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Aspects of the failure of large steel pressure vessels

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Summary

Work is described which throws light on the processes leading up to catastrophic failure of a pressurized structure. Measurements are given of crack opening displacements relevant to failures initiating from pre-existing defects. Particular attention is paid to the case of structures which have been loaded on previous occasions. This information is then related to data on strain ageing of cracked bars subjected to simulated operational cycles. The material properties important in high strain fatigue crack propagation have been examined experimentally, and a correlation between propagation rates and measured crack tip strains is discussed. The final stage of failure of a structure, extension of a fast running crack beyond the immediate region where it initiates, is considered in terms of the fracture toughness at appropriate crack velocities. Measurements of this parameter involving destruction of large pressurized vessels are described.

Introduction

In the nuclear energy industry we are concerned for particularly serious reasons with the avoidance of failure of pressurized steel structures. Since all important vessels in generating plant are proof tested, the possibility of fast fracture hinges upon a chain of events after this safeguard. Our paper is essentially a progress report on four facets of the question being studied at Berkeley Laboratories; the general approach is based upon measuring events at the tips of pre-existing crack-like defects.

Measurements of crack opening displacement (C.O.D.)

We consider that a basic requirement for understanding the behaviour of a defect in yielding material is measurement of the plastic displacement at its tip under realistic loading conditions [1, 2]. This displacement, δ, is related to the length of the defect, and since there is a critical crack opening displacement for crack extension [3] the concept of critical crack length is related directly to events at the defect tip.

The special circumstances of loading a defective structure for the first time can be described readily for particular cases only, for example a centrally-notched plate in plane stress [4]. In practice of course we are rarely concerned with such simple geometries or with the first loading case. Measurements aimed at more practically relevant circumstances are given in

Fig. 1 and Table 1. Fig. 1 shows the case for a 4 ft diameter cylindrical pressure vessel containing a 5 in through slot, oriented axially. The initial crack opening displacement, δ_1 was measured at various nominal stress levels. Bulging at the slot played a significant part in the opening of the crack of course, and this was reflected in the large crack tip strains observed initially.

The theoretical curve in Fig. 1 is calculated from the expression:

$$\delta_1 = \frac{8\sigma_y a}{\pi E}\left(1 + 1{\cdot}6\,\frac{a^2}{Rt}\right) \ln \sec \frac{\pi}{2} \cdot \frac{\sigma}{\sigma_y}$$

Where σ_y is yield stress, a is semi crack length, E is Young's modulus, R is vessel radius, t is plate thickness and σ is the hoop stress. This is based on the flat plate expression of Goodier and Field [4], with a correction term $[1 + 1{\cdot}6\,(a^2/Rt)]$ derived from the work of Folias [5], to allow for elastic bulging only. The result for the 15 in crack (Fig. 2) gives somewhat better agreement with theory, possibly because of the lower stress levels, since the Folias correction contains no allowance for the pronounced plastic bulging expected when the general stress approaches the yield stress.

Similar measurements made on a small scale model of a special vessel, containing a gas duct, show effects of geometry on through thickness cracks in locations of high stress. In Table 1 these values, after linear scaling up to full size, are compared to the flat plate case [4] for the same nominal stress. For convenience the geometrical effect is related in this table to the local elastic stress concentration factor in the absence of a crack. There is of course no reason to expect a general relation to hold, since different features with the same SCF can produce stresses which will be very differently affected by the relaxations which a crack allows. Scaled-up measurements of this kind from model tests can be used to predict critical crack lengths on initial loading of the full size structure if a critical C.O.D. for failure is assigned to the material. Because of our incomplete understanding of the influence of such factors as specimen dimensions and location of measurement, critical C.O.D. in a simple bend test cannot presently be established within a factor of two, even when the specimen is of full plate thickness. Further, the influence of stress configuration on critical C.O.D. may prevent realistic measurement in a separate test if plane strain conditions are approached. For the case of reasonably tough material however the procedure is likely to be acceptably accurate.

