GF09/2

EXCLUSION OF RUPTURE FOR WELDED PIPING SYSTEMS OF POWER STATIONS BY COMPONENT TESTS AND FAILURE APPROACHES

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SUMMARY

Tests on large pipes loaded by internal pressure and a superimposed external bending moment were performed to demonstrate that even in presence of large circumferential flaws in circumferential welds the critical crack length will not be attained under realistic service and upset conditions.

For the tests high - temperature seamless pipes of dimensions O.D. x T x L = 457 x 15 x 5500 mm made from 15 NiCuMoNb 5 material were used. 27 tests were performed at room temperature with different flaw geometries and flaw positions in the base metal, the weld metal or the heat affected zone.

Depending on the geometric conditions the load bearing and failure behaviour of the investigated pipes could clearly be represented in a common failure diagram. Significant differences in maximum loads depending on the position of the flaws in the structure or whether inside or outside could not be detected. Maximum loads were compared with calculations using applied engineering failure approaches, based on concepts of local flow stress and plastic limit load.

1 OBJECTIVE

Ferritic pipes of the size and importance of feed water lines are used in conventional power plants as well as for safety relevant systems of light water reactors. To demonstrate the safety of such pipes against massive fracture (break) both under upset conditions and in the presence of circumferential cracks in the welds, a research programme was launched. Under combined loading conditions, load bearing behaviour and the Leak-Before-Break (LBB)-Criteria were to be determined by component tests and calculations based on engineering approaches /1/.

2 TEST MATERIAL AND PROGRAMME

The component tests were performed on high temperature seamless pipes of dimensions O.D. x T x L = 457 x 15 x 5500 mm made from 15 NiCuMoNb 5 material, Table 1. To cover unfavourable material conditions, a lower bound heat was selected with an upper shelf energy of about 50 J. Partlength pipes were joined for test purpose by circumferential welds using a weld metal similar to the base metal.

The pipes were loaded under constant internal pressure and a superimposed bending moment at room temperature. As seen in Fig. 1 circumferential flaws of specific dimensions were machined into the base metal (BM), weld metal (WM) or the heat affected zone (HAZ) located on either the inside or outside of the pipe.

For the tests a 4-point bending device was designed for a maximum bending moment of 3 MNm and built with a distance of 5000 mm between the reaction bearings, Fig. 2. To guarantee constant loading conditions in the phases of crack initiation and propagation and for realizing a testing system with high stored energy, air was used as the pressure medium in the actuator and as a reservoir in the pipes.

The flaws were placed in the area of the maximum bending load on the side stressed in tension. With increasing bending moment, loads, deformations, strains, crack opening displacement and crack initiation were measured on-line up to failure of the pipe.

3 TEST RESULTS

Altogether 27 tests were performed, which are represented in this paper by a selection having regard to nature of flaw, flaw position, flaw size and maximum load, Table 2.

The basis for the evaluation of piping failure behaviour is given by the Leak-Before-Break (LBB)-curve in the load bearing diagram. This boundary separates the areas of massive fracture (break) and leakage for flaws of different geometries. The LBB-curve has to be determined experimentally by tests with wall penetrating slits (through-wall flaws) which are sealed on the inside against internal pressure. Thus the LBB-curve was determined for the test specimens and test conditions for slits of different lengths positioned in the base metal, Fig. 3. Following the initiation of the cracks, the loading increases in both cases with crack length up to maximum values until instability occurs corresponding to the LBB-curve.

Load bearing behaviour of the pipes with surface flaws has no clear dependence on either the flaw position in the structure nor on the location (inside or outside of the pipe) whereas the influence of the flaw size is dominant, Fig. 4. All tests performed with high system energy failed by leakage or break as expected from the position of the LBB-curve with the exception of test Nr. 12 (leakage instead of break) where a stiff testing system was achieved by using liquid for pressurizing the pipe and the actuator.

4 ENGINEERING FAILURE APPROACHES

The maximum loads (bending moments) attained in the bending tests were compared with calculations using applied engineering failure approaches based on the concepts of local flow stress and plastic limit load, Fig. 5. The concept of local flow stress $/2, 3/$ is based on the assumption that in the net cross-section of a ductile material a flow stress will be achieved locally. The stress in the weakened cross-section is calculated with the aid of linear elastic bending theory considering the actual moment of inertia for the weakened cross-section and the internal bending moment from internal pressure. Notch and supporting effect are disregarded.

Assuming flow stress has a value between yield stress and tensile strength, the calculated loads for surface and through wall flaws are below the results from experiments with the exception of flaws of 90 % of the wall thickness in depth, Fig. 6.

Using materials of high toughness, the plastic limit load concept /4/ presumes that local yielding propagates at the most highly loaded position until a condition of whole cross-section yielding has been reached for the weakened cross-section and plastic collapse occurs at failure. Calculations are based on elastic-plastic material behaviour and considerations of equilibrium in the weakened section. This approach fits the LBB-curve and small flaws best whereas for all others, the estimation is non-conservative, Fig. 7.

