Experimental Fatigue Analysis of Girth Butt Welded Austenitic Stainless Steel Pipings

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Abstract

In order to avoid a too conservative simplified elastic-plastic fatigue analysis of PWR main primary system, using ASME or RCC-M codes, a fatigue resistance test program has been carried out by FRAMATONE and the Commissariat à l'Energie Atomique, to determine the k2 and C2 stress indices and the k0 factor of girth butt welds in pipings.

Austenitic stainless steel tubes 102 mm external diameter and 6.25 mm thickness are subjected to four points bending fatigue, with a 0.15 % to 1.5 % strain range.

The influence of flushing of the internal weld bead as well as influence of its shape are presented in this paper.

lower values of (k2 x C2) and k0 are obtained for girth butt welds.

1. Introduction

For simplified elastic-plastic analysis of pipings, RCC-M /1/ and ASME /2/ codes determine the alternating stress intensity S_{alt}, defined as k0 times half of the peak stress intensity range S_{p}(i,j).

In case of pure bending, S_{p}(i,j) is given by the equation (11) of the codes /1/ ; /2/ as the nominal bending stress range M_{i}(i,j).D_{o}/2.r.I, multiplied by the (k2.C2) factor. The latter is given in tables B 3683-2 (RCC-M) and NB 3681(a)-1 (ASME).

For "as welded" girth butt welds, the actual C2 and k2 indices are 1.0 and 1.8 respectively. In the case where the primary plus the secondary stress amplitude reaches the (3.m.S_{o}) value (Eq. 10 of the codes), a recommended k0 value of 3.33 is reached, so that a k0.k2.C2 factor of 6.00 is applied to the nominal bending stress.

This seems to be too much conservative. The purpose of this analysis is to determine more adequate k2 index and k0 elastic-plastic concentration factor, in order to avoid a too conservative elastic-plastic fatigue analysis.

2. Principle of the Investigation

In order to determine the usage factor for a given loading level on pipings, the alternating stress S_{alt} must be calculated, and the number of occurrence of this loading must be compared to the number of cycles allowed by the design curve, corresponding to the same S_{alt} level. For the pure bending case, S_{alt} is given by /1/ , /2/ :

\[
S_{alt} = k_0 \left[ \frac{1}{2} S_{p}(i,j) \right] = k_0 \left[ \frac{1}{2} (k_2.C_2.D_{o}/2.r.I).M_{i}(i,j) \right]
\] (1)
where \( (q_0 H_i(i,j)/21) = \Delta d_i \) is the elastically calculated longitudinal bending stress amplitude, \( K_2 \) and \( C_2 \) are stress indices, and \( K_e \) is the elastic-plastic concentration factor.

The \( (K_e, K_2, C_2) \) factor can therefore be determined by the alternating stress to half the elastic bending stress amplitude ratio. In the elastic field, \( K_e = 1 \), and this ratio gives the \( K_e, C_2 \) factor.

This analysis can be achieved, using \( \varepsilon_{alt} = S_{alt} / E \), and the longitudinal bending strain amplitudes in place of stress amplitudes. The fatigue data used in the codes are obtained from strain controlled tests, and \( S_{alt} \) is calculated as \( E \) times \( \varepsilon_{alt} \). The relation (1) is equivalent to:

\[
S_{alt} = K_e \left[ K_2 C_2 \Delta d_i \varepsilon_{alt} \right] \quad \text{with} \quad \Delta d_i \varepsilon_{alt} = E \Delta \varepsilon_{i \varepsilon_{alt}}
\]

This leads to:

\[
\varepsilon_{alt} = K_e, K_2, C_2, \varepsilon_{i \varepsilon_{alt}}
\]

since in our experiment, we use a symmetrical cyclic loading with \( \Delta \varepsilon_{i \varepsilon_{alt}} = 2 \varepsilon_{i \varepsilon_{alt}} \).

These \( \varepsilon_{alt} \) and \( \varepsilon_{i \varepsilon_{alt}} \) strain values are obtained from our experimental investigation, as developed below.

3. Description of tests

3.1. Principle of tests

The aim of these tests is to submit the fourteen tubes to a cyclic bending fatigue. The testing device allows a circular bending of the tubes (Figure 1). The requested longitudinal strain value is obtained by controlling the deflection in the middle of the central span of the specimens. The measure of deflection corresponds to a span of 340 mm.

3.2. Instrumentation - Measurements

The following measurements are achieved:

- The real elastic-plastic longitudinal strain is measured on the upper line of the tube, using a strain-gage sticked thirty millimeters beside the middle of the span.

