Correlation between full scale and small scale steady state (S4) tests for rapid crack propagation in plastic gas pipe

C. J. Greenshields and P. S. Leever

The full scale and small scale, steady state (S4) tests are the principal methods for measuring the critical pressure above which rapid crack propagation can occur in a gas pressurised plastic pipe. The full scale test delivers a critical pressure which directly reflects service performance. The S4 test is less costly, but produces a critical pressure which is significantly lower than that of the full scale test. The discrepancy in critical pressures is due largely to differences in gas dynamics of the two tests. A well known gas dynamics analysis, which has previously been incorrectly applied, is used in the present work to derive a correlation function, which compares well with limited experimental data. Further experiments and analysis illustrate some other factors that influence the correlation and suggest that the application of a more precise correlation function is impractical.

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INTRODUCTION

Fast brittle fracture in a pressurised plastic pipe is characterised by long cracks extending axially at a speed in excess of 100 m s^{-1} , closely followed by rapid escape of the contained fluid. The discharge alone from a fuel gas pipe can be extremely destructive and the threat of an explosion presents an even greater hazard. The axiom for design against brittle fracture is therefore to ensure that any running fracture will promptly arrest, thus insuring against any unforeseen crack initiation event.

At a sufficiently low temperature there exists a critical pressure p_c above which a crack can propagate indefinitely and below which it will promptly arrest. At a critical temperature, there is a sudden transition from brittle to tough behaviour above which rapid crack propagation (RCP) can no longer occur at any attainable pressure. The critical pressure and transition temperature together provide a clear delineation between crack propagation and arrest regimes and therefore form the basis for assessing pipe performance.

The current method of classifying polyethylene (PE) pipes is based upon the minimum required strength (MRS), which is the long term hydrostatic strength extrapolated to 50 years life at 20°C . Polyethylene pipes with an MRS of 10.0 MPa are referred to as PE100 and those with an MRS of 8.0 MPa as PE80. This nomenclature does not give any guarantee for RCP performance, although the PE100 class materials generally outperform PE80s: as a general rule, a PE100 pipe is expected to exhibit a brittle-tough transition temperature T_{BT} below 0°C , whereas a PE80 pipe is not. The (European) gas industry requires that all gas pipes demonstrate adequate resistance to RCP, usually at 0°C . The primary measure of RCP performance for grades that show brittle crack propagation at this temperature is p_c . The principal methods used to measure p_c are the

full scale (FS) and small scale steady state (S4) tests, developed by British Gas and Imperial College, respectively, and now both ISO standards.^{1,2} This paper discusses some factors which affect p_c in each test and therefore the correlation between them.

STANDARD RCP TESTS

The FS test is designed to reproduce some idealised service conditions for a pipe in service. It defines the absolute standard for RCP testing and delivers the final judgement on the pressure carrying capacity of a pipe. The S4 test attempts to simulate the same conditions within the confines of a laboratory and is preferred for materials development and research because it offers significantly shorter test times and lower costs.

Full scale test

The test uses a pipe specimen of at least 14 m in length, which is placed in a trough with cooling water circulating around it to maintain a consistent test temperature. The pipe is buried in gravel, of size $20\text{--}40 \text{ mm}$, to at least 100 mm above its upper surface. This both simulates recommended installation conditions and helps to prevent the pipe from floating during preconditioning in the cooling water. The pipe is extended by a steel pipe, of at least the same diameter and twice its length, in order to simulate an infinitely long pipe by attenuating decompression wave reflections from the specimen end. For reasons of safety, the pipe is pressurised with air or nitrogen rather than natural gas. A crack is initiated by a steel blade, driven radially into the pipe wall near one end, where it has been cooled locally to approximately -60°C . Crack propagation is treated as being continuous when this crack extends for more than 90% of the specimen length; otherwise the crack is considered to have arrested.

A pipe specimen, 7 diameters in length, is sealed at both ends and pressurised with air (Fig. 1). A sharp, chisel ended striker impacts the pipe near one end and drives a fast running crack into the main test section of the pipe. While the crack propagates along the pipe, axial decompression is suppressed by internal disc baffles, spaced along the pipe length. A containment cage surrounds the pipe to limit outward radial deformation, or 'flaring', of the fractured pipe during a test. Its purpose is to restrict the failure process to one of steady propagation, rather than one of transient bursting which can produce a spurious crack arrest at supercritical pressures. The cage does not simulate the constraint on crack opening imposed by backfill in a buried pipeline because it does not reproduce the inertia, friction, or constitutive behaviour of soil or gravel.

