Fatigue Behavior of Welded Junctions Submitted to Thermal Shocks

J. C. Masson, D. Moinereau, M. Rioland
Electricité de France, Moret sur Loing, France

INTRODUCTION

Socket welded junctions (S.W.) are generally used in connecting small pipes, because they are easier to realize than butt welds (B.W.). They are located on PWR's auxiliary pipes and some of them are submitted to severe thermal shocks ; application of french design rules (RCCM ≈ ASME) gave excessive usage factors (20 to 30) and consequently the replacement of these S.W. junctions by B.W. in all french plants was about to be decided. To avoid this expensive and delicate operation, EDF led an experimental and numerical program on both types of welded junctions to prove that the behaviour of S.W. was satisfying and the replacement needless.

1 - EXPERIMENTATION ON MOCK-UPS

Five mock-ups (Fig. 1) including 30 S.W. and 32 B.W. have been placed on the thermal shocks facilities of EDF at "Les Renardières". In these loops (G.B. and CYTHERE), pressurized at 168 bar with water (the same as in P.W.R. plants), shocks are produced by diversion of hot (280°C) or cold (60°C) water flow (~ 9 kg/s) through the testing section.

The duration of a cycle is approximately 1 h 30 min and two campaigns of 1000 and 907 cycles (220°C range) were carried out. Two mock-ups (1 B.W. and 1 S.W.) were taken off after the first campaign, and the rest after the second (1907 cycles) for destructive examinations.

Different kinds of socket welds were manufactured :
- standard with a normal, a convex or a concave weld,
- with a shorter end or with a nil gap,
- with extra thickness to simulate a valve connection (slope 1/4 and 2/3).

For butt welds, differences related to geometrical shapes (standard as welded, with an excess of penetration, with a chamfer and two of them with extra thicknesses simulating a valve connection) ; they related also to different post-treatments (mechanical such as grinding and shot peening or thermal, such as supertempering or IHSI). In order to have a comprehensive view and to evaluate the effect of residual stresses, a weld bead was simulated by machining.

2 - RESULTS OF DESTRUCTIVE EXAMINATIONS

The destructive examinations revealed fatigue cracks on both types of junctions. Only the two B.W. improved by internal grinding were exempt of cracks (even after 1907 cycles) ; shot peening was effective on crack initiation only (no crack after 1000 cycles) and the simulated weld bead presented cracks as in standard welds.

The decrease of residual stresses by post welding heat treatments was indecisive, as man could think, considering the large fatigue cycle imposed by thermal shocks. The geometrical effect is the principal parameter in the present case, and also in other structures, as it has been observed [1, 2].

The cracks were not very deep (0,8 mm maximum after 1000 cycles and 1,4 mm after 1907), and the discrepancy according to azimuth location was more important than according to welds' differences. Extra thicknesses and excess of penetration gave the worst results.

In S.W. 2" junctions, cracks were slightly shorter than in the 3" B.W. ones ; they were located in the weld (singular zone with a notch effet) but also in the fillet of the socket, where they were deeper, especially in valves' end simulation (Fig. 1) ; this fact is directly related to the thickness (0.5 mm depth instead of 0.3 after 1000 cycles). A great discrepancy of the results was observed, due perhaps to different shapes of the "nozzle" (see gaps figure 9). Nevertheless, one can conclude that the sensitivity of S.W. to thermal shocks is very low and not higher (in fact lower) than in B.W. case.

3 - TEMPERATURE MEASUREMENTS

In order to perform finite elements computations and to validate a thermal model, temperatures were measured inside the metal of the socket (Fig. 2). The first results were not easy to understand, and then, a second socket was added on the last S.W. mock-up ; this socket (standard shape) was instrumented with 16 thermocouples (Fig. 2a) and put into operation during the second campaign.

