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 FRAMATOME and the Commissariat à l'Energie Atomique, to determine the K_2 and C_2 stress indices and the K_e 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, within 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 (K_2 x C_2) and K_e 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 K_e 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 $M_i(i,j).D_o/2.I$, multiplied by the $(K_2.C_2)$ 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 C_2 and K_2 indices are 1.0 and 1.8 respectively. In the case where the primary plus the secondary stress amplitude reaches the $(3.m.S_m)$ value (Equ (10) of the codes), a recommended K_e value of 3.33 is reached, so that a $K_e.K_2.C_2$ 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 K_2 index and K_e 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 Salt 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/ :

$$S_{alt} = K_e \left[\frac{1}{2} S_p(i,j)\right] = K_e \left[\frac{1}{2} (K_2.C_2.\frac{D_o}{2I} M_i(i,j)\right] \quad (1)$$

where $(D_o\ M_i(i,j)/2I) = \Delta\sigma_L^{el}$ 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 $K_2.C_2$ 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 ε_{alt}). The relation (1) is equivalent to :

$$S_{alt} = K_e \left[\frac{1}{2} K_2.C_2.\Delta\sigma_L^{el}\right] \text{ with } \Delta\sigma_L^{el} = E.\Delta\varepsilon_L^{el} \qquad (2)$$

This leads to : $\varepsilon_{alt} = K_e\ K_2\ C_2.\ \varepsilon_L^{el}$ since in our experiment, we use a symetric cyclic loading with $\Delta\varepsilon_L^{el} = 2\varepsilon_L^{el}$.

These ε_{alt} and ε_L^{el} strain values are obtained from our experimental investigation, as developped 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 tubes, 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_R) ; the number of cycles to failure ; the elastic-plastic longitudinal strain (ε_L^R) ; the deflection (fm) ; the variation of external diameter (ΔD) ; the load (force of the jack) (F).

A second strain gage was sticked on one tube in order to measure the elastic-plastic circumferencial 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 slendered 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 fictitions weld.

. The tubes nos 3 to 7 are straight pipes with fictitions machined weld bead in the middle span, on the external surface of the tube.

. The tubes 8 to 12 have real welds with as welded internal bead.

. The tubes 13 and 14 have real welds with flushed internal bead.

All the real welds are flushed 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_m, S_u, E. Twenty tensile fatigue tests within a 0,25 % to 1,4 % 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 = 188200 MPa ; yield strength S_y = 230 MPa ; ultimate strength S_u = 550 MPa ; S_m = 153 MPa ; Elastic POISSON's ratio ν = 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

. <u>The reference fatigue curve</u> 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 :

$$S = E.\varepsilon = \left(\frac{E}{4\sqrt{N}} \ln \frac{100}{100 - A}\right) + B \qquad (3)$$

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 ε_{alt} seen at the point of crack initiation.

. <u>The longitudinal elastic strain ε_L^{el}</u> 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 : $\varepsilon_L^{el} = \frac{D_o}{a^2} . f$, where "a" is half the span length over which the deflection is measured, "D_o" is the external diameter of the tube, and "f" is the real deflection of the tube neutral axis. ($f = f_m + \Delta D_o/2$).

. <u>The (K_e K_2 C_2) factor</u> can now be calculated by the ratio $\varepsilon_{alt}/\varepsilon_L^{el}$, and plotted versus ε_L^{el}.(§ 2).

. <u>The ($K_2.C_2$) elastic factor</u> is obtained on the former graph when the calculated elastic longitudinal strain is equal to the 0 % elastic limit, obtained from the monotonic tensile tests (§ 3.4). In our case, it is found as 0,1 % strain.

. <u>The K_e factor</u> can be determined by the ratio of the former values of ($K_e.K_2.C_2$) to ($K_2.C_2$). If plotted versus S_n/S_m ratio, it will be easily compared to the actual recommended K_e value of the codes. Since $S_n = C_2.(M_i(i,j)\ D_o/2I)$ in the codes (with C_2 = 1), S_n/S_m will herein be given as :

$$S_n/S_m = (2.E.\varepsilon_L^{el})/S_m$$

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 ($K_e.K_2.C_2$) values. Figure 4 shows the deduced K_e values versus (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 $\varepsilon_c = - \nu\varepsilon_L$ during the elastic behaviour. On the contrary, elastic-plastic behaviour does not lead to such a simple relation, even using Nadaï's relations /3/ with the sequent modulus and the rational Poisson's ratio. This means that the radial strain ε_r is probably not negligible, and not equal to ε_c. 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 fictitions 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_e 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_e 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_e 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_e factor. We obtain a 1.6 value for great S_n/S_m ratios on real welds, and 1.4 on smooth pipings instead of 3.33 as recommended.

