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LEAK-BEFORE-BREAK TESTS WITH CARBON STEEL PIPES

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ABSTRACT

Leak-Before-Break (LBB) test serie was performed from November 1988 to November 1991 in NPO Central Boiler and Turbine Institute (NPO CKTI) in St. Petersburg, Russia. The tests were performed in co-operation with CKTI-laboratories, Imatran Voima Oy, Finland, and Technical Research Centre of Finland. Totally nine test series were performed and 21 full-scale pipes were tested.

Nominal pipe sizes in tests were 465 x 16 mm, 273 x 16 mm and 356 x 38 mm. The first one is same as used in VVER-440 type PVR plant primary loops. Length of the test pipe was typically 3000 mm. Material of the two first named pipe sizes was carbon steel St.20. The third pipe size material was perlitic carbon steel 10GN2MFA with 9 mm austenitic stainless steel cladding inside. Initial defects were made inside the pipe wall. Both circumferential and longitudinal flaws were used. The test pipes were loaded by inside water pressure or by inside water pressure and four point bending up to bursting. The tests were performed at 50 to 60 degrees centigrade temperature in order to guarantee tough material behaviour. The pressure, the crack mouth opening and the strains were measured during the tests.

The initial crack sizes were determined so that the test will cause a break in some cases and only a leak in other cases. The burst pressure varied from 10 MPa up to 47 MPa. The test results show that the plastic limit load method will estimate the bursting load and stability reasonably accurately with low calculation costs, if the material is ductile and the pipe and flaw geometry and loading are simple. One of the main problems is how to choose the flow stress for the calculation. One possiblity is to determine the flow stress from the bust pressure tests.

1 INTRODUCTION

The aim of the research work described in this paper has been to investigate the leak before break-phenomenon. The goal of work conducted has been to get information about pipe ruptures in order to show the probability of a guillotine break in nuclear power plant piping small enough and possibly to avoid expensive emergency restraints in future power plants and further to remove emergency pipe support or absorbers from plants in operation now. Under favourable circumstances so called leak before break phenomenon is some orders of magnitude more probable than a large break.

2 TEST ARRANGEMENT

The ends of the straight cylindrical pipes were closed with flat caps. To avoid the interaction between the flaw and the end closure, the flaw was fabricated at about 0.5 m from the end of the pipe. The pipes were made of carbon steel St 20 chemical composition C = 0.17 - 0.24 (%), Si = 0.17 - 0.37, Mn = 0.35 - 0.65, S < 0.025, P < 0.03, Cr = 0.25, Ni < 0.25 and Cu = 0.30.

The fabrication of a flaw profile is illustrated in fig. 1. First a groove with square section shape and width of about 2 mm was machined in the wall. The depth of the groove was constant with the exception of the ends of the groove, where the depth decreased to zero towards the ends of the flaws. After machining a groove a sharp notch was hammered to the bottom of the groove by a simple chisel with a sharp head. This fabrication procedure leads to a rather sharp notch bottom, but compressive yield stresses remain at the tip area of the notch. The effect of the fabrication procedure described above was investigated by simple test specimens made of same material as the test pipes. Two identical specimens were made. The specimens differed from each other only by the fact that in the first specimen the flaw was fabricated in a way described above and in the second the specimen a crack was made by fatigue. The specimens were broken and the breaking loads deviated only some percentages from each other. The test was repeated with the same result. It should be emphasized that these two tests give too little statistics for making reliable judgement.

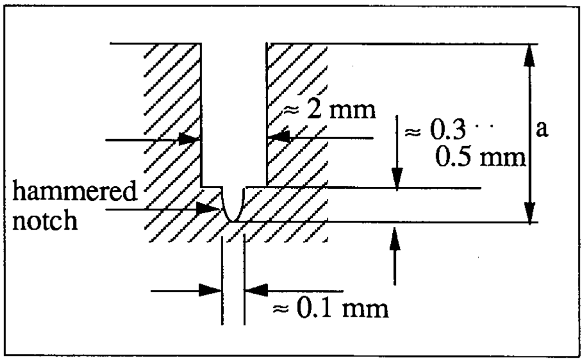

Figure 1. Cross section of a machined and hammered flaw.