A brief review of gas dynamics of RCP is presented for the sake of completeness, although more detailed descriptions can be found elsewhere.³⁻⁵ The process of decompression due to fracture occurs in two phases (Fig. 2). First, axial backflow follows a decompression wave which travels ahead of the propagating crack tip. The remaining pressure is then lost by transverse discharge through the crack opening.

Following the arrival of the decompression wave-front at any point along the pipe, the pressure begins to decay from its initial value p_0 . The pressure at the crack tip p_t gradually decreases until it stabilises when the total crack opening area becomes larger than the internal cross-section of the pipe. For a constant crack speed $\dot{a}$, one-dimensional gas flow analysis gives

where γ is the ratio of specific heats at constant pressure and volume and c_0 is the speed of sound in the pressurised gas. In practice the crack speed fluctuates during RCP so equation (1) cannot be rigidly adhered to when discussing axial decompression. Expansion wave theory shows that as crack

speed decreases, p_t decreases instantaneously according to equation (1). Following an increase in crack speed, however, p_t responds only gradually as the crack overtakes regions of increasing pressure, each travelling at a characteristic speed, which form an 'expansion fan' behind the decompression wavefront.

Pressure decay accelerates considerably behind the crack tip as axial flow is augmented by flow through the crack opening (Fig. 2). The rate of discharge depends on the size of the crack opening which, in turn, depends on the gas pressure. It is primarily the action of pressure on the flaring pipe wall behind the crack tip that generates the work to drive the crack.

An FS test critical pressure p_{cFS} is always higher than a critical pressure measured in the S4 test p_{cS4} . The latest experimental evidence⁶ shows the $p_{\text{cFS}}/p_{\text{cS4}}$ ratio ranges between 5 and 9. These values set bounds for a correlation factor between p_{cFS} and p_{cS4} , which is primarily attributed to differences in gas dynamics between the two tests. Variations within these bounds may be attributed to backfill, pipe wall residual stresses, and crack dynamics.

In the S4 test, the decompression baffles practically eliminate axial backflow in order to suppress the transient process of pressure reduction ahead of the crack tip that occurs in the FS test. The consequence is, however, that the initial pipe pressure contributes fully to drive the crack whereas in the FS test only the crack tip pressure, which survives axial decompression, can contribute. The assumption that transverse gas discharge is similar in both tests allows the relationship between p_t and p_o in equation (1) to be simply translated into p_{cS4} and p_{cFS} at critical conditions. The FS–S4 correlation then becomes a function of $\dot{a}$, but the assumption $\dot{a} = 0$ has been adopted⁷ to produce a single correlation factor of 3.6 which is used by industry to date. This assumption is probably best justified by the fact that, during RCP in PE, the crack tip often arrests momentarily in a process commonly known as ‘stick–slip’. During arrest the

3 Predicted (—) and measured critical gauge pressures in S4 and FS tests: (□) single surface cooled pipe with backfill (after Ref. 6); (○) dual surface cooled pipe with backfill (after Ref. 6); (■) single surface cooled pipe without backfill (after Ref. 8)

pressure can fall almost instantaneously to 28% ($1/3.6$) of p_0 , and will recover only gradually following re-initiation.

Early collaborative FS and S4 experiments⁷ indicated a ratio p_{cFS}/p_{cS4} of 3.6, which immediately lured the RCP research community to think that all S4 critical pressures, presented as gauge pressure, i.e. excess pressure above atmospheric pressure, could be simply scaled up to the FS by a factor of 3.6. However, the S4 test standard was later modified to ensure that the crack initiation event should not significantly influence subsequent propagation: an arrester was introduced to prevent impact between the main body of the initiation striker and the pipe wall. This significantly improved test consistency⁶ but also allowed the pipe wall to open freely during fracture, thereby reducing p_{cS4} and increasing the FS–S4 correlation factor to more than 5. The discrepancy between measured and theoretical correlation factor has caused much debate for several years but further reflection has revealed an error in the interpretation of equation (1), which is expressed in terms of absolute pressure. Denoting pressure as gauge pressure in units of bar (10^5 Pa) by $\tilde{p}$ gives the correlation

$$\frac{\tilde{p}_{cFS} + 1}{\tilde{p}_{cS4} + 1} = 3.6 \quad \dots \dots \dots (2)$$

or more simply

$$\tilde{p}_{cFS} = 3.6\tilde{p}_{cS4} + 2.6 \quad \dots \dots \dots (3)$$

Equation (3) shows the FS–S4 correlation factor is not a unique value. A useful example to illustrate the correct application of equation (1) is that the correlation factor for a FS critical gauge pressure of 9 bar is 5.0, not 3.6. The correlation relationship of equation (3) is illustrated in Fig. 3 by a single line against which are plotted all available experimental data.^{6,8}

4 S4 test with backfill: a front view; b top view

Some of the discrepancy between prediction and experiment could be due to complexities of the gas flow in the FS test, which are not considered in the axial decompression analysis represented by equation (1). However, other factors that may influence the correlation function are discussed below.