Measurements on first loading are of little use in specifying what will happen in a pressure vessel later in its history, as the initial plastic strains at the tip of a defect affect subsequent local events. Crack opening displacements (δ_2) have been measured on loading several times in the experiments outlined above; these are relevant to the practical issues of fatigue

crack propagation under repeated loading and the possibility of failure in operation due to embrittlement. Figs. 1 and 2 show measured crack tip displacements on unloading and reloading the slotted vessel. A very simple model, [1, 6, 7, 8] allows calculation of the displacements, and modification of this, using the Folias bulging correction, gives the comparison curves dashed in Fig. 1*. The agreement is as good as can be expected within the limits of the simple model and the purely elastic correction; again the 15 in crack gave a better fit to the theoretical treatment. Agreement for both cases is better than on first loading perhaps because the plastic component of bulging, responsible for significant discrepancies in initial loading, has no tendency to reverse on unloading. For a given nominal stress, of course, very significant reduction in crack opening displacement after the initial loading is shown. The point is also illustrated in Table 2 where the reloading crack opening displacements are quoted for the complex model. The proportionate reduction in displacement is approximately constant in 4 of the 5 cases.

Fatigue crack extension

In fatigue it has been suggested that the stress intensity factor plays a role in deciding the rate at which a crack extends [9]. In so far as this parameter is representative of events at the tip of a crack, there is justification for this, and experiments support the view [10, 11]. However, it has not been clear what material properties affect the crack propagation rate. The basis of our study of this point was the very naive view that separation of the material at the crack tip is the controlling feature and the only material property which remotely describes such a process is the fracture toughness K_c (or the critical value of δ in low strength materials), although any influence of toughness on crack propagation has been denied [10, 12]. Fig. 3 shows high strain fatigue crack propagation rates under repeated tensile stress related to fracture toughness in a variety of heat treated steel plates. As K_c increases the cracks propagate more slowly for a given value of ΔK. Clearly the higher capacity for absorbing crack tip strain without failure, which higher toughness implies, is carried over into the fatigue regime. The single result on 2½ in thick mild steel plate is obviously badly out of line, regardless of arguments about the value of K_c attributed. The two sets of high strength steel data might be described by individual equations of the form:

$$\frac{dl}{dN} = B\,\frac{\Delta K^4}{K_c}$$

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* δ_2 is given by $\delta_2 = \dfrac{16\sigma_y a}{\pi E}\left(1 + 1{\cdot}6\,\dfrac{a^2}{Rt}\right) \ln \sec\left(\dfrac{\pi}{4} \cdot \dfrac{\sigma_2}{\sigma_y}\right)$

Where σ_2 is $(\sigma_{\max} - \sigma)$ during unloading and σ during reloading) with different values of B. The need for two values can be ascribed to the need to take material strength into account. If the plastic strains at the crack tip play any part, the applied stress is not controlling in absolute terms; it has to be related to the strength of the material, perhaps through the yield stress. Taking this view leads to an equation:

$$\frac{dl}{dN} = A \frac{\Delta K^4}{K_c{}^2 \sigma_y{}^2}$$

which describes empirically all the results (Fig. 4), including the single mild steel case, A being independent of material and equal to $2{\cdot}5 \times 10^{-3}$.

In so far as this equation is empirical, it is unsatisfactory, but it actually compares very well with the theoretical analysis carried through by Weertman [8]. This assumes a crack tip failure criterion based solely on strain. To the extent that, for a fixed degree of plane strain, a given crack tip displacement is associated with a characteristic stress, this is a sufficient criterion. However, material separation at the tip of a crack generally occurs at a strain which depends on the stress system. The above equation therefore might not be adequate to describe propagation rates for wider variations of the degree of plane strain, even though changes in K_c itself would partially compensate. This view is given support when mild steel data on thinner sections is considered, where the degree of plane strain is smaller. Much lower crack propagation rates are obtained than would be predicted from Fig. 4 [11, 13].

