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MECHANICAL ASPECTS CONCERNING THERMAL FATIGUE INITIATION IN THE MIXING ZONES OF PIPING

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ABSTRACT

Following the incident (through-wall crack and crazing zones) of May 1998 on the principal mixing zone of the residual heat removal system at CIVAUX nuclear plant, EDF has initiated a R&D programme to understand the incident and assess the risks of damage on other nuclear plant mixing zones. The programme includes different sectors of developments : assessment of temperature fluctuations in mixing zones, study of high-cycle thermal fatigue behaviour of austenitic steel and development of mechanical methodologies for damage assessment and propagation of crazing zones (thermal striping).

The paper develops the mechanical part of the programme. It describes analytical thermal fatigue tests performed on a pipe structure using the bench test INTHERPOL. It also describes an attempt to calculate the spatial and temporal variations of fluid thermal fluctuations in a mixing zone like CIVAUX, using a Large Eddy Simulation method (LES). Distribution of temperature in the wall is evaluated in the same calculation. This result is used afterwards to estimate the stress variations on the pipe by using finite elements calculation or simplified methods.

Keywords: Thermal fatigue, mixing zones, thermal fluctuations, thermal stresses, damage evaluation

1. CONTEXT

1.1 CIVAUX Reactor Heat Removal systems

In May 1998, a through-wall crack was discovered on the residual heat removal system (RHR) of CIVAUX 1 power plant (PWR type N4 – 1400 MWe), which was then in the hot shutdown condition (Faidy, 2000). This crack occurred downstream of the main mixing tee of the system. The configuration of the system is shown in Figure 1. The mixing tee was supplied with cold flow (smaller) by the main leg and with hot flow (larger) by the auxiliary leg. Immediately after the tee there was a 90° elbow consisting of two half shells welded by plasma welding and extended by a straight pipe of the rolled welded type.

The through-wall crack was located on the upper side of the elbow, along the plasma weld (Fig. 2). Its external length is 18 cm and its internal length is approximately 30 cm (Cipiere, 2002). Other non-through cracks were found on the TIG welds at the tee/elbow and elbow/straight pipe junctions and at the longitudinal weld on the straight pipe. In addition, there are networks of cracks (crazing zones) at the weld taper areas and even on normal zones (Fig. 3). All the cracking was attributed to high-cycle thermal fatigue. The cycles are due to the turbulent mixing of hot and cold fluids, which occurs at the tee and in the upstream sections (elbow, straight pipe).

EDF replaced the faulty mixing zone by making line modifications (Fig. 4) and construction modifications: lengthened mixing tee so that the first weld upstream is further away, polished surface condition, flush grinding of welds, etc..

The appearance of the through-wall crack at CIVAUX led to the inspection of the RHR mixing zones at other EDF power plants. Cracks (crack networks or isolated cracks) were detected (Molinie, 2002), whatever the configuration of the mixing zones.

1.2 Dealing with the problem – Need to acquire knowledge

The appearance of the through-wall crack on the residual heat removal system (RHR) at CIVAUX 1 raised the question of how to deal with high-cycle thermal fatigue in nuclear power plants. In France, the RCC-M code (AFCEN, 2000) did not cover this type of damage (no fatigue curves for high cycle fatigue). A first step was to replace the section of faulty pipe as indicated above. The modifications made were based on parameters specified in literature. In addition, a first method of assessing high-cycle fatigue was proposed and implemented. This method was a basic one that meets the urgent need to differentiate mixing zones that are liable to involve damage related to the mixing of two fluids at different temperature. It undoubtedly gives pessimistic results with regard to mechanical resistance in many cases.

For EDF, the following new knowledge should be acquired (Stephan, 2002) :

- Better knowledge of the thermal solicitations in mixing zones. For instance, the actual damage assessment method does not differentiate between a zone where fluid mixing takes place near the pipe wall and would thus be damaging and a zone where mixing takes place at the centre of the pipe and is thus less damaging.
- Better knowledge of the behaviour of materials in high-cycle fields, especially with regard to surface conditions,
- A more realistic method for assessing the damage on components.

These new items of knowledge should lead to a new approach for assessing high-cycle thermal fatigue in mixing zones.

2. DESCRIPTION OF EDF R&D PROGRAMME

2.1 Thermal Solicitations

The aim is to get evaluations of the fluid temperature fluctuations and estimations of heat transfer to the wall must be assessed.

Temperature fluctuations in the fluid can be assessed using the following different approaches.

- The numerical approach may be used to access fluctuations with respect to time at all points. This approach will be developed further,
- The experimental approach, which allows specific measurements with respect to time in the fluid and on the wall and also may allow the evaluation of heat transfers.
- Measurements on sites when possible.

