Break Opening Times for Axial Rupture of a Gas Pressurized Pipe

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Summary

The consequences of a major rupture of a pressurised pipe are strongly influenced by the break characteristics (i.e. fracture orientation, opening time and final breach area). For example, the amplitude of the blast wave generated in the external atmosphere is dictated by the rate at which energy is released through the developing breach and hence is a function of opening time. A pipe is assumed to be fully open when the breach area is twice the cross-sectional area of the pipe, thus allowing full flow from each leg of the pipe.

This paper describes experiments where the development of an axial rupture in large gas-pressurised steel pipes was observed by high speed photography. The tests were performed on 610 mm diameter pipes, with wall thicknesses of either 6.2 mm or 9.3 mm, apart from the final test where a 915 mm diameter, 12.5 mm wall thickness pipe was ruptured. Rupture pressures ranged from 19 bar to 40 bar.

Measured breach opening times are compared with data from earlier small scale tests (102 mm diameter pipes with 1.6 mm wall thickness) where rupture pressures ranged from 50 bar to 120 bar. Both sets of data are shown to be in general agreement with a theoretical model which combines an upper limit ductile fracture propagation velocity with a simple inertia model for the displacement of the free edges of the breach. For large pipes the measured and predicted opening times are significantly longer than the maximum of 1 ms specified in the current U.S. design codes.

1. Introduction

A programme of pneumatic pipe rupture tests is being performed with the objective of characterising internal and external fluid dynamic forces generated by failure of high-pressure pipework.

The breach opening rate is the principal factor determining the variation in the initial energy and momentum fluxes from the system and hence is a major influence on the magnitude of the forces generated. For example, the amplitude of the blast wave generated in the external atmosphere is dictated by the rate at which energy is released through the developing breach. A very rapid opening will therefore produce an intense blast wave whereas a long opening time will result in a blast wave with a much reduced amplitude. Different rates of breach growth will occur depending on whether the rupture propagates by ductile shearing or by brittle fracture. In the case of ductile failure, the orientation of the initial defect and its direction of propagation are important parameters controlling the opening rate.

For nuclear applications, the current design assumptions relating to breach development are described, for example, in the U.S.N.R.C. Standard Review Plan [1]. Both circumferential and longitudinal breaks are assumed to reach full size within 1 ms unless slower opening times can be analytically or experimentally substantiated. The variation of breach area with time (e.g. linear, quadratic etc.) is not defined.

In the initial phase of the programme [2], the development of a breach, initiated by an axial defect which propagated axially by ductile shear fracture, was investigated in small-scale tests (102 mm diameter pipes with rupture pressures ranging from 50 bar to 120 bar). The present paper describes part of a subsequent test programme using large-diameter pipes.

Data are presented for the variation of breach area with time and the time for the breach to become 'fully open'. A 'fully open' breach is defined to have an area of twice the cross-sectional area of the pipe (i.e. $2\pi R^2$). The measured times to 'fully open' are compared with a simple theoretical model.

2. Experiment

Ten steel pipes (A.P.I.Grade B Linepipe) of 610 mm diameter (2R) with 6.2 mm and 9.3 mm wall thickness and 915 mm diameter with 12.5 mm wall thickness were used in the experimental programme. The fracture toughness of the material, as indicated by a 2/3 size Charpy specimen, was typically 60 J/mm^2. In all cases the test pipe was ten diameters long. A part-through axial defect was machined in the outer surface at the mid-point of each pipe.

Rupture was achieved by pressurising with air until the ligament at the bottom of the defect failed. Rupture pressures were in the range 19 bar to 40 bar. Initial defect lengths, L, were R, 1.3R or 2R. Apart from three tests where the pipes were supported on a frame, the pipes rested on the ground with the defect at the top.

