THE DRIVING FORCE for RAPID CRACK PROPAGATION along PRESSURISED PIPELINES

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Pressurised pipelines can fail catastrophically by axial propagation of a fast-running crack, if some material-dependent *critical pressure* is exceeded. Determination of the crack extension force for fracture-mechanics prediction of critical pressure is complicated by large fluid-structure interactions. Results are presented from a study of this problem, combining simple analytical modelling, numerical solution of a steady-state dynamic model using the Finite-Volume method, and experimental evidence from critical pressures and decompression profiles recorded in the Small-Scale Steady-State (S4) pipe test currently proposed as a standard for pipe testing.

INTRODUCTION

Full-scale tests by British Gas and others have shown that even the ductile polyethylenes used for water and fuel gas distribution pipe can suffer catastrophic brittle failure by axial Rapid Crack Propagation (RCP), if a material-dependent *critical pressure*, p_c, is exceeded. Tests by British Gas (1) on 25 m long sections of pipe buried under service conditions (but pressurised by air) at 0°C have consistently demonstrated RCP in standard medium density polyethylenes (MDPE) at pressures well below those at which similar or inferior materials were, until recently, in service in Eastern Europe. New modified high density PE (HDPE) grades, on the other hand, perform extremely well. Predicting p_c involves equating the dynamic fracture resistance G_D of the material (which is itself difficult to measure) to the crack driving force G developed by the fluid-pressurised pipe structure, which is a complex function of the pipe dimensions and material, and of the contained fluid properties.

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A test for RCP susceptibility will almost certainly be included in forthcoming International and European Standards for PE pipe. Since the British Gas full-scale test method is too expensive, attention has focussed on laboratory tests using short (5-7 diameter) specimens. The main problem for such tests is the correct simulation of contained fluid decompression, which tends to relieve the crack of the extension force needed to sustain propagation. Our Small-Scale Steady State ('S4') test (1) tackles this problem by aiming to eliminate axial decompression, using baffles which divide the internal volume of a 5*D* gauge length into a series of short chambers which must decompress radially. The S4 test identifies a critical pressure p_{cS4} much lower than p_c measured using the full-scale test. This paper concerns the influence of differences in fluid decompression and outflow between S4 and full scale tests on differences in the RCP extension force *G*, as computed using a new Finite Volume method — and, hence, on differences between p_c and p_{cS4}.

DECOMPRESSION DURING RCP at SMALL and LARGE SCALES

Assuming the crack extension force *G* to be provided entirely by unloading of the circumferentially stressed pipe wall, yields a reference value

$$G_0 = \frac{\pi p_0^2 D^3}{8\,Eh^2}\,, \qquad (1)$$

where p_0 is the initial pipeline pressure, *D* and *h* are the pipe diameter and thickness and *E* is the tensile modulus of its material. RCP can only proceed while *G* exceeds the material's dynamic fracture resistance G_D, so that, if Eq. (1) is correct, p_0 must exceed a *critical pressure*

$$p_c = \frac{h}{D}\sqrt{\frac{8EG_D}{\pi D}}\,. \qquad (2)$$

This 'Irwin-Corten' model is undermined by the presence of the pressurising fluid itself, which can contain a thousand times as much internal energy as the pipe wall. It is because the dynamics of this vast energy source dominate *G* that critical pressures for gas pressurisation are much lower than for water (2).

As the crack runs, fluid escapes through it. Before a crack front propagating at a velocity $\dot{a}$ (less than the sonic velocity C_0 of the fluid) arrives at any fixed cross-section, therefore, a decompression wavefront sweeps past and the pressure begins to decay from p_0 to some proportion of it which depends only on $\dot{a}$, and the pipe wall unloads. According to a simple one-dimensional analysis, the crack tip pressure will fall to

$$\frac{p_1}{p_0} = \left[1 - \frac{\gamma - 1}{\gamma + 1}\left(1 - \frac{\dot{a}}{C_0}\right)\right]^{2\gamma/(\gamma-1)} \tag{3}$$

and replacing p_0 by p_1 in Eq. (1) might provide a better estimate of G. At low $\dot{a}$, p_1 tends to $0.28p_0$. There is evidence to suggest that p_{cS4} is lower than p_c by this factor, suggesting that the S4 configuration, by maintaining the initial pressure p_0 back to the crack tip, models the region around the tip of a slow crack in a full-scale test at which the pressure has already fallen from p_0 to p_1. However, the remaining pressure does not collapse immediately behind the crack tip, but decays steadily over a characteristic length. Since it is within this 'outflow' zone that the exhausting gas can develop a large crack extension force as it expands against the pipe flaps liberated by the crack, it is important to know the axial pressure profile. Experimental evidence appropriate to brittle RCP in PE pipe is rare.