EDF uses a combination of these approaches to assess the thermal fluctuations applied to the walls. The experimental approach comprises:

- Full-scale tests on a mixing tee of type RHR (FATHER mock-up, Fig. 5) currently being conducted at CEA on the basis of EDF/CEA/FRAMATOME partnership (Fissolo, 2004). This programme will be developed further.
- Tests on reduced-scale mock-ups for dimensions and temperature, such as the tests on feed line configuration conducted by FRAMATOME under EDF contract. These tests concern different geometric configurations (unequal tees) and fluid circulations, which differ from the previous tests.

Furthermore, EDF conducted a large number of measurements on RHR systems on sites (Vindeirinho, 2002).

2.2 Materials fatigue in high-cycle conditions

It is very expensive and long to carry out high-cycle tests on standard specimens under imposed strain conditions : most tests are performed under imposed stress conditions. However, in the case of austenitic stainless steels which presents ductility even under small loads, the results obtained in imposed load conditions may be different from those obtained in imposed strain conditions.

EDF has carried out tests under imposed strain conditions:

- A set of tests in air with a load ratio R of –1 for numbers of cycles of up to 10 millions,
- A set of tests in water to study the effects of environment (Solomon, 2004).

In addition, a study of the possible difference between thermal and mechanical fatigue, under displacement-controlled (< 10^6 cycles) and load-controlled (> 5 10^5 cycles) conditions did not reveal any differences yet (Haddar, 2003).

2.3 Mechanics

The problems raised in the assessment of damage due to high-cycle fatigue on a structure include, for example:

- Fatigue strength reduction factors (effect of size, environment and geometric singularities such as welds),
- The combination of high and low amplitude cycles,
- The propagation of a crack network (thermal crazing).

The study of these questions is based on:

- Analytical tests on structures (INTHERPOL tests),
- Full-scale tests on a mixing tee (FATHER tests, see before).

The analytical tests include tests on EDF's INTHERPOL installation (Stephan, 2002). Five tests have been completed and analysed (Curtit, 2004, Curtit 2005). Comparison of the experimental and numerical results makes it possible to assess fatigue strength reduction factors (FRSF) under high-cycle fatigue and to confirm surface effects.

3. INTHERPOL TESTS

3.1 Description of INTHERPOL tests

The purpose of the INTHERPOL installation is to conduct fatigue tests on pipe components by reproducing the site conditions by heat exchange on the inside wall. The main goal of the tests is to assess the fatigue strength reduction factors due to the effects of the size, the surface finish and the material and geometric singularities such as welds. In order to simplify the interpretation of the results, the INTHERPOL facility is designed to apply thermal cycles controlled in frequency and amplitude. The tests are conducted under chemically controlled atmosphere inside an isolated vessel.

INTHERPOL specimen consists of a 300 mm length section of pipe with an internal diameter of 386 mm and a thickness of 10 mm. Each specimen comprises a circumferential welding located at 200 mm from the bottom of the specimen (fig. 6). According to the test considered, the models can have various industrial surface finish (brushed with flap wheel, shot blasted, rough-cast, grinded) and various configurations of welded joints (grinded or rough of realization, with or without taper).

During the test, the bottom of specimen is clamped on a support by three mounting device distributed at 120°. External heating elements are used for initial homogeneous heating of the specimen, and to maintain the mean temperature of the specimen during thermal cycling. A view of testing facilities is given in figure 7.

Thermal cycling is applied to a 70 mm broad sector of internal surface. The cold part of the cycle is obtained by pulverization of a water spray on hot surface, and the heating is obtained by infrared radiation. During the test, the specimen is moved with an alternated rotation in order to expose the test sector alternatively to the spray (blue sector) and to the infrared radiations (red sector) as shown in figure 8. The cycle breaks up into fixed positions in front of spray nozzles and infrared modulus and fast transitions between these two positions. The load frequency is imposed by the frequency of alternated rotations. The regulation of the power of infrared flux and the time of spray exposure allows controlling the thermal amplitude on the internal surface. The thermal fluctuations could be lower in the upper and the lower part of the test sector and are regulated at the level of the weld.

The instrumentation is reduced at the minimum during the fatigue test. After the fatigue test, thermocouples are added on the internal surface of the specimen (see fig. 9) for a better knowledge of the thermal fields in this sector.

3.2 Experimental RESULTS

At the present time, four tests have been carried out on INTHERPOL testing facilities, considering several thermal amplitudes, welded joint configurations and surface finishes (see table 1).

Table 1 : List of specimen configuration and tests results

Reference	Weld type	Surface finish	Cycle	ΔT	Nb of cycles	Results
Test 01	Rough with taper	Rough-cast	5 s	120°C	264 000	18 fissures (1st indication at 124 000 cycles)
Test 02	Grinded	Brushed	6 s	120°C	489 000	No cracks
Test 03	Grinded	Brushed	8 s	140°C	552 000	No cracks
Test 04	Grinded with taper	½ brushed ½ grinded	8 s	140°C	552 000	2 indications (grinded area) at 370 000 cycles, 1 indication (brushed area) at 552 000 cycles

Destructive inspection have been performed by EDF/CEIDRE laboratory on the INTHERPOL 01 mock-up. A polished section in the middle of the test sector shows 45 cracks. Two cracks are observed on the root of the weld seam. For all the observed cracks, the propagation is transgranular and perpendicular to the internal surface as expected for a fatigue test (Fig. 10).