The development of the breach was recorded using high-speed cine cameras mounted near the pipe axis at a position ∿4m above the ground and at a horizontal distance of ∿12 m from the centre of the initial defect. Two cameras were used to extend filming time and hence improve the chances of capturing the rupture event. The second camera was automatically switched on by the first camera when the run time of the first camera was almost complete.

The early stages of defect deformation before rupture was observed by simultaneous monitoring of the pressure and the output from a crack-opening displacement (C.O.D.) meter positioned half-way along the axial defect (Figure 1). While the ligament at the bottom of the defect is elastic there is a linear relationship between pressure and C.O.D. However, once the stress in the ligament is sufficient to cause yielding, small changes in pressure produce large changes in C.O.D. as the ligament deforms plastically. Typically the time taken from the onset of yield to rupture was 100 sec. Thus the cameras, with a total run time of 60 sec (500 pictures/sec), were switched on ∿30 sec before the projected instant of rupture.

Prints from the cine film of rupture of a 915 mm pipe (rupture pressure, P_o, = 19 bar) are shown in Figure 2. In most cases moisture in the escaping gas condensed and tended to obscure the breach although this did not become significant until the breach area exceeded πR^2. Only three films gave a complete record of the growth to 'fully open'. Taking account of alignment and perspective, together with positional information on the fracture tip from strain gauges, it is possible to construct a plan view of the breach from each cine frame and hence determine the growth from frame to frame. Combining this with the framing rate gives breach growth as a function of time. Similarly the fracture velocity can be derived from the progress of the breach tip.

A further indication of the deformation of the pipe and the fracture velocity was obtained from the output from strain gauges positioned along the fracture path.

In each test the pressure transient within the pipe was monitored at various distances from the initial defect. Rupture initiation was assumed to precede the arrival of the leading edge of the transient by the time taken for the initial pressure disturbance to propagate (at the velocity of sound in the undisturbed gas) from the initial defect to the observation point. Electrical pulses generated by the operation of the camera shutter were used to relate the individual cine film frames to the instant of rupture. The depressurisation transient also gives an indication of the rate of breach development [3].

This present paper is restricted to examples of the cine film data where it is possible to determine the time to a 'fully open' breach. A full description and analysis of the data for fracture velocity, strain, strain rate and the internal depressurisation transient is currently being prepared.

3. Results and Discussion

The first visual evidence of rupture was the appearance of free edges generated by failure of the ligament at the bottom of the defect. In all cases, the initial defect length was supercritical and the resultant stress at the crack tip initiated fracture propagation in the full-thickness material. The internal pressure subsequently plastically deforms the free edges causing the stress at the breach tip to remain at the level necessary for continued fracture propagation.

In all cases the fracture propagated by 100% shear of the material, exhibiting a characteristic 45° inclination of the fracture plane to the pipe surface. In Figure 3 the fracture velocity derived from the typical film record shown in Figure 2 is compared with the velocity indicated by the strain gauge measurements. It can be seen that the fracture achieved a constant peak velocity after it had propagated a distance of approximately one pipe radius (R).

Breach area growth is the result of the combined effect of free edge displacement and fracture extension. Figure 4a shows the typical variation in breach area with time derived from the cine film prints in Figure 2. Here the plan area, A, is expressed as a fraction of the 'fully open' area $A_f (=2\pi R^2)$. The time to 'fully open' is 13.2 ms.

It can be seen from Figure 2 that, close to the fracture tip, the free edge displacement is predominantly radial, while in the central region of the breach the free edges are moving horizontally. The plan area of the breach does not take account of the resultant curvature of the breach surface and is therefore an underestimate of the true breach area. However, since the curvature is local to the fracture tip, the discrepancy between the plan and true breach areas reduces as the breach extends axially. Typically the discrepancy is estimated to be $\sim 5\%$ at $A/A_f = 0.5$ falling to $\sim 1\%$ at $A/A_f = 1.0$, and is substantially smaller than the estimated accuracy of determination of the plan area ($\sim\pm 10\%$). Thus plan area and true area may be taken to be synonymous.

