EXPERIMENTAL STUDY OF THE DYNAMICS OF RAPID CRACK PROPAGATION IN PLASTIC PIPES

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Rapid crack propagation in gas and water pipes has been studied using an optical device to measure the radial displacement of the pipe wall during fracture. Results are compared with a numerical simulation of pipe fracture and show inward radial dimpling of the pipe wall ahead of the crack tip caused by flaring of the pipe walls in the wake of the crack. Evidence from further tests using high speed photography and soil backfill surrounding the pipe give an explanation for the characteristic sinusoidal crack path observed in gas pressurised pipe fractures. For a water pressurised pipe fracture, the assumptions behind the classical analysis for pipe RCP of Irwin and Corten are supported by experimental measurements.

INTRODUCTION

The problem of Rapid Crack Propagation (RCP) in gas and water plastic pipes has been well documented in recent years. Following an initiation event, a crack can propagate indefinitely if the operating pressure exceeds a critical value p_c. RCP is characterised by long cracks extending axially at high speed (typically exceeding 100 ms^{-1}). The fracture surfaces appear brittle, even in polymers which are usually recognised for their tough behaviour. In gas pipes, the crack will often follow a path which deviates from the longitudinal axis and at a speed which oscillates at the frequency of this 'sinusoidal' crack, illustrated in Fig. 1 by a high speed photograph of an RCP event. This curious phenomenon has been the focus of some interest (1) but its effect on RCP performance is rarely discussed. This study aims to ascertain the causes of the sinusoidal crack by monitoring pipe wall displacements, acoustics and crack velocity in a series of experiments on 125 mm diameter medium density polyethylene (MDPE) and 114 mm diameter unplasticised PVC (uPVC) pipes. Experimental data are compared to results from a numerical procedure which can be developed to simulate sinusoidal crack propagation.

DYNAMIC FRACTURE

In the case of water pressurised pipe, we can assume that negligible energy is stored within the pressurising fluid, due to its relatively high bulk modulus.

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Therefore, the crack driving force G is simply provided by the strain energy released from the pressurised pipe wall during fracture which can be equated to the dynamic fracture resistance G_D of the pipe material to predict p_c (2,3).

For a gas pipe, substantial energy is released from the pressurising fluid which expands through the crack opening into the surrounding atmosphere over a finite time. G is generated predominately by the action of internal pressure, sustained in the vicinity of the crack tip during gas escape, which bends the pipe walls adjacent to the crack along both the axial and circumferential directions. The fracture process is strongly influenced by inertia forces within the pipe wall and any perturbation in the pressure loading will introduce an asymmetric stress field at the crack tip. Axial backflow of the pressurising fluid will occur ahead of the crack tip if, as is usual, the fluid wave velocity exceeds the crack speed. The crack tip pressure is then directly related to the crack velocity history and can rapidly fluctuate over time.

EXPERIMENTAL METHOD

The International Standardisation Organisation small scale steady state (S4) test method (4) was used to study RCP in a laboratory environment (Fig. 2). The test uses a pipe specimen, seven diameters in length, which is sealed at both ends and pressurised. In the Standard S4 test, crack tip pressure is maintained at a steady level by suppressing axial decompression of gas using internal baffles spaced at equal intervals along the pipe length. A containment cage is positioned around the pipe to limit flaring of the pipe walls which restricts the failure process to one of steady propagation rather than transient bursting. A chisel ended striker is driven radially into the pipe at one end of the specimen and initiates a fast crack along the pipe. Depending on the pressure, the crack will either propagate along the full length of the specimen or promptly arrest; p_c separates these two regimes.

A variant of the S4 test, known as the 'hydrostatic S4' test was also used to study RCP in liquid filled pipes (3). The main distinction of this test is that axial decompression is eliminated by the introduction of a large coaxial mandrel along the pipe bore which effectively lowers the sonic velocity of the fluid below the crack speed, allowing RCP to occur.

An optical method was introduced to measure displacements of the pipe wall during an S4 test. Two pairs of 1 MHz emitter-receiver phototransistors were mounted onto a modified ring of the containment cage located 400 mm along the pipe from the crack initiation region. The phototransistor pairs were attached at positions ± 30° around the circumference from the top of the ring, aligned longitudinally with the point of initiation. The emitter uniformly illuminated the pipe wall with infrared light and the intensity of the reflected light measured by the receiver was linearly proportional to the radial displacement of the pipe wall within the ranges of the test.

The location of the crack with respect to the optical gauges was measured using six conductive silver timing lines painted around the pipe circumference at 30 mm intervals. Each line was connected to a Wheatstone bridge circuit, which provided a step change in voltage as each line was broken.