Temperatures measured on this mock-up during a hot shock are shown on figure 3 ; they are distributed in a very good order referring to the deepness of thermocouples and it can be concluded in favour of a model with conductive pieces. On the contrary, during a cold shock, temperatures located in the space between pipe and socket (TC14, TC15) decrease quicker than TC2 and TC13 ; moreover temperatures behind the space (TC3 to TC10) are less regularly distributed. It was thus proved that the anomalies observed during cold shocks were due to an unexpected cooling in the space between pipe and socket : probably a cold water flow when thermal expansion opens this space.

It was then necessary to take account of this phenomenon in thermomechanical computation, in order to estimate its consequences on initiation and growth of a crack.

4 - SIMPLIFIED CALCULATIONS

Nuclear primary pipes are dimensionned by RCC-M French Code (similar to ASME) chapter B3600. For welds, different coefficients are used to take account of type and shape. In our case, temperature only is cycled ; pressure and moments are constant or very low.

Temperature distribution is computed in the two extremities by F.E.M. ; then equations 10 and 11 of the code give Sn and Sp. In the table 1 results are given for different types of welds for 2 thermal exchange coefficients (10 000 and 20 000 $W/m^2.°C$).

TABLE 1 – RESULTS FROM SIMPLIFIED METHODS

Type of weld		Δ Sn (MPa)	Δ Sp (MPa)	S' alt (MPa)	Admissible number of cycles Nadm
B.W. constant thickness	Flushed	650-690	1190-1290	1800-1950	71 to 82
	As welded	650-690	1580-1700	2400-2580	32 to 36
B.W. «valve end»	Flushed	1450-1520	2070-2200	3140-3330	18 to 20
	As welded	1450-1520	2940-3110	4450-4700	9 to 10
S.W.	Standard	1560	5020	7600	3,5 (47 if Ke = 1 as in ASME)
S.W.	«Valve end»	1960-2060	6380-6720	9670-10180	2.5 to 3 for various thermal conditions

It appears that the code is extremely severe, especially RCC-M with Ke = f (Sn) for thermal loads [see ref. 3]. It is more severe for S.W. and this seems not to be justified reffering to experimental results (in fact the code is not applicable for so high loads, but nevertheless, it is interesting to compare different types of welds between them and to experimentation).

5 - REFINED CALCULATIONS OF SOCKET WELDS

To have a better estimation of initiation and growth of the cracks, FEM computations were performed and interpreted by the mean of the opening stress $\sigma_{\theta\theta}$ method (RCC-M annexe ZD) [4, 5]. It was also interesting to verify if the methodology used for thermal sleeves [6] was valid in this other application and if the analysis performed by the manufacturer were safe.

A part of the mesh used in FEM computation is shown on figure 4 with a very refined radial mesh round the "notch" end. Thermal calculations were performed with different hypothesis, in particular with an internal cooling (see fig. 5). On figure 6 we can see that it is thus possible to approach thermal evolution in the socket.

Then thermoelastic computations give the stress field and notably the maximal values of the "opening stress" $\sigma_{\theta\theta}$ at a distance d = 0.059 mm from the notch end (fig. 7). To estimate the number of cycles for "initiation" (crack of 2 mm depth) it is necessary to combine hot and cold shocks results as it is shown on figure 8. The case of internal cooling gives the worst number of cycles and the effect of a contact between socket and pipe's end is favourable. Principal results are presented in table 2 (stresses and admissible numbers).

TABLE 2 – RESULTS FROM OPENING STRESS RANGE METHOD

Type of socket	Type of calculation	$\sigma_{\theta\theta}$ (hot) MPa	$\sigma_{\theta\theta}$ (cold) MPa	$\Delta\sigma_{\theta\theta}$ MPa	Number of cycles to «2 mm»	
					$R \geqslant 0$	$R \geqslant -4$
Standard socket	Water conduction	–262	630	892	9 700	20 600
	Internal cooling	–280	810	1 090	4 300	8 200
	Internal cooling + contact	–103	766	869	10 700	13 900
Valve simulation	Water conduction	–426	763	1 189	3 000	8 200
	Internal cooling	–429	884	1 313	2 000	4 900

The correction of R factor = $\sigma_{min}/\sigma_{max}$ (if $R < 0$) takes account of the closure of the crack, and increases the admissible number of cycles. These results are in a reasonable agreement with extrapolations from experimental results ; however it is very "audacious" to extrapolate the results and it would have been preferable to perform experiments up to 5000 cycles.