An example of the small-scale test data is shown in Figure 4b. The breach growth histories at large and small scale have the same general form with the breach growth to $A/A_f = 0.5$ significantly slower than the subsequent increase from $A/A_f = 0.5$ to $A/A_f = 1.0$.

Times to 'fully open' in the small-scale tests were of the order of 0.5 ms (i.e. less than the 1 ms specified in the design codes [1, 4 and 5]) whereas, in the present tests, the opening times were all greater than 4 ms. Thus it would appear that, while no increase in opening time can be claimed for small pipes, significant increases are possible for large pipes.

In order to provide a convenient means for determining the conditions under which an opening time in excess of 1 ms can be claimed and to estimate its magnitude the following simple model has been developed.

4. Minimum Breach Opening Time

The breach area growth is dictated by the progress of the propagating fractures and the rate at which the free edges are displaced. In the earlier study of axial breach development using small pipes, the upper limit to the ductile fracture propagation velocity, ν_p, was shown to be the propagation velocity of a displacement wave in a plastic membrane,

$$\text{i.e. } \nu_p = \sqrt{\frac{\sigma_y}{\rho_s}},$$

where σ_y is the yield stress at the prevailing strain rate and ρ_s is the density of the pipe material.

As noted earlier, after the initial radial movement, the motion of the free edges of the developing breach is predominantly horizontal. An upper bound to the rate of displacement of the free edges may therefore be obtained by assuming they are accelerated horizontally by the rupture pressure P_o, and the local material behaves as a free mass. That is:

$$P_o = m\frac{d^2x}{dt^2}$$

where x is the horizontal displacement and m is the mass per unit area of the pipe wall.

The plan view of the idealised breach defined by these equations is as shown in Figure 5 and the breach area after time, t, is given by:

$$A = \frac{2P_o\nu_p t^3}{3m} + \frac{P_o L t^2}{m}, \qquad (1)$$

where L is the initial defect length.

For a wall thickness h, the hoop stress prior to rupture is $\sigma_o = P_o R/h$ and the mass per unit area is $\rho_s h$. Hence, from (1) the time for the breach to achieve the 'fully open' area of $2\pi R^2$ is defined by:

$$2\pi\alpha^3 = \frac{2}{3}t^3 + \frac{L}{\nu_p}t^2, \qquad (2)$$

$$\text{where } \alpha = \frac{R}{\nu_p}\left[\frac{\sigma_y}{\sigma_o}\right]^{\frac{1}{3}} \qquad (3)$$

is a characteristic time for the rupture process. It can be seen that α is proportional to the time required for the breach to grow to 'fully open' when the area exposed by the propagating fracture dominates the growth from the outset (i.e. L small). When L is large, the area generated by the separation of the free edges of the initial defect dominates breach growth until $t > 3L/2\nu_p$, when the area generated in the propagated fracture region becomes the major contributor. In the small-scale tests, $0.13 \text{ ms} < L/\nu_p < 0.52$ ms and in the present large scale tests $1 \text{ ms} < L/\nu_p < 3.3$ ms.

For the purposes of calculating α, ν_p is derived by the method described in the report on the small-scale tests. First, the high-strain-rate yield stress for steel, σ_y, is related to the yield stress in a standard (low-strain-rate) tensile test, $\bar{\sigma}_y$ by Manjoine's (1944) correlation:

$$\sigma_y = \bar{\sigma}_y \left[1 + \left\{ \frac{\frac{de}{dt}}{40.4} \right\}^{0.2} \right] \tag{4}$$

Second the strain rate, de/dt, is approximated by $0.1\ \nu_p/R$. This expression was observed to be a good approximation for both the small and large-scale tests (i.e. typically 10% axial strain developed in the time taken for the fracture to propagate a distance R at peak velocity).

Taking, as an example, the case of a steel pipe with $\alpha = 10$ ms (i.e. a large diameter, lowly stressed pipe) and $L/\nu_p = 2$ ms, the model predicts the opening time to be 21 ms.

