FRACTURE TOUGHNESS AND CRITICAL PRESSURE EVALUATIONS FOR POLYETHYLENE PIPELINES; A COMPUTATIONAL METHODOLOGY AND EXPERIMENTAL VALIDATION

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ABSTRACT

An approach to assess the likelihood of dynamic fracture in polymer gas pipelines is described in this paper. This problem is of importance when a crack can propagate in a rapid manner in the axial direction of a pressurised pipeline. This requires a procedure to determine both the fracture toughness of the pipe material and also the crack driving force for propagation in a pipe. The experimental work involved an instrumented test on a relatively short section of pipe and this is referred to as the Small Scale Steady State test. A computational scheme using a finite element package called PFRAC is then used to analyse the test and extract the fracture toughness. Further, the PFRAC package can be used to simulate the pipe under operating conditions and, in this way, the crack driving force and subsequently the critical pressure for crack propagation can be determined. To establish the validity of the scheme, comparisons of the numerical predictions are also made with available experimental data.

KEYWORDS

polymer, dynamic, propagation, fracture toughness, numerical simulation

INTRODUCTION

Polyethylene (PE) pipes are frequently used for gas distribution and the recent industrial trend has been the move to larger diameter and higher pressure systems. Based on the experience for steel gas transmission pipelines, this has prompted an increased awareness of the possibility of rapid crack propagation (RCP) in the axial direction. Over the past ten years, this has been the focus of considerable interest from the research community. Several studies have been carried out (Greig, 1985; Krishnaswamy et al., 1986; Yayla and Leevers, 1989; Kanninen et al., 1989; Vanspeybroeck, 1992) to investigate the problem of RCP in the PE pipes used in gas distribution.

This paper takes the view that the problem of RCP must be resolved using a fundamental fracture mechanics approach. Essentially, the dynamic fracture toughness is a basic material property which can be determined through laboratory experimentation and, in this instance, appropriate structural analyses. Once this quantity is known, it can then be applied to field operating conditions to establish if continued fracture will take place.

BACKGROUND

Fracture Mechanics Concepts

Crack propagation in PE gas pipes cannot be totally excluded as initiation can occur at the site of a slow crack growth, as a result of third party damage or as the result of some other unforseeable mechanism. It is however highly desirable that these cracks should arrest after travelling a short distance. In the present application, dynamic fracture can be viewed as a competition between the driving force of the gas pressure and the material resistance to fracture. For crack propagation to occur, the following equality must be satisfied:

$$J(p_L, D, SDR, E_D) = J_D(T, v, h) \tag{1}$$

The driving force, J, is a function of the initial internal pressure, p_L, the pipe diameter, D, the SDR (ratio of the outer diameter to the wall thickness) and, to a lesser extent, the dynamic modulus, E_D. The material fracture toughness, J_D, depends on the temperature, T, the crack velocity, v, and also the wall thickness, h. When the equality expressed by Equation (1) is satisfied, conditions are conducive to the undesirable situation of steady state crack propagation, with the crack travelling at a constant velocity over a long distance.

Computational Procedures

A significant obstacle in the analysis of pipeline fracture has been the lack of a suitable computational tool for the complex fluid/structure/fracture behaviour that occurs. This impediment has now been overcome by a Southwest Research Institute computer simulation package, PFRAC which has been specifically customised for axial propagation in pipelines. This was initially developed for steel gas transmission pipelines (O'Donoghue et al, 1991) and was subsequently modified for gas distribution pipelines (Kanninen et al., 1991). Through comparisons with available full scale data, the program has been successfully used to predict cases of crack propagation and arrest.

There are three basic segments to this code; a structural mechanics unit, a fluid mechanics unit and a fracture mechanics unit. The structural mechanics portion incorporates a Lagrangian finite element description with four node quadrilateral elements that allow for geometric nonlinearities. An explicit finite difference scheme is used to march forward in time. This code is ideally suited for shell like structures undergoing large deformations such as the flap opening exhibited by ruptured pipes. A node release algorithm was implemented to numerically simulate crack propagation in the finite element code. The crack driving force is then calculated using the work done by the release of nodal forces. Finally, a three dimensional finite difference scheme was used to model the complex, highly transient flow that takes place when the pipeline is fractured. The shell finite element module and the finite difference module are linked such that the gas pressures are used to calculate the forces on the opening wall and this in turn defines the containment for the gas.