Three cracks have been opened for SEM observations. At the beginning of the cracks (near the internal surface) the fracture surface is typical of stage II growth with fatigue striations (Fig. 11). The crack growth rate decreases through the thickness of the mock-up. Near the cracks tip, the fracture surface is typical of very low crack growth (Fig.12).

3.3 Numerical Simulation

As described in the experimental part, the internal surfaces of the specimens are instrumented with thermocouples at the end of the fatigue test. Strain gages are also located on the external surface in order to not perturb the thermal flux on the test sector. Consequently, the strain and stress state of the specimen during thermal cycling is only accessible by numerical simulation. Each test is simulated with the finite element code *Code_ASTER* (Code_ASTER, 2005) developed by EDF. All the material data used for this simulation are taken from the RCC-M French design code (AFCEN, 2000). All parameters are depending from the temperature.

The first step of the calculation is the thermal simulation of the test. The temperature recorded during the thermal characterization test is imposed instant by instant on the internal surface on the mesh corresponding to the test sector (blue part of the mesh described on figure 13). The recorded thermal cycle load is applied on the test sector several times in order to obtained the stabilization of the thermal cycle throughout the thickness of the mesh. Comparing the temperature measured on 5 thermocouples welded on the external surface of the specimen and the temperature calculated on the corresponding points on the mesh validates the result of the thermal simulation. The thermal field calculated during the last cycle is recorded and used as input data for the mechanical simulation.

The boundary conditions defined for the mechanical simulation are applied at three points of the lower end of the mesh breaking down with an angle of 120° in order to obtain isostatic conditions. The behavior is elastic and the material parameters are considered as dependant from the temperature. The strain and stress fields are calculated for the cycle with a time step of 0.1s.

Calculation results are validated by comparing calculated and measured strain on the external surface of the specimen. An example of validation for test 03 is given on figure 14 with an excellent agreement between measured and calculated strain in the two considered directions.

3.4 Numerical results

The evolutions of the stress during the cycle are comparable for the four tests. On the surface internal surface, only axial σ_{zz} and circumferential σ_{yy} components are significant. The difference of stress ranges between the two directions during the thermal cycle leads to a higher stress range for σ_{zz} could explain the cracks orientation observed on INTHERPOL mock-ups.

For each test, the maximum stress amplitude is observed in the middle axis of the test sector. This amplitude decrease progressively up to the border of the sector. A view of the stress amplitude field is given on figure 15 for the internal surface of mock-up 03.

The frequency of thermal cycles leads to a fast decreasing of the thermal shock through the thickness of the specimen. At one millimeter under the internal surface, the stress amplitude is approximately divided by a factor of 2, and the stress variations become very low after 2 mm depth.

3.5 Fatigue analysis

According to RCC-M (AFCEN, 2000) design Code , the alternating stress is defined by :

$$S_{alt} = \frac{1}{2} . \frac{E_C}{E} . K_e . S_p \, , \qquad (1)$$

with: E_c : conventional Young modulus used for the construction of codified fatigue design curve
E : Young modulus used for the simulation
S_p : local peak stress
K_ε : plasticity correction factor

The Peak stress S_p is defined as the maximum value of TRESCA modulus of stress variation during the cycle:

$$S_p = \max_{t_1, t_2} \left\{ TRESCA\left([\sigma]_{t_1} - [\sigma]_{t_2} \right) \right\} \qquad (2)$$

The plasticity factor K_e used for fatigue analyze of mixing zone is equivalent to the expression of K_v proposed by RCC-MR code (AFCEN, 1993). This correction factor is based on the local equivalent strain calculated on the surface :

$$K_v = Max\left[1; \left(1{,}35 - \frac{0{,}026}{\varepsilon_e} \right) \right] \qquad (3)$$

with:

$$\varepsilon_e = \frac{\sqrt{2}}{1+\nu} * \sqrt{\left(\Delta\varepsilon_1 - \Delta\varepsilon_2\right)^2 + \left(\Delta\varepsilon_2 - \Delta\varepsilon_3\right)^2 + \left(\Delta\varepsilon_3 - \Delta\varepsilon_1\right)^2} \qquad (4)$$

The alternating stress is calculated for several point of each mock-up.

Each point is reported on a diagram describing alternating stress versus number of cycles corresponding to crack initiation. The design curve from RCC-M (or ASME curve) and the Mean curve of Langer are plotted on the same diagram. The points with a right side arrow correspond to locations without crack initiation.

The two points (green square) corresponding to the current area of raw surface finish have the lowest level of alternating stress and are located slightly under the design curve. All the other points are located between design and mean curves.

4. FATHER TESTS

4.1 Description of the FATHER experimental tests

4.1.1 Father mock-up

The FATHER program is an experimental study on mock-ups, close to real mixing tee in plants (RHR new configuration type), carried out by CEA under EDF/CEA/FRAMATOME agreement.