In general for a particular class of materials (e.g. steels) the yield stress and fracture toughness tend to be inversely related properties. From the ranges of values generally encountered, and the manner in which these properties occur in the expression for dl/dN, the observations that material properties do not have a systematic effect [10, 14] is understandable. However, the value of taking account of K_c and σ_y in describing crack propagation rates is shown by comparison of the range of values of the arbitrary constants M and A in:

$$\frac{dl}{dN} = \frac{\Delta K^4}{M} \quad \text{and} \quad \frac{dl}{dN} = \frac{A \, \Delta K^4}{K_c{}^2 \sigma^2}$$

required to cover the actual dl/dN values observed. The range of M needed to describe the results is an order of magnitude greater than the corresponding range of A.

An extension of this work takes account of the fact that, particularly in repeated tension [15], the stress intensity factor K is related to the crack opening displacement, itself a better indication of crack tip events in mild steel. Measurements were made of δ_2 directly on cracks advancing in mild steel plates, and a significant correlation established (Fig. 5) in accordance with expectations from the approximate relation:

$$(\Delta K)^4 \, \alpha \, \delta_2^2$$

In the particular case of the results in Fig. 5, the δ_2 measurements were made at a distance of 0·3 mm from the crack tip. Although the absolute value of δ_2 depended on the position at which the measurement was made, the relation

$$\frac{dl}{dN} \, \alpha \, (\delta_2^2)$$

was observed not to be very sensitive to position in the range 0·3-3·0 mm from the crack tip.

This correlation suggests that δ_2 can be used in estimating fatigue crack propagation rates in a way which is analogous to the use of δ_1, in fast fracture initiation studies.

Strain-age embrittlement

Knowledge of δ_2 is also important because this is the crack opening displacement of significance if a structure is to fail as a result of embrittlement in operation. As Figs. 1 and 2 and Table 1 show, δ_2 is much smaller than δ_1 for a given stress, and this must be especially so in a proof tested structure where the subsequent stressing is to a lower level. However, there is evidence that plastic strain occurring at the tip of a crack in mild steel in the range 150-350°C can produce embrittlement in subsequent stressing at 20 °C due to dynamic strain ageing [16]. For a particular structure the seriousness of this may be gauged by comparing the failure conditions (critical δ values, δ_c) in say a cracked beam after simulating the real heating regime, and the loading conditions, controlled through measurement of δ.

Three initial experiments of this kind have been carried out. C-Mn steel beams (22 × 4 × 2 in) were notched to a depth of 2 in, the tips being 0·007 in wide. The critical δ value for such samples at 20 °C was rather small (0·021 in). The beams were first bent at 20 °C to give initial crack openings of $0{\cdot}8\delta_c$ and $0{\cdot}6\delta_c$, to simulate the conditions at the tips of very serious cracks in proof testing. Simulating the effect of unloading required controlled bending in the reverse sense. Assuming the notional proof test to have been 1·6× operating stress, the results and calculations of section 1 inferred a crack tip displacement during operation $\frac{1}{5}$ of that sustained in the proof test. The specimens were therefore heated to 200 °C, reloaded to give these smaller crack opening displacements (a treatment equivalent to a period of operation), subjected to a simulated unloading while hot and then finally fractured at 200 °C noting δ values at failure. Table 2 compares these values with the δ_2 appropriate to the equivalent cracks in a power generating plant vessel at the pressures demanded in the lower temperature range of the start up procedure. These δ_2 values are so very low because the 'cold filling' pressure is only ⅓ of the proof test pressure. A major difficulty in these experiments was simply that sudden but limited crack extension was detected at various values of δ before final cracking to failure occurred. It is not clear exactly why these cracks stopped, and whether they would do so in a pressurized structure. However, Table 2 shows that if the first sign of cracking is taken to indicate a failure condition, then, for any crack approaching the critical length in the proof test, the material was sensitised to give failure at 20 °C with small crack tip displacements, close to the very low values characteristic of δ_2 of cold filling stresses.

The question of whether this limited cracking can lead to catastrophic failure requires examination. Probably study of similar sequences on pneumatically loaded vessels will be required to clear this up properly.

