Analysis of Different Cracks Observed on a Loop's Section for Testing PWR Components Under Thermal Shocks

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ABSTRACT

In recent years, a number of cracks have been discovered in the pipe elements of EDF's «thermal shock testing section» at Les Renardières. The large number of shocks and their variety, together with the relatively full knowledge that we have acquired of them, are of particular interest. Varied pipe elements, with welds and different diameters, have been subjected to very different stress histories (thermal shocks). It is possible to evaluate the risk of cracking using simplified methods and in particular with the help of the American (ASME) and the French (RCCM) codes. Calculation of the cumulative usage factors establishes a boundary between the cracked and uncracked elements. This boundary is always greater than one, but varies considerably depending on the code used.

1. Introduction

It is very important for nuclear power plants to be able to evaluate the risk of cracking through thermal shock. The use of rules and codes has become general for solving this problem, by checking that the cumulative usage factor is greater than one. The French Code for PWR plants is based on the ASME 77 Code ; it differs from ASME 80 in respect of the elastoplastic correction in cases of thermal gradients ; the French Code for fast breeder reactors (F.B.R.) is quite different, and suggests a new and more physical approach.

A comparison of these codes is particularly useful for the pipe elements of the «thermal shock testing section». They are subjected to numerous thermal shocks of different kinds, and are representative of the piping in PWR power plants.

2. The thermal shock testing section and its associated loops

The 2 loops GB1 and GB2 were built at the beginning of the 1970 s at Les Renardières with the object of testing various PWR components (valve, etc.) , they can work independently or in association to create thermal shocks by diverting the water flow from the cold loop into the hot loop through the test section (figure 1).

An example of thermal shock is given in figure 2. The test section is formed of removable pipe elements ; thus, various components such as valves, heat-exchanger mock-ups and thermal-sleeve mock-ups can be connected in.

This variable configuration permits the subjection of the various elements to different stress histories (amplitude and number of thermal shocks).

3. History of shocks

In 1978, a leak appeared on an elbow, and this was immediately replaced. Before beginning a new intensive testing campaign, crack detection by sweating was carried out on certain welds : many circumferential cracks were revealed. All the elements were progressively replaced and examined (figure 1). To analyse the risk of cracking, it was first of all necessary to reconstitute the exact history of each element. Fortunately, this was easy, by referring to the tests of components and to the corresponding configurations of the test section.

The piping elements had been classified by their reference numbers in terms of their diameter and history (Tables 1 and 2).

4. Simplified thermal calculation

To calculate the thermal stresses, it is necessary to resolve the temperature across the wall into an average term Δ Tm, a linear term Δ T1 and a non-linear term Δ T2. The last two terms are given by the diagrams (figure 3) in which L1 and N1 are a function of time (NF) and the Biot number (Bi). This number is calculated by the equation $Bi = \alpha * tm / \lambda$, in which tm is the thickness of the pipe, and λ the coefficient of conduction ; the coefficient of convection α is given by the formula $\alpha = K.V^{0.8}$, in which V is the velocity of the water and K is given by a diagram (figure 4) in terms of the temperature and internal diameter of the pipe.

The linear and non-linear parts of the temperature range are as follows :

$$\Delta T1 = L1 * \Delta T \qquad \Delta T2 = N1 * \Delta T \qquad (1)$$

5. Making the stress-range calculations

In the present study the pressure and moment terms are neglected in the fatigue analysis. Three stress ranges are used in the codes :

— Primary + secondary stress intensity range, with two formulations :

$$Sn = E\alpha / (1 - \nu) * \Delta T1 \qquad \text{(French Code RCCM and ASME 77)} \qquad (2)$$

$$Sn \cong 0 \qquad \text{(ASME 80)}$$

omitting pressure, moments and gross discontinuities.

