LEAK-BEFORE-BREAK BEHAVIOUR OF A PIPING SYSTEM DN 425 SUBJECTED TO TRANSIENT LOADING BY WATER HAMMER

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1 INTRODUCTION AND OBJECTIVE

In the course of the national German Nuclear Reactor Safety Research Program initiated in 1976 several test series have been devoted at the HDR test facility to transient pipework loadings like with water hammer and blowdown. Initially, the behaviour of the valves and the effects of different valve closing times (damping characteristic) on the response of the pipeline were given priority in the studies [1]. In a second step the load carrying capacity of the pipeline was investigated on components loaded beyond the elastic limit [2]. As a consequent continuation of the tests on integer piping systems blowdown experiments on a piping system with degraded components were performed within phase III of German HDR Safety program.

The objective of the investigations was to study the failure behaviour (leak or break) of a weakened piping system subjected to a level D event and to improve analytical and numerical tools used in safety analyses. Analytical methods (plastic limit load concept, the two-criteria-approach, moment method) [3] are used to describe the leak-before-break-behaviour. Furthermore, numerical calculations were performed to describe the elastic-plastic time dependent component behaviour.

2 SET-UP AND SEQUENCE OF EXPERIMENTS

The test piping system used in the experiment, Figure 1, corresponds to the feedwater line of a boiling water reactor as regards its nominal width, length, number of pipe elbows, and the flexible mode of pipe routing. The component investigated in detail was a straight pipe section with the dimensions outer diameter Dₜ = 457 mm and wall thickness t = 16 mm. The test pipe section was made from low alloyed ferritic material 20 MnMoNi 55 similar to ASTM A 508 Cl 3 and integrated at the point of maximum loading of the piping system consisting of the ferritic material 15 MnNi 63 (Dₜ = 475 mm; t = 25 mm) near the reactor pressure vessel (RPV) nozzle. The selected flaw con-
figurations had been inner circumferential cracks with the dimensions $2\alpha = 60^\circ$ and $a/t = 0.3$ (experiment E31.2) and $a/t = 0.5$, respectively (experiment E31.3). In the experiments carried out at the HDR test facility the RPV provided the energy potential needed to maintain the conditions of loading ($p_i = 9.2$ MPa, $T = 240$ °C).

Figure 2 is a representative illustration of measured pressure versus time curves in the pipeline in experiment E31.2. In order to attain pipework loading in the maximum permissible range for a level D event or even beyond, the valve was closed undamped which, on account of design measures, cannot occur in practical application. The pressure peak reached was $p_{\text{max}} = 23.7$ MPa. The initial outflow and valve closure gave rise to a fluid dynamics response which made the pipeline vibrate. Between 100 ms and 120 ms after onset of blowdown the crack was subjected to the maximum loading. The maximum bending moment in the crack cross-section was about 1270 kNm in the first experiment (E31.2: $a/t = 0.3$) and caused the crack to grow deeper by 1.5 mm; Figure 3. In the second experiment (E31.3: $a/t = 0.5$) the maximum bending moment was estimated at 1380 kNm. The greater depth of the initial flaw caused the flaw penetrating the wall (leak) with an extension $2\alpha_0 = 43^\circ$ on the outer surface; Figure 4.

3 NUMERICAL CALCULATIONS

Numerical analyses by means of finite element programmes (ABAQUS, ADINA) were performed parallel to the experiments [4]. The global behaviour and the loading of the non-damaged parts are determined by structural dynamics computations of the integer pipeline sections. The influence of predamaging on the global behaviour can be estimated by coupling structural dynamics with fracture mechanics computations using simple flaw elements (LINE-SPRING elements). Detailed fracture mechanics analyses using 3D-volume elements ultimately allow a statement to be made on crack loading.

The structural dynamics computations of the overall structure, taking into account the true material characteristics already yielded good agreement with the measured data. The comparison with the linear-elastic computations has shown that the behaviour of the pipework is heavily influenced by plastification processes.

It has been shown by the coupled structural-dynamics fracture mechanics computations in which the test pipe section of the overall structural model was modeled by shell and LINE-SPRING elements (simple cracked elements) that predamaging means but little changes in the global behaviour. The calculated crack tip loading was above the value of crack initiation for both flaw depths.

The numerical results are discussed in detail in [5].
4 ANALYTICAL METHODS

For pipes with circumferential cracks there are several methods available to calculate the failure load [3]. A crack extending in the circumferential direction will arise as soon as the axial and bending stresses exceed the hoop stress. This is usually the case in piping systems in which an external bending moment acts in addition to the internal pressure. Consequently, the methods chosen to calculate the failure load of pipes with circumferential cracks take into account not only the internal pressure but, in particular, the external bending moment.

