Experimental tests of 'integral' thermal sleeves submitted to thermal shocks – Interpretation by elastic and plastic calculations

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1 INTRODUCTION

In nuclear P.W.R. power plants, the connection of auxiliary pipes on the primary system are sensitive parts called nozzles ; during operation they can be submitted to strong flow rate variations ; this induces numerous thermal transients, some of them being shocks with a range more than 200°C.

To protect them, a thermal sleeve is generally installed to make a screen between the water flow and the nozzle. The first sleeves are connected to nozzles by welding (either with two small tongues or girth welds) ; they make singular zones with a sharp notch effect leading to high stresses and then to fatigue cracks (fig. 1).

It is the reason why new "integral" sleeves have been installed in recent French PWR plants ; their design avoids the notch effect but however there is a zone, between sleeve and nozzle, which forms a groove with a radius of 4 mm where stresses are concentrated.

After testing the first mock-ups with singular zones, it was concluded that, when the initiation was rather quick, the propagation, in contrast, was very slow and without great danger for the nozzle's integrity. To study the behaviour of the new sleeves, two mock-ups of this type were placed in the thermal shock testing loop, in series with the others.

2 EXPERIMENTATION

The thermal shock testing facility of EDF (Les Renardières) is made up of two similar water loops, one hot (280°C) and the other cold (60°C). The instantaneous operating of four valves produces the thermal shock (fig. 2 and 3).

Physical and chemical parameters are the same as in primary PWR system. The duration of a cycle is approximately 1 h 20 mn and the pressure is maintained at 160 bars.

The two mock-ups of "integral" sleeves were submitted to a first campaign of 1000 cycles in a range of 220°C. Then one was taken off and the other was submitted to a second campaign of 1000 cycles. This mock-up was then destroyed for examination after 2000 cycles ; two cracks were found in the bottom of the groove (fig. 1 and 12) with depths between 1 and 2 mm ; their angles were 0° and 30° from the axis of symmetry.

Fatigue striation were also measured (1,4 to 1,7 µm) and showed a crack propagation speed three times greater than that measured on welded sleeves ; the estimated number of cycles to initiation was about 900 cycles instead of 400-500. The effect of the singularity of the groove is twice weaker than for a notch.

The examination also showed that there were some fine scratches with a depth of 30 to 60 µm in the area where the cracks began (fig. 12). The stress concentration due to these defects is probably the reason for the sensitivity of these "integral" mock-ups to fatigue cracking.

So a numerical analysis is particularly interesting to clarify this case.

3 THERMOELASTIC CALCULATIONS

These calculations were made by a finite-element bidimensionnal thermal and mechanical code, ALIBABA, developed by EDF. The axisymmetric model is cut in the middle of the thick area, because of symmetry (fig. 4) ; this method is convenient not only for the mock-up but also for the actual geometry of the nozzle in power plants.

The physical parameters for thermal calculations have been adjusted in a previous study [1] ; conductivity of water in the annular space is 8 times the value of still water, and heat exchange on inner surface is 2 times that given by classical formulae for smooth pipes.

3.1 Codes and methods

Different meshes have been used for calculations to compare the effect of mesh fineness and to evaluate the role of minor defects.

At first, two models with a coarse mesh (2 mm) and a fine one (15 and 59 µm along the inner surface of the groove) were used (fig. 5).

The classical method for fatigue analysis (ASME or French code RCCM [2]) were applied to analyse the stress field. Linearisation and use of B 3200 formulae give the alternating stress S_{alt} ; the plastic correction factor K_e is calculated from "primary + secondary, membrane + flexion" stress range S_n :

(1) $S_n = \Delta (P_L + P_b + P_e + Q)$

(2) $K_e = 1$ if $S_n < 3*S_m$ $K_e = 3.33$ if $S_n > 5.1*S_m$
and a linear variation between

(3) $S_p = \Delta (P_L + P_b + P_e + Q + F)$

(4) $S_{alt} = 1/2*K_e*(E_c/E)*S_p$.

A second elastic calculation was made using an extension of the stress-opening method ($\Delta\sigma_{\theta\theta}$) usually applied to singular zones [2] [3].

It is here considered that the groove is a stress concentration area and its radius (4 mm) is not much greater than the maximum radius for which the "$\sigma_{\theta\theta}$" method has been validated (0.5 mm). Moreover the existence of a machine fault, a scratch of approximatively 50 µm justify the use of this method in this case.

Two meshes, one corresponding to a small scratch and the other to a small crack of 200 µm depth were made to compare the effect of such defects (fig. 6).

3.2 Results

The results of the different elastic calculations with coarse and fine meshes are presented in table 1 ; for one of them the evolution of stresses during time is presented in fig. 7.