The mock-up (Fissolo, 2004) is composed of an equal 6" T-junction and of its inlet and outlet branches (Fig 5). The thickness is 7,11 mm in the branches and 22 mm in the T-junction. The outlet branch is divided into three successive 300 mm straight pipes welded together. The first two straight pipes are also divided into 5 sectors with different surface finishes. The welds between the 3 straight pipes and the tee have also different surface finishes.

The thermalhydraulical conditions were defined with respect to the dimensionless numbers that drive the turbulence flow and the wall heat transfer in the RHR systems. In addition, the flow velocities in the inlet branches are close to those in RHR systems. The mock-up is attached to a 8 MW power facility.

4.1.2 Tests programme

The test programme consists essentially of two objectives:

- to acquire knowledge in fluid and wall temperature fluctuations resulting from the mixing ; in complement, to acquire data concerning the heat exchange between fluid and wall. The tests performed are called further "thermalhydraulics tests".
- to submit a mock-up to the thermal fluctuations resulting from one set of thermalhydraulics configurations (temperatures and flow rates at the inlets are maintained constant) in order to produce damage.

For the first objective, a mock-up was instrumented by sensors in the fluid and on the internal and external wall surfaces. The instrumentation of the mock-up for the second objective was reduced at the external surface in order only to survey the stability of thermal conditions of the test. The conditions of the damage (or endurance) test were reproduced during the themalhydraulics tests.

4.1.3 Results

The thermalhydraulics tests produced a large database of fluid and wall temperature and of external surface strains.

The damage test is at this time not achieved. An initial endurance test of 300 h has been performed. US Non destructive examination leaded to the discovery of small cracks on some surface finishes and at welds.

4.2 Numerical evaluation of thermal fluctuations

4.2.1 Model

The methodology to obtain a numerical approach of the instationnary and 3D temperature is described in (Benhamadouche, 2003). For a complete description of the approach for FATHER mock-up, the reader is invited to read (Pasutto, 2005).

The computation of the fluid temperature variations is done with EDF CFD Code_Saturne with a LES model. Code_Saturne is coupled with the EDF thermal code Syrthes, which propagates the temperature fluctuations into the wall thickness. The thermal fluid wall exchange is usually simulated via a classic wall law.

4.2.2 Results and Comments

Different calculations have been performed, each one enhancing the previous one. Due to high-level computer time consuming, all the calculations are limited to simulation of 10 seconds real flow.

There is a good agreement for mean flow between calculation and measurement. Particularly, a fluid recirculation is found near the T-junction at the lower part of the outlet branch and the temperature gradient are well reproduced in this branch.

Fluid thermal fluctuations are also relatively well predicted (Pasutto, 2005). But the modelisation of the fluid wall thermal exchange seems to be not adequate, leading to too small thermal fluctuations in the wall when fluid temperature fluctuations are good.

A non-coupled thermal calculation, with an "estimated" thermal exchange coefficient between fluid and wall, was then used to get a realistic temperature distribution in the wall for mechanical purpose.

4.3 Evaluation of mechanical stresses

4.3.1 Model

The same discretisation of the wall mock-up was used for mechanical computation by code_ASTER and thermal computation by Syrthes. So it was easy to project the Syrthes result to the Code_ASTER model (fig. 16). The model comprises 190423 nodes and it is very refined near the internal wall (the length of the first element in the radial direction is 0,1 mm).

We must remember that the temperature distribution is not a real one but an approached one. Nevertheless, it looks like a real one: when compared with measurements, the level of fluctuations and the frequency distribution seem to be realistic. For our purposes (type of stress distribution, comparison 1D/3D), it is reasonable.

Elastic calculations have been performed.

4.3.2 – Results

The Tresca intensities of stress variations during the transient are plotted in figure 17. Differences are very low. The stress intensities level is low excepted at the T-junction and at the outlet branch near the T-junction. From this, we can conclude that the maximum stress cycle stands in the high cycle fatigue region.

The thermomechanical stress state is at the internal surface a quasi equi bi axial one (Fig 18).

We also have compared these results with the stress variations resulting from 1D calculations relative to a pipe submitted to a uniform spatial temperature fluctuation (MUSI, 2003). Two types of 1D calculations were done, differing with the data used: the first one considered the temperature at the internal wall and the thermal propagation in the wall; the second one consider the fluid temperature, the same thermal exchange coefficient than for the 3D calculations and the thermal propagation in the wall.

The first type of 1D calculation leads to results close to 3D calculations, in general more elevated results, up to 14%. The second type of 1D calculations was applied along one circle where a high temperature gradient exists. The conclusion is the same.