6 - CONCLUSION

This confrontation between experimental works and design rules based on numerical analysis is of great interest. It was proved that codes give very conservative prediction of fatigue cracks when simplified methods are used ; in the other case results are reasonable but it is necessary to make a refined analysis of physical phenomenons wich are not always simple. In all cases it appears that socket welds are very resistant to thermal shocks, as well as butt welds. So, the expensive replacement of all S.W. in french power plants was avoided.

REFERENCES

[1] J.C. MASSON and al., Transactions of 9th SMIRT (Vol. D, p. 367) 1987.

[2] D. MOINEREAU, International Conf. on valves for power plant, SOUTHAMPTON 1989. Effect of fillet design on the thermal fatigue behaviour of check valves.

[3] J.C MASSON, Transactions of 8th SMIRT (DFG 1.5) 1985.

[4] J.C. DEVAUX and al., Transactions of 4th SMIRT (G8) 1979.

[5] J.C. MASSON, Nuclear Engineering and Design 105 (1987) p. 139-145. Use of local approach for predicting fatigue cracks in sleeves.

[6] J.C. MASSON and al., Transactions of 8th SMIRT (DFG 1.6) 1985.

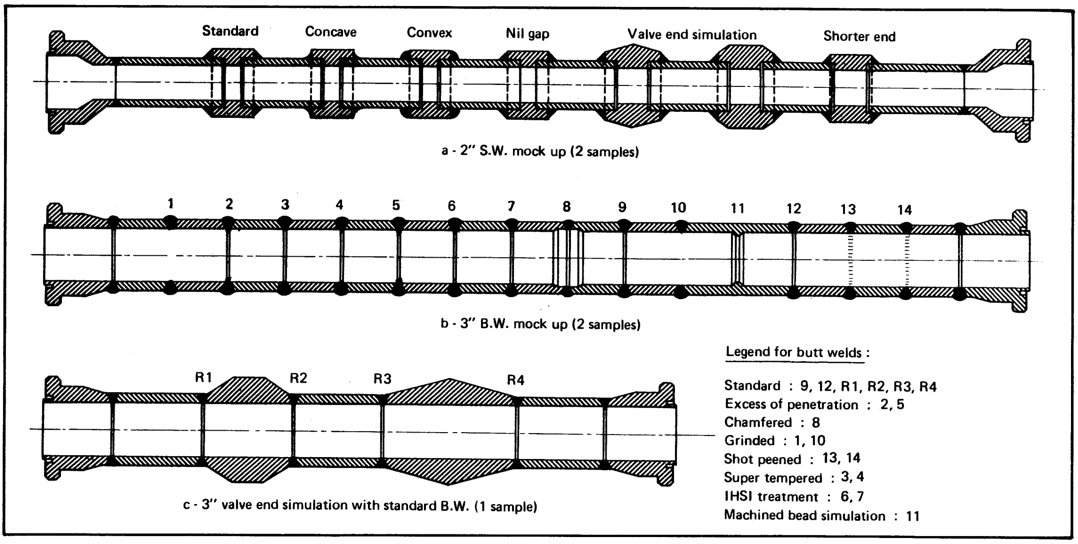

Figure 1 – The 3 types of mock-ups (socket and butt welds).