Measurements of pressure profiles in the S4 test outflow zone

Using a 250 mm S4 test rig, decompression was studied using piezoelectric pressure gauges mounted internally 1, 2, 3 and 4*D* along the gauge section. Fig. 1a illustrates typical decompression profiles, showing that the internal chambers decompress successively in a steady state manner, and that the pressure decay within each is essentially linear. S4 tests combining pressure transducers and conventional on-specimen electrical crack gauges have shown that the pressure drop in each chamber due to axial backflow preceding crack arrival is less than 10%. Numerical differentiation of decompression profiles (Fig. 1b) highlights characteristic points during discharge. The axial crack velocity estimated from points of maximum decompression rate agrees closely with that from the crack gauge, even tracing local crack acceleration and deceleration. Using these results, outflow can be characterised by a single *decompression length*, the product of decompression time and axial crack velocity. For MDPE 250 mm SDR 11 pipes S4 tested at 0 °C, decompression lengths at critical pressure are 3-4*D*, in good agreement with those measured in full scale tests (3).

COMPUTATION of the CRACK DRIVING FORCE FOR RCP

The strongest previous attempts to compute G for the pipe problem employ a dynamic finite-element simulation of transient axial crack growth from zero length (4). G, computed at each time step, rises steadily as the crack extends before stabilising at a plateau which is assumed to represent the steady state. This plateau value, plotted as a function of crack speed, exhibits a peak within the subsonic regime. For slower cracks, *G* is assumed to have been reduced by prior decompression, whilst for faster cracks it has been depleted by inertial effects. As before, the critical pressure is assumed to be that at which this peak *G* becomes equal to the fracture resistance.

Formulation and solution using a steady state dynamic finite volume method

We have developed an economical alternative approach based on *a priori* assumption of a steady state, and using the Finite Volume rather than the Finite Element method. The formulation allows *G* to be computed for a control volume extending from a plane ahead of the crack tip, at which the pipe wall is in equilibrium with the partially decompressed fluid contents at p_1 as given by Eq. (3), to a plane behind the crack tip at which the fluid has completely escaped. *G* is equal to the total (strain plus kinetic) energy per unit pipe length lost between these planes — plus the total forward axial force exerted by pressure against the flared-out walls — per unit crack width (*i.e.* wall thickness). Whilst inertial effects are fully accounted for, this steady-state approach eliminates time from the problem, allowing the crack driving force *G* to be calculated, for a given pressure profile, from a 'snapshot' evaluation of the displacement field.

The full equations of motion are solved for displacements using the Finite Volume method, first employed for the solution of stress analysis problems by Demirdzic *et al.* (5), rather than the Finite Element method. Comparison against several static analytical stress analysis solutions for pipe geometries verified the accuracy and efficiency of our FV code: it is much faster than the Finite Element method. For the cracked pipe geometry, the pressure distribution is specified as a linear decay from p_1 to atmospheric pressure over a decompression length *L*. For a 6*D* long control volume of 250 mm MDPE SDR 11 pipe at initial pressure p_0=1 bar, *G* versus $\dot{a}$ results are presented in Fig. 2 for decompression lengths $L = 2D$, $2.25D$, $2.5D$ and $3D$. *G* depends strongly on *L*, and, for each value of *L* reaches its maximum at a different crack speed. Whilst analytical modelling of the decompression profile remains a future objective, experimental measurement of *L* is still a key element of *G* computation.

CONCLUSIONS

Direct dynamic decompression measurements within the gauge section of an S4 test for RCP in plastic pipelines have shown that the pressure drop prior to arrival of the crack is minimal. These measurements support the idea that the S4 critical pressure for rapid crack propagation is much lower than that measured in full scale tests due to prior decompression in the latter. Decompression due to outflow *after* the crack passes can be used to measure the crack velocity in the S4 test. The crack extension force, computed using a steady-state Finite Volume formulation, depends critically on the length over which this outflow is completed. This appears to be similar in S4 and full-scale tests.