Dynamic fracture toughness

The final stage in a fast fracture catastrophy is the extension of a rapidly moving crack beyond the region of high stress or limited toughness where it initiated, into the bulk of the structure. The crack arrest philosophy has dealt with this aspect to some extent, but it falls short of treatment from the fracture mechanics standpoint because the fracture conditions are not normally related to any measure of crack length. Work carried out at the UKAEA, Culcheth [17] in fact cast a great deal of doubt on the usefulness of the crack arrest concept by showing that there was no real transition in the conditions required to fail a slotted pneumatically loaded structure. Basically, arrest of a crack depends upon the stress, the instantaneous crack length, and some value of a material property, similar to fracture toughness, for a crack moving at the appropriate velocity. To clarify this issue, an attempt has been made to measure dynamic fracture toughness values on pneumatically loaded, 5 ft diameter cylindrical vessels of 1 in thick C-Mn steel. The experiments involve pressurizing vessels to a number of pre-determined membrane stresses. At each successive stress level a crack was initiated in a partial penetration, axially oriented groove. The crack was started by a combination of high stress and low ductility induced in the centre of the groove by severe local cooling, resembling the practical situation of a crack emerging from a low ductility, high stress region. Knowing the stress level which was just sufficient to cause the crack to extend beyond the end of a given length of groove (where the temperature approximates to that of the vessel) and destroy the vessel allows calculation of a dynamic fracture toughness. Fig. 6 gives the first results of these tests; the groove in this case was 12 in long.

Dynamic fracture toughness is probably a meaningful concept for the lower failure stress measurement. A value of 108 kpsi $\sqrt{\text{in}}$ is arrived at for the case at 8 °C where the failure was fully brittle, after applying the Folias bulging correction. It is possible to correlate this with the measured through thickness reduction in the region of the groove tip. Measuring the thickness profile and assuming constant volume we arrive at a value of 0·007-0·020 in for the value of δ_c at the tip of the running crack. Taking an appropriate strain rate to be 50-500/sec suggests a yield stress of 65-75 kpsi for the vessel material. The thickness measurement shows a plastic zone diameter of approximately 4 in indicating deformation approximating to plane stress which allows the relation $K_c^2 = E\sigma_y\delta_c$ to be used. This gives K_c in the range 100-200 kpsi $\sqrt{\text{in}}$, consistent with the value derived from the failure stress. Jones and Turner [18] and Irwin and Wells [19] give estimates of this property ranging from 40-120 kpsi $\sqrt{\text{in}}$.

At high temperatures, where the fracture was a completely ductile 45° shear failure, the stress necessary to destroy the vessel was higher, well into the range where linear elastic fracture mechanics has no meaning and where bulging was very significant. For the particular groove length used, the failure stress at 70 °C was similar to that measured in the UKAEA crack initiation studies at an equivalent temperature [17]. The very severe contractions close to the fracture surface argued very large δ_c values for the ductile fast running crack, in excess of 0·15 in. This suggests that the differences in behaviour between the ductile and brittle cases would be very large in a flat plate, a factor of 20 or so in critical crack length. The fact that this is not really reflected in very large differences in the conditions to give failure in the vessels is an indication of the part which bulging played. In practise this form of plastic collapse is likely to be regularly significant for ductile failures even of very large pressure vessels. The point is very important because, whilst there may be some safety to be gained by operating pressurized structures above a temperature at which fast running cracks will be ductile, the benefit is not generally so significant in terms of failure conditions as might be anticipated from simple measurements of δ_c, crack arrest temperature, and the like.

Conclusions

1. Crack opening displacement measurements have been described with particular reference to the service behaviour of pressurized steel structures.
2. High strain fatigue crack propagation has been characterized in terms of fracture toughness and yield stress, and correlated with measured crack opening displacements.
3. The effects of strain ageing have been considered, and experiments described in which the simulation of operational history was attempted, so as to quantify the dangers from this cause.

4. Dynamic fracture toughness measurements have been described, allowing fracture mechanics significance to be placed upon crack arrest testing.
5. The significance of bulging of a defective vessel during failure was discussed.

