Strength And Fracture Behavior of Pipes With Circumferentially Orientated Cracks Under Monotonic Bending Loading

W. Stoppler, D. Sturm, J. Schiedermaier, K. Hippelein
Universität Stuttgart, Stuttgart, FRG

Abstract

Pipes with the dimensions of the main coolant piping system of a pressurized water reactor (PWR) weakened by circumferential flaws and loaded by internal pressure as well as an external bending moment were tested to define the critical flaw length under service and upset conditions.

Introduction

Design, construction and service of a primary cooling system of German Light-Water-Power-Plants is based on the concept of basis safety, which is incorporated into the KTA-rules 3201.1 and 3201.2 /1/. A catastrophic failure of a pressurized component can be excluded observing these rules. The aim of the research project "Phenomenological Vessel Burst Test", /2, 3, 4, 5/ which is sponsored within the scope of the reactor safety research program, Fig. 1, of the Federal Ministry for Research and Technology (BMFT) is to prove the integrity of the piping loaded under all possible in service and emergency conditions. In accordance with the KTA-rules, emergency conditions such as earthquake, waterhammer or airplane crash can cause stresses higher than the yield strength. The design of the component as well as the used material have to be able to reduce stress peaks by local yielding.

Objectives

Pipes with an O.D.-800 mm and a wall thickness of 47 mm, which are the main dimensions of the primary cooling piping of a German 1300 MW, PWR, were investigated under service conditions referring to internal pressure (-15 MPa) and temperature (up to 300 °C). Additionally, a monotonic increasing outer bending moment was applied. Most of the pipes were weakened by machined cracks in circumferential direction. Fig. 2 shows the investigated parametric field regarding the kind of flaws, inner and outer surface notches resp. through-wall cracks (slits), as well as the flaw dimensions, length and depth. To investigate also the influence of toughness, the pipes were fabricated of two kinds of fine grain ferritic steels with nearly the same strength properties (300 °C) such as ultimate strength $R_m \approx 605$ MPa and a yield strength $R_{y0.2} \approx 428$ MPa. One material, 20 MnMoNi 5 5, had a high upper shelf impact energy of $> 150$ J (HUSE), and the other, NiMoCr-melt, had a low upper shelf impact energy of $\sim 50$ J (LUSE).
Methods

The 5 m long pipes were mounted into a four-point bending device with a capacity of 14 MNm. The bending moment could be applied by means of an actuator, positioned above the center line of the pipe, Fig. 3. To achieve a system which is as soft as possible air was used as pressure medium for the actuator and the pipe. Electric power heat pads were wrapped around the pipe to obtain the elevated temperature.

Results

In Table 1 the results are listed of all performed tests. First of all, the load (bending moment)–strain behavior of the unweakened pipe was determined, Fig. 4. A bending moment \( M_p = 9.3 \text{ MNm} \) was found at the end of the elastic range and at the point of an equivalent plastic strain of 0.2% a bending moment \( M_{p, pl} = 11.5 \text{ MNm} \). As shown in the lower part of Fig. 4 the experimentally determined bending moment–strain curve corresponds very well with a calculated one /6/, taking into account the deviation of material properties and dimensions.

The load bearing capacity of pipes, weakened by circumferentially orientated slits are plotted for both materials as scatterband in Fig. 5. These curves represent also the leak–before break curves, which separates the area of "leakage" from that of the "catastrophic failure". It becomes obvious, that the load bearing capacity is significantly influenced by the roughness of the material. The critical slitlength of pipes made of the HUSE-material amounts more than twice the quantity achieved for the pipes made of the LUSE-material. From the path of the curves it can also be seen that the critical length of a defect can become relatively small when increasing the external bending moment. Following KTA-rules for level D (emergency and upset conditions), a stress limitation of 3 Sm is given. This means, that a bending moment of 10 MNm has to be considered if the specified material properties were used for calculation or a moment of 11.5 MNm if the actual ones were used. Both figures are within the range of \( M_{p, pl} \) of the unweakened pipe. The corresponding critical slit length is given by Fig. 5 to 390 mm (56°) resp. 240 mm (35°) for pipes of HUSE-material. These values shrink to 180 mm (26°) resp. 100 mm (15°) in pipes of LUSE-materials. The last value stands for the worst case consideration and it has to be kept in mind, that this value is at least 3 times greater compared with the permissible length of a surface defect which according to /7/ is approx. 30 mm. The results of the experiments with pipes weakened by circumferential surface–flaws show also a determinative influence of the material toughness to the load bearing capacity, Fig. 6 and 7.