TABLE 1 – CALCULATION OF ALTERNATING STRESS AND USAGE FACTOR FOR A CYCLE

Mesh type	S_n	S_p	K_e	S_{alt} (cycle)	N adm.	Usage factor (2000 c)
Coarse	860	1120	2.44	1370 MPa	150	13 (0.75)
Fine	930	1500	2.83	2120 MPa	60	33 (2)

The values for S_n and S_{alt} are automatically computed from the finite-elements stress field at the inner side for a cold shock. The range for a cycle is majorated by considering that a cycle is equivalent to two times the range for a cold shock (see fig. 7).

The usage factor is very high and it is probable to have a crack in these conditions. The values in parenthesis are calculated with $K_e = 1$ considering that there are only secondary stresses and then no correction factor for plasticity.

The "singular zone" method is applied to four calculations using the two precedent meshes and two others with a small defect (scratch) and a small crack. Results are presented in fig. 8 and in table 2.

TABLE 2 – CALCULATION OF INITIATION FACTOR BY «$\sigma_{\theta\theta}$» METHOD.

Mesh type	$\sigma_{\theta\theta}$ (59 µm)	N_a	N_2 (2 mm)	Initiation factor	Damage factor
Coarse	630 MPa	200	3640	10	0.55
Fine	740 MPa	100	1900	20	1.05
Scratch	930 MPa	37	760	54	2.65
Crack	1100 MPa	19	390	106	5.15

N_a is the number of cycles for which a crack initiation is very improbable (10^{-6})
N_2 that one for which a crack of 2 mm can occur with a probability of 5/1000.

4 THERMOPLASTICITY CALCULATIONS

When stresses are very high and overpass the yield stress in large areas, it is preferable to make a plastic analyse. This was done for one and a half cycle (1 cold + 1 hot + 1 cold shock). The strain range calculated as the difference between the hot shock's strain and the average of the 2 cold shock's strain is very close to the stabilised value for the third (or more) cycle.

Two methods were used :

- the first refers to ASME and RCCM codes ; the plastic correction factor K_e is calculated as the rate of plastic and elastic strain range. Then the method is the same than in 3.1 but with a more accurate K_e value ;
- the second refers to RCC-MR French code [3] ; the plastic computed strain range is introduced in a classical fatigue graph to obtain the number of cycles to rupture N_R.

The results of plastic calculations are showed on figures 9, 10 and 11. There is a plastic zone in the bottom of the groove where the cracks appeared, but a larger one is under the inner surface of the pipe.

The evolution of the equivalent strain during time gives the strain range $\Delta\varepsilon_{eq}^{P} = 1.212\ \%$, $S_{alt} = 1/2\ E_c \Delta\varepsilon_t = 1084$ MPa and then $N_{adm} \simeq 400$ cycles (300 cycles for a refined mesh : 60 µm instead of 600 µm). The value of K_e is 1.9, that is weaker than when estimated by S_n (2.4 or 2.8).

The other method (RCC-MR) uses the total equivalent stress range (plastic computation) and two correction factors K_ε and K_v. The total equivalent strain range is then $\Delta\bar{\varepsilon}_{tot} = 1{,}275\ \%$. By the mean of the fatigue curve the number of cycle is found to be approximately 200.

5 CONCLUSION

The examination of the different results shows that RCCM rules give usage factors corresponding to an initiation of a crack on a surface without defect. The propagation of a 1 or 2 mm crack is probable if there is an initial defect. Plastic calculations give "usage" factors from 5 to 10 at 2000 cycles ; they are less sensitive to the mesh refinement and to the choice of the method than elastic calculations ("usage" factors from 0.5 to 33). In all cases there is a probability of a crack in the groove after 2000 cycles but these cracks are rather short and the risk of rupture is very low.

REFERENCES

[1] J.C. MASSON and al. Transactions of 8th SMIRT (DFG 1/6) 1985
[2] J.C. DEVAUX and al. Transactions of 4th SMIRT (G8) 1979
[3] RCC-M and RCC-MR - AFCEN 1985 - PARIS

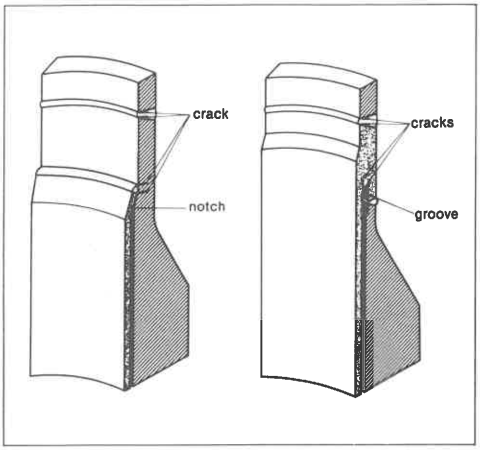

Fig. 1 – With notch and «integral» sleeves.