- The deflection is measured using a special device mounted on the neutral axis of the tube (Fig. 1).

- The diameter variation.

- The displacement of the hydraulic jack.

- The potential drop measurements allow to detect the crack initiation.

All these informations are recorded on X.Y recorder, such as load versus longitudinal strain and load versus deflection.

Other readings are recorded versus time.

For each tube, it has been noted: the number of cycles to crack initiation \( (N_g) \); the number of cycles to failure; the elastic-plastic longitudinal strain \( \varepsilon_R \); the deflection \( (f_m) \); the variation of external diameter \( (\Delta d) \); the load \( (f) \).

A second strain gage was sticked on one tube in order to measure the elastic-plastic circumferential strain. As this test was carried out at a 0.87 \( \% \) longitudinal strain, the relationship between these two strains could be known until this specific level.

All the experimental results are presented in Table 1.

3.3. Geometry of tubes

All the specimens have a nominal external diameter of 111 mm, and a nominal internal diameter of 87.5 mm. They have been slenndered in the central span to get a 102 mm external diameter, and a 6.25 mm thickness.

- The tubes nos 1 and 2 are smooth straight pipes, without any real of fictitious weld.
- The tubes nos 3 to 7 are straight pipes with fictitious machined weld bead in the middle.
span, on the external surface of the tube.

. The tubes 8 to 12 have real welds with a welded internal bead.
. The tubes 13 and 14 have real welds with a fluxed internal bead.

All the real welds are fluxed on the external side.

3.4. Mechanical properties

The material of the tubes is a 316L austenitic stainless steel. The real material properties are obtained from two types of tests. Three usual monotonic tensile tests gave us the material properties such as $S_y$, $S_u$, $E$. Twenty tensile fatigue tests within a 0.25% to 1.0% strain range gave us the fatigue data to crack initiation (fig. 2).

All these properties are obtained at room temperature, using specimens taken from original non-hardened material. YOUNG's modulus $E = 186200$ MPa; yield strength $S_y = 230$ MPa; ultimate strength $S_u = 550$ MPa; $S_m = 153$ MPa; Elastic POISSON's ratio $\nu = 0.3$.

3.5. Bending Tests Procedure

The significant dimensions of the tubes have been measured before the tests. Once the tube is mounted on the press, the deflection range is slowly increased until the requested longitudinal strain value is obtained at a low frequency. As the right strain is obtained, the frequency is increased. Here starts the test which is then controlled by the deflection. Mechanical properties of the tubes are kept constant by internal air cooling.

During the test, the cycling is regularly stopped to carry out visual inspection inside and outside the tube. In this way, the crack initiation can be visually detected.

The test is definitely stopped when a through crack is obtained.

4. Analysis of test results

4.1. Methodology

The reference fatigue curve is obtained from the tensile fatigue data to crack initiation (§ 3.4). Since the obtained curve is parallel to the best fit curve of the ASME criteria, our reference curve shall have the same type of law:

$$ S = A \cdot \frac{E}{\sqrt{f}} \cdot \ln \left( \frac{4R}{f} \right) \left( \frac{100}{100 - A} \right) $$

The calculated $A$ and $B$ parameters are: $A = 75.6$ and $B = 290$ MPa. Now using this graph with the number of cycles to initiation of each bending test, we shall be able to determine the real alternating strain $E_{alt}$ seen at the point of crack initiation.

The longitudinal elastic strain $E_{L,el}$ cannot be calculated from the measured force of the jack, which takes into account some external phenomena. On the other hand, it can be calculated from the measured deflection, using the beam theory.

This leads to $E_{L,el} = \frac{B_0}{a}$, where "a" is half the span length over which the deflection is measured, "$B_0$" is the external diameter of the tube, and "f" is the real deflection of the tube neutral axis. ($f = f_d + \Delta f_d$).

The $(K_0, K_2, C_0)$ factor can now be calculated by the ratio $E_{alt}/E_{L,el}$, and plotted versus $E_{L,el}$ ($\phi$).

The $(K_0, C_2)$ elastic factor is obtained on the former graph when the calculated elastic longitudinal strain is equal to the 0.1% elastic limit, obtained from the monotonic tensile tests (§ 3.4). In our case, it is found as 0.1% strain.

The $(K_0)$ factor can be determined by the ratio of the former values of $(K_0, K_2, C_0)$ to $(K_0, C_2)$.