5. DISCUSSION

5.1 INTHERPOL tests

The comparison of INTHERPOL crack initiation results with fatigue curves on the same diagram is not perfectly correct because of different initiation definition for each case. For normalized fatigue test as used for design curve, the initiation of cracks corresponds to a 25% fall down of the alternating stress, which corresponds approximately to a 2 mm depth crack for usual specimen. Concerning INTHERPOL results, the initiation correspond to the first observation of the indication during intermediate dye penetrant inspection, with a detection threshold of less then 0,5 mm. Consequently, the presented comparison underestimates the number of cycles for INTHERPOL results. However, this representation is a practical way to compare results with various levels of alternating stress.

The relative position of the test results shows clearly the influence of the surface finish on the sensibility to crack initiation which could be classified as following: The raw surface finish presents the highest level of sensibility to crack initiation, followed by turned surface of the taper. The best resistance to crack initiation is observed on soft grinded surface and finally on brushed surface.

A detailed optical examination of the raw surface finish of the first mock-up shows numerous machining surface defects like material striping or locally depth scratches. The detailed destructives examinations performed on this mock-up shows that all significantly depth crack (which correspond to first cracks observed during the test) have been initiated on such defects. This probably explains the highest sensitivity of raw surface to fatigue damage.

Several welds configurations have been tested on INTHERPOL mock-ups, but cracks initiation was observed only on the un-flushed weld on the mock-up 01. No cracks were observed on the three other mock-ups in the flushed weld area. The whole experimental results leads to consider that higher sensibility to fatigue damage of welded area is related to the geometrical singularities of un-flushed weld instead of material particularity.

5.2 FATHER evaluation

We must remember that the used temperature distribution across the wall was obtained by applying and estimated heat exchange coefficient and is close to a realistic one when considering its level and its power spectral density. So we think that it can be used for relative conclusions.

The results came mainly from the temperature distribution across the wall. The temperature fluctuations are restricted to a small part of the thickness near the internal surface. In addition, the temperature distribution at the internal wall did not show large surfaces of cold or hot temperature but a distribution of mean or small ones. We have concluded that the variations of thermomechanical states of the wall are of strain-imposed type.

A second conclusion is that 1D calculations may be used for stress variations estimations. For instance, if we own temperature measurements at the inner wall, the stresses at the point of measurements can be estimated. Nevertheless, if the measurements are fluid temperature ones, we must fit the thermal exchange coefficient. Estimations from few measurements lead to a value less than 2 times the value obtained by the Dittus-Boelter correlation.

6. CONCLUSION

After a brief description of the Civaux incident, the EDF R&D programme is developed in its main lines. A focus is then made on two items of the mechanical part of the programme: INTHERPOL tests on structure in high cycle fatigue and 3D calculations performed on the FATHER mock-up. The results of INTHERPOL tests are compared to the RCC-M codified fatigue curve and give access to the influence of surface finishes. The 3D calculation of the FATHER test allows to use a 1D simplified method to evaluate the risk of damage in this configuration of mixing zone.

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FIGURES

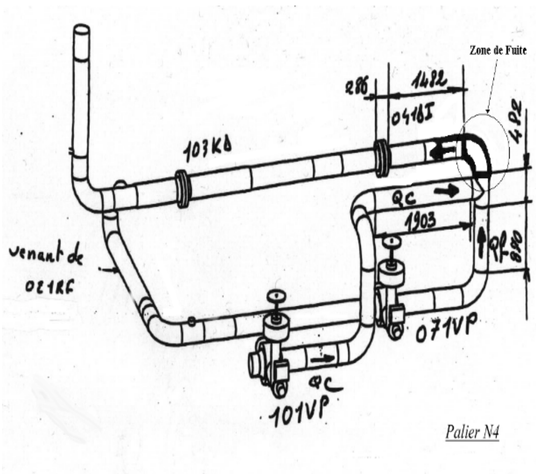

Figure 1 - Residual heat removal system (RHR) at CIVAUX 1 - Former configuration (Qc = hot flow ; Qf = cold flow)

Figure 2 - View of crack on upper surface of residual heat removal system (RHR) elbow at CIVAUX 1

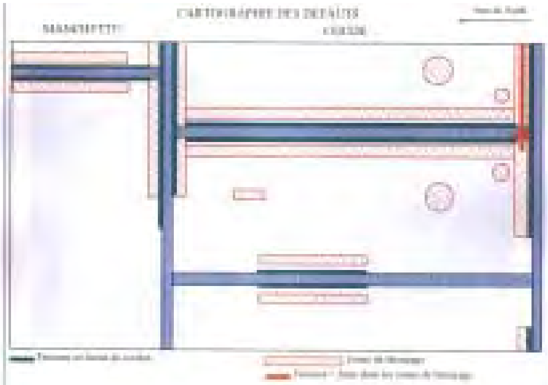

Figure 3 - Overall view of faults on residual heat removal system (RHR) at CIVAUX 1 (zone de faïençage = striping zone ; fissures = cracks ; coude = elbow ; manchette = straight pipe)