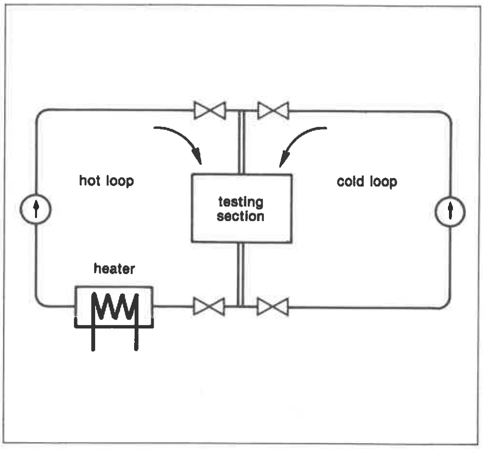

Fig. 2 – Thermal shocks facility.

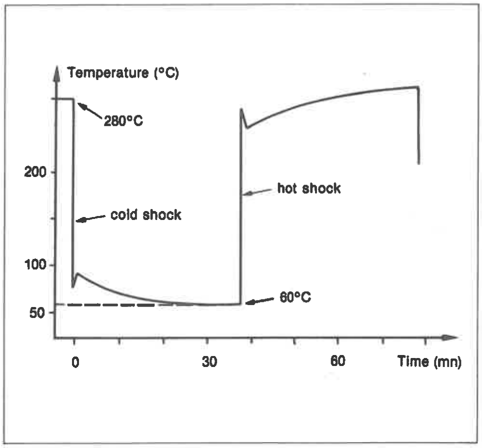

Fig. 3 – Thermal cycle.

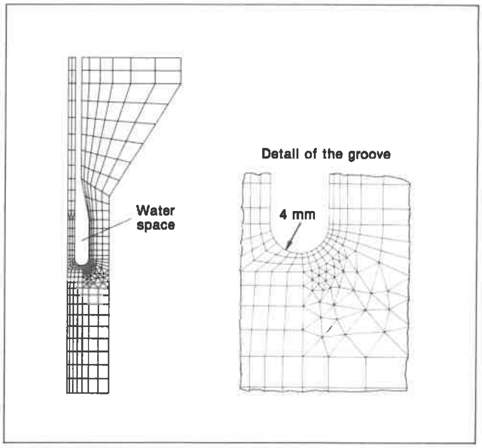

Fig. 4 – Mesh of integral sleeve (for plastic calculation).

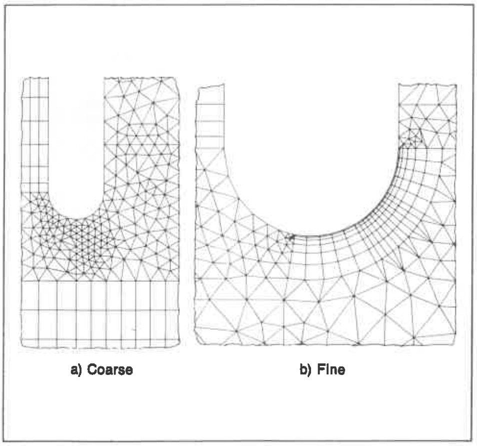

Fig. 5 – Coarse and fine mesh for elastic calculation.

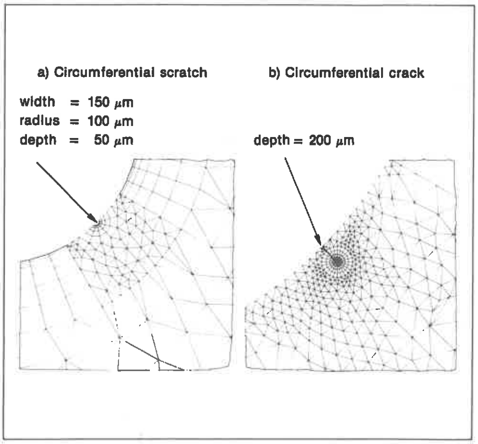

Fig. 6 – Mesh with a scratch (a) and with a crack (b).

