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COMPARING CALCULATED AND EXPERIMENTALLY DETERMINED FAILURE PRESSURE OF PIPES WITH LONGITUDINAL SURFACE FLAWS

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Abstract

A post–calculation by means of four engineering approaches based on toughness,– yield stress–, plastic–instability– and ligament stress–criteria was made for the failure pressure on 134 pipes and vessels. The different calculations were assessed by comparing the calculated pressure p_{calc} with the experimentally determined pressure p_{ex}. A statistical based evaluation was made out since the results from the calculation and the experiment are influenced amongst others by natural scattering of characteristic values, such as material properties and geometrical dimensions. It was possible to find for each equation an individual weighting factor *W*, which helped to improve considerably the approximation of the calculation to the experimentally determined failure pressure.

1 Introduction

In the case of designing and calculating vessels and piping loaded by internal pressure a flawless condition is initially assumed. However, the non – destructive inspection proved that flaws may occur in various positions and sizes in the base material and welded joints of pressurized components. This is due to manufacturing defects and operating influences. If a flaw has been found during non–destructive examinations it is necessary to carry out a safety analysis. In doing so it has to be decided whether repair or exchange is required and the safe operating time of a defective component has to be determined. Apart from crack growth laws the knowledge of the failure pressure is of utmost importance in the safety analysis.

The failure pressure may be calculated with expensive finite element calculations or with simple analytical approximation methods. This report examines whether four frequently applied engineering approximation methods (toughness criterion ⇒ p_{Cv}, flow stress criterion ⇒ p_{fl}, plastic instability criterion ⇒ p_{pli} and ligament stress criterion ⇒ p_{lig}) are sufficient for the determination of the failure pressure of pipes and vessels containing longitudinal flaws and the efficiency of these methods / 1 /.

It has to be remarked that the evaluation of the tests with the J–Integral or R6–methods could not be carried out, because the necessary material property data were not available for most of the tests.

2 Databasis, experimental test results

134 burst tests, which were carried out on pipes containing longitudinal flaws, were analysed. These tests were conducted at Staatliche Materialprüfungsanstalt (MPA), University of Stuttgart, Battelle Memorial Institute, Columbus, Ohio, and Siemens AG (KWU), Erlangen. The test temperature ranged between room temperature and 350 °C. Detailed description of the tests can be found in / 2 /, / 3 /,

/ 4 /, / 5 /, / 6 / and a summary in / 7 /, / 8 /.The tests evaluated include pipes and vessels with outer diameters d_a between 88.9 mm and 914.4 mm, wall thicknesses t between 4.0 mm and 47.2 mm, ferritic and austenitic steels with yield strengths $R_{p0.2}$ (0,2 % offset) between 155 MPa and 703 MPa, tensile strengths R_m between 416 MPa and 750 MPa and Charpy–V notch impact values C_v between 33 J and 214 J.

3 Description of the calculation methods

A cylindrical, flawless, thin–walled pressure boundary will fail if the equivalent stress $\sigma_v = \frac{p\, d_m}{2t}$ reaches the tensile strength R_m of the material. Therefore, the failure pressure of the unweakened vessel is $p_{max} = \frac{2t}{d_m} R_m$.

Compiled in Table 1, the following semi–empirical calculational methods for pipes with longitudinal flaws are based on the assumptions that failure will then occur if the ligament (remaining wall thickness in the flaw area) becomes fully–plastic because such that it cannot bear anymore loads. This is the case under the prerequisites of an ideal–plastic material behaviour if the equivalent stress σ_v attains the yield point in the ligament. Strain hardening as it occurs in real materials is considered by the flow stress σ_f, which is higher than the yield strength $R_{p0.2}$.

The so–called flow stress σ_f is generally calculated as the average of the tensile strength R_m and yield stress with 0.2% strain offset $R_{p0.2}$. The decisive stress in the ligament is approchingly calculated by multiplying the nominal stress of the unweakened wall with a geometry and notch–shaped depending factor. The factors in Table 1 with dimensions were converted in SI–units.

4 Comparison of the calculational result

The failure pressure p_{calc} of each test was calculated using the mentioned methods and then compared with the experimentally determined p_{ex}. In order to assess the scattering of the results from various calculation methods and to determine items for improvement, the tests data were distributed into 7 classes, Figure 1.