For pipes fabricated of ductile materials local yielding in the region of crack tips can spread out until under limit load conditions the entire pipe is subjected to plastic deformation at its cracked cross section (plastic limit load concept). Failure will be assumed if the stress \( \sigma_f \), resulting from the loads applied, corresponds to a material property, normally the flow stress \( \sigma_y \). The flow stress \( \sigma_f \) can be expressed in terms of \( R_\infty \) and \( R_m \) : \( \sigma_f = a_1 R_\infty + a_2 R_m \), where the parameters \( a_1 \), \( a_2 \) are usually fitted by experimental data to guarantee more or less conservative results. In [3] it is shown that for \( a_1 = a_2 = 0.5 \) the experimentally determined borderline between failure by leakagge and catastrophic break (slit curve) is described well for high-toughness ferritic material but the allowable loading values of pipes with part-through cracks are overestimated.

The local flow stress concept (moment method) is based on the fact that a circumferential crack in the pipe wall reveals a shift of the centre of gravity of the cracked cross-section. The effective stress is determined in accordance with Bernoulli’s bending theory under consideration of the actual section modulus and of the location of the centre of gravity. Failure is postulated to occur when the calculated stress at the maximum loaded position reaches a critical stress limit. This critical stress limit normally is assumed in safety analyses to be equal to the flow stress, \( \sigma_f \). As has been demonstrated in experiments, the failure load can be determined more precisely if the effective stress at the point of maximum loading, expressed as the critical stress limit, is indicated by the ultimate stress, \( R_\infty \), of the material. Regarding the above equation the parameter \( a_1 \) is set to 0 and \( a_2 \) is set to 1. For high-toughness materials the moment method tends to underestimate the experimental data of pipes for both part-through cracks and slits.

The two criteria approach (R6-method, failure assessment diagram) and similar to it the R-curve method include in the failure analysis not only the strength but also the fracture mechanics characteristics of the material. The R6-method can be applied over the whole range of toughness (lower shelf, transition, upper shelf), covering both failure by brittle fracture and failure by fully plastic conditions (plastic collapse). If the two criteria approach is to be employed, the plastic limit load as a function of the applied forces, moments and internal pressure as well as the stress intensity factor \( K_I \) for the
crack contour and the loading mode of pipe must be known. The plastic limit load can be calculated as described above. The stress intensity factor $K_c$ is determined from Finite Element analyses for pipes with circumferential defects under combined internal pressure and bending loads. The fracture mechanics characteristics ($J_R$-curves, $J_I$-value) are determined from compact tension (CT) specimens. The instability load is calculated under the assumption of stable crack growth by comparison of the slopes of the $J_R$-curves and the R6-curve.

In Figure 5 the failure load (plastic limit load concept, moment method) resp. initiation load and instability load (R6-method) for the two experiments ($M_{exp}$ = 1300 kNm) are tabulated. The plastic limit load concept predicts leakage for both crack depths, the moment method predicts leak for the experiment E31.2 ($a/t = 0.3$) and break for the deeper flaw (E31.3, $a/t = 0.5$). Assessing the initial crack sizes of the two experiments by means of the R6-method instable crack growth (break) is to be expected.

5 SUMMARY AND CONCLUSIONS

Within the scope of piping research during phase III of the HDR Safety program two blowdown induced waterhammer tests under operational conditions of $T = 240$ °C and $p_i = 9.2$ MPa were carried out at a feritic test piping system (DN 425) with almost realistic isometry.

In the first experiment ($a/t = 0.3$) a crack growth of only 1.5 mm occurred, and in the second one ($a/t = 0.5$) the component failed by leakage. The analytical results predict leak in case of $a/t = 0.3$. For the deeper flaw ($a/t = 0.5$) depending on the individual analytical procedure both leak and break is predicted to be possible. Consequently, the used analytical methods offer a conservative estimation of the real failure behaviour. A good description of the real piping behaviour was obtained by the numerical methods even in the case of high plastification processes.

The examinations have shown that the ductile piping materials used in power plants nowadays have an inherent high safety margin against catastrophic failure (large break). To get a more realistic description of the experimental failure behaviour, further assessments are focussed on revised applications of the R6-method.

ACKNOWLEDGMENT

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REFERENCES


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Fig. 1: Test Piping System
**Fig. 2:** Measured Characteristic Time Plots of Fluid Dynamics

**Fig. 3:** Metallographic Cut (Experiment E31.2) Detail A

**Fig. 4:** Metallographic Cut (Experiment E31.3)

<table>
<thead>
<tr>
<th>analytical method</th>
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<td>plastic limit load concept failure load</td>
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<td>R6-method initiation load instability load</td>
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**Fig. 5:** Critical Loads Determined by Analytical LBB-Methods