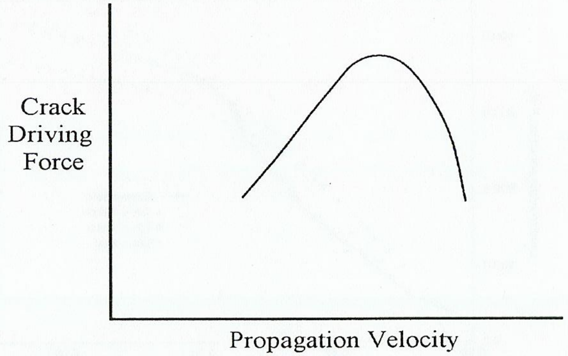

Fig. 1. Schematic Illustration of driving Force Variation with Steady State Velocity

As mentioned above, this code can be used to calculate the crack driving force for a crack propagating in a pipe. To examine the conditions of steady state crack propagation, parametric computational studies have been carried out with different imposed constant velocities for a given set of operating conditions (Kanninen et al., 1991). These analyses show that when each steady state crack driving force value is plotted against the corresponding velocity, the curve takes on a dome like shape. This is schematically illustrated in Fig. 1. Thus, there is a maximum, J_{max}, for some velocity in the range of typical crack propagation velocities. The presence of this maximum, which can be justified on theoretical grounds (Kanninen et al., 1991), is a key factor in the approach that will be used here to determine the critical pressures.

Fracture Toughness

A small scale steady state (S4) test has been developed by Yayla and Leevers (1989) and here small sections of pipe are used to measure critical pressures for propagation. The S4 test facility is illustrated in Fig. 2. Crack initiation is achieved when the air driven chisel impacts against the PE pipe. The crack then propagates along the pipe in the axial direction. Baffles, placed inside the pipe at regular intervals in the axial direction, have the effect of preventing gas decompression and maintaining the initial line pressure. In this way, the steady state condition will be achieved in a shorter section of pipe. The containment cage rings are made from sectioned steel pipe and limit the flaring of the pipe walls to no more than 110% of the outer diameter of the pipe. An insulated refrigerated chamber is used to bring the pipe section to the required test temperature.

A modification to this test has recently been proposed by Grigory et al. (1995) and this can be used to extract the dynamic fracture toughness for the pipe material. The idea is to perform an instrumented S4 test where the crack velocity and the pressures are recorded. As described in the next section, a PFRAC analysis is then carried out to determine the dynamic fracture toughness. The crack velocity was determined from a series of timing wires that break as the crack propagates axially. The wires are connected to a high speed data acquisition system that