— Peak stress intensity range (or total stress for RCCM-R)

$$Sp = (E\alpha / (1 - \nu)) * (K3 * \Delta T1 / 2 + \Delta T2) \qquad (3)$$

— Alternating stress range

$Salt = Ke * Sp/2$ In which Ke is an elastoplastic correction factor

for austenitic steel 316 : $\begin{cases} Ke = 3.33 \text{ if } Sn > 3 * 1.7 * Sm \\ Ke = 1 \quad \text{if } Sn < 3 * Sm \end{cases}$

To simplify the work, only two calculations were done with Ke = 1 (ASME 80) and Ke = 3.33 (RCCM), as Sn is almost always greater than the limit.

Two cases were considered :

— piping (K3 = 1), and a non-flushed weld (K3 = 1.7).

From equations (1) and (3) we deduce :

$$Sp = M1 * \Delta T * (E\alpha / (1 - \nu))$$

in which $M1 = \max (K3 * L1 / 2 + N1)$ (figure 4)

The results for $\Delta T = 100°C$ are given in table 2 for Sp and Salt (Ke = 1).

6. Fatigue analysis

The cumulative-usage factor is calculated from the ASME curve (Sa in terms of N). An example for Ke = 1 is given in table 3.

The French rules for F.B.R. (RCCM-R) are used by calculating the elastoplastic strain range from the total elastic strain range, using NEUBER's rule ($\sigma * \epsilon = \text{cst}$)

$K_\epsilon = E\, \Delta\epsilon \,/\, \Delta\sigma_e$ is given in RCCM-R.

From $\Delta\sigma_e = Sp$ (= 2 * Salt with Ke = 1) we obtain $\Delta\epsilon$ and introduce it into a classical fatigue curve ($\Delta\epsilon \leftrightarrow N$ = number of cycles to failure). A cumulative usage factor is calculated using the classical formula.

7. Comparison of the codes

The results for all the pipe elements are presented in figures 6, 7 and 8 by the 3 methods given by the 3 codes. There is always a boundary between the cracked and non-cracked elements :

- this boundary is approximately 2.5 to 3 for the American Code ASME 80, and appears to give a rather poor guarantee ;
- it is approximately 60 for the French Code RCCM (equivalent to ASME 77) and would appear to be too restrictive ;
- it is approximately 20 for the French Code RCCM-R, and this appears more satisfactory.

8. Conclusion

The comparison of 3 codes applied to a real problem of thermal fatigue shows great differencies.

A new method, already incorporated in RCCM-R French Code for Fast Breeder Reactors, gives more realistic evaluation of the cumulative usage factor. It is possible to improve this estimate by reducing the safety margin on the fatigue curve which is approximately 20 for all the number of cycles.
But it is still necessary to continue the investigations and tests in order to validate this promising method.

TABLE 1 – PIPES CHARACTERISTICS

Element Description with reference number	Diameter (mm)	Thickness (mm)	Water speed (m/s)		α(W/m^2°C)				Number Biot			
					Cold shock		Hot shock		Cold shock		Hot shock	
			min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
Right parts (6" sch 160) ①	131,9	18,2	2	3	8 009	11 078	10 795	14 931	8,1	11,2	12,3	17
Elbows A1,B,D,E (6" sch 160) (1 bis) forgé	131,9	18,2	"	"	"	"	"	"	"	"	"	"
Elbow A0 (6" sch 160) ②	131,9	25	"	"	"	"	"	"	11,1	15,4	16,9	23,3
Double elbow C (8" sch 160) ③	173,1	23	1,2	1,8	4 975	6 882	6 705	9 275	6,36	8,8	9,65	13,3
Sleeve (12" sch 160) ④	257,3	33,3	0,534	0,801	2 422	3 350	3 270	4 522	4,5	6,2	6,8	9,4
Sleeve (3" sch 160) ⑤	66,7	11,1	7,95	11,92	27 830	38 500	36 760	50 850	17,2	23,7	25,5	35,5