For measuring the strains uni-axial gages were located transversely to the flaw line on the ligament. On the area outside the flaw ends bi-axial and tri-axial gages were located. Mostly the strain gages were positioned symmetrically from the centre line of a flaw. Comparing the strain values in symmetrical gages it was possible to find out possible interaction between the flaw and the end cap of the pipe and initiation moment of ligament necking. For crack mouth opening (CMO) measurements three linear - variable - displacement - transducers (LVDT) were installed symmetrically from the centre line of the flaw and inside the pipes.

3 CALCULATION PROCEDURE

At every phase of performing the tests calculational considerations were essential. The dimensions of flaws, burst pressure and stability of burst crack were determined by precalculations. The plastic limit load method for pressure and bending moment loading in a cylinder having an axial or circumferential crack in the wall described in [*Rodabaugh*] and [*Kanninen*] and applied in tests has proved to be reliable, simple and quick to use.

Critical stress σ_c far from crack causing growth of both ends of a through wall crack is related to flow stress σ_{flow} for tough material according equation [*Kanninen*]

$$\sigma_c = \frac{\sigma_{flow}}{F_F}, \tag{1}$$

where σ_{flow} is the flow stress attempting to take into account work hardening and the through-thickness constraint and F_F shape factor dependent on geometrical dimensions. For a through wall axial and circumferential crack in a thin walled cylinder under pressure loading and circumferential crack under bending critical stress σ_c far from the crack and shape factor F_F are [*Rodabaugh*]

axial crack, pressure load $\quad \sigma_c = \frac{R^2}{R_i t} p_c \,, F_F = \sqrt{1 + 1.255\ \lambda^2 - 0.0135\ \lambda^4}$, valid, if $\lambda = c\,/\sqrt{R\,t} < 4.4$

circumf. crack, pressure load $\quad \sigma_c = \frac{R^2}{2R_i t} p_c \,, F_F = 1 + 0.0237\lambda + 0.1449\lambda^2$

$$- 0.0344\ \lambda^3 + 0.00255\ \lambda^4 \,,\ \lambda = \theta\sqrt{R/t}$$

circumf. crack, bending load $\quad \sigma_c = \frac{1}{\pi R^2 t} M_c,\ F_F = \sqrt{1.0 + 0.26x + 47x^2 - 59\,x^3}\,, x = \theta\,/\pi \qquad (2)$

where R is average radius, R_i internal radius, t wall thickness, c crack half length and θ crack half angle. The factor $1/F_F$ (< 1) describes the decreasing of the critical stress of a cracked cylinder compared to critical stress of an uncracked cylinder. In the limit as $R \to \infty$, $F_F \to 1$ and flat panel is recovered. For an axial through wall crack the formula for F_F was derived by Folias and valid, when Poisson's ratio $\nu = 0.3$.

In case of seeking for bursting stress or pressure for a partially through wall crack it is proposed that the formulas presented above are still valid, if the shape factor F_F is modified to the shape factor F taking into account the depth of the crack. Experimentally confirmed shape factor F for a square shaped crack with depth a is [*Kiefner*]

$$\frac{1}{F} = \frac{1 - \frac{a}{t}}{1 - \frac{1}{F_F}\frac{a}{t}} \tag{3}$$

and critical stress σ_{cb} far from the crack to cause rupture partially through the wall is

$$\sigma_{cb} = \frac{\sigma_{flow}}{F}. \tag{4}$$

The factor $1/F$ (< 1) describes the decreasing of the bursting pressure of a crack partially through the wall compared to critical pressure of an uncracked tube. The simple mathematically well behaving function (3) fulfils four requirements: when $a \to 0$, $1/F \to 1$; when $a/t \to 1$, $1/F \to = 0$ and $\sigma_{cb} \to 0$ meaning that small pressure is enough to burst the crack through the wall. Further when c (or θ or x) $\to 0$, $1/F \to 1$ and when c (or θ or x)$\to \infty$, $1/F \to 1 - a/t$. So it can be anticipated that function (3) describes well also the intermediate area.