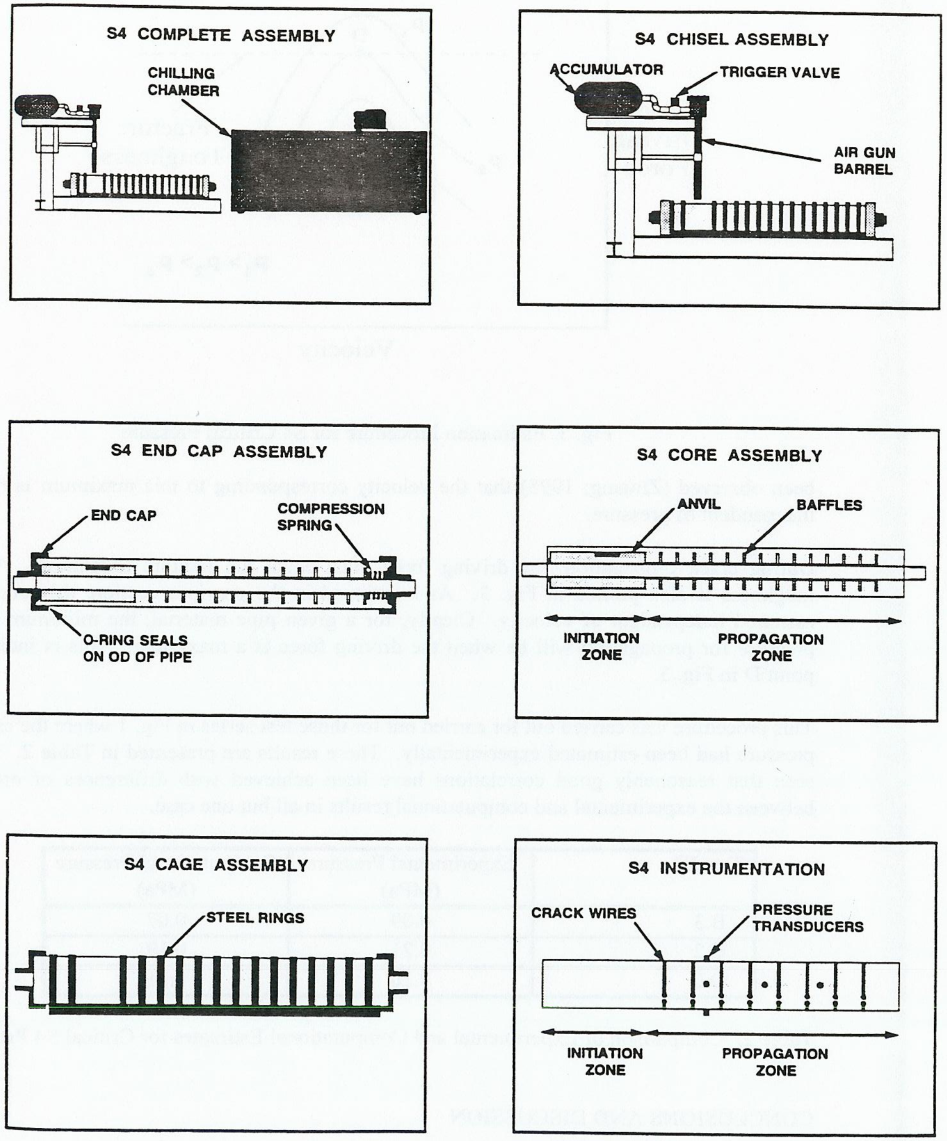

Fig. 2 Schematic of S4 Test Apparatus

detects the precise time that the circuit is broken by the crack. In addition, a group of pressure transducers was installed in through wall holes at various locations to record the pressure profile inside the pipe during propagation.

DETERMINATION OF THE DYNAMIC FRACTURE TOUGHNESS

Several instrumented S4 tests have recently been conducted (Grigory; 1995) and the results of these tests are analysed here to obtain the corresponding material fracture toughnesses. All tests were conducted on either 10" (254 mm) or 12" (305 mm) diameter pipe sections and in each case the propagation zone was 6 diameters. This length was selected after some initial scoping experiments to ensure that steady state propagation was achieved over a measurable distance. Variables in these tests included the pressure, temperature and wall thickness in addition to different materials. In all, data from five different manufacturers are included and can involve different material types from the same manufacturer in some cases. The specifics of these tests are recorded in Table 1. From observations of the experimental data, as seen in Grigory at al. (1995), the crack velocity is reasonably constant in the region of interest. This indicates that steady state propagation conditions are likely to exist. This is the velocity that is recorded in Table 1.

In each analysis, the crack driving force is calculated as a function of position. It has been observed that the driving force is reasonably constant in the region where steady state propagation is observed. This constant driving force is the material fracture toughness, J_D, at the corresponding velocity. These values are also presented in Table 1 for each of the tests. A number of points will now be made concerning these results.

The PFRAC code was then used to simulate each of the tests in Table 1 in order to determine the material fracture toughness. A key input to the computer analysis was the measured crack

Test ID	Diameter (mm)	SDR	Temp (^oC)	Pressure (MPa)	Velocity (m/s)	Toughness (kPa m)
A.1	254	11	0	0.31	192	4.9
A.2	254	11	0	0.21	182	4.5
A.3	254	11	10	0.31	136	9.1
A.4	254	13.5	0	0.21	180	4.9
A.5	254	13.5	0	0.31	190	5.4
A.6	254	13.5	10	0.41	117	11.7
B.1	254	11	0	0.10	210	2.3
B.2	254	11	0	0.14	251	3.1
B.3	254	11	0	0.12	221	1.8
C.1	305	11	0	0.31	219	4.4
C.2	305	11	0	0.31	195	6.1
C.3	305	11	0	0.31	152	8.4
D.1	254	11	0	0.21	221	2.6
D.2	254	11	0	0.17	193	2.9

Table 1: S4 Instrumented Tests with Average Crack Velocity and Fracture Toughness Data

velocity record as a function of position. Essentially the computer program is used to perform a generation phase analysis of the experiment. The measured pressures can also be used but in most cases, these are calculated directly using the PFRAC code. As the time frame of the test is relatively short (less than 0.05 seconds), a rigorous viscoelastic material model is not required as the compliance will not change significantly. However, strain rate effects are significant and a strain rate material model must be included to capture the high rates that are exhibited near the crack tip.