The experimentally determined failure moments were compared with calculated ones, Figs. 8 and 9, by means of two mainly used engineering methods /5, 9, 10/, Table 2. Regarding the investigated dimensions of the pipes as well as the materials, the following statements could be made:

- The "Moment Method" underestimates the load bearing capacity of the HUSE-pipes by roughly 30 % and
- overestimates by roughly 20 % the load bearing capacity of the LUSE-pipes.
The "Plastic collapse method" delivers values which are in the range of the experimentally determined, if the failure moment lies above the yield moment $M_{y} > 9$ MNm, Fig. 10. Otherwise, a higher failure moment is calculated than received by the experiment.

Conclusions

The experimentally determined critical slit length for main cooling piping of a PWR is much greater than the detectable one by means of NDT even if a bending moment under emergency conditions is applied and the toughness of the material is in the EOL-status. The leak-before-break criterion could be proved. The toughness has a significant influence on the load bearing capacity and the failure mode. The engineering calculation methods need more improvement to take into account material toughness.

Literature

/1/ Sicherheitstechnische Regeln des kerntechnischen Ausschusses, KTA 3201.1 und KTA 3201.2. Carl Heymanns Verlag KG, Köln


Table 1: Summary of Test Results

<table>
<thead>
<tr>
<th>Test Identification</th>
<th>Crack Type</th>
<th>Depth (mm)</th>
<th>Temp. (°C)</th>
<th>Internal Pressure (atm)</th>
<th>Max. Bending Moment (kNm)</th>
<th>Slit Ligation</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>BVS-090</td>
<td>0</td>
<td>15.2</td>
<td>12.110</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>BVS-161</td>
<td>Outer S</td>
<td>20</td>
<td>47.2</td>
<td>12.910</td>
<td>13.910</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>BVS-161</td>
<td>Outer S</td>
<td>20</td>
<td>47.2</td>
<td>9.650</td>
<td>9.200</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>BVS-160</td>
<td>Outer S</td>
<td>50</td>
<td>47.2</td>
<td>6.970</td>
<td>5.000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>BVS-160</td>
<td>Outer S</td>
<td>50</td>
<td>47.2</td>
<td>6.970</td>
<td>5.000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>BVS-160</td>
<td>Wall A</td>
<td>10</td>
<td>20</td>
<td>11.130</td>
<td>-</td>
<td>12.090</td>
<td>Leakage</td>
</tr>
<tr>
<td>BVS-160</td>
<td>Wall A</td>
<td>10</td>
<td>20</td>
<td>7.050</td>
<td>-</td>
<td>7.050</td>
<td>Leakage</td>
</tr>
<tr>
<td>BVS-160</td>
<td>Thick I</td>
<td>10</td>
<td>20</td>
<td>11.130</td>
<td>-</td>
<td>10.700</td>
<td>Leakage</td>
</tr>
<tr>
<td>BVS-150</td>
<td>Neck A</td>
<td>90</td>
<td>20</td>
<td>15.7</td>
<td>9.300</td>
<td>-</td>
<td>B rupture</td>
</tr>
<tr>
<td>BVS-140</td>
<td>Neck A</td>
<td>110</td>
<td>20</td>
<td>15.7</td>
<td>8.700</td>
<td>6.390</td>
<td>B rupture</td>
</tr>
</tbody>
</table>

