used in addition to the visual plus chevron marking method.

Photographs of a crack tip, pre-initiation and post-initiation are shown in Fig 4. These show the blunting of the crack tip prior to initiation and the marked difference between the pre and post initiation forms of the crack tip.

CRITERION FOR CRACK INITIATION

A comparison of the pre initiation and post initiation appearance of the crack tip as shown in Fig 4 indicates that, for a very small increase in the applied stress, a marked structural change has occurred. Thus the crack surface changes from concave in the pre initiation stage to convex after initiation. From these observations it might be hypothesized that crack initiation is influenced by a structural parameter coupled with the material tensile properties.

Clearly the test data could be used to test various hypotheses but only one will be presented here and this is "that crack initiation in centrally defected flat plates subject to a uniformly distributed loading occurs when the average value of shear stress on a particular plane from the crack tip to a plate boundary, which is a maximum of the values for all such planes, becomes equal to the shear yield stress as defined by the von Mises criterion".

THEORY

Consider, first, the equilibrium of the segment ABCD of the test plate shown in Fig 2. The following forces act:

a) along DC a uniform vertical stress σ_g is applied. There is no horizontal loading;

b) on DA, the vertical centre line, because of symmetry no shear stresses act along DA. A stress system normal to DA exists such that the stresses toward D are tensile and compressive toward A. However the net tensile and compressive stresses are in load balance, that is the horizontal resolved forces acting on DA are zero. This is because BE is also a line of symmetry and therefore no shear stresses exist on BE, and since for the quadrant AEFD no horizontal forces act on the faces BE, EF or FD, therefore the net horizontal force on DA must be zero; However the tensile and compressive distribution of normal stresses on DA will generate a bending moment;

c) on BC the shear stress are averaged to give the mean shear stress q and similarly the normal stresses are averaged to give the mean normal stress, σ_n

Thus for the segment ABCD and considering unit thickness horizontal equilibrium requires that:

$$\sigma_n . BC . \cos\theta = q . BC \sin\theta \quad (1)$$

and vertical equilibrium requires $\sigma_n . BC . \sin\theta + q . BC \cos\theta = \sigma_g . DC$ (2)

hence
$$\sigma_g (a + h \tan\theta) = q . h . \sec^2\theta \quad (3)$$

where 2a = crack length, and 2h = plate height, AD.

Differentiating, $\frac{dq}{d\theta} = 0$ gives the angle of the plane on which the average shear stress has a maximum value. Let this value of θ be θ_1 and the maximum value of q be q_{max}.

Hence
$$\theta_1 = \frac{1}{2} \tan^{-1} \frac{h}{a} \quad (4)$$

and from eqn 3,
$$\sigma_g = 2 q_{max} \tan\theta_1 \quad (5)$$

or
$$\frac{\sigma_g}{2 q_{max}} = \left(\sqrt{\left(\frac{a}{h}\right)^2 + 1} - \frac{a}{h} \right) \quad (6)$$

Summarising, for a test plate such that point C lies on the top edge of the test plate, eqn 4 gives the angle defining the plane along which the average shear stress has a maximum value, q_{max}, and either of eqns 5 or 6 defines the relation between q_{max} and the applied stress σ_g.

Consider, now, the equilibrium of the plate segment ABCFD, as shown in Fig 3, where in this case the plane along which the maximum average shear stress acts intersects the vertical edge at C of the plate.

Here vertical equilibrium requires that

$$\sigma_g W = q(W-a)\cot\theta + \sigma_n (W-a) \tag{7}$$

and horizontal equilibrium requires that

$$\sigma_n = q \tan\theta \tag{8}$$

hence

$$\sigma_g W \sin 2\theta = 2q(W-a) \tag{9}$$

differentiating, $dq/d\theta = 0$ gives the maximum average shear stress q_{max} and this occurs when $\theta = 45°$

and from eqn (9)

$$q_{max} = \frac{\sigma_g W}{2(W-a)} \tag{10}$$

It should be noted that it is because of this particular method of applying the load to the specimen that it is possible to perform this method of analysis. If the loading technique had applied either unquantifiable horizontal forces along the plate boundary or a nonuniformly distributed load, of unknown distribution, then it would not have been possible to persue this analysis. The system of forces would have been indeterminate.