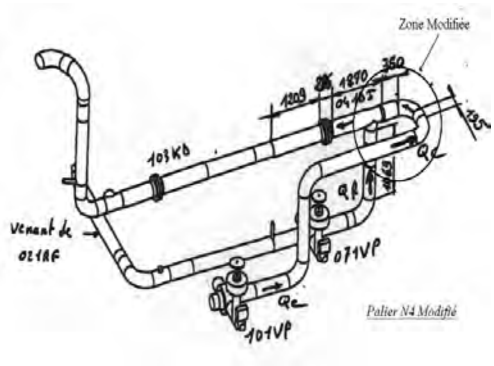

Figure 4 - Residual heat removal system (RHR) at CIVAUX 1 – New configuration

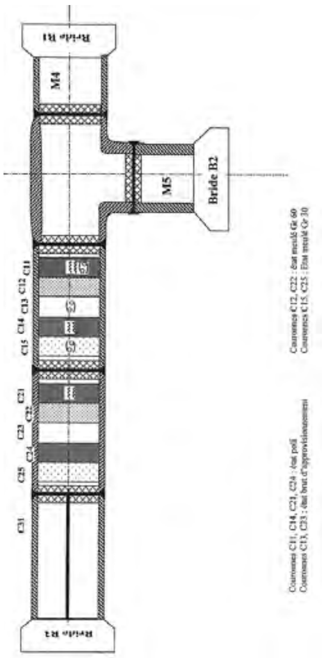

Figure. 5 – FATHER mock-up

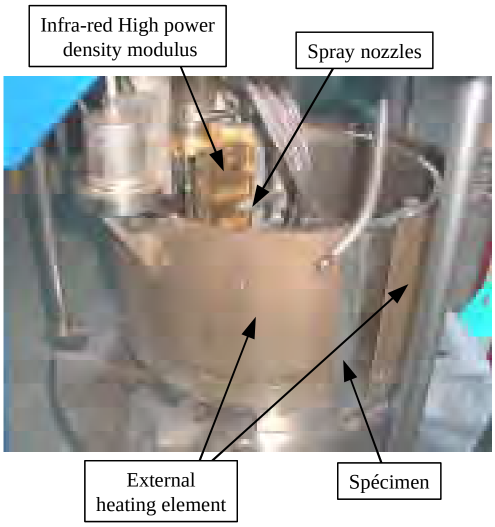

Figure 7 : INTHERPOL : view of the testing facility

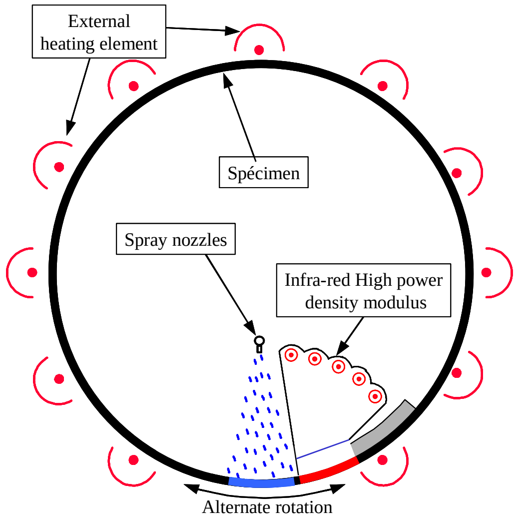

Figure 8 : INTHERPOL : principle of operation

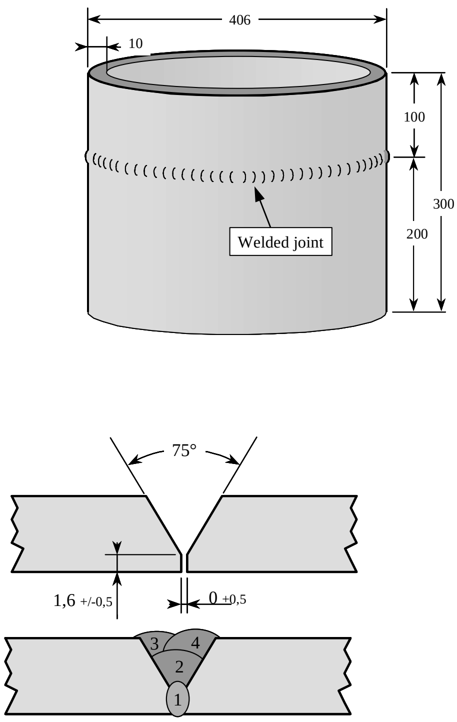

Figure 6 : INTHERPOL : geometry of the specimens

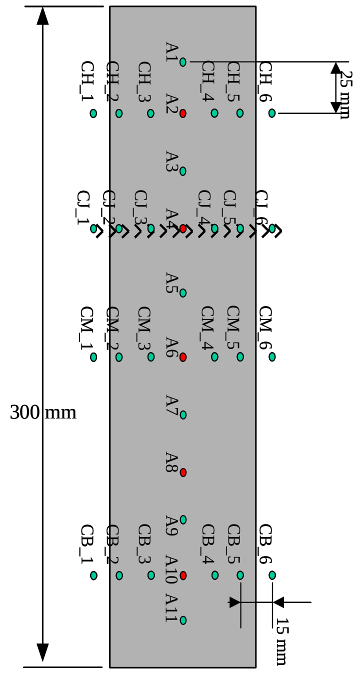

Figure 9 : Detail of the instrumentation of the sector submitted to thermal cycling during thermal test