If plotted versus $S_n/S_m$, ratio, it will be easily compared to the actual recommended $K_0$ value of the codes. Since $S_n = C_2 \cdot (M_i(1,i) \cdot D_0/2)^{1/2}$ in the codes (with $C_2 = 1$), $S_n/S_m$ will
herein be given as:

\[ \frac{S_n}{S_m} = (2.35E^{0.5})/S_m \]

4.2. Results - Discussion

All data and results of calculations can be seen in Table 1. Figure 2 shows the fatigue data. Figure 3 shows the calculated (K₂, K₁C₂) values. Figure 4 shows the deduced K₀ values versus \( \frac{S_n}{S_m} \) ratio.

The two smooth specimens show the loading effect on fatigue results. The stress-strain state on the upper line in case of elastic bending is equivalent to a tensile test, with a uniaxial stress state. Since our elastic-plastic bending fatigue results do not fit with our tensile fatigue curve, it could be necessary to use a bending fatigue reference curve. We herein only have two tests, which is not enough to define a bending fatigue curve. Therefore, the tensile fatigue curve is used as the reference for all bending tests.

It has been checked with the two gages that \( c_\varepsilon = -\varepsilon_{\varepsilon} \) during the elastic behaviour. On the contrary, elastic-plastic behaviour does not lead to such a simple relation, even using Nadai's relations /3/ with the sequent modulus and the rational Poisson's ratio. This means that the radial strain \( \varepsilon_r \) is probably not negligible, and not equal to \( c_\varepsilon \). It is supposed that this is a specific effect of elastic-plastic bending on tubes which needs to be studied.

The five specimens having a fi ctions machined weld bead seem to withstand less strain than real welds. The crack initiation took place in the root of the "welds", except for the tests nos 4 and 5 for which it was situated in a little machining defect, at a few millimeters from the root. The results from these two tests are somewhat affected and the \( K_0 \) \( K_2 \) \( C_2 \) values must be considered as a little too high.

It can be seen on figures 2 and 3 that the flushing of the internal real weld bead does not create any significant difference with non flushed specimens. A single curve can be fitted to the tests 8 to 14. It must be noted that the crack initiation always took place on the flushed external side of the welds, instead of the internal bead root as expected. In this way, despite the small thickness of the tubes, this discontinuity seems to have no significant effect on the fatigue resistance, in comparison with the metallurgical effect.

Because of the scatter of data on specimens 3 to 7, it is not really possible to obtain an accurate value of \( K_2 \) \( C_2 \). Nevertheless, these tests give results getting closer to the others for low values of longitudinal strain.

The tests on real welds allow us to get a 1.3 \( K_2 \) \( C_2 \) value. This is significantly lower than the 1.8 value recommended in the codes /1/, /2/.

The tests nos 1 and 2 on smooth specimens directly give the \( K_0 \) factor since as a definition, \( K_2 \) and \( C_2 \) are given as 1.0 by the codes. When the elastic behaviour is attained, the \( K_0 \) value is 1.0. This can be checked on figures 3 and 4. It must be noted on figure 4 that a great conservatism is applied to the \( K_0 \) factor. We obtain a 1.6 value for great \( S_n/S_m \) ratios on real welds, and 1.4 on smooth pipeings instead of 3.33 as recommended.

5. Conclusion

An experimental investigation of the \( K_2 \), \( C_2 \) and \( K_0 \) factors for girth butt welds on austenitic stainless steel pipe, of 102 mm external diameter and 6.25 mm thickness has been presented.

- For girth butt welds, a \( K_2 \) \( C_2 \) factor of 1.3 seems to be more realistic than the 1.8 value recommended in the codes.
- A maximum \( K_0 \) value of 1.6 is obtained from this investigation, compared to the 3.33
recommended value.

- The geometrical discontinuities of non flushed internal welds seem to have no significant effect on fatigue results, since the crack initiation took place on the external side of the tubes.

- Elastic-plastic bending fatigue tests seem to give significantly different results than those from tensile fatigue tests.

The present experimental investigation will be completed by the analysis of the following parameters: mismatch of assemblies, temperature, previous strain hardening and thickness of the tubes.

References

/1/ RCC-M – Règles de Conception et de Construction des Matériels Mécaniques des Flots nucléaires FWR.

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/2/ ASME boiler and pressure vessel code/Section III/div. 1.


### TABLE 1: SUMMARY OF DATA FROM TESTS AND CALCULATIONS

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(1) Measurements  (2) Calculations
FIGURE 1: Testing device and specimen

FIGURE 2: Data from the fatigue tests

FIGURE 3: \((K_e - K_2C_2)\) factor versus longitudinal elastic strain

FIGURE 4: \(K_e\) elastic-plastic concentration factor versus \(S_a/S_m\) ratio