In the classes 1 to 3 the calculation provide "unsafe" values, i. e. a higher failure pressure is calculated than determined in the experiment. The classes 5 to 7 show "safer" (conservative) values, i. e., the experimental failure pressure is higher than calculated.

The relative frequency histograms based on a sample of 90 tests, with flaw depth to wall thickness a/t < 0.85 are represented in Figure 1. For some reasons in this particular investigation, the tests with a/t > 0.85 had to be skipped.

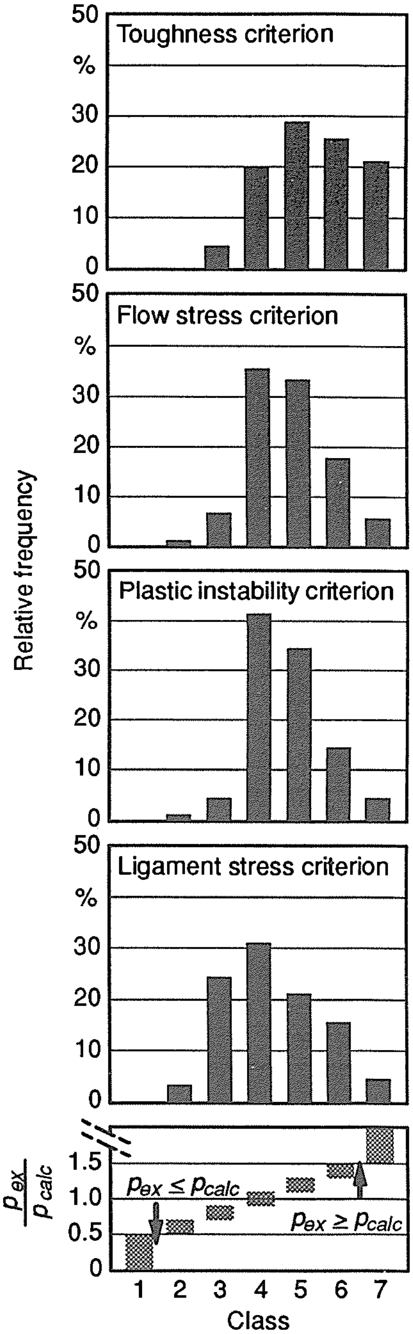


Figure 1: Relative frequency distribution of the failure pressure

All four calculated methods provide results which deviate somewhat from the ideal class 4. However, in most cases the calculated failure pressure is lower when compared with the experimentally determined pressure. The smallest deviation between calculations and test results was for the plastic instability criterion. It can be found that only for 5 % of 90 test data sets the experimentally determined failure pressures are considerably lower (class 3) than the calculated pressures by means of the thoughness criterion, Figure 1.

The flow stress criterion calculation method was applied to the total set of tests without any known limitations, Table 1. The results are represented in Figure 1. The experimental determined failure pressures for about 90 % of the 90 tests is near equal to or higher than the calculated pressures, and about 70 % are in classes 4 and 5 (p_{ex}/p_{fl} = 0.9 ÷ 1.3). The tests of class 7 have normally short and deep flaws. The tests distributed to class 4 have mostly "longer" flaws and are of high–tough materials.

The results according to the plastic instability criterion are represented in Figure 1. The results are similar to one obtains when using the flow stress criterion. The results determined according to the ligament stress criterion are represented in Figure 1. The experimental failure pressures are greater than the calculated values of 44 tests (≈ 50 %). 28 tests (≈ 30 %) are distributed to class 4, as expected for pipes containing long flaws.

Since the relative frequency of class 4 is only between 30 % and 40 %, independent of the calculation method, it becomes necessary to consider how to improve the individual calculation methods. It is felt that the following variables require a special weighting in the individual calculation methods:

- notch impact energy C_v
- ratio of flaw depth to wall thickness a/t
- ratio flaw length to reduced flaw length l_{red}.

$$l_{red} = \frac{l}{\pi \sqrt{2\, d_m\, t}}$$

5 Weighting function

It has been proved that none of the mentioned calculation equations covers the complete spectrum of geometry of the pipes, flaw dimensions, and material properties with sufficient reliability. Therefore, it will be attempted to assess an appropriate weighting function W for each method. Multiplication of the conventional calculated failure pressure p_{calc} with the function W should improve the agreement with the experimentally determined values. The empirically determined weighting function W will be a function of the variables l_{red}, a/t and C_v because of the recently gained knowledge.

