Transactions of the **14th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 14), Lyon, France, August 17-22, 1997

**F06/3**

# Feature tests in support to rules for creep-fatigue analysis in welded joints

**Berton M.N.**[(1)], **Guis M.**[(1)], **Waeckel N.**[(2)], **Turbat M.**[(3)]
*(1) CEA, France*
*(2) EDF, France*
*(3) Framatome, France*

ABSTRACT :

The SOFA experiments are creep-fatigue tests in thin cylinder-thick cylinder junctions subjected to combined thermal and mechanical loads. They allowed a comparison of incipient crack initiation in a welded structure and in a machined structure with the same geometry.
A best-estimated analysis according to the RCC-MR, using thermal and mechanical calculations (in the elastic domain) with the CASTEM 2000 finite elements code, shows that the RCC-MR is conservative both in the weld and in the parent metal.
This work is part of a more extensive program the objective of which is to improve the way the welds are dealt with in analysis rules.

## 1- INTRODUCTION

In the RCC-MR [1], the evaluation rule for creep-fatigue and fatigue damage uses the concept of joint coefficient. The purpose of this coefficient is to take into account globally the difference between the weld and the parent metal. It was determined using a comparative test procedure involving failure tests with a parent metal test specimen and with a welded test specimen.

As for the SOUFFLE [2] program, the SOFA experiments were used to apply these rules to more complex structures submitted to more realistic stress loading, and to assess the margins before failure.

## 2- TESTS

### *2.1 The mock-ups*

#### *2.1.1 The geometry (Figure 1 and Photo 2):*

The mock-ups are axisymmetrical and plane-symmetrical, perpendicularly. The section studied is the central thin cylinder (A)-thick cylinder (B) junction section. It is machined on one of the thick cylinder (B) side and welded on the other. At the ends of the ligaments (A), two other thick cylinder sections (C) ensure that the low temperature is maintained during cycling.

The thick cylinder (B) is 58 mm thick for the SOFA1 test and 19 mm for the SOFA2, SOFA3 and SOFA4 tests.

The ligament (A) is 8 mm thick for the four test specimens.

*2.1.2 The materials:*
The parent metal used for the SOFA experiments is 316SPH austenitic steel. The weld is done using 16Cr 8Ni 2Mo stainless steel coated electrodes.

These two materials are fairly well documented. The 316SPH is the RCC-MR's 1S material [1]. Several characterisations (monotonous tension, fatigue failure and creep failure) were carried out in order to readjust the material's properties in relation to the standard properties. The test established that the SOFA materials were very similar to the reference materials.

*2.1.3 The welds (Figure 2):*
The welds are done with one TIG root pass and six MMA passes using 16Cr 8Ni 2Mo stainless steel coated electrodes. The mechanical and chemical qualifications are those specified in the RCC-MR [1].

An additional mock-up was used to carry out thermal measurements during the weld sequence, and to measure the residual stress loads (cutting method).

*2.2 The loading*

*2.2.1 The test facility (Photo 2):*
The test facility comprises:

- a 'high frequency' heating element used to heat the central thick cylinder (B) of the mock-up and maintain it at a temperature of 600 °C during each cycle,
- a 'giloterm' coolant system maintaining the mock-up's cool temperature at 100°C and ensuring part of the cooling during each cycle,
- a mechanical system applying a constant beam type bending load to the mock-up,
- a computer ensuring control and safety functions, as well as data acquisition.

*2.2.2 Thermal loading:*
The test specimen has an initial temperature of 100°C. It is submitted to the following cycle:

- the central thick cylinder (B) is heated by induction, and the external thick cylinders (C) are simultaneously maintained at 100°C by 'giloterm' coolant. A central cavity filled with helium prevents heat exchanges between the giloterm coolant and the hot section (Figure 3).
- The temperature rise is stopped when the temperature at the weld reaches 600°C. This load is maintained during one hour.
- The complete test specimen is then cooled down to 100°C. The specimen is cooled both by the giloterm coolant and by natural air convection around the mock-up.

*2.2.3 Mechanical loading:*
The SOFA1 specimen was not submitted to mechanical loading.