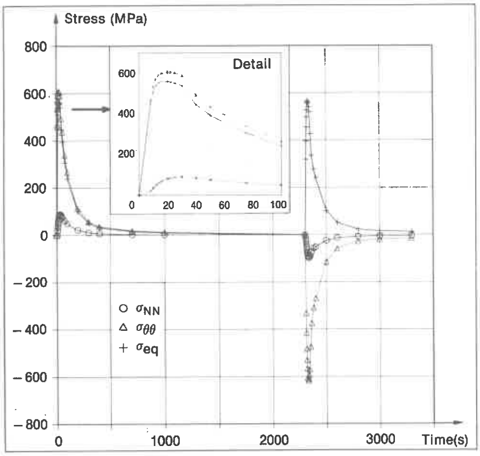

Fig. 7 – Elastic stresses.

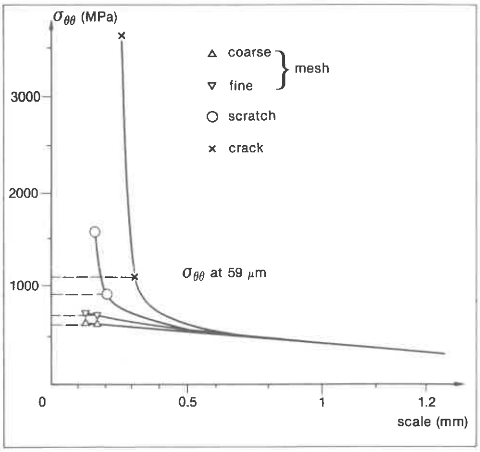

Fig. 8 – Effect of mesh and defects on $\sigma_{\theta\theta}$

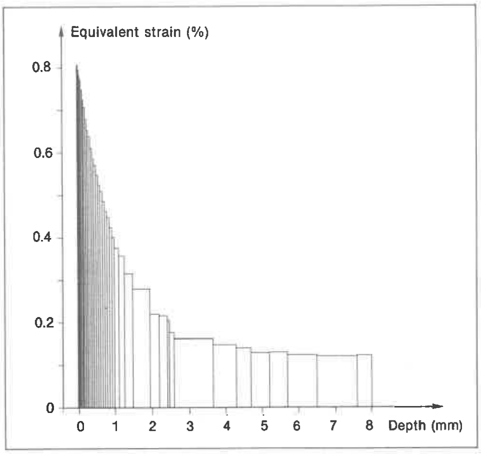

Fig. 9 – Strain versus depth.

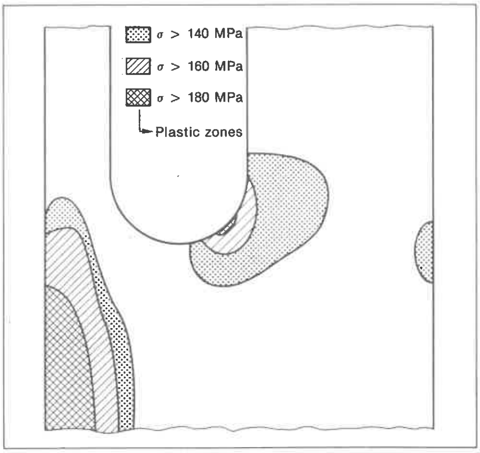

Fig. 10 – Plastic zones.

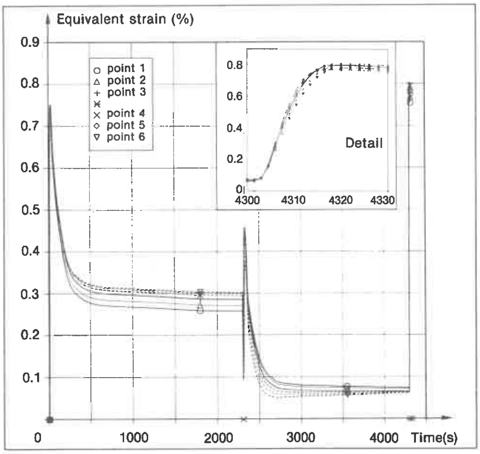

Fig. 11 – Thermoplastic cycle.

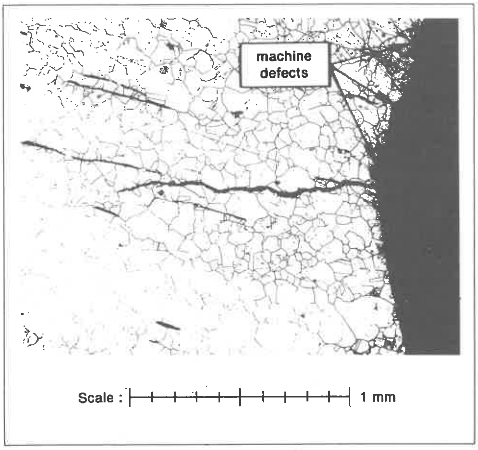

Fig. 12 – One of the cracks observed $\ell = 1200\ \mu$m.