$$W = e^{\left(a^{*} + b_1\, l_{red} + b_2 \frac{a}{t} + b_3\, C_v\right)}$$

Coefficients a^*, b_1, b_2 and b_3 will be determined by calculating a regression curve using the method of the least squares / 9 /. The 90 evaluated tests provide a sufficiently broad data base for this assessment. In Figure 2 the calculated coefficients are indicated in form of bar graphs and in Figure 3 as numerical values. The values of the weighting coefficients are based on a confidence level of 99 %. It has been proved that the weighting coefficients become extremely small if the distribution is likely leptokurtic (having a relatively high peak). This applies to the weighting coeffi-

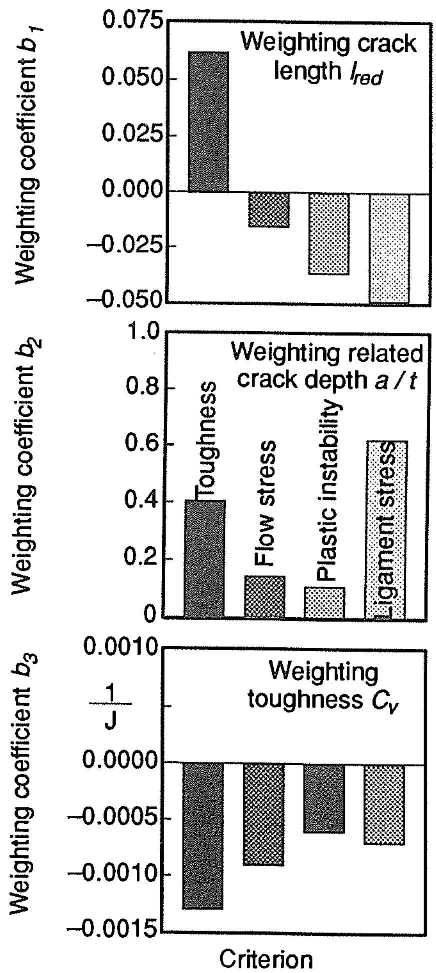
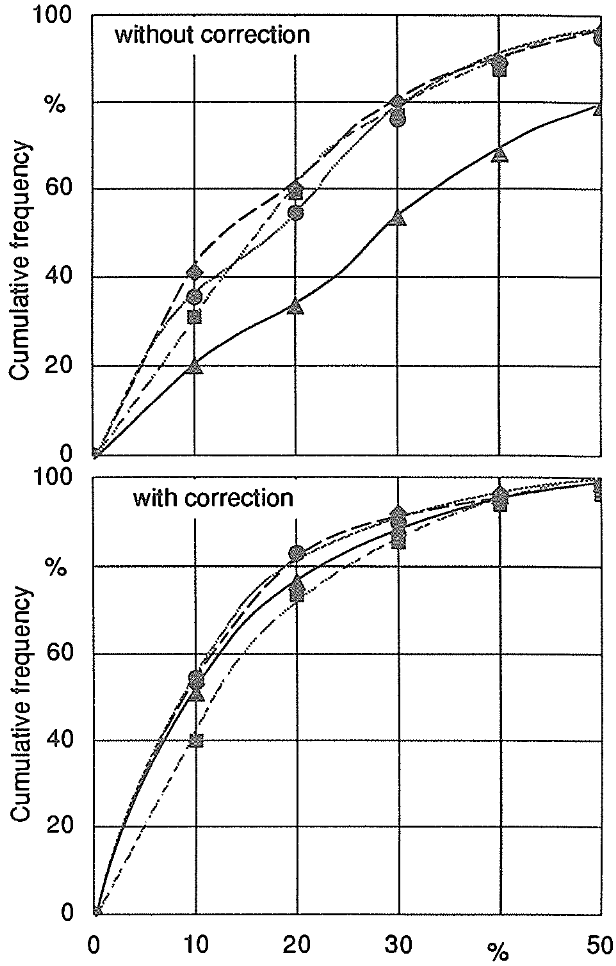


Figure 2: Weighting coefficients for each methods

cient b_1 (flaw length l_{red}) and weighting coefficient b_2 (flaw depth ratio a/t) in the case of the flow stress criterion and plastic instability criterion. The same applies to the weighting coefficient b_3 (toughness C_V) for the plastic instability criterion and ligament stress criterion.