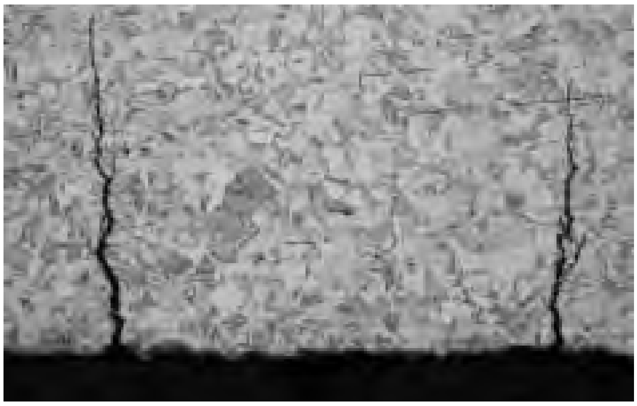

Figure 10 : Trans-granular crack propagation

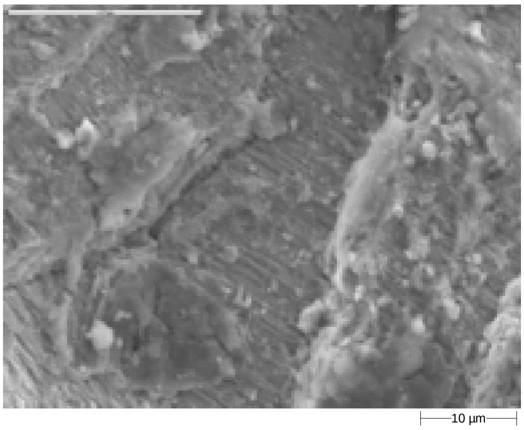

Figure 11 : Fracture surface near the internal surface

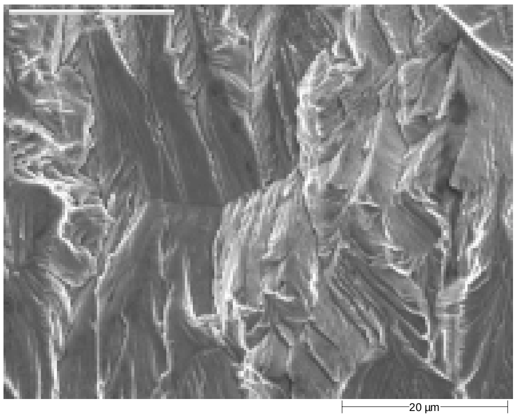

Figure 12 : Fracture surface near the tip of the crack

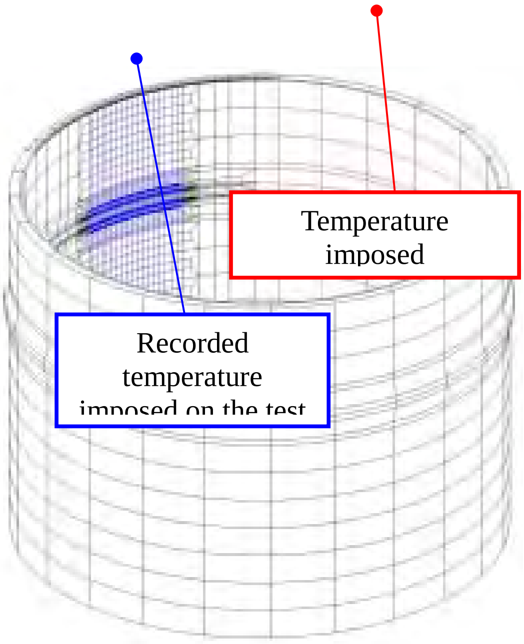

Figure 13 : Boundary conditions for the thermal simulation

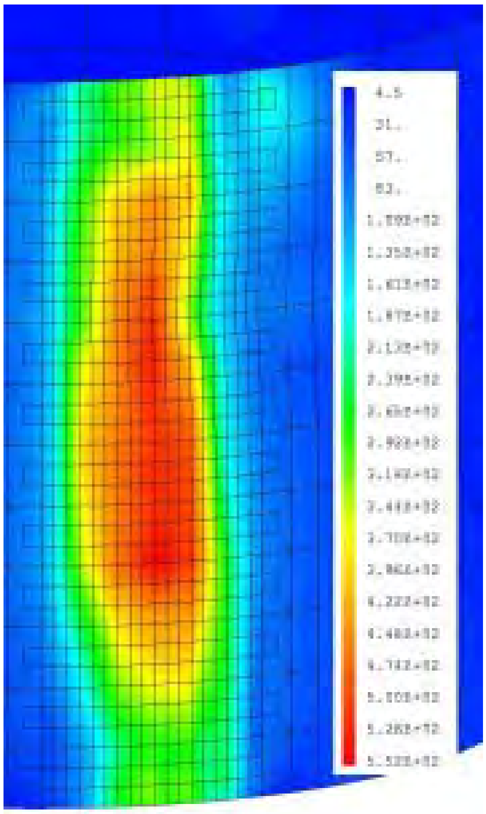

Figure 15 : Calculated alternating stress field on the internal surface for the INTHERPOL 03 mock-up