None of the failure approaches permits a reliably conservative prediction for the whole spectrum of test parameters. Depending on the particular failure theory there are individual results or sections in which calculation and experiment agree well. The plastic limit load concept, however, describes the Leak-Before-Break-curve very well, especially in the region of short flaws, because stable crack growth allows greater plastic zones to arise in the flawed cross-section.

5 CONCLUSIONS

According to the KTA-guidelines based on linear-elastic considerations, in the case of upset conditions a primary membrane stress of R_{mT} (tensile strength at service temperature) is permitted. With the tensile strength R_m (RT) = 680 MPa a maximum bending moment $M_m = R_m \cdot W_b \approx 1500$ kNm is acceptable. For this peak bending load the critical crack size is determined as $2\alpha = 40$ deg., Fig. 8. Considering a safety factor $S = 2$ against massive fracture, an allowable circumferential flaw angle $2\alpha = 20$ deg. results giving a flaw length of about 80 mm for the test pipes. Smaller cracks can only fail by leakage provided they are deeper than 70 % of the wall thickness. Larger cracks will be detected by means of routine non-destructive examination before growing to critical dimensions.

ACKNOWLEDGEMENT

The test programme was performed under contract from Siemens AG, UB KWU and VGB-Kraftwerkstechnik. The authors would like to acknowledge the funding and support received.

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Table 1. Chemical analysis and material property values of 15 NiCuMoNb 5 material

PIPE SPECIMEN, O.D. x T = 457 x 15 mm															
MATERIAL: 15 NiCuMoNb 5															
CHEMICAL ANALYSIS															
CONSTITUENTS IN %															
C	Si	Mn	P	S	Cr	Ni	Mo	V	Al	Cu	Nb	Sn	Ti	As	Sb
.16	.29	1.02	.015	.02	.30	1.12	.31	<.01	.03	.65	.025	<.01	<.01	.01	<.01
MATERIAL PROPERTY VALUES AT ROOM TEMPERATURE															
SAMPLING IN TRANSVERSE PIPE DIRECTION	TENSILE TEST			IMPACT TEST											
	R _{p0.2}	R _m	A ₅	A _v											
	MPa	MPa	%	J											
MINIMUM	555	662	20	42											
MAXIMUM	585	702	24	57											
AVERAGE	560	680	22	55

Fig 1. Flaw geometry and position

Fig 2. 3 MNm-pipe bending device

Table 2. Parameters and results of pipe bending tests

MATERIAL:				15 NiCuMoNb 5		
DIMENSIONS:				O.D. x T = 457 x 15 mm		
INTERNAL PRESSURE:				$p_i = 8 \text{ MPa}$		
TEST NO.	CIRCUMFERENTIAL FLAW				BENDING MOMENT	MODE OF FAILURE
	POS. OF FLAW ¹⁾	TYPE	DEPTH	ANGLE	$M_{\max}$	
					d/T	
1	BM	TWF	1.0	45	1280	-
2		TWF	1.0	90	794	-
3		ESF	0.9	60	521	LEAKAGE
4		ISF	0.9	60	544	LEAKAGE
5		ESF	0.9	120	147	LEAKAGE
6		ESF	0.9	180	21	LEAKAGE
7		ESF	0.7	20	1605	LEAKAGE
8		ESF	0.7	60	925	LEAKAGE
9		ISF	0.7	115	595	LEAKAGE
10		ESF	0.7	120	567	LEAKAGE
11		ESF	0.7	120	540	LEAKAGE
12		ESF	0.7	180	544	LEAKAGE
13		ESF	0.7	180	528	BREAK
14		ESF	0.7	240	550	BREAK
15		ESF	0.3	20	1730	LEAKAGE
16		ESF	0.3	60	1520	BREAK
17		ESF	0.2	120	1770	BREAK
18		ESF	0.1	120	1910	COLLAPSE
19	WITHOUT FLAW				1810	COLLAPSE
20	WM	ISF	0.9	45	420	LEAKAGE
21		ISF	0.9	90	140	LEAKAGE
22		ISF	0.7	45	1150	LEAKAGE
23		ISF	0.7	90	755	LEAKAGE
24		ISF	0.7	180	575	BREAK
25	HAZ	ISF	0.7	30	1405	LEAKAGE
26		ISF	0.3	30	1670	LEAKAGE
27		ISF	0.3	120	1570	BREAK

- 1) BM = BASE METAL WM = WELD METAL
HAZ = HEAT AFFECTED ZONE
TWF = THROUGH WALL FLAW ESF = EXT. SURFACE FLAW
ISF = INT. SURFACE FLAW

Fig 3. Determination of the Leak-Before-Break-curve

Fig 5. Engineering failure approaches