A NOVEL TECHNIQUE FOR THE STUDY OF RAPID CRACK PROPAGATION IN PLASTIC PIPES

P. Yayla * and P.S. Leevers *

Rapid crack propagation in pressurised polyethylene pipes is studied using a recently developed small scale test technique. Experimental results show that this test develops fast, steady state crack propagation above a well defined critical pressure. The effects of parameters such as pipe wall thickness, temperature and material grade, believed to affect the critical pressure, are studied.

INTRODUCTION

Because of its competitive short and long term performance, cost effectiveness and easy installation, the majority of the pipe being installed in gas and water distribution systems is made of plastic, specifically of polyethylene (PE). Two criteria dominate the design of these pipeline networks: resistance to Slow Crack Growth (SCG) and to Rapid Crack Propagation (RCP). RCP may ensue if a fast crack is initiated by 'third-party' damage or from a stress concentration, and can result in extensive damage to the pipeline system and pose a hazard to the public. Since the damage and failure mechanisms of these potential failure modes differ in many ways, a material with good SCG performance does not necessarily have high RCP resistance, so that a safe pipeline system must satisfy two criteria independently. Since the time scale considered for SCG is 50 years, quite reliable accelerated test techniques have been developed and used successfully to evaluate the performance of the pipe grade material. To define the RCP performance of PE pipes, full-scale (FS) field tests have been carried out by a number of test centres, but there can be little argument that British Gas has established the largest database during a series of tests since the late 70's, Greig and Ewing (1), Greig (2). Although these FS tests are widely accepted as authoritative, they are time consuming, laborious and very expensive.

* Imperial College of Science, Technology and Medicine,
Mechanical Engineering Department, London, UK

RAPID CRACK PROPAGATION IN PE PIPES

If the operating pressure exceeds a certain value (the critical pressure, p_c) an initiated crack may run axially at very high and relatively constant speed (100 to 350 ms^{-1}) for great distances along the pipeline. The crack propagation path is not usually straight but follows a regular sinusoidal snaking along the top of the pipe. Although under normal circumstances PE materials are known for their high ductilities, RCP results in very brittle and smooth fracture surfaces.

RCP is a very complex event. It involves strong interactions between the dynamics of the escaping gas, the deformation and dynamics of pipe wall and backfill in front of and behind the crack tip, and dynamic fracture mechanics. Thus, the complete analysis of the problem requires the solution of coupled nonlinear equations even for linear materials. However, the non-linear viscoelastic nature of PE, Wheel and Leevers (3), introduces further difficulties. The accumulation of non-linearities makes analysis of the problem almost insolubly complex.

Using fracture mechanics principles, the first and simplest attempt to propose a design criterion came from British Gas, Greig and Smith (4). It is assumed that all of (and only) the strain energy stored in the pipe wall drives the fracture process. This formulation leads to:

$$p_c = \frac{t}{D}\sqrt{\frac{8\,E\,G_D}{\pi D}} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \qquad (1)$$

(known as the Irwin-Corten equation), where t is the wall thickness and D the outside diameter of the pipe, and E and G_D are the dynamic modulus and dynamic fracture toughness, respectively, of its material. To some extent this equation seems to be satisfactory in that it includes the parameters believed to dominate RCP. In particular, FS tests reveal that p_c increases as the pipe diameter increases and the thickness decreases. However, the analysis rests a number of arguable simplifying assumptions:

1) The initial line pressure rather than the actual crack tip pressure is taken into account in calculating the strain energy ahead of the crack tip.

2) The only crack driving force is assumed to be the strain energy stored in the pipe wall; no consideration is given to work done by the pressure acting on separated flaps behind the crack tip.

3) No account is taken of residual stresses, which may make a significant contribution to the crack driving force.

4) All of the strain energy in the pipe is considered to have been absorbed in creating new fracture surface. Other energy sinks may include permanent pipe wall deformation.

5) The properties and dynamics of the contained fluid, *i.e.* water, air or natural gas, are not considered.

A NEW TEST TECHNIQUE FOR STUDYING RCP

The use of Equation (1) requires dynamic fracture resistance and dynamic elastic modulus data for the material, Wheel and Leevers (3). However pipe acquires its own structural properties the manufacturing process, and its service performance may not be completely characterised by a small specimen. Thus the expense of FS tests, the complexities of analytical and numerical analysis, and doubts about material properties have motivated the development of a SS test to characterise as-extruded pipe. The objective of such a method is to observe the behaviour of an already initiated brittle fast crack. The test must be designed in such a way that whether the initiated crack propagates to the end of test pipe or arrests, decompression in front of the crack tip should be suppressed. This condition is essential to SS tests; if it is not satisfied, a longer pipe length is needed to attain the steady-state gas dynamic of an actual pipeline system.