From a comparison of equations (6) and (10) it can be said that q_{max} for θ as defined by Fig 2 will be greater than q_{max} for θ as defined by Fig 3 if

$$h < \frac{2W(W-a)}{2W-a} \tag{11}$$

So if h is less than RHS of eqn (11) the maximum average shear stress on a plane at θ_1 to the crack tip will be given by eqn 6 and θ_1 will be given by eqn 4.

If h is greater than the RHS of eqn (11) the maximum average shear stress will be given by eqn 10 and θ_1 will be 45°.

CRACK INITIATION STRESS

Clearly the test data could be used to test various theories, however here the hypothesis that crack initiation occurs when the maximum average shear stress on a plane from the crack tip to a plate bounding edge becomes equal to the shear yield stress as defined by the von Mises criterion, $\sigma_y/\sqrt{3}$, is suggested and compared with the experimental data. For this hypothesis to hold, then in equations (6) and (10),

$$q_{max} = \sigma_y/\sqrt{3} \tag{12}$$

where σ_y is the uniaxial tensile strength.

Crack initiation would then occur when either, from eqn (6)

$$\sigma_g = \frac{2}{\sqrt{3}}\sigma_y \left(\sqrt{\left(\frac{a}{h}\right)^2 + 1} - \frac{a}{h}\right) \tag{13}$$

or, from eqn (10)

$$\sigma_g = \frac{2}{\sqrt{3}}\sigma_y \left(\frac{W-a}{W}\right) \tag{14}$$

Eqn (13) will control initiation for plates described by Fig 2 and eqn (14) will control initiation for plates described by Fig 3.

The test data, as far as it relates to crack initiation, is shown in Table I. One column indicates the gross area stress σ_g at initiation as observed either visually or instrumentally and, for comparison, the initiation stress calculated by either eqn (13) or (14) whichever was relevant to the plate geometry (in effect the lowest value of σ_g from either eqn (13) or (14)).

Two of these tests MSTP1 and CSTP2 require explanation. MSTP1 was a test plate with an edge crack, however the same equilibrium equations (6) or (10) are still valid. This is because there are no shear or direct forces on the vertical edge of the plate from which the crack is cut. In effect this flat edge corresponds to the centre line AD of a centre cracked plate. A difference between centre and edge cracked plates would have arisen if it had been necessary to invoke moment equilibrium.

The material properties of the test plate CSTP2 were very anisotropic. Thus the yield stress in the horizontal direction, that is parallel to the crack axis, was 417 MN/m^2, whilst in the vertical direction it was only 284 MN/m^2. So that if it is assumed that the yield stress varied uniformly with rotation, then the yield stress in a direction normal to a plane at θ to the vertical, Fig 5, is given by

$$\sigma_{y\theta} = (417 - 1.47\,\theta) \quad MN/m^2 \tag{15}$$

Now this test plate geometry indicates that crack initiation will follow Fig 2, so that from

$$\sigma_g\,(a + h\tan\theta) = q\,h\sec^2\theta \tag{3}$$

and with

$$q = \sigma_y/\sqrt{3} \tag{12}$$

where σ_y is given by equation (15).

Combining equations (3) (15) and (12) gives

$$\sigma_g\left(\frac{a}{h} + \tan\theta\right)\cos^2\theta = 241 - 0.85\,\theta \tag{16}$$

from which $\theta = 37°$ for σ_g to be a minimum, and σ_g is then 268 MN/m^2.

CONCLUSION

The agreement between the calculated and observed crack initiation stress is good, and it can be said that at least for the test plates of this investigation, crack initiation for both centre and edge cracked plates can be very adequately described by equating the von Mises stress for yielding $\sigma_y/\sqrt{3}$, to the maximum average value of shear stress acting on a plane from the crack tip to the plate boundary. That is for planes drawn from the crack tip to the plate boundary the average value of the shear stress acting along such planes can be calculated. For a particular plane, the orientation of which is dependent on plate width, height and crack length, this average value of shear stress will be a maximum. Crack initiation occurs when this average shear stress equates to $\sigma_y/\sqrt{3}$, the von Mises yield criterion.