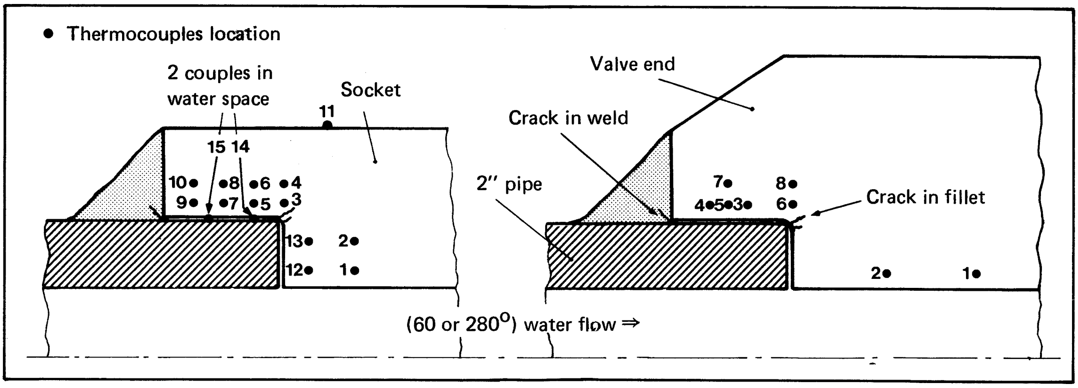

Figure 2 – S.W. connections (standard - valve simulation).

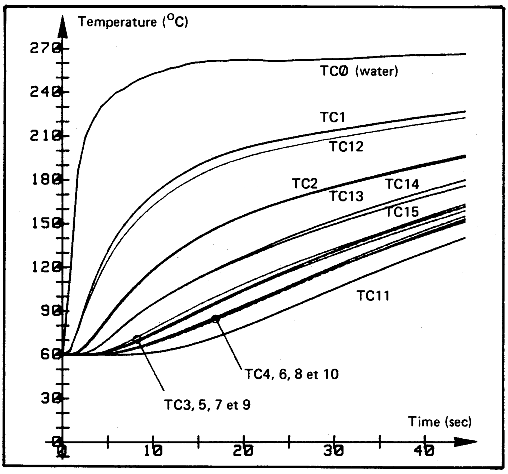

Figure 3 – Temperature evolution in the standard S.W. during a hot shock.

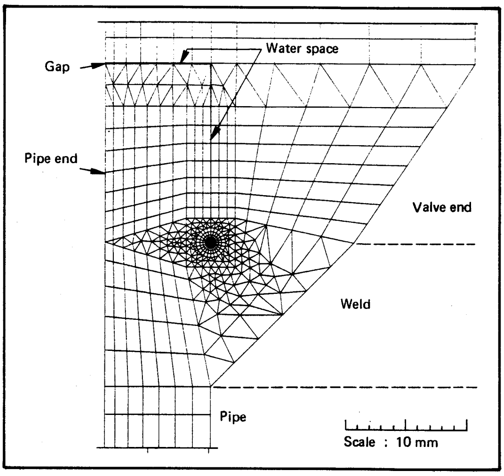

Figure 4 – Detail of the mesh for valve S.W.

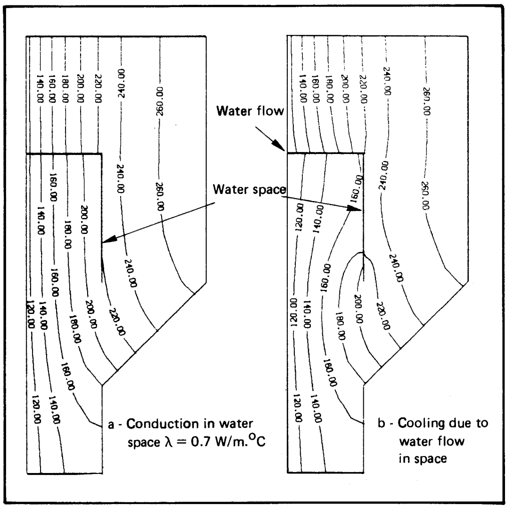

Figure 5 — Thermal field during cold shock.