In figure 6, using α as the basis for comparison, the observed times for the breach area to grow to $2\pi R^2$ are compared with equation (2). The form of the variation of measured opening times with α is well described but the measured opening times are systematically $\sim$60% greater than predicted. This is not unexpected since the model (particularly the assumption that the driving pressure remains at P_o throughout the breach development) maximises both the fracture velocity and the displacement of the free edges and hence minimises the opening time. If the theoretical values are taken as a lower bound to the experimental data, the results suggest (for L/ν_p typically <2 ms) that when α is greater than 0.75 ms, opening times greater than the 1 ms specified in the design codes can be claimed. If the experimental data are used to define the critical value of α, then longer opening times are valid if $\alpha > 0.5$ ms.

5. Conclusions

The development of axial breaches in large gas-pressurised steel pipes have been successfully observed using high-speed photography. The breach area variation with time has the same general form as observed in small-scale tests but the opening times (> 4 ms) are an order of magnitude longer and clearly exceed the maximum of 1 ms specified in the design codes.

A simple model has been developed to predict the minimum breach opening time, which combines an upper limit ductile-fracture propagation velocity with a simple inertial description of the displacement of the free edges. This model has been shown to correlate the experimental breach opening times over a wide range of pipe sizes, although the measured values are systematically 60% higher than predicted.

Based on this correlation, a criterion is suggested whereby less onerous design conditions (i.e. opening times greater than 1 ms) can be claimed for large diameter piping systems. This requires the group $\{R/\nu_p\}(\sigma_y/\sigma_o)^{\frac{1}{3}}$ to exceed 0.5 ms, where R is the pipe radius, ν_p is the fracture propagation velocity and σ_y/σ_o is the ratio of the dynamic yield stress of the pipe material to the initial hoop stress in the pipe wall.

Acknowledgement

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References

[1] USNRC Standard Review Plan, 1975.

[2] BAUM, M.R., "The development of the breach generated by axial rupture of a gas-pressurised steel pipe", A.S.M.E.Journal of Pressure Vessel Technology, Vol.104, pp 253-261, 1982.

[3] BAUM, M.R., "The relationship between breach development and the depressurisation transient during axial rupture of a gas-pressurised steel pipe",A.S.M.E. Journal of Pressure Vessel Technology, Vol.104, pp20-24, 1982.

[4] ANSI N176, 1974.

[5] USAEC Reg.Guide 1·46, 1973.

[6] MANJOINE, M.J., "The influence of rate of strain and temperature on yield stresses in mild steel", Journal of Applied Mechanics, Vol.11, p211, 1944.

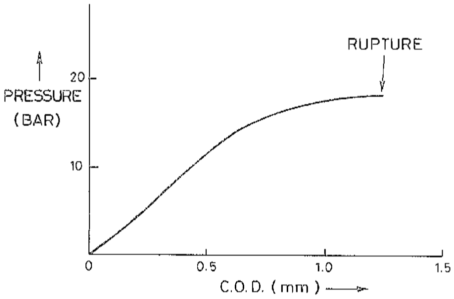

Figure 1 Variation of Crack Opening Displacement with Pressure for the Case 2R = 915 mm and L = 2R.

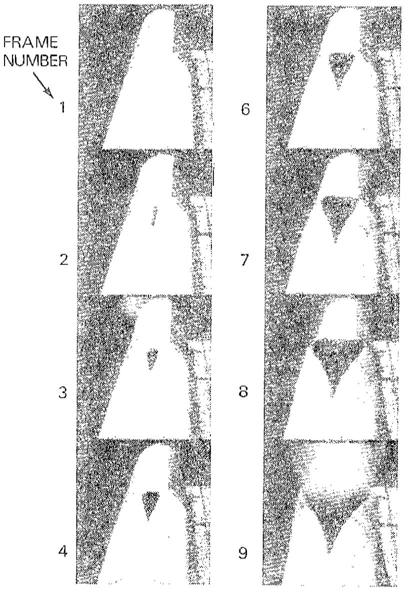

Figure 2 Rupture of a 915 mm Diameter Pipe (500 Pictures per Second).