References

1. Quirk A and Irvine W H, An Engineer's View of the Phenomena of Stable Growth and Pop-In. G/F/4/11, SMIRT 7, Chicago.
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3. Quirk A and Crook C E, Philosophy, Design and Testing of a Uniform Applied Load Flat Plate Testing Machine. Int J of Pressure Vessels and Piping. 9 (1981), 41-62.
4. Quirk A, An Investigation into the effect of residual stresses on the fracture strength of 25 mm thick stainless steel plates containing flawed weld metal. Proc of the LMFBR Safety Topical Meeting, Lyon-Ecully, France, July 19-23, 1982.

TEST NO	MATERIAL	YIELD STRESS (0.2%) MN/m	PLATE SIZE 2h, Height, Width 2W/Thickness mm/mm/mm	CRACK SIZE mm	OBSERVED INITIATED STRESS MN/m^2	CALCULATED INITIATED STRESS MN/m^2
SSTP1	As received 316 Stainless St	264	762/819/25.4	254	210	218
SSTP2	Stress Relieved Type 316 SS	281	762/819/25.4	254	231	224
SSTP3	As Received Type 316	264	711/819/25.4	124	303	281
SSTP4	Stainless St 316. As welded. Transverse Weld	264	737/819/26.6	127	307	281
SSTP5	Stainless St 316 Transverse Weld. Stress Relieved	281	737/819/25.4	128	264	274
SSTP6	STAINLESS ST 316. T weld As Welded	264	711/See Fig 6/25.4	230	227	209
SSTP7	Stainless St 316 Weld Repair	264	711/819/25.4	263	209 (instrument) 238 (visual)	205
SSTP8	Stainless St Stress Relieved	281	762/2032/25.4	610	146	149
SSTP1	Mild Steel (Edge Crack)	321	699/822/20.6	210	196	210
SSTP1	Mild Steel	316	787/1638/25.4	347	248	238
SSTP2	0.36%C Steel	Long 284 Trans 417	787/1638/25.4	371	244	268

