LOW CYCLE FATIGUE OF STEELS FOR NUCLEAR PRESSURE VESSELS IN HOT WATER

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SUMMARY

Low cycle fatigue analysis is a very important problem in structural mechanics, especially for nuclear pressure vessels. The design procedure is based on the knowledge of the experimental results on test specimen. The design curves are based on tests in air at room temperature. But the fatigue behaviour may be affected by hot water environment when light water reactors are concerned. So it would be useful to get experimental results for reactor steel samples in such conditions. A general program on low cycle fatigue in hot water is in progress at Saclay in order to assess the conservatism of design fatigue curves.

In order to keep control of water chemistry, the test rig is connected with the PRIMEAU loop and therefore a constant flow of water is obtained through the specimens. Tested samples are small strips of rectangular cross section (2 x 10 x 61 mm). They are loaded in circular bending with controlled deflection. Practically they are placed between four supports, two moving and two fixed. The water temperature is kept near 265 °C while the oxygen and hydrogen contents and the pH are monitored. A frequency as low as 0.1 cpm has been chosen in order to take into account time effects. Calibration tests in air at room temperature are also made with the same type of device.

Tests are now in progress on austenitic alloys and the available results are given. Tests on a ferritic steel have been completed. The steel is the French steel for light water reactor vessels, its specification is roughly according to the specification ASTM 508 (Cl 3), but with special requirements. For these test results, the best fit curve can be written:

\[ \varepsilon_a = 5.6 N^{-0.3} \]

\( \varepsilon_a \) strain amplitude,
\( N \) number of cycles at failure.

There is no noticeable difference between hot water test results and air-room temperature results. Comparison is made with ASME criteria (for section III): the results are near the ASME best fit curve for ASTM 302 steel.
1. **Purpose**

Fatigue investigations in hot water are designed to estimate the extent to which the temperature and composition of the water in primary reactor circuits affect the fatigue of the materials employed.

More precisely, an attempt is made to determine, in each case, the curve giving the number of cycles corresponding to failure, as a function of the strain amplitude.

The tests dealt with in this note are concerned with a French steel used for pressurized water reactor vessels. This steel substantially meets specification ASTM-508 class 3. The tests were performed in pressurized water at a temperature above 265°C.

2. **Principle of Test**

The test pieces were subjected to pure alternative bending motion, of which the variation in curvature was fixed.

Test pieces consisted of metal strips held between four pairs of pins, two fixed and two moving, as shown in Plate 1. The travel of the moving pins was imposed by the testing machine mechanism.

The portion of the test piece lying between the two moving pins was subjected to bending with a uniform moment and hence with uniform strain (provided that thickness was constant).

The test consisted essentially of counting the number of cycles of deflexion variations leading to failure.

Tests were also performed in hot water and air at room temperature, in order to derive the most accurate possible estimate of the combined effects of water and temperature.

3. **Testing Installation**

Tests were performed on the "Primeau" test facility, to which the specific testing stations were connected.

The testing machine consisted of an enclosure fitted with a removable cover, connected to the Primeau test facility by means of a pipe and flange system. Hot water flowed through the machine from one end to the other.

The mechanical device designed to produce strain in the test pieces was placed within the vessel.

The test pieces were placed between four cylindrical pins, of which two were fixed (see Plate 1) and the remaining two moving, mounted on the central slide. The latter moved in relation to the fixed portion on a ball race.

The alternating motion of the travel was obtained by a system of bolts and nuts transferred into the testing vessel by a rod.

The testing machine was fitted with transducers, inductive for measurement and recording of travel, and resistive for the measurement of stresses. Plate 2 shows a photograph of the open machine.
4. Test specimens

4.1 Material
As stated above, this French steel met specification ASTM-508 (class 3). It was obtained from the nozzle holes of a pressure vessel under construction.

4.2 Test specimen geometry
Two types of test piece were used, a solid test piece called A2, and a second test piece with a thinned central portion called B1,4.

4.3 Correspondence between deflection imposed and strain
By the use of certain hypotheses, this correspondence was determined by a calculation. A sample calculation in the Appendix makes it possible to determine this correspondence. The result for test pieces A2 was a follows:
\[ \text{strain } \frac{\Delta L}{L} = 0.00435 \ f \text{ (deflection in mm).} \]

However, not all the computation hypotheses were verified, particularly the following:
- the lever arms were not constant, owing to the use of cylindrical pins and to the clearance likely to occur,
- the appearance of plastic strains altered the linearity of the relationship between curvature and moment.

Hence it appeared preferable to calibrate the deflection/strain relationship by means of a prior test for each type of test piece and for each deflection. These tests generally included several cycles, in order to obtain stabilized values.