The SOFA2, SOFA3 and SOFA4 specimens were submitted to global beam type bending load. It was checked that this stress load, obtained by displacements applied at the ends of two 1.2 m levers (Photo 3), had the behaviour of a primary stress load. This cold calibrated arrangement generates in the ligaments a maximum membrane stress load (in the 'shell' sense of the term) of:

100 MPa for SOFA2
150 MPa for SOFA3
75 MPa for SOFA4

*2.3 Measurements and inspections*

*2.3.1 Measurements during the test:*

- The temperatures at 25 points, by means of surface type thermocouples (a specially instrumented mock-up (SOFA0) also contained thermocouples inside the test specimen),
- The pressure of the helium in the central cavity (in order to detect possible through cracks),
- The bend on the test specimen (in order to check the bending arrangement).

*2.3.2 Inspections during the test:*
The following inspections are carried out every 50 cycles in order to detect cracks in the sensitive areas:
- dye penetrant inspections,
- ultrasonic inspections,
- visual inspections with 30 X magnification.

*2.3.3 Metallurgic assessments at the end of the test:*
At the end of the test, the test specimens were cut. Samples were taken from the sensitive areas and examined under an optical microscope.

*2.4 Results*
The results of these four tests are given in Table 1:

**Table 1 : SOFA tests results**

| Mock-up | Loading (MPa) | | Cycles | Hold time | Side | Inspection during test | | |
|---|---|---|---|---|---|---|---|---|
| | meca. (*) | ther. (**) | number | (h) | | Ultrasonic | Dye penetrant | Visual |
| SOFA1 | 0 | 1163 | 500 | 1 | Welded | | 200 | |
| | | | | | Machined | | 200 | |
| SOFA2 | 100 | 770 | 400 | 1 | Welded | 50 | 200 | 200 |
| | | | | | Machined | 250 | 250 | 250 |
| SOFA3 | 150 | 770 | 400 | 1 | Welded | 50 | 200 | 200 |
| | | | | | Machined | 200 | 200 | 200 |
| SOFA4 | 75 | 770 | 400 | 1 | Welded | 100 | 200 | 200 |
| | | | | | Machined | 200 | 200 | 200 |

(*) Membrane mechanical stress in 8 mm ligament
(**) Maximal thermal stress

The following was observed for the four tests:
- intergranular cracking with crack tip creep cavities (Photo 4),
- the initiation appears faster on the welded side than on the machined side. It is located in the heat affected area.
- the cracks grow less on the welded side than on the machined side. The cracks grow into the parent metal.
- on the machined side, the cracks occur further on in the radius as shown in Figure 4:
- the primary loading does not seem to have a significant influence.

## 3 CALCULATION OF THE BEST ESTIMATED CRACK INITIATION VALUE ACCORDING TO THE RCC-MR

*3.1 Thermal calculations*
Thermal calculations were carried out with readjustments on the measurements during the hold time using the CASTEM 2000 [3] code. The Figure 5 shows the temperatures obtained for SOFA2.

*3.2 Mechanical calculations*
Mechanical calculations (in the elastic domain) were carried out using the CASTEM 2000 [3] code:

- for the thermal loading previously calculated (axisymmetrical calculations). Figure 6 shows the Von Mises stresses obtained for SOFA2,
- for the mechanical loading (Fourier 1 mode calculation). Figure 7 shows the Von Mises stresses in the most heavily loaded azimuth obtained for SOFA2.

*3.3 Predictions of crack initiation*

As the objective is to predict crack initiation as precisely as possible, all the conservative measures introduced by the RCC-MR[3] creep-fatigue rule were eliminated.

The number of cycles to failure was thus estimated using the RCC-MR[1] creep-fatigue rule as follows:

- eliminating the safety and transposition coefficients from the number of failure cycles, from the stress entered in the failure creep curves and from the failure stress,
- considering that the thermal loading is purely secondary (elimination of Neuber's law ($K_\varepsilon = 1$)) and considering a nul elastic follow-up ($C_r = 1$) for stress relieving. Visco-plastic calculations indeed show that the elastic follow-up is practically insignificant in this structure,
- using the following formula to calculate the primary stress :

$$Pm + Pb = \frac{\pi}{4}\left(\sigma_m + \frac{\sigma_f}{1{,}5}\right)$$

where $\sigma_m$ and $\sigma_f$ correspond to the equivalent membrane and bending stresses due to mechanical loading, respectively,

- using a joint coefficient $J_r = .77$ in the weld ($J_f = 1$).

*3.4 Results and comparison with the tests*

Table 2 shows the results of the calculations and enables a comparison with test results. Calculation I corresponds to the parent metal and calculation II corresponds to the weld (with $J_r$).