Photographs were taken during pipe fracture using a camera unit with six image intensified, charge coupled device (CCD) arrays with an exposure time of 10 μs. The six CCDs were triggered sequentially with a 0.5 ms delay between each one to generate a sequence which follows the growth of the crack during the test.

NUMERICAL MODEL

The finite volume (FV) method, which dominates computational fluid dynamics, has been adopted for dynamic fracture problems. The details of the method have been described previously in general terms (5) and with reference to the model implemented here for pipe RCP (6). The crack front is modelled as a straight line through the pipe thickness which is initiated from zero length and propagated according to a specified crack history, which can be measured from an S4 test. As the crack crosses each column of computational cells, the forces they carry are relaxed to zero and the work done per unit area is the computed G. The restriction of the current model is that the crack is forced to propagate in a straight line; since the pipe is therefore symmetric about the crack plane, only one half is modelled.

RESULTS

Fig. 3 shows the radial displacement of the pipe wall as a function of time, measured by the optical gauges and predicted by the FV model using the crack history from an S4 test on MDPE pipe at a pressure of 3.5 bar. At initiation (t = 0), no pipe wall motion is recorded by the gauges at the displacement monitoring position 400 mm ahead of the crack. The crack advances along the pipe and before it arrives at the monitoring position a negative (i.e. inward) radial displacement is recorded, where the pipe wall in front of the moving crack tip forms a 'dimple' due to flaring of the pipe wall in the wake of the crack. It is known from crack shape profiles that the crack leads along the bore of the pipe and, in this region, the dimpling creates an axial tensile stress into which the crack front must travel. This is known to be a condition for crack path instability (7), which would explain why the crack initially deviates from the axial line.

The accelerations of the pipe wall were calculated by taking the second derivative of the displacement records from a test on MDPE (Fig. 4). The pipe wall acceleration oscillates at a frequency of approximately 1 kHz which corresponds very closely to the frequency of the sinusoidal crack path (typically, 150–200 mm wavelength at a mean crack speed of 150–200 ms^{-1}). In addition, the accelerations on both sides of the crack face are out of phase.

In the case of gas pressurised pipes the escaping fluid is highly turbulent and is capable of exciting the natural modes of vibration of the pipe. A simple single experiment was conducted using a partially slit pipe mounted on the S4 rig in an attempt to simulate fracture under steady state propagation conditions. High pressure gas was pumped into the S4 rig and allowed to escape through the slit. The escaping gas excited frequencies of approximately 1 kHz, measured using a microphone connected to a transient recorder.

High speed photographs reveal the S4 test fracture comprises of two regions: an initiation region and a steady state propagation region. The (foreshortened) photograph of a 300 mm section of MDPE pipe within the propagation region (Fig. 1) shows the pipe walls opening behind the crack tip, which causes the dimple ahead of the crack as measured by the optical gauge. Photographs taken from the side of the pipe show some dimpling ahead of the crack in the propagation region, but none in the initiation region, where the crack travels in a straight path at high speed.

Further S4 tests were undertaken in which pipe specimens were subjected to axial compression in addition to the internal fluid pressure. In successive tests, sinusoidal crack paths were seen to reduce in amplitude with increasing compressive strains until, at a strain of 0.7 %, the crack path was entirely straight. Other tests in which the outer wall of the pipe is constrained by a layer of soil backfill also show straight crack paths.

Hydrostatic S4 tests were carried out using water pressurised uPVC pipe specimens in which the pipe wall deformation was monitored using the optical gauge. For a test pressure of 6 bar the optical gauges registered the deflection of the pipe walls to be less than 0.3 mm and the crack paths are typically straight. For an air pressurised (Standard) S4 test on uPVC pipe at a pressure of 2.5 bar, the radial displacement exceeds 6 mm.

CONCLUSIONS

Evidence suggests that the crack deviates from a straight line in gas pressurised pipes due to a dimpling of the pipe wall ahead of the crack tip which produces a tensile stress at the pipe bore and makes the crack directionally unstable. The dimpling is caused by flaring of the pipe walls behind the crack tip, and if this does not occur, e.g. in the initiation region of a gas pipe or in a water pressurised test, or it is suppressed by soil backfill, then the crack follows a straight path. Reducing the tensile stress at the bore by introducing an additional compressive stress across the whole pipe section, also provides directional stability.