The results show a wide variation in toughness between the specimens. These are not only dependent on the manufacturer but also, as expected, are dependent on temperature velocity and thickness. For example, consider the results from set A. Here the same material is used in each case. It can be seen by comparing A.1 and A.3 that the toughness is almost doubles as the temperature rises by 10°C. This is consistent with the fact that toughness rises with temperature. The toughness variation with velocity can also be examined. Considering cases A.4 and A.5, it can be seen that there is a slight rise in toughness as a function of crack velocity. This is consistent with the trend in other materials. However this increase is not very large and is within the experimental scatter. Thus, in the analyses in the next section, the toughness will be assumed constant with temperature.

CRITICAL PRESSURE FOR PROPAGATION

One of the objectives of the S4 test methodology was to determine the critical pressure for crack propagation. This is the lowest pressure at which a crack propagated the length of the pipe. At lower pressures, the crack will simply arrest after travelling a short distance into the propagation zone. It is important to point out that the critical pressure in the S4 test does not and should not be the same as for a pipe under full scale operating conditions. Under full scale conditions, axial gas decompression takes place ahead of the crack so that the actual crack tip pressure and, consequently, the driving force are reduced. This gas decompression is prevented by the baffles in the S4 test. Thus, the critical pressure in the full scale configuration will be considerably higher than in the S4 test (Greig; 1996).

The instrumented tests described in Table 1 were not carried out at the critical S4 pressures. Rather, these tests were carried out at pressures significantly above the critical S4 pressure to ensure propagation. However, in some instances, the tests in Table 1 were part of a larger series of (uninstrumented) tests in which the S4 critical pressure was determined by a trial and error procedure (Yayla and Leevers; 1989). An obvious challenge is to use the dynamic fracture toughness to *predict* the critical S4 test pressure. This will serve as additional validation of the numerical procedure and also invokes the fundamental dynamic fracture principle given by Equation (1).

There are a number of key steps required in order to make this prediction. Fig. 1 indicated that the driving force attains a maximum value in the range of typical crack speeds. This concept is now extended in Fig. 3. For a given S4 test pressure, a computational study is again carried out at a range of different crack velocities. This is now repeated at several different pressures. The resulting series of curves is schematically illustrated in Fig. 3. It is important to remember that a point on one of these curves represents the available crack driving force for that pressure if the crack was to propagate at that velocity. Each of these curves has a maximum and it has been observed (Zhuang; 1995) that the velocity corresponding to this maximum is relatively independent of pressure.

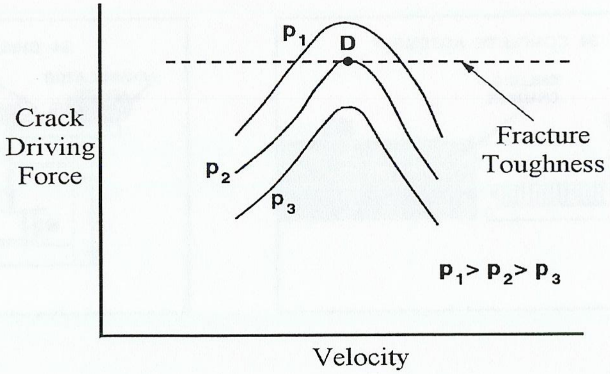

Fig. 3. Estimation Procedure for S4 Critical Pressure

During crack propagation, the driving force must equal the fracture toughness. A typical toughness is also plotted in Fig. 3. As mentioned in the previous section, the toughness is assumed independent of velocity. Clearly, for a given pipe material, the minimum (critical) pressure for propagation will be when the driving force is a maximum. This is indicated by point D in Fig. 3.

This procedure was carried out for carried out for those test series in Fig. 1 where the critical S4 pressure had been estimated experimentally. These results are presented in Table 2. It can be seen that reasonably good correlations have been achieved with differences of order 10% between the experimental and computational results in all but one case.

Test ID	Experimental Pressure (MPa)	Computational Pressure (MPa)
B.3	0.09	0.07
C.2	0.21	0.19
D.2	0.10	0.11

Table 2: Comparison of Experimental and Computational Estimates for Critical S4 Pressure

CONCLUSIONS AND DISCUSSION

The agreement between the experimental and computational estimates for the S4 critical pressure is certainly encouraging. The obvious next step is to determine the (higher) critical pressure for continued crack propagation in the case of full scale operating conditions. These results will obviously be of great practical importance to the gas industry. While this is a reasonably straight forward task using PFRAC, very limited test data are available for comparison due to the size and expense of full scale experiments. It is hoped that more experimental data will be available for these comparisons in the near future.

The success of the approach outlined here demonstrates that some problems of dynamic fracture can only be solved through an integrated experimental/computational scheme.

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