**Table 2 : Best-estimated crack initiation value (RCC-MR)**

| | Machined side | | | Welded side | | |
|---|---|---|---|---|---|---|
| | Test | Calculation I | Test/Calculation | Test | Calculation II | Test/Calculation |
| SOFA1 | 200 | 131 | 1,5 | 200 | 76 | 2,6 |
| SOFA2 | 250 | 24 | 10,4 | 50 | 3 | 16,7 |
| SOFA3 | 200 | 10 | 20,0 | 50 | 1 | 50,0 |
| SOFA4 | 200 | 46 | 4,3 | 100 | 8 | 12,5 |

The location of crack initiation is slightly different between the calculation and the test. During the test, the crack appears at the point where the cycle stress variation reaches a maximum, whereas in the calculations it appears at a point close to the maximum temperature.

*3.5 Comments*

The following teachings were drawn from the results:

- both calculations and tests predict crack initiations on the welded side before the machine side,
- in all cases, the best-estimated calculation is conservative. RCC-MR design rules are therefore very conservative,
- the influence of primary stress is greater in the calculations than in the test,
- the location of the crack differs slightly between the test and the calculations.

4- CONCLUSIONS

On a realistic structure submitted to heavy localised secondary loading (and thus characterised by a very low elastic follow-up), SOFA tests showed that the RCC-MR's creep-fatigue rule is very conservative.

These test results are currently being subjected to more precise analysis (complementary calculations and metallurgic assessments). This should improve the interpretation of the phenomena involved.

Moreover, the estimated redistribution of strains between a weld and the parent metal (reference [4] for fatigue) is currently being studied, which should provide an approach of welds which is less global than that provided by the $J_r$ and $J_f$ joint coefficients.

REFERENCES :

1. RCC-MR May 1993 *Edition AFCEN.*

2. Le Ber L. - Sainte Catherine C. - Waeckel N. - Turbat A. Recent Developments in Support to Rules for Welded Joints *SMIRT 14 August 97 Lyon.*

3. Hoffmann A. - Combescure A. *CASTEM :* a System of Finite Element Computer Programs Conference on Structural Analysis Design and Construction in Nuclear Power Plant *Porto Alegre, Brazil, 1978.*

4. Berton M.N. - Cabrillat M.T. - Martin Ph. Allowance for Welds in Elastic Fatigue Analysis - Elastic Follow up in Welded Structures
*SMIRT 11 - August 91 - Tokyo - L7/4.*