The ends of a crack do not grow, if the critical stress for the burst crack is greater than the critical stress of the surface crack of the same length. In pressure load cases it is provided that the pressure is kept constant in spite of the through wall crack. This is nearly possible, if the contents of the pipe is steam or gas or the energy accumulated in the fluid and the structure is large enough.

From eqs. (1) and (4) we get the condition for the stability for a burst crack ($\sigma_c > \sigma_{cb}$)

$$\frac{1}{F_F} > \frac{1}{F} = \frac{1 - \frac{a}{t}}{1 - \frac{1}{F_F}\frac{a}{t}} . \tag{5}$$

In this inequality the left side is related to through burst crack and right side to partially through crack. The stress σ_{flow} is not any more present in eq. (5), because σ_{flow} related to bursting of partially through crack is chosen same as in stability consideration of burst crack. This is not possibly correct, because the constraint effect is not the same in the crack front of a partially through crack and through wall crack.

If the depth of a partially through crack is constant, from eq. (5) it follows

$$\frac{1}{F_F} > \frac{1 - a/t}{a/t} , \quad a/t > 0{,}5 . \tag{6}$$

The right side of this equation is 1, if $a/t = 0.5$. Because $F_F > 1$, LBB-condition of a square shaped axial crack under pressure load is never achieved, if $a/t < 0.5$.

4 RESULTS OF TESTS AND CALCULATIONAL CONSIDERATIONS

For the test safety reasons the contents of the pipes was water and thus large breaks were impossible. For judging failure mode - leak or break - the fracture surface was investigated after the test and the measured burst length 2c* was compared to the original maximum length $2c_{max}$ of the flaw. The crack growth rate was so high and on the other hand the accumulated elastic energy in the pipe wall and in the water was so great that in case of a break the crack could grow over the original flaw length $2c_{max}$ before arrest. So, if $c^*/c_{max} > 1$ as in fig. 2, the burst crack was concluded to be unstable (break) and stable (leak), if $c^*/c_{max} < 1$, respectively.

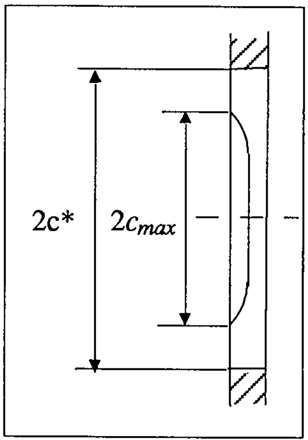

Figure 2. A burst crack after a test.

Bending moment applied in tests 14 - 21 was arranged by supporting the pipe at two points the span being 3.0 m and forced by two lateral forces at a distance of 0.6 m from each other. In this four point bending system a crack was centrally located at constant bending moment area. The relation between critical bending moment M_{cb} and total respective lateral force F_{cb} was thus $M_{cb} = (3.0\text{ m} - 0.6\text{m})/4 * F_{cb} = 0.6 * F_{cb}$.

The effective length $2c_{eff}$ in table 1 used in the calculation is the length of a flaw with constant depth having the same area as the real flaw and the same depth as the maximum depth of the real flaw. In combined loading case the contribution of pressure and bending loading to flow stress was simply summed. After tests the fracture surface was investigated by microscope and the fracture mechanism was always found to be ductile.