5. Conclusion

An experimental investigation of the K_2, C_2 and K_e factors for girth butt welds on austenitic stainless steel piping, 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_e 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 îlots nucléaires PWR.
Tome 1 - Volume B - AFCEN - Paris - janvier 83

/2/ ASME boiler and pressure vessel code/Section III/div. 1.
"Nuclear Power Plant Components" - ASME - New York - 1983.

/3/ NADAI A. Theory of flow and fracture of solids.
Vol. 1 - 2nd edition - Mc Graw Hill book Co., Inc., 1950.

TABLE 1 : SUMMARY OF DATA FROM TESTS AND CALCULATIONS

Test Number	(1) ε_L^R (%)	(1) N_R	(2) ε_{alt} (%)	(1) fm (mm)	(1) ΔD (mm)	(2) f (mm)	(2) ε_L^{el} (%)	(2) $\frac{\varepsilon_{alt}}{\varepsilon^{el}_L}$	(2) $\frac{S_n}{S_m}$	(2) K_e
1	0,304	38000	0,287	0,75	-	0,75	0,265	1,083	6,52	1,08
2	0,804	1088	1,222	2,07	0,876	2,508	0,885	1,381	21,77	1,38
3	0,184	100633	0,265	0,478	0,0448	0,500	0,177	1,50	4,35	(1,15)
4	0,22	29200	0,360	0,540	0,0332	0,557	0,196	1,84	4,82	(1,42)
5	0,27	9120	0,523	0,676	0,026	0,689	0,243	2,15	5,98	(1,65)
6	0,52	1510	1,061	1,297	0,258	1,426	0,503	2,11	12,37	(1,62)
7	1,57	50	5,136	3,90	-	3,90	1,376	3,73	33,85	(2,87)
8	0,222	72200	0,285	0,528	0,252	0,541	0,191	1,49	4,70	1,15
9	0,284	43300	0,324	0,672	0,0156	0,680	0,240	1,35	5,90	1,04
10	0,395	7809	0,553	0,968	0,028	0,983	0,347	1,59	8,54	1,22
11	0,578	1780	0,989	1,43	0,112	1,486	0,524	1,89	12,89	1,45
12	0,87	649	1,537	2,02	0,396	2,218	0,783	1,96	19,26	1,51
13	0,22	75000	0,283	0,552	0,023	0,564	0,199	1,42	4,90	1,09
14	0,82	525	1,692	2,10	0,584	2,392	0,844	2,00	20,76	1,54

(1) Measurements (2) Calculations

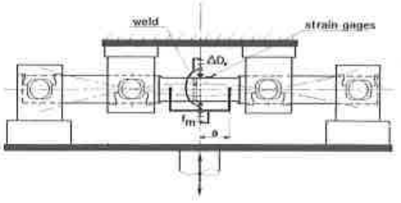

FIGURE 1 : Testing device and specimen

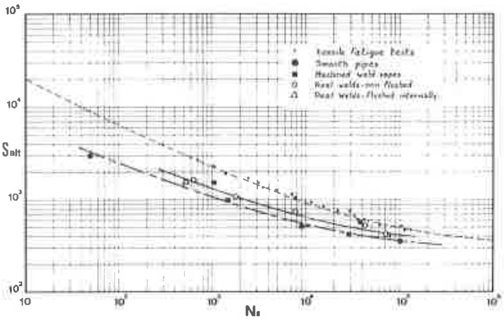

FIGURE 2 : Data from the fatigue tests

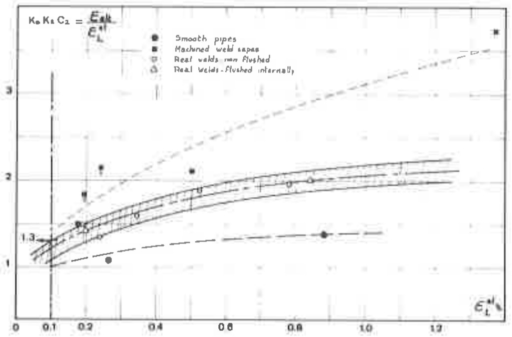

FIGURE 3 : $(K_e.K_2.C_2)$ factor versus longitudinal elastic strain

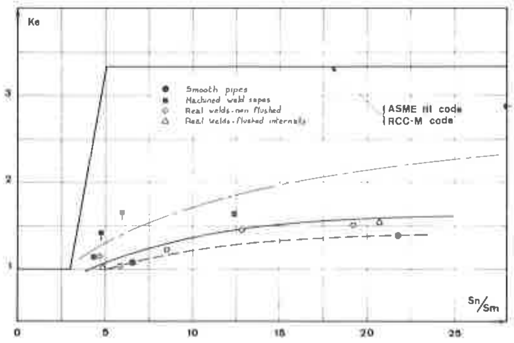

FIGURE 4 : K_e elastic-plastic concentration factor versus S_n/S_m ratio