Although the first SS ('Modified Robertson') test technique, proposed by Vancrombrugge (5), did allow RCP to be studied, the gas dynamics aspect introduced uncertainties which have raised doubts about its definition of a reliable 'propagate-arrest' criterion. The near-tip pressure changes during crack propagation so that it is impossible to determine whether crack arrest is due to lower initial pressure or continuously decaying crack tip pressure. The lack of a sound correlation between this SS technique and FS tests was also another aspect which encouraged us to develop a new SS test technique.

The method developed with these observations in mind is shown schematically in Fig. 1. The main design features can be summarised as follows. A fast crack is initiated by impact of a gas-gun fired chisel projectile, with a blade of a 70 mm length and 15° tip angle, on a well supported initiation zone. This eliminates specimen preparation procedures such as super-cooling or a specially machined initiation zone, achieving embrittlement by strain rate alone. The artificially initiated crack is injected into a propagation zone along which internal gas flow baffles, and external containment cage against flaring, suppress decompression and control the crack tip environment.

EXPERIMENTAL RESULTS

Using this method, experiments were carried out on various medium and high density PE gas and water pipes at various test pressures and temperatures. All pipes tested so far were of 180 mm diameter, of Standard Dimensional Ratio (SDR, the ratio of the outside mean diameter to pipe wall thickness) 11 and 17.6. The effect of pipe grade on RCP performance has also been studied. A series of pipes were instrumented with timing wires to measure the crack propagation velocities under different conditions.

Crack Propagation and Arrest

After calibration tests on each material to set crack initiation conditions, critical pressure definition tests were performed between pressures of 0 bar to 15 bar (in some cases up to 25 bar). For each test the corresponding final crack length was measured. Typical results (Fig. 2) illustrate crack arrest up to 2 bar, at which there is a sharp transition to complete propagation. This well defined critical pressure is the most characteristic feature of FS tests.

Using timing wires, a series of experiments were carried out to observe the nature of crack arrest and propagation, Yayla and Leevers (6). These tests showed that crack velocity decreases as the crack crosses the transition seal, and then either rapidly falls to zero or settles to a constant value along the pressurised gauge length. Similar instrumented tests with higher propagation pressures have shown that the crack velocity increases steadily with pressure, asymptotically approaching the maximum attainable value predicted by Kanninen (7).

Temperature Effect

Since FS tests show strong temperature effects on RCP performance of PE pipes mentioned in references (1) and (2), the present method was used to measure p_c at different temperatures. For a medium density PE pipe, increasing the temperature from -15°C through 0°C to 10°C increased p_c from 2.05 bar through 2.1 bar to 4 bar, respectively. A further temperature increase from 10°C to 15°C eliminated RCP for any test pressure up to 15 bar.

Underlying this dramatic effect of temperature on p_c is a variation of crack speed with temperature at constant pressure. The average crack velocity for a series of tests on MDPE 180 mm SDR 17.6 pipe at 2.5 bar, at different temperatures, is plotted in Fig.3. The crack speed decreases slightly with temperature as the temperature is increased from -20°C to -5°C, but a small further increase in temperature above 0°C drastically reduces steady state crack velocity.

Pipe Wall Thickness Effects

A major concern of PE pipe manufacturers and users is the effect of thickness on pipe performance. This was studied in two different ways. Firstly, the SDR ratio was decreased from 17.6 to 11 (i.e. wall thickness was increased) and a number of tests were performed at different temperatures. For 0 °C, 10°C and 15°C p_c was 2.25 bar, 4.5 bar and 13 bar, respectively. These results are surprising: a thickness increase of about 60% has improved p_c by only around 10% at 0°C and 10°C. For higher temperatures, thicker pipe actually becomes worse.

The effect of thickness was studied more directly by turning down the thickness of 180 mm SDR 11 pipe, in graduated steps of one-diameter length, from initial value of 17.1 mm to a final value of 4.5 mm. A fast crack was injected into this stepwise-tapered section - using the standard technique - at a pressure of 3.5 bar, some 55% above the critical value.

The measured crack velocity fell at each decrease in thickness, then quickly stabilised again, until the crack arrested as it entered 7.1 mm thick wall (Fig.4). Post-mortem investigation of the fracture surfaces revealed an increase in ductility and width of 'tear lips' at each decrease in thickness. This can seen as a plane-strain to plane-stress transition in which both rate and constraint participate. A significant observation from these experiments is that there is a minimum crack velocity limit below which steady propagation of the crack cannot be sustained. Our experimental measurements have indicated that the value of this minimum crack velocity strongly depends on the temperature but is independent of the pipe wall thickness.

Material Grade Effect

If the technique which we have described is to be a serious contender as a type or quality control test, it must show a similar discrimination to *type* as the full scale test. Our ability to prove this has been limited by the need to ensure that identical grades of two contrasting materials are similarly extruded into pipe of 250 mm diameter (as tested by British Gas) and of 180 mm diameter for our own tests.

