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Prediction of failure strain and burst pressure in high yield-to-tensile strength ratio linepipe

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Abstract

Failure pressures and strains were predicted for a number of burst tests as part of a project to explore failure strain in high yield-to-tensile strength ratio linepipe. Twenty-three methods for predicting the burst pressure and six methods of predicting the failure strain are compared with test results. Several methods were identified which gave accurate and reliable estimates of burst pressure. No method of accurately predicting the failure strain was found, though the best was noted.

Keywords: Pipe; Burst pressure; Failure strain

1. Prediction of failure strain and burst pressure

The failure pressures and strains have been predicted for a number of burst tests as part of an Australian Pipeline Industry Association (APIA) sponsored research project on the effects of yield–to-tensile strength (Y/T) ratio on failure strain in high-strength seam welded pipe. Twenty equations (Table 1) and two other methods based on plastic collapse (described later) were used to predict the burst pressure. The pipe tests were all carried out on well-characterised modern thin-walled high-strength linepipe, where the yield strength was measured in a consistent and accurate manner using ring expansion testing and tangential tensile specimens (TT).

Four equations (see Table 2) and two methods based on plastic collapse (described later) were used to predict the failure strain (the average hoop strain at failure). The failure strain estimate of half the uniform strain is an industry rule of thumb. The Liessem–Graef equation is based on curve fitting to published data, and is valid for Y/T values from 0.7 to 0.95 based on round bar tests.

2. Plastic instability and cylindrical instability stress (CIS) methods

In a tensile test the rate of strain hardening is greater than the increase in stress due to loss of cross-section due to straining up to the ultimate tensile strength (UTS). At the UTS, plastic instability and necking occurs as further straining reduces the load the specimen can support. Pipe failure is also due to the onset of plastic instability. The stress increases for two reasons: reduced cross-sectional area (as in the tensile test), and increasing inner diameter (which raises the stress via $\sigma = PD_i/2t$). For a pressure vessel the condition of instability is that $\sigma = 1/2\,\mathrm{d}\sigma/\mathrm{d}\varepsilon$ [21]. The stress where this occurs is termed as the cylindrical instability stress (CIS) and is close to the flow stress (the average of the yield stress and the UTS) for many pipe steels. In a material that follows power law plasticity, the failure strain will be half the uniform strain (the uniform strain is the strain at maximum load).

This project offered the opportunity of testing five well-characterised pipes, each providing stress–strain curves and wall thickness data taken from 14 TT around the pipe circumference. Other methods of deriving material data in the hoop direction may involve flattening the pipe material that strongly affects the measured material properties of

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Nomenclature

D, D_i, D_o, D_{ave}	diameter, inner, outer, average
t	wall thickness
e	2.718, etc.
E	Young's modulus
ε_u	uniform strain
k	R_o/R_i
n	strain hardening exponent, $n = \exp(1+\varepsilon_u)]$
R_o, R_i	outer radius, inner radius
σ_{YS}, σ_{flow}, σ_{TS}	yield, flow, and tensile strength
v	Poisson's ratio
v_{secant}	failure secant Poisson's ratio $= 0.5-(0.5-v)\,\sigma_{TS}/(\varepsilon_u E)$
YT	yield-to-tensile ratio

Table 1
Equations for predicting burst pressure

ASME [1]	$P_{max} = \sigma_{TS}\left(\frac{k-1}{0.6k+0.4}\right)$	Marin [2]	$P_{max} = \frac{2}{\sqrt{3}}\frac{\sigma_{TS}}{(1+\varepsilon_u)}\ln(k)$
Barlow OD, ID, or flow,	$P_{max} = \sigma_{TS}\frac{2t}{D_o},\ \sigma_{TS}\frac{2t}{D_i},\ \text{or}\ \sigma_{flow}\frac{2t}{D_i}$	Marin (3) [3]	$P_{max} = \frac{2t}{(\sqrt{3})^{(n+1)}}\frac{\sigma_{TS}}{R_i}$
Bailey-Nadai [4]	$P_{max} = \frac{\sigma_{TS}}{2n}\left(1-\frac{1}{k^{2n}}\right)$	Max. shear stress [5]	$P_{max} = 2\sigma_{TS}\left(\frac{k-1}{k+1}\right)$
Bohm [6]	$P_{max} = \sigma_{TS}\left(\frac{0.25}{0.227+\varepsilon_u}\right)\left(\frac{e}{\varepsilon_u}\right)^{\varepsilon_u}\frac{2t}{D_i}\left(1-\frac{t}{D_i}\right)$	Nadai [7]	$P_{max} = \frac{2}{\sqrt{3}}\sigma_{TS}\ln(k)$
DNV [8]	$P_{max} = \sigma_{Flow}\frac{2t}{D_{ave}}$	Nadai [9]	$P_{max} = \frac{\sigma_{TS}}{\sqrt{3}n}\left(1-\frac{1}{k^{2n}}\right)$
Faupel [10]	$P_{max} = \frac{2}{\sqrt{3}}\sigma_{YS}(2-YT)\ln(k)$	Soderberg [11]	$P_{max} = \frac{4}{\sqrt{3}}\sigma_{TS}\left(\frac{k-1}{k+1}\right)$
Fletcher [12]	$P_{max} = \frac{2t\sigma_{flow}}{D_i(1-\varepsilon_u/2)}$	Svenson [13]	$P_{max} = \sigma_{TS}\left(\frac{0.25}{0.227+\varepsilon_u}\right)\left(\frac{e}{\varepsilon_u}\right)^{\varepsilon_u}\ln(k)$
Margetson [14]	$P_{max} = \frac{4t}{D_i\sqrt{3}}\sigma_{YS}\exp\left(-2\varepsilon_u\frac{(1+v_{secant})}{\sqrt{3}}\right)$	Turner [15]	$P_{max} = \sigma_{TS}\ln(k)$
Marin [16]	$P_{max} = 2.31(0.577)^n\frac{t\sigma_{TS}}{D_i}$	Zhu and Leis [17]	$P_{max} = \left(\frac{2+\sqrt{3}}{4\sqrt{3}}\right)^{(1+0.239((1/YT)-1)^{0.596})}\frac{4t\sigma_{TS}}{D_{ave}}$

Table 2
Equations for predicting hoop failure strain

Half uniform strain	$\varepsilon_{FAILURE} = \frac{\varepsilon_u}{2}$	Liessem and Graef ($Y/T = 0.7$–0.95) [18]	$\varepsilon_{FAILURE} = -2608\,YT^4 + 8406.8\,YT^3 - 10149.8\,YT^2 + 5424.9\,YT - 1075.34$
Gaessler and Vogt [19]	$\varepsilon_{FAILURE} = \frac{\varepsilon_u}{2} - \frac{n\sqrt{3}}{3e}YT^{(1/n)}$	Zhu and Leis [20]	$\varepsilon_{FAILURE} = 0.1195\left(\frac{1}{YT}-1\right)^{0.596}$

high strength pipe [22]. Analysis was performed with these data based on the CIS, taking the wall thickness variation into account. This method does not assess properties variation along the pipe. The pipes have longitudinal seam welds made by high-frequency electric resistance welding (HF-ERW); these welds are autogenous (the joint is made by heating and upsetting the parent metal). These welds are shown by production testing to be stronger than the pipe material, they are also locally thicker; for this reason the welds have not been included in the analysis. In other production methods the weld may require analysis also.

The first method used data from all positions around the pipe wall; this was referred to as the CIS-full method and is detailed further in the appendix. An empirical curve fitting