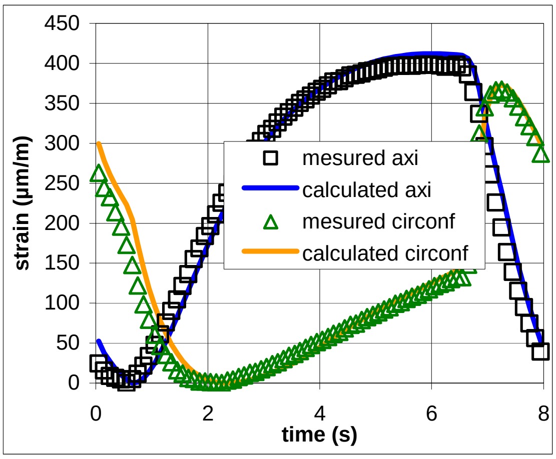

Figure 14 : comparison of measured and calculated strain on the external surface (INTHERPOL test 03)

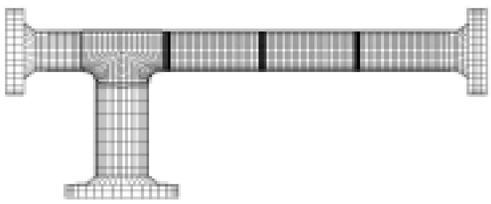

Figure 16 – FATHER modelisation

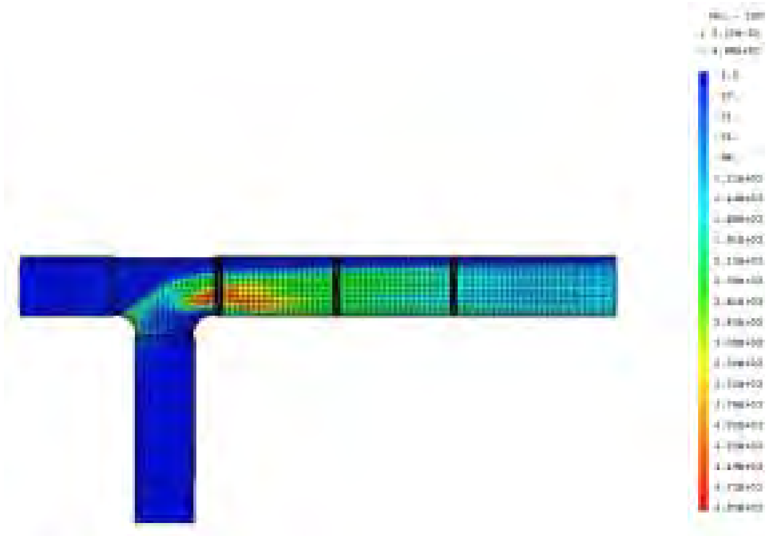

Figure 17 – Tresca stress intensities (MPa) at the internal wall – Elastic calculations

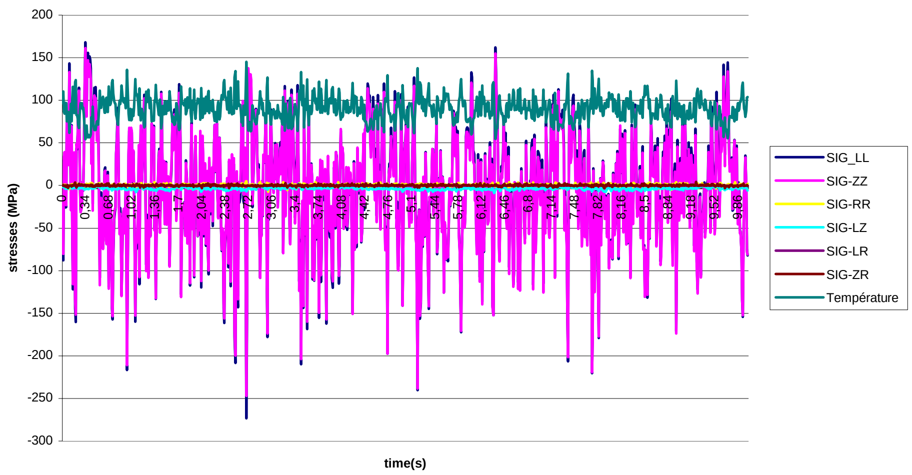

Figure 18 –Stresses versus time – Elastic calculation