To define the effect of resin type on RCP performance, pipe of a high density PE, given a higher pressure rating by British Gas on the basis of FS tests, was tested using the present technique. Although cracks were successfully initiated at 0°C, albeit at the considerably higher chisel impact velocity of 40 m/s, RCP could not be sustained at any pressure up to 25 bar. Reducing the temperature to -15°C, however, again demonstrated a clear RCP transition at 10 bar, illustrating the dramatic improvement in RCP performance over standard grades already signalled by its 7-bar British Gas service pressure rating. At - 30 °C, the critical pressure has fallen to 3 bar, indicating that there may be a similar temperature-activated transition to that seen in the MDPE grades, but occurring at a much lower temperature.

REFERENCES

(1) Greig, J.M. and Ewing, L., "Fracture Propagation in Polyethylene Gas Pipes", Plastic Pipe V, York, September, 1982, pp. 13.1-13.11.

(2) Greig, J.M., "Fracture Arrest Conditions in Polyethylene Gas Pipe", Plastic Pipe VI, York, March, UK, 1985, pp. 20.1-20.8.

(3) Wheel, M.A. and Leevers, P.S., This Conference.

(4) Greig, J.M.and Smith, T.R., "Plastic Pipes — Fracture Considerations", PRI Conference, Designing to Avoid Mechanical Failure, Cranfield, 1973.

(5) Vancrombrugge, R., "Fracture Propagation in Plastic Pipes", Plastic Pipe V, York, September, 1982, pp. 11.1- 11.8.

(6) P.Yayla, P. and Leevers, P.S., "A New Small Scale Pipe Test for Rapid Crack Propagation", Proceedings 11th Plastic Fuel Gas Pipe Symposium, San Francisco, October 3-5, 1989.

(7) Kanninen, M.F., Int. J. of Fracture Mech., Vol.9, 1970, pp. 94-95.

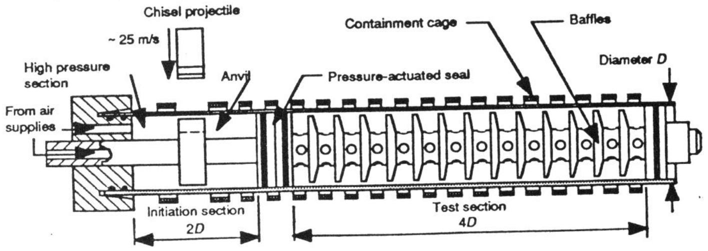

Figure 1 Schematic representation of SS pipe test device

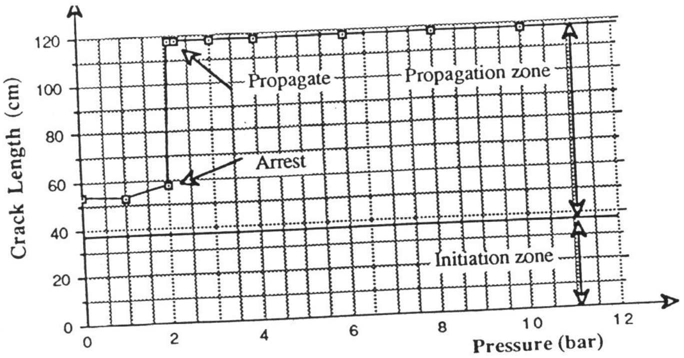

Figure 2. Variation of final crack length with test pressure showing a sudden transition from crack arrest to crack propagation at a pressure about 2.05 bar for MDPE-1 180 mm SDR 17.6 pipe at -15°C

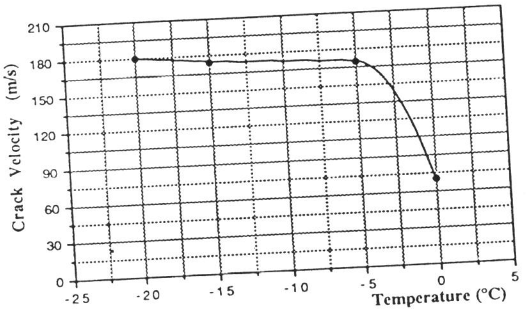

Figure 3. Variation of test temperature upon crack velocity for the pressure of 2.5 bar for MDPE-1 180 mm SDR 17.6 pipe

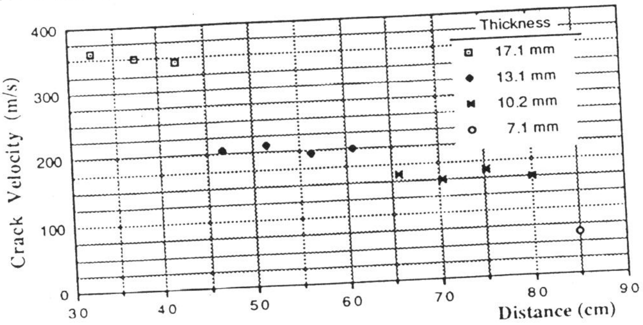

Figure 4 Variation of the crack speed with pipe thickness showing a stable crack speed for each different thickness.