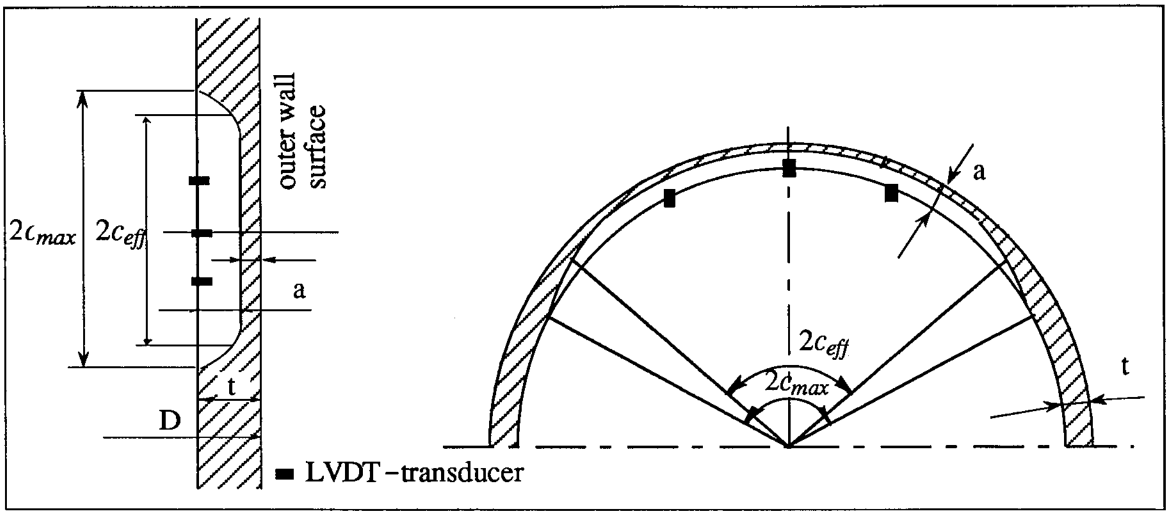

Figure 3. Notations for the flaws (numerical values in table 1).

Table 1. Pipe and flaw dimensions (notations in fig. 3). p_{cb} is measured burst pressure, F_{cb} measured lateral force pressure and σ_{flow} flow stress calculated according to the bursting pressure and bending moment. From the stability indices calculated from eq. (5) first is related to pressure loading and second one to bending load (value < 1 means burst and > 1 break).

Test	D [mm]	t [mm]	a[mm]	$2c_{max}$	$2c_{eff}$	p_{cb}[bar]	F_{cb}[kN]	σ_{flow}[MPa]	stability	c^*/c_{max}	
1(1)	465.0	18.0	11.0	310.0 mm	264.0 mm	275.0	-	610.0	1.46	4.40	break
2(2)	468.0	18.8	15.3	525.0 mm	447.0 mm	108.0	-	497.7	1.01	0.88	leak
3(3)	465.0	18.0	12.6	366.0 mm	334.0 mm	172.5	-	504.6	1.27	1.77	break
4(4)	466.0	18.0	13.5	160.0 mm	128.0 mm	202.0	-	464.3	0.86	3.44	break
5(5)	465.1	19.3	15.5	365.0 mm	334.0 mm	128.0	-	498.7	0.85	1.14	break
6(6)	465.0	17.8	12.8	162.0 mm	132.0 mm	207.0	-	453.7	0.92	0.69	leak
7(7)	465.1	17.1	13.6	365.0 mm	334.0 mm	113.0	-	495.7	0.91	1.10	break
8(21)	274.0	17.0	13.2	200.0 mm	169.2 mm	315.0	-	605.3	0.87	0.98	leak
9(8)	463.3	15.9	13.4	128.0 ^{0}	121.0 ^{0}	180.0	-	409.2	0.55	0.94	leak
10(9)	463.1	13.3	11.4	188.0 ^{0}	176.0 ^{0}	119.0	-	418.3	0.56	0.94	leak
11(10)	461.0	16.0	13.1	186.0 ^{0}	174.5 ^{0}	181.5	-	401.8	0.66	1.02	break
12(11)	460.3	17.1	13.7	99.0 ^{0}	86.8 ^{0}	229.5	-	341.2	0.67	0.75	leak
13(22)	270.5	13.7	10.5	124.9 ^{0}	74.5 ^{0}	420.0	-	338.7	0.90	0.27	leak
14(23)	271.1	13.9	12.2	138.0 ^{0}	104.0 ^{0}	-	115.0	418.6	0.49	0.48	leak
15(24)	270.8	14.6	9.8	175.0 ^{0}	147.0 ^{0}	344.0	110.0	444.2	1.02/1.10	0.61	leak
16(25)	270.3	14.7	12.1	98.8 ^{0}	75.5 ^{0}	357.0	98.0	528.3	0.68/0.67	0.34	leak
17(26)	272.3	16.7	11.4	80.2 ^{0}	52.3 ^{0}	454.0	192.0	416.7	1.01/1.05	0.41	leak
18(108)	326.7	26.7	20.2	125.2 ^{0}	106.2 ^{0}	467.0	296.0	446.7	0.79/0.83	0.66	leak*
19(27)	269.9	14.3	11.1	52.6 ^{0}	52.6 ^{0}	448.0	111.0	466.9	0.75/0.71	0.85	leak
20(28)	269.3	14.7	10.1	142.4 ^{0}	142.4 ^{0}	429.0	138.0	568.4	0.91/1.00	0.95	leak
21(201)	356.8	38.8	33.8	223.4 ^{0}	212.0 ^{0}	471.0	300.0	583.7	0.46/0.47	-	leak*