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Table 1

Scaled-up crack opening displacements, measured at particular locations in a scale model of a structure with deliberately introduced fine cracks. The results are compared (case 1) with a flat plate for the appropriate membrane stress level ($0{\cdot}6\sigma_y$)

Crack no.	*Scaled up total crack length (in)*	*Elastic S.C.F. perpendicular to crack*	*Initial crack opening displacement,* δ_1 *(in × 10^{2-3})*	*Crack opening displacement on reloading,* δ_2 *(in × 10^{2-3})*	*Comments*
1	3·4	1	1·8	0·75	Calculated for a flat plate, assuming plane stress and plastic behaviour.
2	4	1·1	<1		
3	5·6		6·2	<1	Gauges in wrong orientation to measure S.C.F.
4	3·4	2·7	8·1	3·7	
5	3·4	2·2	9·5	4·6	Very large bending component present, tending ing to open crack at outside surface.
6	3·4	5·1	19·1	5·8	

Table 2

Results on strain-age embrittlement in simulated operation. The initial critical value of δ *for these samples was 0·021 in at 20°C. All values of* δ *were measured 0·1 in from the crack tip.*

Case	Crack length *(assuming flat plate* case)	δ_2 *for cold filling* (in × 10^{-3})	δ *value in final fracturing* (in × 10^{-3}	*Indication in final fracture procedure*
1	0·6 × acrit in proof test	0·6	5·8	Sharp 'ping'
			6	Sharp 'ping' with load drop
			15	Considerable crack extension on surface.

Table 2—continued

2	0·8 × acrit in proof test	0·8	2	Sharp 'ping'
			6	Sharp 'ping' with load drop
			32	Considerable crack extension on surface.
3	0·8 × acrit in proof test	0·8	3-6	Sudden considerable crack extension without prior warning.

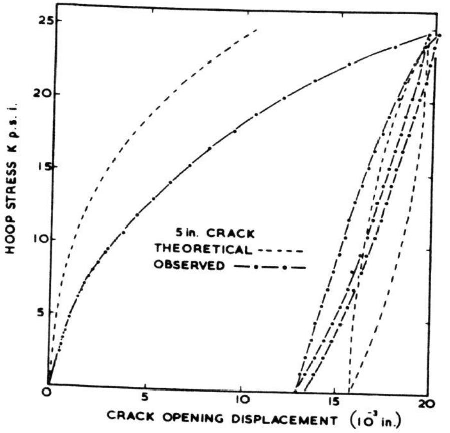

Fig. 1. Crack opening displacements measured during repeated loading and unloading of a pressure vessel. The vessel was a mild steel cylinder, 4 ft in diameter and 1 in thick. The defect was a sharp 5 in long axial slot in the cylindrical portion.

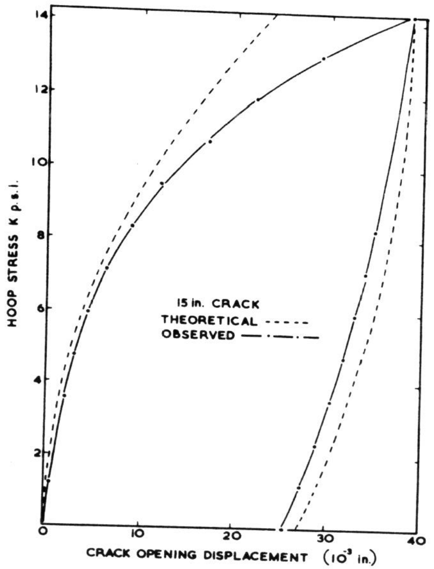

Fig. 2. Crack opening displacements measured as in Fig. 1, but with a 15 in long slot.

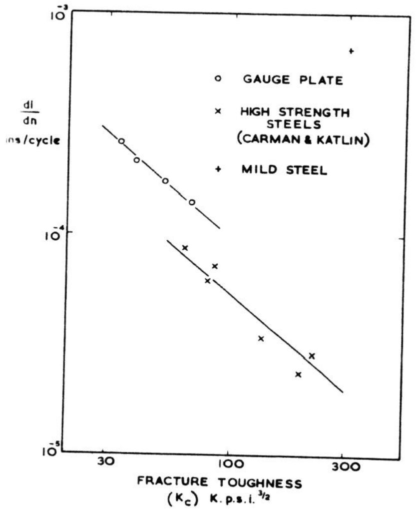

Fig. 3. High strain fatigue crack propagation rates in a variety of steel plates, expressed as a function of fracture toughness (slopes of straight lines are approximately −1). The gauge plate samples were 0·155 in thick, heat treated to various strengths (Jurevics, to be published). The values of dl/dN quoted refer to results extrapolated to a particular value of ΔK(60 kpsi $\sqrt{\text{in}}$).