4.4 Preparation of test specimens
The test pieces were machined on the milling machine and finished by grinding.

After machining and dimensional checks, the test pieces were degreased by immersion in a bath consisting of alcohol:toluene:acetone::1:1:1. The cleaning operation was completed by rinsing with demineralized water and helium drying.

5. Operating conditions

5.1 Cycle form selected
As a function of time, strain varied cyclically in accordance with the trapezoidal distances:
- stroke + and -: 1 mm
- strain increase time: 2 min
- strain holding time: 1 min
- reversal of strain: 4 min
- holding of negative strain: 1 min
- load removal: 2 min
Total: 10 minutes.
This corresponds to 0.1 cycle per minute.

The form of the cycle is shown in Plate 3.

5.2 Testing of water quality

The test assembly was filled with demineralized water previously degassed by boiling (pressurization was provided by helium).

The water temperature was measured at the inlet and outlet of each testing machine by means of thermocouples.

The pressure was measured by means of an electrical resistance sensor.

It was recorded permanently.

5.2.1 pH measurement

The pH was measured on samplings taken from a cold by-pass. A Taccussel pH meter was employed and the value for the different tests ranged from 7.8 to 8.5.

5.2.2 Resistivity measurement

Similar to the pH, the resistivity was measured by means of a Taccussel CD.6N resistivity meter, and the mean value of the measurements ranged from 30 to 100 kohms at 20°C.

5.2.3 Analysis of dissolved gases

Oxygen and chloride ions were also determined on samplings made under helium blanket. These analyses were made by the DRA-SAECNI. The results were entered in reports.

In general, the O ion concentrations were lower than 0.5 ppm, and the chlorides lower than 0.35 ppm.

\[
\begin{align*}
\text{O} & \quad 0.450 \text{ to } 1.8 \text{ ppm}^* \\
\text{Cl} & \quad 0.110 \text{ to } 2.5 \text{ ppm}^*
\end{align*}
\]

6. Performance of the test

Each test was characterized by the followings:

- the type of test specimen used, A or B,
- the amplitude of the variation in deflection imposed (f), in other words, the deflection oscillated cyclically between + and -f.

For each test, four test specimens were inserted into the testing machine, the cover replaced, the vessel filled with water and vented, and the Primeau test facility placed under heating in order to reach the test pressure and temperature. The pressure was 90 bars at 265°C. The test facility was then put into service to carry out the cyclings.

Apart from the measures and determinations mentioned above, and the monitoring of the imposed deflection, the test was essentially followed by monitoring the force necessary for performing the test. This force was recorded permanently on a recorder.

*The peak values were accidental, owing to the reconditioning of a cable gland. The values were lowered below 0.5 ppm by rinsing.
The force varied only slightly during performance of the test, and then terminated by a sharp drop. The test was stopped when the force declined significantly, in other words, more precisely when the force dropped to 3/4 of its initial value. The testing machine was stopped at this moment, and the test specimens withdrawn for inspection. In general, at least one test piece was fractured, while the others exhibited extensive cracks.

Tests in air at ambient temperature were performed in a similar way.

Furthermore, each test dealt with a batch of four identical test pieces.

7. Test results

For each test, the amplitude of deflection and hence the amplitude of strain was known, and determination was made of the number of cycles at failure, as well as the period of immersion in the water at the end of which this fracture occurred.

The corresponding results are shown in the tables in Plates 4 and 5.

Photographs of fractured test specimens are given in Plate 6.

These photographs show that in addition to fracture, the test piece is extensively cracked throughout the central zone, confirming that fatigue was widespread over this wide zone.

The number of cycles to fracture as a function of strain amplitude $\varepsilon_a$ (1/2 range) is also shown in Plate 7.

8. Interpretation and comments

A glance at Plate 8 shows that the fatigue strength in water at 265°C is substantially the same as that in air at ambient temperature, so that no significant effect of the environment was observed.

It may be noted that the results obtained with test pieces B1,4 were more dispersed than those obtained with test pieces A2. This is perhaps due to the more complex geometry, namely, to the influence of stress raisers which may occur at the connection radii of certain test pieces.

The results obtained with test pieces A are practically on the curve: $\varepsilon_a = 5.6 \times 10^{-0.30}$ (\%) and the results obtained with test pieces B are generally slightly removed.

Comparison with fatigue curves in the ASME code

The stress amplitude is derived from the strain amplitude $\varepsilon_a$ by multiplying the latter by $E/1-y^2$, substantially equal to 20,000 daN/mm². This stress amplitude was plotted as a function of the number of cycles in Plate 9. The results can be seen to match well.

Plate 7 shows the "best fit curve" relative to tests on steel A-302, as given in the ASME "criteria", namely, by the following equation:

$$\varepsilon_a = \frac{1}{4Y}\log_{10} \frac{100}{100 - 61.4} + \frac{0.689 \times 38500}{E}$$
9. Conclusions and suggestions

The conclusions to be drawn are extremely simple.