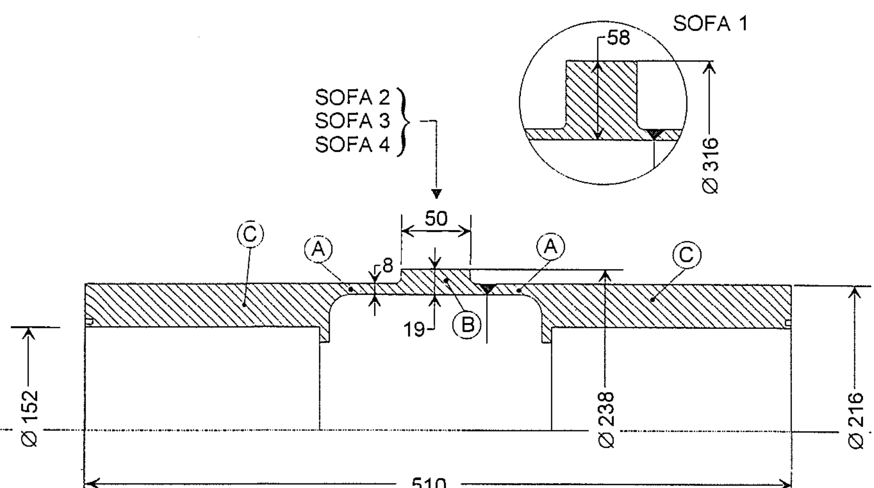


Figure 1 : SOFA MOCK-UP

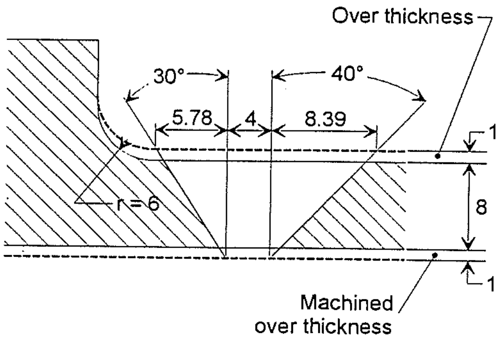


**Figure 2 : DIAGRAM OF THE WELD**

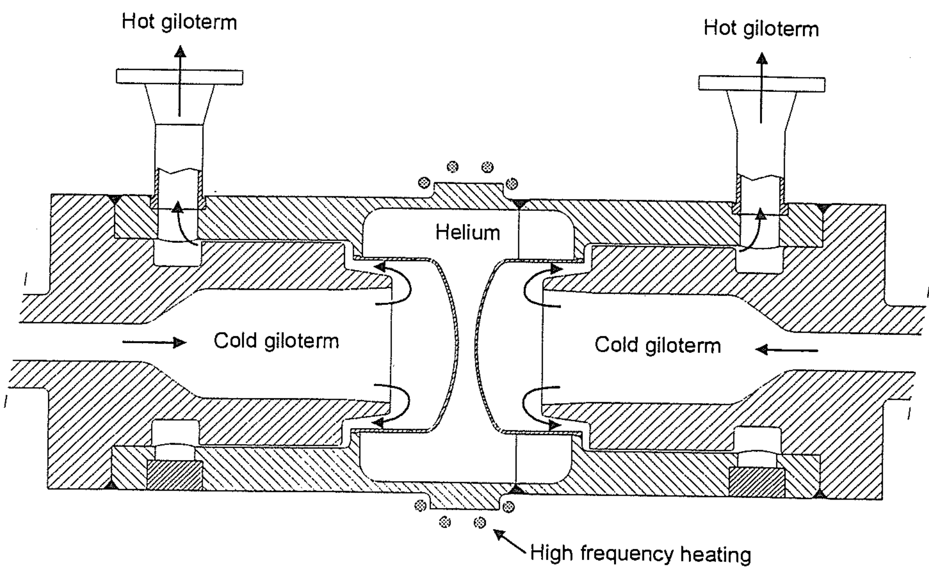


**Figure 3 : THE TEST FACILITY**

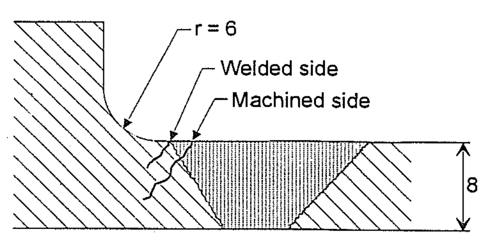


**Figure 4 : ILLUSTRATION OF CRACKING**

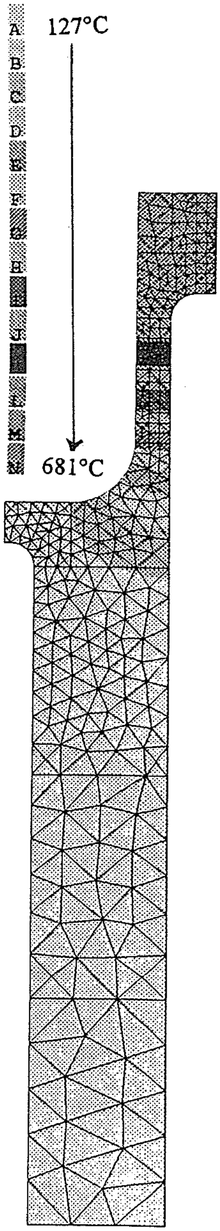


Figure 5 :
TEMPERATURES
IN SOFA2
DURING THE
HOLD TIME

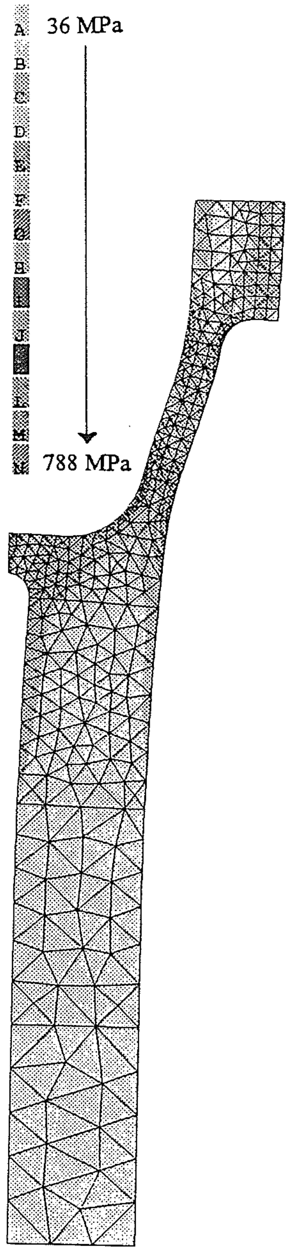


Figure 6 :
THERMAL
VON MISES
STRESSES
(displacements
ampli. = 50)