Figure 3 shows the percentage cumulative distribution for the deviation of experimentally determined and calculated failure pressures for both with and without (delineated from Figure 1) using the appropriate weighting function. Applying the individual weighting function for all four engineering approaches results in distinctly improved agreement between experimental and numerically determined failure pressures. Consequently, for approx. 55 % of the tests failure pressures are calculated within the range of ± 10 % of the experimentally determined values. Comparatively, applying the non–corrected calculation using the plastic instability criterion in the most favorable case 40 % of the tests, and using the toughness criterion in the most unfavorable case only 20 % of the tests lay within the range of ± 10 % of the experimentally determined value.



Deviation $\left| \frac{p_{ex} - p_{calc}}{p_{calc}} \right| \times 100\ \%$

Criterion

Coefficient	Toughness	Flow stress	Plastic instability	Ligament stress
	—▲—	⋯●⋯	—◆—	⋯■⋯
a =	0.0253	0.1468	0.1578	0.2033
b_1 =	0.0620	−0.0155	−0.03644	−0.0492
b_2 =	0.4036	0.1433	0.1079	0.6215
b_3 =	−0.0013	−0.0009	−0.0006	−0.0007

Figure 3: Comparison of the cumulative frequency using the calculation method with and without the weighting function

6 Conclusion and recommendation

The failure pressures of 134 pipes and vessels containing longitudinal surface flaws were calculated with different engineering approaches, i. e., toughness–, flow stress–, plastic instability–, and ligament stress – criteria. They were then compared with the experimentally determined failure pressures. For all calculation methods it could be shown that each of the calculated failure pressures deviated more or less from the experimental failure pressures.

These deviations cannot be explained solely by the fact that the tests were carried out at various institutes. Also, this result cannot be explained fully by accounting for statistical uncertainties in the data, such as geometry and material properties. A considerable cause for these results are the individual components of an equation and its mathematical weighting. To recognize the influence of the most important variables:

- flaw length related to pipe geometry,
- flaw depth related to wall thickness,
- notch impact energy of material (upper shelf),

the tests data were distributed to appropriate classes and represented in histograms. Tests with very deep notches ($a/t \geq 0.85$) proved to have a significantly high deviation of the experimental from the analytical failure pressure and an exceptional scattering. The results of these tests were not used in order to obtain a safe data basis for additional evaluations.

The remaining 90 tests served as a basis for the statistical based analysis. For the four engineering approaches an individual weighting function was found, which improved decisively the agreement of analytically and experimentally determined failure pressures.

When using the weighting function, the equation using the flow stress criterion is to be preferred because of the handling and simplicity of the semi–empirical approach. The range of the application of the weighted calculation methods has been appropriately extended. This is due to the evaluation of 90 tests, representing pipe diameters of approximately 90 mm to 915 mm, wall thicknesses ranging between 4 mm and 50 mm, ferritic and austenitic steels with yield stresses (0.2 % offset) between 155 MPa and 700 MPa, tensile strengths between 400 MPa and 750 MPa and upper shelf notch impact energies between 33 J and 214 J.