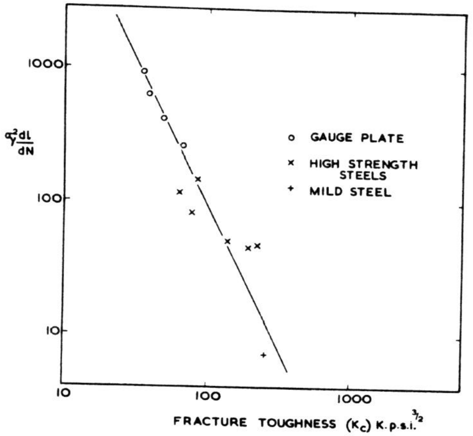

Fig. 4. Fatigue crack propagation rates as a function of fracture toughness and yield stress. These are the results of Fig. 3 re-expressed to illustrate the empirical equation

$$\frac{dl}{dN} = A\Delta K^4 \quad \text{(Slope of straight line = −2)}$$

The values on the ordinate depend upon the ΔK selected for the condition under which the crack propagation rate was measured. For σ_y in kpsi, dl/dN in/cycle × 10^2 the appropriate ΔK is 40 kpsi $\sqrt{\text{in.}}$

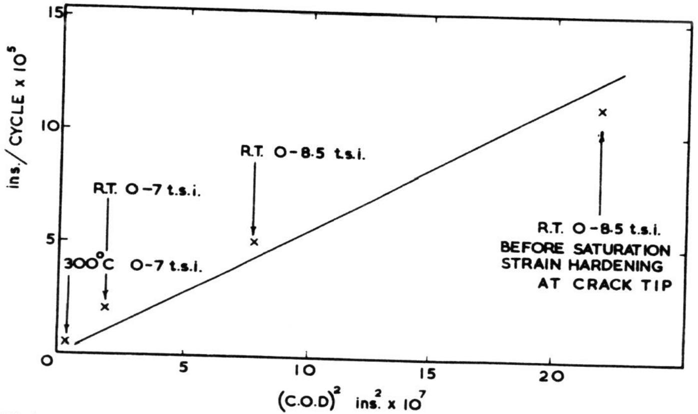

Fig. 5. High strain fatigue crack propagation rates as a function of crack opening displacement δ_2. The tests were carried out at 20° C and 300° C in repeated tension on mild steel plates, 6 ft × 3 ft × ½ in, containing a central sharp 9 in slot.

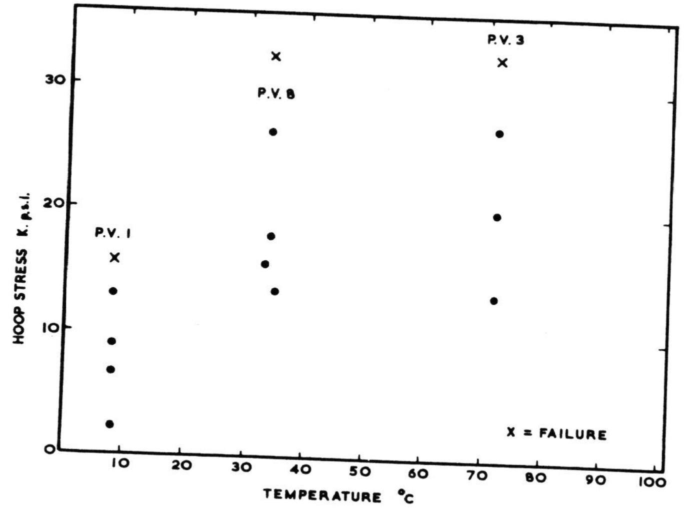

Fig. 6. Failure stresses at three temperatures, for a 5 ft diameter, 1 in thick vessel, loaded pneumatically. Failure was caused by injecting a fast running crack from a 12 in long groove and the temperature range spans the transition from the flat to the 45° failure mode.