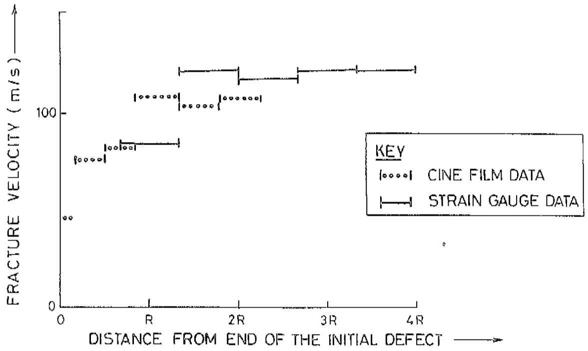

Figure 3 Variation of Fracture Velocity for the Case 2R = 915 mm and L = 2R.

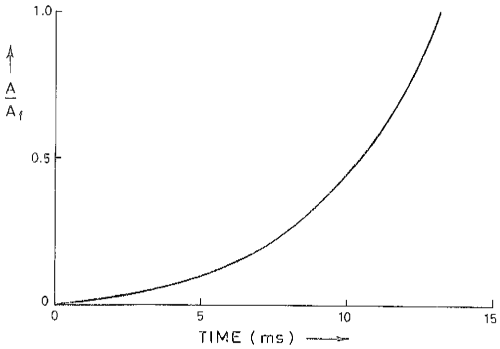

Figure 4a Variation of Breach Area with Time for the Case 2R = 915 mm, L = 2R and P_o = 19 Bar.

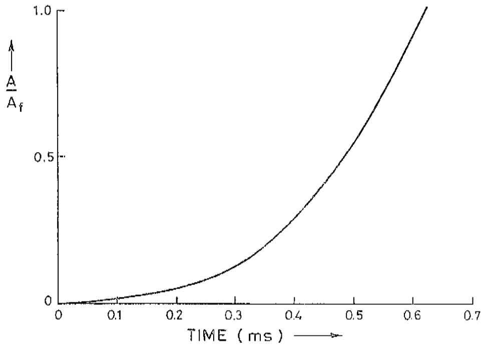

Figure 4b Variation of Breach Area with Time for the Case 2R = 102 mm, L = 2R and P_o = 86 Bar.

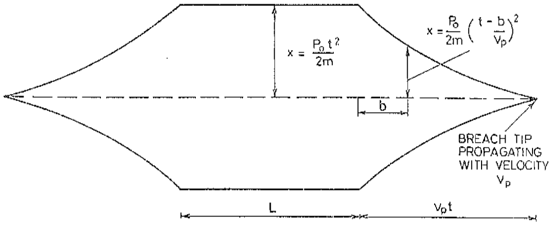

Figure 5 Idealised Breach.

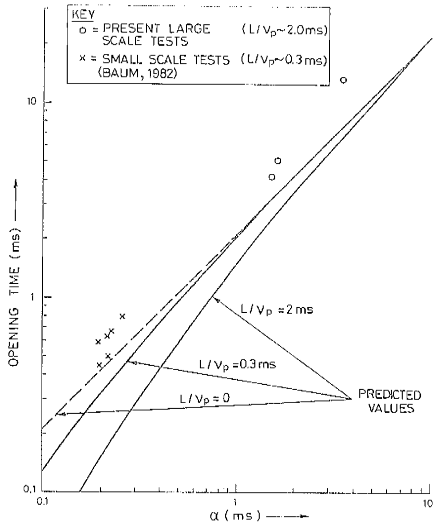

Figure 6 Comparison of Measured and Predicted Opening Times.