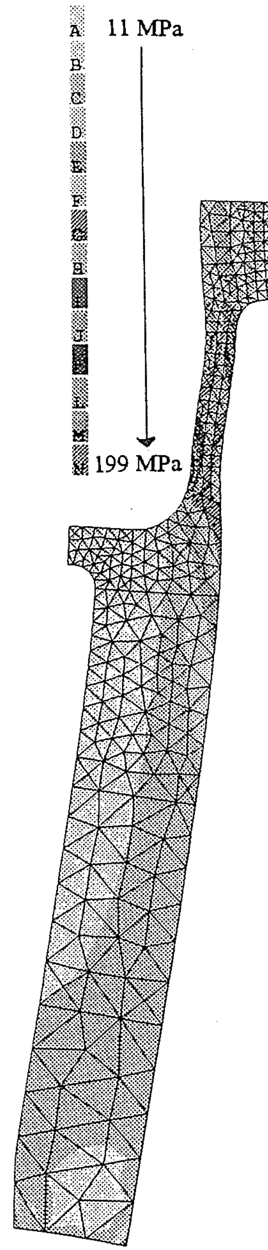


Figure 7 :
MECHANICAL
VON MISES
STRESSES
(displacements
ampli. = 50)

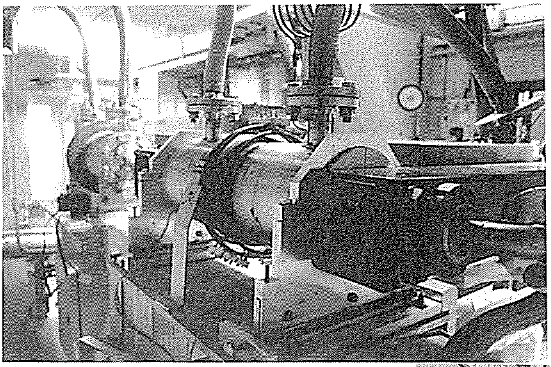

Photo 1 :
SOFA1 MOCK-UP

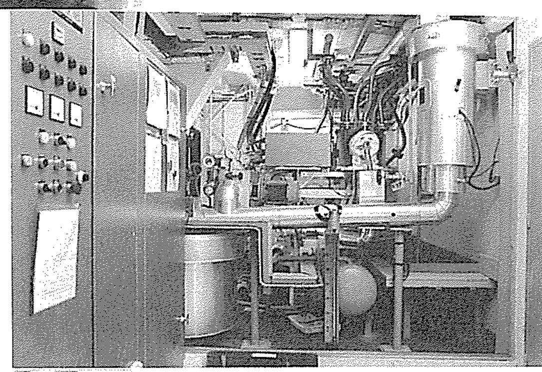

Photo 2 :
THE TEST FACILITY

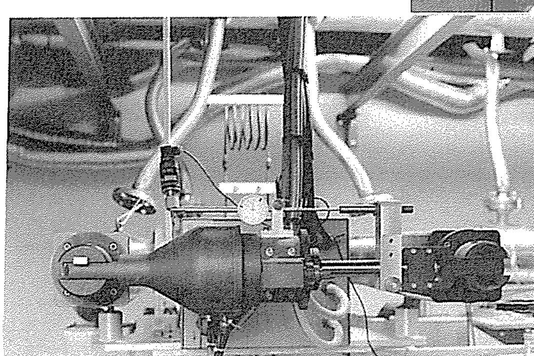

Photo 3 :
BENDING LOAD
DEVICE

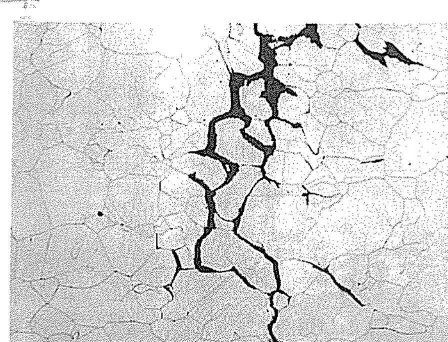

Photo 4 :
CRACKS EXAMINED UNDER
THE MICROSCOPE