TABLE 2 – ALTERNATING STRESS FOR $\Delta T = 100^oC$

Reference number	Sp cold shock				Sp hot shock				Salt			
	$K_3 = 1$		$K_3 = 1,7$		1		1,7		1		1,7	
	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
1 et 1 bis	300	360	420	500	340	400	465	545	320	380	440	525
2	330	395	455	630	365	425	500	565	345	410	475	550
3	280	340	385	470	320	380	440	515	300	360	410	495
4	240	300	340	415	280	345	395	480	260	325	365	450
5	370	430	495	565	395	450	520	590	380	440	505	580

TABLE 3 – USAGE FACTORS FOR ① AND $K_e = 1$

	$K_3 = 1$						$K_3 = 1,7$					
	minimum			maximum			minimum			maximum		
	Salt	Na	usage factor	Salt	Na	usage factor	Salt	Na	usage factor	Salt	Na	usage factor
156,5 cycles à 220°C	700 →	1 120	0.140	836 →	660	0.237	968 →	480	0.326	1 155 →	270	0.580
1037 " 210°C	670 →	1 290	0.804	798 →	710	1.460	924 →	535	1.938	1 102 →	320	3.240
10 " 170°C	540 →	3 000	0.004	646 →	1 560	0.008	748 →	915	0.011	892 →	580	0.017
556 " 157°C	500 →	4 000	0.139	597 →	1 900	0.293	690 →	1 170	0.475	824 →	675	0.675
30 " 140°C	450 →	6 700	0.005	532 →	3 250	0.009	616 →	1 730	0.017	735 →	960	0.031
5 " 110°C	350 →	19 800	0.001	418 →	9 000	0.001	484 →	4 900	0.001	577 →	2 200	0.002
2028 " 100°C	$\boxed{320}$ →	31 800	0.064	$\boxed{380}$ →	14 000	0.145	$\boxed{440}$ →	7 000	0.290	$\boxed{525}$ →	3 500	0.580
250 " 70°C	220 →	285 000	0.001	266 →	80 000	0.003	308 →	45 000	0.006	367 →	16 000	0.016
250 " 60°C	190 →	700 000	0.001	228 →	250 000	0.001	264 →	10^5	0.003	315 →	32 000	0.008
250 " 50°C	160 →	∞	0	190 →	∞	0	220 →	3.10^5	0.001	262 →	10^5	0.003
240 " 40°C	130 →	∞	0	152 →	∞	0	176 →	∞	0	210 →	∞	0
Cumulative usage factor			1.160			2.155			3.062			5.152