TABLE I

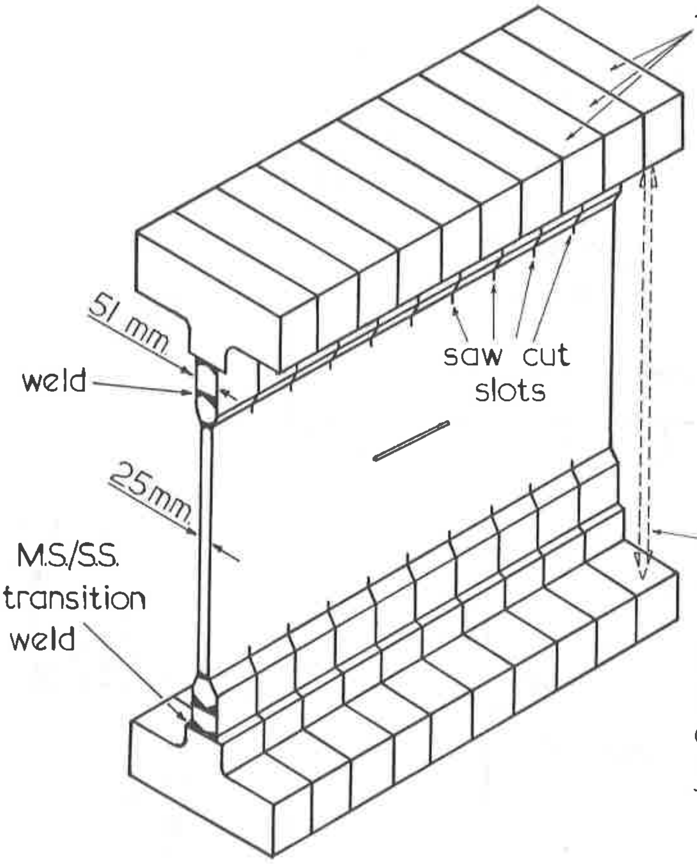


Fig. 1 Stainless Steel Uniform Applied Load Specimen

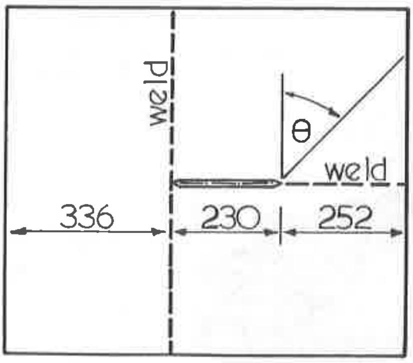


Fig.6 Test Plate SSTP6 With "T" Weld. Showing Asymetric Location Of The Crack.

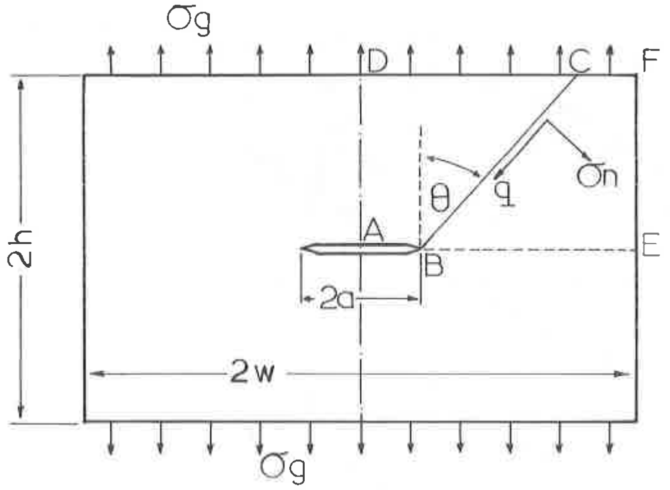


Fig. 2

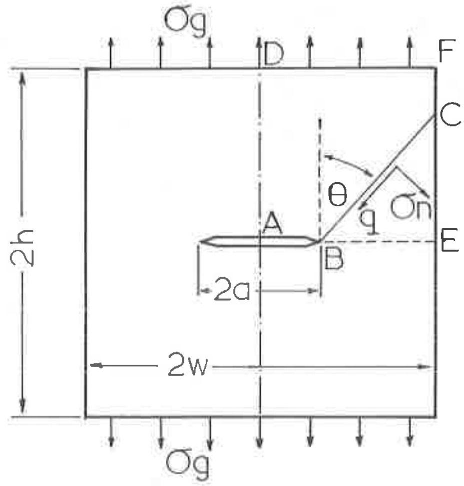


Fig. 3

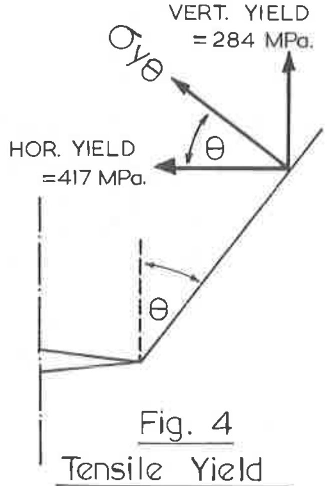
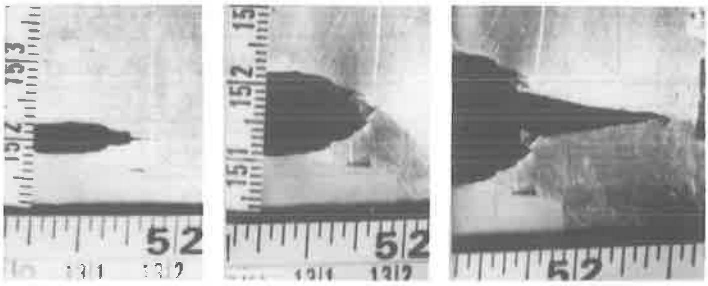


Fig. 4
Tensile Yield
Variations For
Test Plate CSTP2



INITIAL

PRE-INITIATION
σ_g = 145 MPa

POST-INITIATION
σ_g = 153 MPa

Fig. 5
Crack Tip
Development
(SSTP8)