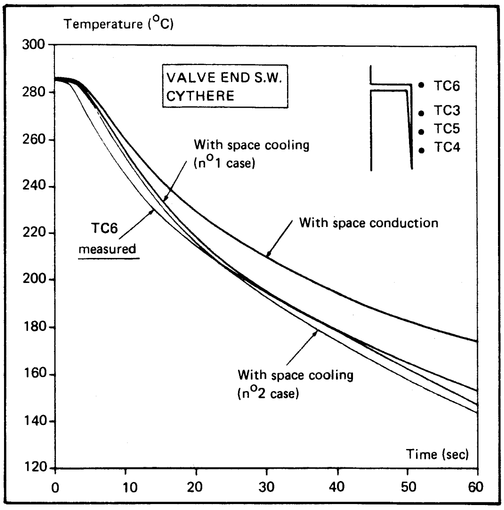

Figure 6 — Adjustement of calculation by introducing a cooling hypothesis.

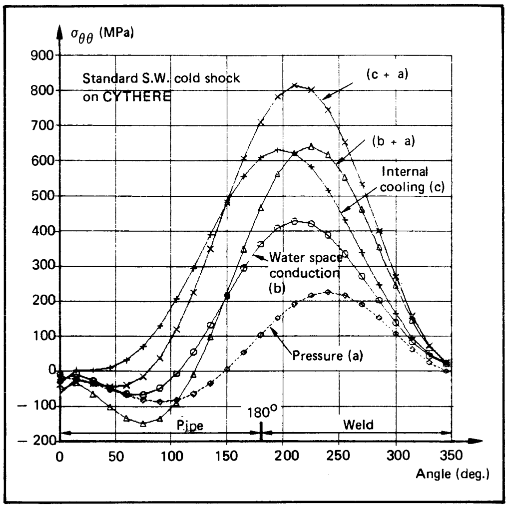

Figure 7 — Opening stress versus θ angle for 2 hypothesis for cold shock.

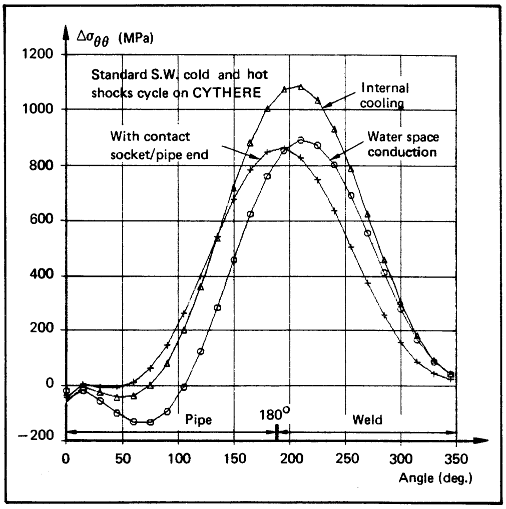

Figure 8 — Opening stress range versus angle.

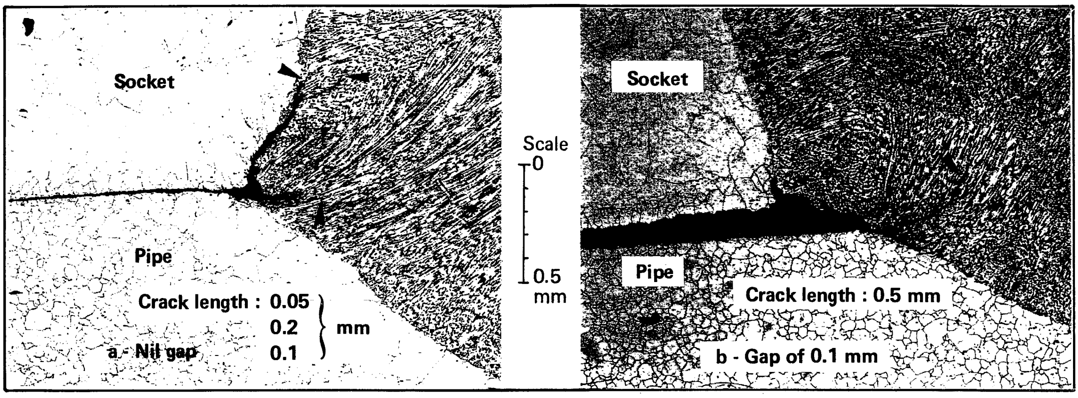

Figure 9 — Two examples of cracks observed in the socket weld.