* In the test 18(108) the material was austenitic stainless steel and in the test 21(201) perlitic carbon steel 10GN2MFA with 9 mm austenitic stainless steel cladding inside the pipe.

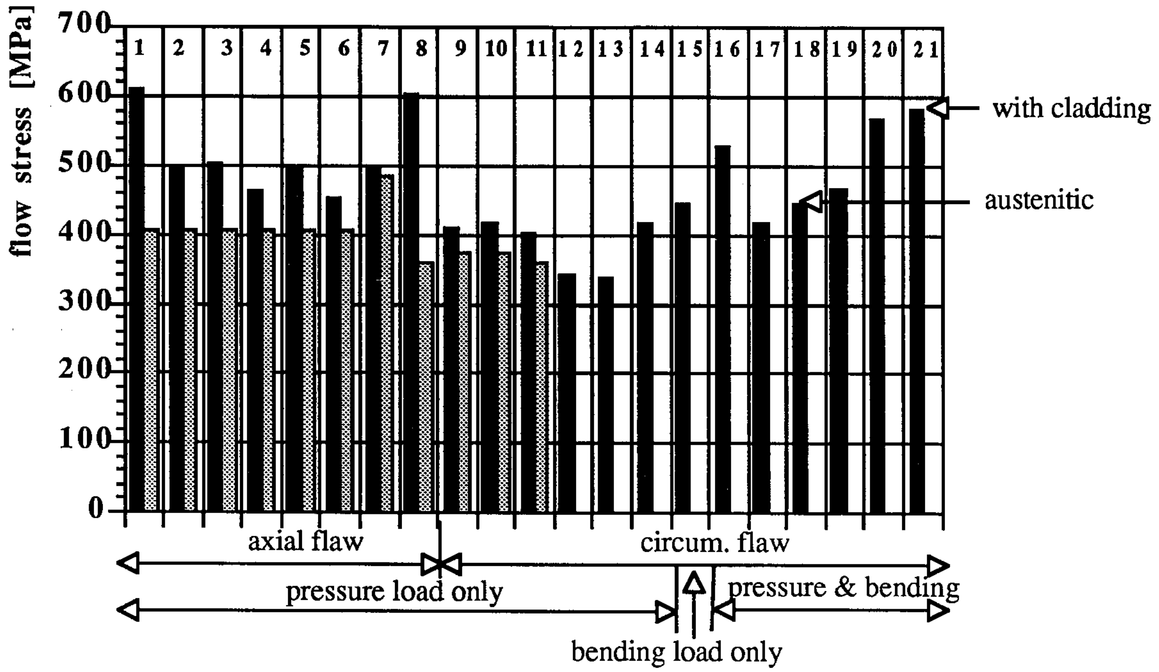

Figure 4. Calculated flow stress (black columns) and the average of the yield and ultimate strength (grey columns, only in tests 1 - 12).

Average calculated flow stress for axial flaws became σ_{flow} = 540 MPa and related relative standard deviation 8.8 %. For circumferential flaws average flow stress became σ_{flow} = 477 MPa with relative standard deviation 16.4 %.

CONCLUSIONS

The results show that if the material is ductile, as it was in all the performed tests, and the geometry and loading condition is simple, i.e. cylindrical geometry and axial or circumferential crack orientation, the variance in the flow stress values is reasonable. Thus it can be anticipated that the bursting and the stability of a burst crack load can be estimated with low calculating costs and acceptable accuracy, if the relevant flow stress is known. One recommendation is to calculate the flow stress value from burst pressure tests as was done in work described in this article.

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