For the tests discussed here, no effects were observed owing to the presence of water at 265°C. The results in air and water are comparable to those used as a basis for the design curve in Section III of the ASME CODE for low alloy steels (in other words, comparable to the "best fit curve" mentioned above).

However, these tests may advantageously be supplemented in order to investigate the influence of the following factors:

- influence of cycle form and period,
- influence of hold times in hot water (see results of tests B Nos. 31 and 41),
- effects of water chemistry, and particularly of the presence of boric acid and lithia. The influence of a strongly basic pH likely to favor an electrolytic effect should also be investigated.
PRINCIPAUX RESULTATS

Essais réalisés dans l'eau à 265°C

<table>
<thead>
<tr>
<th>Test</th>
<th>Test specimen</th>
<th>Immersion time</th>
<th>Deflection amplitude</th>
<th>Al ( \times 10^{-3} )</th>
<th>No of cycles</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>A 2</td>
<td>126 &amp; 129</td>
<td>7.430 h</td>
<td>± 0.55</td>
<td>2.3</td>
<td>46.760</td>
</tr>
<tr>
<td>31</td>
<td>B 1,4</td>
<td>130 &amp; 133</td>
<td>960 h</td>
<td>± 0.61</td>
<td>3.25</td>
<td>5.500</td>
</tr>
<tr>
<td>34</td>
<td>B 1,4</td>
<td>148 &amp; 151</td>
<td>240 h</td>
<td>± 1.4</td>
<td>9.25</td>
<td>710</td>
</tr>
<tr>
<td>35</td>
<td>A 2</td>
<td>152 &amp; 155</td>
<td>1.440 h</td>
<td>± 1.35</td>
<td>6.6</td>
<td>1.160</td>
</tr>
<tr>
<td>38</td>
<td>A 2</td>
<td>164 &amp; 167</td>
<td>170 h</td>
<td>± 1.89</td>
<td>9.45</td>
<td>357</td>
</tr>
<tr>
<td>39</td>
<td>B 1,4</td>
<td>168 &amp; 171</td>
<td>320 h</td>
<td>± 1.89</td>
<td>12.6</td>
<td>450</td>
</tr>
<tr>
<td>41</td>
<td>B 1,4</td>
<td>176 &amp; 179</td>
<td>840 h</td>
<td>± 0.83</td>
<td>4.8</td>
<td>1.460</td>
</tr>
<tr>
<td>43</td>
<td>A 2</td>
<td>184 &amp; 187</td>
<td>720 h</td>
<td>± 1.00</td>
<td>4.7</td>
<td>3.430</td>
</tr>
<tr>
<td>53</td>
<td>B 1,4</td>
<td>203 &amp; 206</td>
<td>500 h</td>
<td>± 0.83</td>
<td>4.8</td>
<td>2.470</td>
</tr>
</tbody>
</table>

Plate 4
### PRINCIPAUX RESULTATS

**Essais réalisés à l'air ambiant**

<table>
<thead>
<tr>
<th>Test</th>
<th>Test specimen</th>
<th>Immersion time</th>
<th>Deflection amplitude</th>
<th>$\Delta \frac{1}{e} \cdot 10^{-3}$</th>
<th>No of cycles</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>B 1,4</td>
<td>134 à 137</td>
<td>1.650 h</td>
<td>$\pm$ 0.64</td>
<td>3.45</td>
<td>14.068</td>
</tr>
<tr>
<td>33</td>
<td>A 2</td>
<td>144 à 147</td>
<td>5.200 h</td>
<td>0.67</td>
<td>2.85</td>
<td>33.000</td>
</tr>
<tr>
<td>36</td>
<td>A 2</td>
<td>156 à 159</td>
<td>300 h</td>
<td>1.35</td>
<td>6.55</td>
<td>1.240</td>
</tr>
<tr>
<td>37</td>
<td>A 2</td>
<td>160 à 163</td>
<td>110 h</td>
<td>1.90</td>
<td>9.5</td>
<td>360</td>
</tr>
<tr>
<td>42</td>
<td>B 1,4</td>
<td>180 à 183</td>
<td>500 h</td>
<td>0.83</td>
<td>4.8</td>
<td>2.950</td>
</tr>
<tr>
<td>44</td>
<td>B 1,4</td>
<td>188 à 191</td>
<td>150 h</td>
<td>1.4</td>
<td>9.25</td>
<td>700</td>
</tr>
<tr>
<td>50</td>
<td>A 2</td>
<td>197 à 200</td>
<td>7.000 h</td>
<td>0.67</td>
<td>2.85</td>
<td>47.700</td>
</tr>
</tbody>
</table>

Plate 5

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**Cracks in a sample tested in hot water (265°c)**

$\Delta 2.3 \cdot 10^{-3}$

46760 CYCLES

Pl n° 6