BVS-090 Length 0 250 15.0 11.500 11.500 11.500 11.500 11.500
BVS-060 Length 0 250 15.0 11.500 11.500 11.500 11.500 11.500
BVS-110 Length 0 250 15.0 11.500 11.500 11.500 11.500 11.500
BVS-150 Length 0 250 15.0 11.500 11.500 11.500 11.500 11.500
BVS-140 Length 0 250 15.0 11.500 11.500 11.500 11.500 11.500

Table 2: Engineering Approaches

Calculation of the Failure Moment of Pipes Exposed to Internal Pressure and External Bending Circumferential Flow Through-Wall Crack

<table>
<thead>
<tr>
<th>Theory</th>
<th>Bernoulli &quot;Moment&quot;-Method</th>
<th>Net Section Collapse</th>
<th>Bernoulli &quot;Moment&quot;-Method</th>
<th>Net Section Collapse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criterion</td>
<td>Tensile Strength</td>
<td>Flow Stress</td>
<td>Tensile Strength</td>
<td>Flow Stress</td>
</tr>
<tr>
<td>Formulas</td>
<td>$\tau_{\alpha} = \frac{B_{\alpha}}{A_{\alpha}} - \tau_{\beta_{\alpha}} - \frac{A_{\beta_{\alpha}}}{A_{\beta_{\alpha}}} - \frac{A_{\beta_{\alpha}}}{A_{\beta_{\alpha}}}$</td>
<td>$\frac{2\alpha_{\alpha}/2}{2\pi_{\alpha}/2}$</td>
<td>$\frac{2\alpha_{\alpha}/2}{2\pi_{\alpha}/2}$</td>
<td>$\frac{2\alpha_{\alpha}/2}{2\pi_{\alpha}/2}$</td>
</tr>
<tr>
<td>Factors</td>
<td>$B_{\alpha} = \frac{1}{\beta_{\alpha}} - \frac{1}{\beta_{\alpha}}$</td>
<td>$A_{\alpha} = \frac{1}{\beta_{\alpha}} - \frac{1}{\beta_{\alpha}}$</td>
<td>$A_{\alpha} = \frac{1}{\beta_{\alpha}} - \frac{1}{\beta_{\alpha}}$</td>
<td>$A_{\alpha} = \frac{1}{\beta_{\alpha}} - \frac{1}{\beta_{\alpha}}$</td>
</tr>
<tr>
<td>$\tau_{\alpha} = \frac{\tau_{\alpha}}{\tau_{\alpha}}$</td>
<td>$\frac{\tau_{\alpha}}{\tau_{\alpha}}$</td>
<td>$\frac{\tau_{\alpha}}{\tau_{\alpha}}$</td>
<td>$\frac{\tau_{\alpha}}{\tau_{\alpha}}$</td>
<td>$\frac{\tau_{\alpha}}{\tau_{\alpha}}$</td>
</tr>
</tbody>
</table>

Stress Distribution

Table 2: Engineering Approaches
Experimental Confirmation of the Postulation of the Exclusion of Rupture in Pipings
Quantification of the Safety Margin against Catastrophic Failure

Operational Loading
Earthquake
Air Craft Crash

Pipe, Component and Vessel Burst Behaviour
Phase I and II
Single Monotonic Loading
Phase III and IV
Alternating Loading with Plastic Deformation

High-Rate-Tensile-Tests on Pipes
Phase III Dynamic Loading

HDR - Safety - Programme Phase II und III
Determination of the Transferability of the Specimen Behavior to Pipings

Accompanying Analytical Calculations

Fig. 1: Research Projects within the Scope of Reactor Safety

Fig. 2: Parametric Field

Equivalent Strain Flawless Pipe BVZ 090 Experiment

Internal Pressure $p = 15.2$ MPa
- Tension Fibre
- Compression Fibre
- Mean Value
Without Internal Pressure
- Tension Fibre
- Compression Fibre
- Mean Value

Fig. 3: 14 MNm Four-Point Bending Device

Fig. 4: Load - Strain Behavior of an Unweakened Pipe