Backfill

In a pipe RCP is affected by any surrounding constraint, such as gravel backfill. The constraint restricts flaring of the pipe wall in the wake of the crack tip and thereby limits the transfer of energy from pressurising fluid to crack driving force. In the most extreme case when radial deformation is completely constrained, p_c will depend only on the release of strain energy from the pipe wall as in fracture of a water filled pipe.⁹ There can be little doubt, therefore, that the presence of backfill increases p_c , but it is

- (□) no backfill
 (■) with backfill
 (■) with compacted backfill
 (■) with backfill compacted in three stages

5 Critical pressures for 110 mm diameter PE80 pipe for different external diameter/thickness (SDR), temperature, and backfill constraint (after Ref. 12)

difficult to assess by how much it is increased for a particular system of backfill and pipe. During ductile RCP in steel pipes, for example, the kinetic energy uptake of the soil is believed to dominate the energy consumption of pipe deformation.¹⁰

A computational model of RCP in PE pipes has been modified to include backfill as a distributed mass of material which is initially in contact with the pipe wall but is able to detach itself during fracture.^{5,11} The results showed that backfill inertia alone causes an increase in critical pressure which becomes appreciable when the distributed mass exceeds that of the pipe. More recently, a 110 mm S4 rig was modified to investigate the effect of gravel backfill on the critical pressure of PE80 pipe (Fig. 4).¹² The pipe was covered in 10 mm sized gravel to a depth of 330 mm, i.e. $3 \times$ diameter. Initially, S4 tests were performed without compacting the backfill. Before subsequent tests, the covering of backfill was compacted by hand and in a final set of tests the compacting process followed each successive filling of a 1 diameter backfill layer. Figure 5 shows an increase in critical gauge pressure with increasing backfill constraint. Evidently, the normal S4 test simulates a worst case, whereas backfill constraint improves the safe pressure carrying capacity of a pipe.

Residual stress

During fracture of a gas pressurised pipe, most of the crack driving force is generated by the pressure of discharging gas which opens the crack flaps. Behind

6 Action of residual stresses on cracked pipe during RCP

the crack tip, residual stresses which generate a circumferential bending moment are released from constraint. In single surface cooled pipe, i.e. extruded pipe which is cooled conventionally by water sprayed onto its external surface downstream from the die exit, this moment tends to close the crack faces. In dual surface cooled pipe, the bending moment is effectively negligible, owing to its symmetrical residual stress profile. A simple analysis has been presented,¹³ which approximates the static pressure p_m required to counteract the moment generated by circumferential residual stresses in single surface cooled pipe before any additional pressure can open the crack. Assuming a residual stress profile, having parabolic form with its maximum stress $\sigma_{\theta B}$ at the bore, gives

$$p_m = \frac{2}{3(D^* - 2)^2} \sigma_{\theta B} \quad \dots \quad (4)$$

where D^* is the ratio of external pipe diameter to thickness. Previous measurements¹³ of residual stress in a typical 250 mm diameter PE80 pipe gave $\sigma_{\theta B} = 2.2$ MPa. By equation (4), the critical pressure for single surface cooled pipe should therefore be higher than that for dual surface cooled pipe by $p_m = 0.2$ bar. Equivalent S4 tests on 250 mm diameter PE80 pipe showed $p_{c,s4}$ to be actually 0.4–0.6 bar higher in single surface cooled pipe. It is quite possible that the difference between analysis and experiment is due to the additional action of residual stresses in the longitudinal direction. These stresses would not generate a moment at the crack face if the crack path were straight, but since the path is typically sinusoidal, a closing moment is able to act on each lobe of the fractured pipe, as shown in Fig. 6.