However, if the tensile component is present, a small perturbation in loading conditions is sufficient to cause the crack to deviate; in practice, any perturbation will probably be fairy large in a gas pipe fracture due to the turbulent nature of fluid outflow. Once the crack deviates from a straight path, the section (or 'flap') of pipe into which the crack extends will exhibit a lower bending stiffness. This flap will then accelerate more rapidly than the opposing flap which will change the direction of the principal opening stress at the crack tip (i.e. where the local K_{II} = 0). The crack will turn along the direction normal to the principal opening stress to follow the path of maximum available energy. When the crack crosses the axial line, the same process is repeated. As we observe from the optical gauge experiments, the flap acceleration oscillates with the change in bending stiffness of the flap, which will be at the same frequency as the crack path oscillations.

The best known analytical solution for the critical pressure for RCP in pipes, developed by Irwin and Corten in the late 60s (2), assumes that all, and only, the strain energy stored in the pipe wall drives the crack. It has been known for many years that this is unrealistic for gas pressurised pipelines since it is the external work of the discharging gas which predominately drives the crack. However, later work suggests that the analysis is applicable to water pressurised pipe provided that the inertia forces in the fractured pipe are negligible (3). Such small measured deflections in the hydrostatic S4 tests appear to support this assumption. Therefore, as previously proposed (3), the Irwin–Corten analysis is valid to calculate G_D for a polymer material from p_c measured by the hydrostatic S4 test.

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SYMBOLS USED

p_c = critical pressure (Nm^{-2})
G = crack driving force (Jm^{-2})
G_D = dynamic fracture resistance (Jm^{-2})
t = time (s)
K_{II} = stress intensity factor (Nm$^{-3/2}$)

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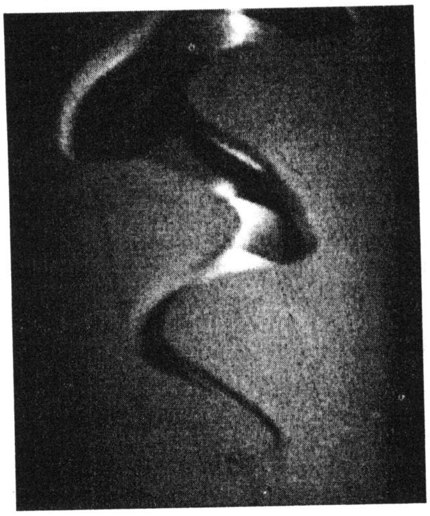

Figure 1 Crack path and deformation of a 125 mm dia. MDPE pipe during RCP

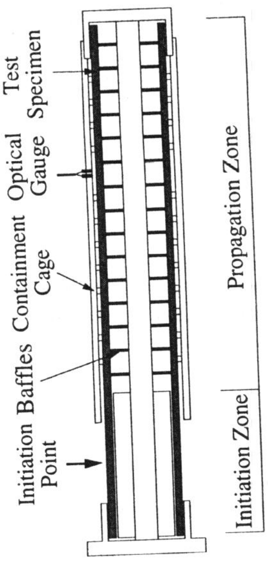

Figure 2 The small scale steady state test with optical gauge

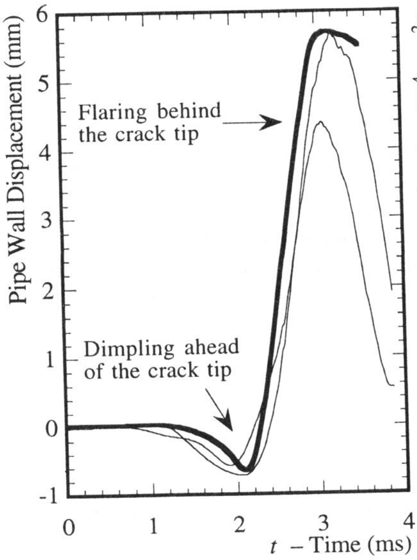

Figure 3 Pipe wall deformation during RCP (— FV Analysis — Optical Gauge)

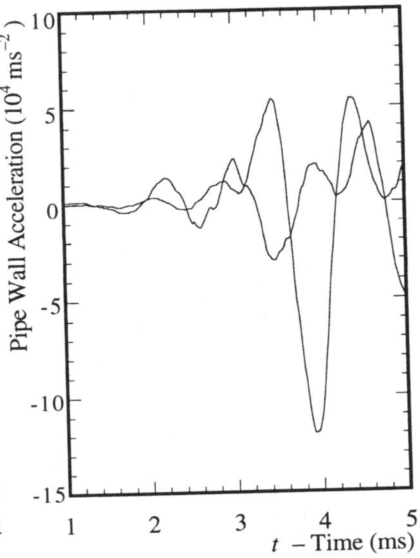

Figure 4 Pipe wall accelerations measured both sides of a running crack