SYMBOLS USED

C_0 = speed of sound in pressurising gas (m s^{-1})
D = pipe diameter (m)
E = dynamic elastic modulus of pipe material (N m^{-2})
G_0 = crack driving force computed from Irwin-Corten analysis (N m^{-1})
h = pipe wall thickness (m)
p_c = full-scale test critical pressure for Rapid Crack Propagation (N m^{-2})
p_{cS4} = S4 test critical pressure for Rapid Crack Propagation (N m^{-2})
p_0 = initial pressure in pipeline (N m^{-2})
p_1 = pressure just ahead of crack tip (N m^{-2})
γ = ratio of specific heats

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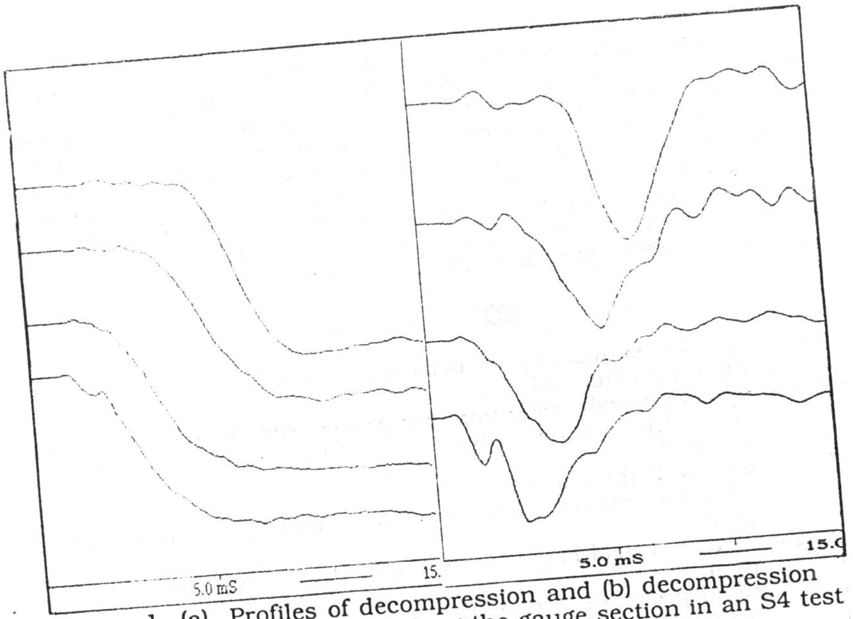

Figure 1 (a) Profiles of decompression and (b) decompression rate recorded at four points along the gauge section in an S4 test on 250 mm MDPE pipe

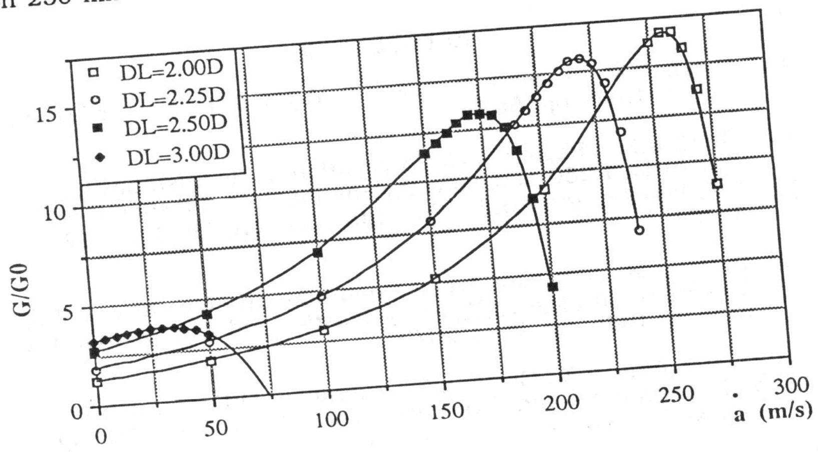

Figure 2 Computed crack driving force G vs crack speed $\dot{a}$ in pressurised pipe, for four decompression lengths.