Crack path

In gas pressurised pipes RCP is usually characterised by a crack path that weaves in a sinusoidal pattern along the pipe axis. This fascinating phenomenon attracts great interest, speculation, debate, and analysis but the most important question is rarely addressed: how does the crack path affect p_c ? Fracture mechanics argues that the energy required to create

unit area of crack surface is a constant G_c . Both analytical and numerical models^{5,9,11} for rapid propagation of a straight crack suggest $p_c \propto (G_c)^{1/2}$ and therefore, $p_c \propto t^{1/2}$, where t is the fracture area created per unit axial crack extension. Experimental evidence shows that the amplitudes A of sinusoidal crack paths range from 0 to $L/2$ where L is the wavelength.¹⁴ Within this range, the arc of a sinusoidal crack is longer than an equivalent straight crack by a factor

$$\lambda \approx \left[\left(\frac{4A}{L} \right)^2 + 1 \right]^{1/2} \quad \dots \dots \dots (5)$$

The critical pressure is expected to be higher by a factor $\lambda^{1/2}$ because t is increased by a factor λ . Substituting $A/L = 0.4$, this simple analysis indicates that the critical pressure for a sinusoidal crack can be up to 50% higher than for a straight crack.

DISCUSSION

There are several factors that can influence the critical pressures in the FS and S4 tests and any correlation between them. The internal baffles in the S4 test purposely alter the gas dynamics of rapid fracture and contribute most to the discrepancy between critical pressures from the two tests. A correlation factor based on simple one-dimensional gas dynamics has been used for several years but with a significant flaw, leading to a prediction of p_{cFS} from p_{cS4} , which is extremely conservative. Equation (3) provides the correct prediction, which agrees well with experimental data and is still fairly conservative. It is of some concern that S4 test requirements based on the erroneous correlation factor 3.6 have been imposed. For example, if the maximum operating pressure of a gas pipe is 4 bar and a safety factor of 1.5 is adopted, the S4 test requirement based on the erroneous correlation factor is $4 \times 1.5/3.6 = 1.7$ bar, which would preclude the use of many PE80 pipes above 100 mm diameter. The correct requirement is $(4 \times 1.5 - 2.6)/3.6 = 0.9$ bar, which almost all commercial PE80 resins would satisfy even in sizes exceeding 250 mm diameter. It can also be argued that a safety factor should be commensurate with the probability that the conditions will arise under which failure could ensue. Essentially RCP is a secondary failure mode, the occurrence of which depends on improbable preconditions. On this basis a safety factor of 1.5 seems unnecessarily high.

Other factors, such as residual stress, can add further small contributions to critical pressure, which may strongly alter the correlation factor. On 250 mm diameter PE80 pipe S4 tests showed p_{cS4} to be 0.4–0.6 bar higher in single surface cooled pipe than in dual surface cooled pipe; analysis shows this disparity could be due solely to the effect of residual stress. The difference in p_c between single and dual surface cooled pipe could appear to be appreciable in the S4 test, e.g. a 40% difference between 1.0 and 1.4 bar, but in the FS test it would be fairly insignificant, e.g. a 4–5% difference between 9.0 and 9.4 bar. In addition, an accurate correlation between FS and S4 test critical pressures would be significantly different for the two methods of cooling (9.0 and 6.7 in this case). The difference in correlation factor is also well

illustrated in Fig. 3, where the results for dual surface cooled pipe are distinguished from those for single surface cooled pipe.

Both numerical simulations and laboratory tests suggest that the presence of backfill in the FS test increases the critical pressure by a small, but not insignificant degree. The closest agreement between test data and the present S4–FS correlation function is for FS tests with no backfill (Fig. 3), supporting the view that p_{cFS} is lower for such a test than for a standard test with backfill. It has now been proposed that the FS test specification should deliver a worst case p_{cFS} and should therefore be performed without backfill.¹⁵

Similarly, if crack path influences p_c , the S4 and FS tests should promote that path which induces a worst case p_c . There may be more than one stable crack propagation state for a pipe, each at a different crack speed and crack path, and therefore with a slightly different critical pressure. The crack dynamics must then be understood quantitatively, rather than qualitatively, in order to predict the propagation states of a test. The problem is complex because the crack path is certainly linked to crack speed which is itself influenced by the ductile nature of PE pipe fracture. The subject of crack path should benefit from basic research on brittle–tough transitions in plastic pipes but it may be some time before any definite answers are forthcoming.

CONCLUSIONS

The full scale–small scale steady state (FS–S4) correlation factor is determined primarily by differences in gas dynamics. The relationship described by equation (3) delivers a fair and conservative estimate of the FS test critical pressure p_{cFS} from the S4 critical pressure p_{cS4} . It is probably neither feasible nor desirable to make further adjustments to the correlation to account for other secondary effects. It seems reasonable that the suitability of pipe for service could be assessed using the S4 test with the revised correlation function, without the need for a FS test. However, failure in the S4 test should not preclude the use of pipe which passes an FS test, since the correlation factor is made over conservative by the influence of certain secondary effects. The dual surface cooled pipe provides the best example to date of a pipe for which performance in an S4 test does not reflect its good p_{cFS} .

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