7 References

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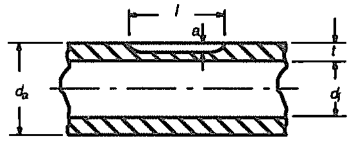
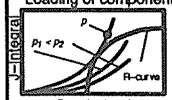
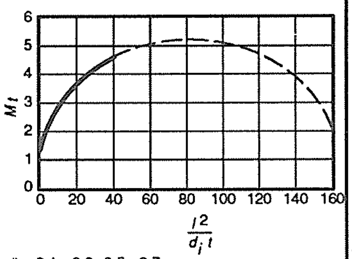
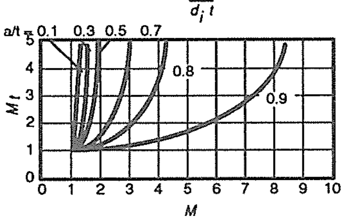
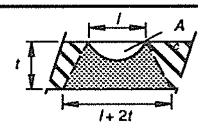
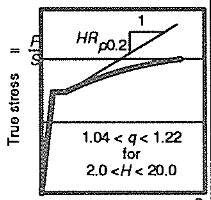
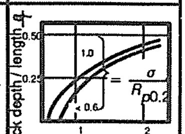
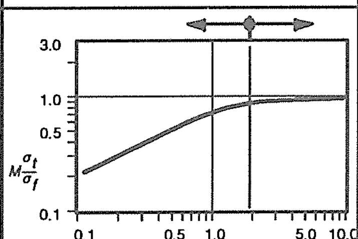
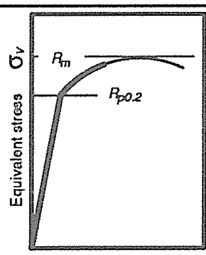
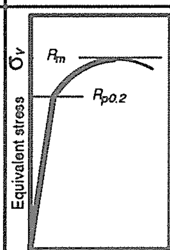
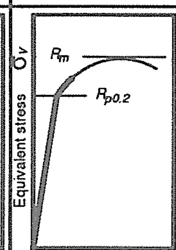
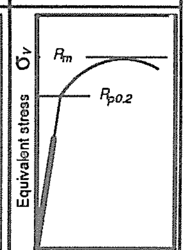
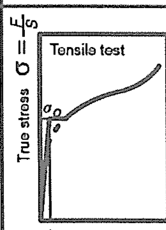
Model	**Calculation of failure pressure of longitudinally flawed cylindric pipes and vessels** 					
Theory	Platic deformation in crack tip near field "Local flow"				Elasto–plastic fracture mechanic	Linear–elastic fracture mechanic
Criterion	Toughness	Flow stress	Plastic instability	Ligament stress (Tensile strength)	J – Integral	Stress intensity factor
	$\frac{2t}{d_i}\frac{\sigma_f}{M}\frac{2}{\pi}\arccos e^{-\left(\frac{3.1 E C_V \pi}{l \sigma_f^2}\right)}$	$\frac{2t}{d_i}\frac{\sigma_f}{M}$	$\frac{2t}{d_i}\sigma_f\left(1-\frac{A_c}{A}\right)$	$\frac{2t}{d_i}\left(1-\frac{a}{t}\right)R_m$	Loading of component  Crack depth t	$\frac{2t}{d_i}\frac{K_{IC}}{\sqrt{\frac{1.21\pi a}{Q}}}$
Factors	$\sigma_f = 0.5\left(R_m + R_{p0.2}\right)$ $M = \frac{1-\frac{a}{tM_t}}{1-\frac{a}{t}}$ $M_t = \sqrt{1+0.6275\frac{l^2}{d_i t} - 0.00338\left(\frac{l^2}{d_i t}\right)^2}$  		 $A = (l+t)\,t$ $\sigma_f = 0.5\left(R_m + R_{p0.2}\right)q$ $q = \frac{\frac{4H}{3}}{e^{\left(\frac{H-\sqrt{3}}{H}\right)} + He^{\left(\frac{1-\sqrt{3}}{H}\right)}}$ $\sigma = \frac{F}{S}$  1.04 < q < 1.22 for 2.0 < H < 20.0; True strain $\phi = \ln\frac{S}{S_o}$		$J = f_1\left(1-\mu^2\right)\frac{p^2}{E} + \left(\frac{t-a}{t}\right)a\alpha\sigma_o\phi_o \cdot h_1\left(\frac{p}{p_o}\right)^{n+1}$ $f_1 = 4\pi a k^2 F^2$ $p_o = \frac{4}{\sqrt{3}}\frac{(t-a)\sigma_o}{d}$ outer surface: $k = \frac{d_i^2}{d_a^2 - d_i^2}$ $d = d_i$ Inner surface: $k = \frac{d_a^2}{d_a^2 - d_i^2}$ $d = d_i + 2a$ F, h_1 ... tabled value	 Parameter Q
Range of validity	 $\frac{l^2}{d_i t} < 40$, $\frac{3.1EC_V\pi}{l\sigma_f^2} = \frac{K_C^2\pi}{4l\sigma_f^2}$		 Equivalent strain ε_v	 Equivalent strain ε_v $l \rightarrow \infty$	 Equivalent strain ε_v $l \rightarrow \infty$	 Equivalent strain ε_v
Remarks	Experimentally proved in the ranges: 168 < d_i < 1066 mm; 6.4 < t < 44 mm; 25 < l < 620 mm; 33 < $\sqrt{d_i t}$ < 158 mm; 220 < σ_f < 843 MPa; 19 < C_v < 244 J				$\sigma = \frac{F}{S}$ Tensile test  True strain $\phi = \ln\frac{S}{S_o}$	Ramberg–Osgood law $\frac{\phi}{\phi_o} = \frac{\sigma}{\sigma_o} + \alpha\left(\frac{\sigma}{\sigma_o}\right)^n$

Table 1: Calculation methods