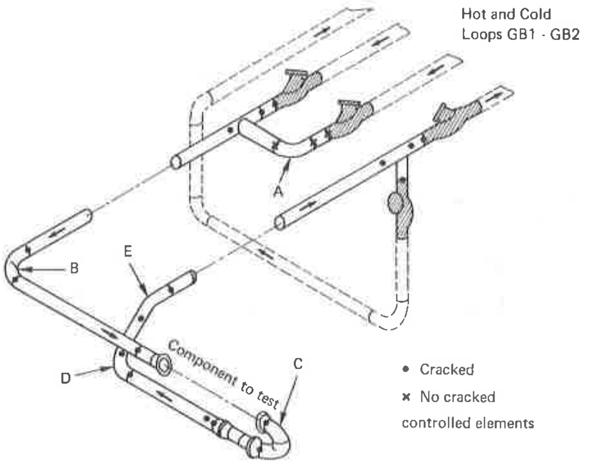

Figure 1 -- Thermal Shock Testing Section

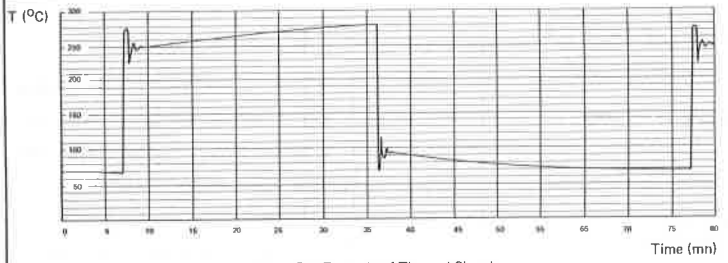

Figure 2 – Example of Thermal Sherck

$\alpha = K . V^{0,8}$

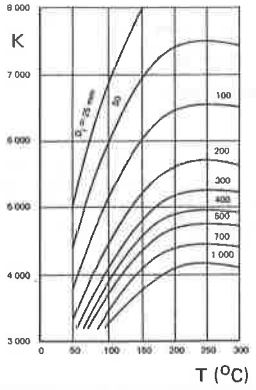

Figure 3 – Convection-factor

$\Delta T_1 = L_1 . \Delta T$ $\Delta T_2 = N_1 . \Delta T$

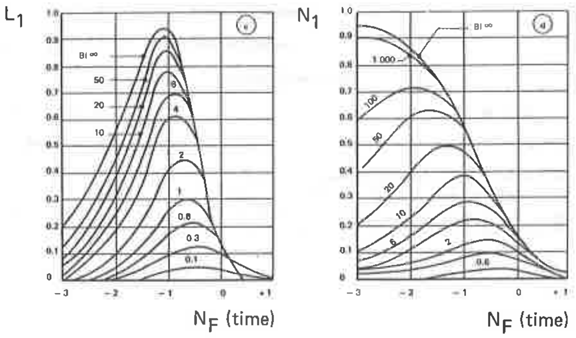

Figure 4 – Coefficients for Linear and Non-linear ΔT

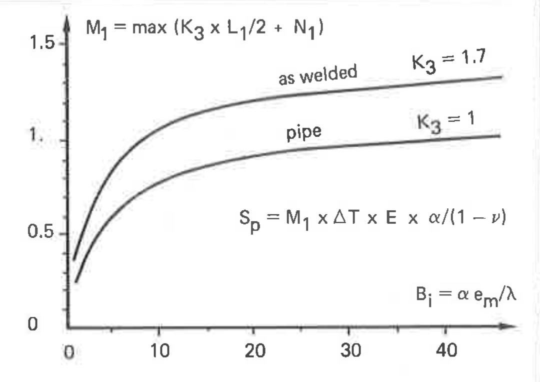

Figure 5 – Coefficient M_1 for S_p calculation

Legends for Fig. 6, 7, 8 :

⊢—⊣ straight pipe

▬ as-welded

☐ no cracked

☒ cracked

① reference number (tables 1, 2)

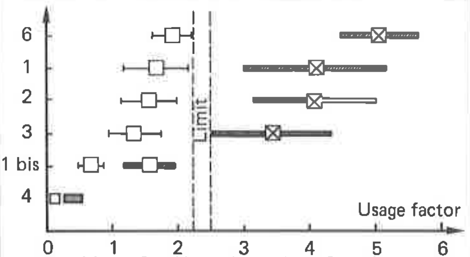

Figure 6 – Usage factor by ASME 80

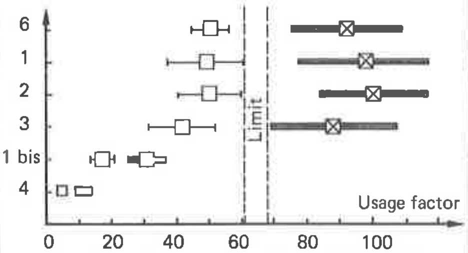

Figure 7 – Usage factor by RCCM (ASME 77)

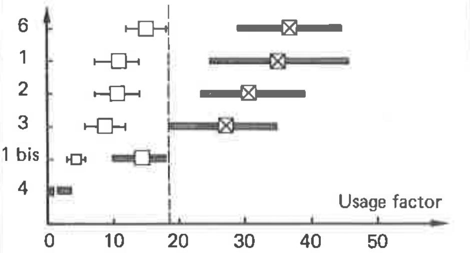

Figure 8 – Usage factor by RCCM-R