

Comparison of the CEA and JNC approaches for creep-fatigue evaluation of weldment (2) : benchmark analysis of bending plates

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ABSTRACT

In the framework of collaboration between Europe and Japan about Fast Breeder Reactor development, a benchmark exercise was conducted in order to apply different methods (RCC-MR for CEA and ETSDDG for JNC) to predict creep fatigue life. An application was made on 316 L steel plates (25 mm thick) subjected at 550°C to cyclic bending tests during the SOUFFLE campaign. 4 fatigue tests and 5 creep fatigue tests are presented and evaluated. The material characteristics used for the evaluation were determined from specimens of actual welded plates.

The difference between both methods are illustrated in the applications performed. The behaviors (cyclic hardening, fatigue, rupture stress) are not taken into account in the same manner for base metal and parent metal. The weld reduction factors for creep and fatigue rupture are loading independent.

The time and number of cycles to rupture calculated by both methods, with best fit data, compare well with experimental ones. However, the lower the loading, the lower the margin given by the prediction. The more conservative results are given by the RCC-MR rule.

BACKGROUND

In the framework of collaborative program between Europe and Japan on structural integrity of welded components, JNC and CEA decided to carry out benchmark calculations [1] in order to compare the French and Japanese rules on welded joints.

A benchmark on thermal creep fatigue of weldments was submitted by N. KASAHARA from JNC [2]. Another benchmark on the same technical topic was proposed by L. LE BER from CEA. The overall objective of these benchmark activities is to compare the methods and rules developed in each country and company.

INTRODUCTION

Many high temperature structures contain welds, which are generally considered to be the life limiting feature, due to their observed inferior performances under fatigue loading. Historically, fatigue and creep fatigue life assessments of welded joints have been based on those of the surrounding parent material, factored by a suitable margin to take account of their inferior properties.

Basically, RCC-MR [3] French codified rules for fatigue and creep fatigue of welded joints are still following these historical way whereas the JNC method is mainly based on the cyclic elastic follow-up aspects between the weld metal and the base metal.

The main purpose of this document is to present the application of the CEA and JNC rules on a simple and analytic experiment : the fatigue and creep fatigue behaviour of high temperature welded 316L(N) plates submitted to reverse bending. The plates are 25 mm thick with a central transverse butt weld. This benchmark has been carried out by both CEA and JNC companies in the framework of a collaborative program between Europe and Japan on structural integrity.

In this paper, the plates tests and the companion characterisation program are presented, then an application and a description of the rules are proposed.

EXPERIMENTAL RESULTS

Bending tests description

Bending tests have been performed in AEA/Risley under a CEA contract on butt 316L(N) austenitic steel welded plates (Figure 1), with varying applied displacements ($\Delta\epsilon$: from 0.3 to 1%), holding time (0, 1 and 5 hours), weld geometry (simple V or double V), plate's thickness (10 mm - 25 mm), and weld direction (longitudinal or transverse). Tests temperature was 550°C [4].

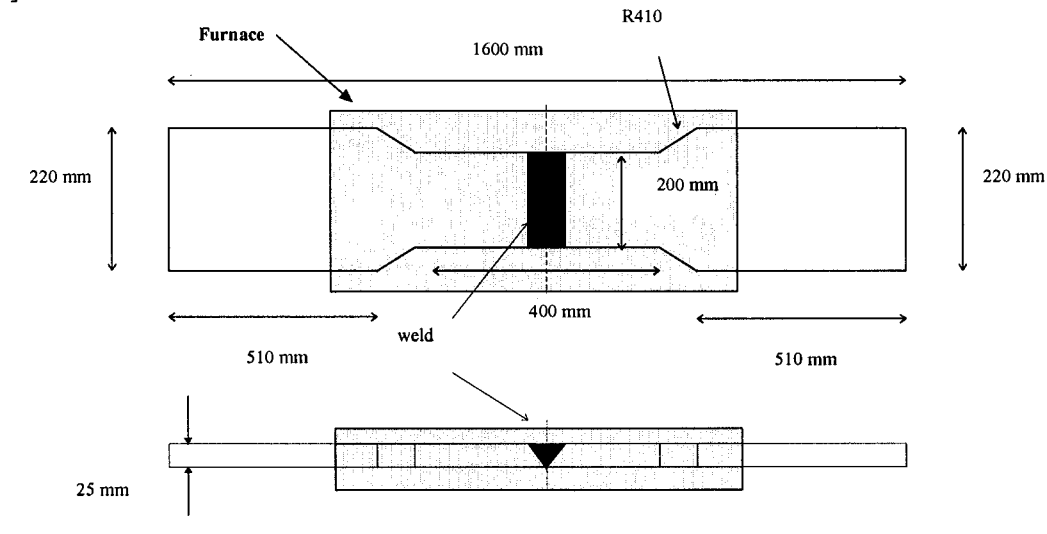


Figure 1 : Schematic of a 25 mm thick plate with transverse butt weld

The experimental device imposes a constant displacement variation (Δd). The strain variation $\Delta\epsilon$, given as the loading of each test, was derived from strain gages measurements at 20°C assuming the hypotheses of pure circular bending. The number of cycles to rupture (plate separation into 2 parts) is given as a result of the test. Concerning the creep fatigue tests, the imposed displacement variation is similar to the fatigue tests but an hold time of 1 or 5 hours is added. Fatigue and creep fatigue tests results are given in the following tables :

Table 1 : Fatigue tests results

Plate (mm)	Weld orientation ⁽¹⁾	strain variation (%)	Rupture	
			N (cycles)	Location
590x125x10	T	0.983	1295	Weld toe
590x125x10	T	0.6	3932	Weld toe
1600x220x25	T	0.3	114670	N/A ⁽²⁾
1600x220x25	L	0.6	8480	Plate & Weld

Table 2 : Creep fatigue tests

Plate (mm)	Weld Orientation ⁽¹⁾	strain variation (%)	hold time (hours)	Rupture	
				N (cycles)	Location
590x125x10	T	0.98	1	723	Weld toe
590x125x10	T	0.6	1	3593	Weld toe
1600x220x25	T	0.595	5	1739	Weld
1600x220x25	T	0.396	1	8833	Weld
1600x220x25	L	0.596	1	6833	N/A ⁽²⁾

(1) T : Transverse weld - L : Longitudinal weld

(2) N/A : Not Applicable i.e. between the weld and the base metal

Characterisation program

A companion characterisation program has been performed by CEA in order to evaluate the cyclic and fatigue behaviour of both base metal and MMA weld. It has been found that MMA metal shows a very slight cyclic hardening as the base metal exhibit a strong cyclic hardening (Figure 2). As a consequence, the over-matching between weld and base metal on the first cycle turns to an under-matching after some cycling, especially for high strain levels. Fatigue tests have shown that base metal 316L(N) fatigue strength is very similar to 316L(N) MMA weld one and relevant to the codified best-fit fatigue curve of the RCC-MR (Figure 3).

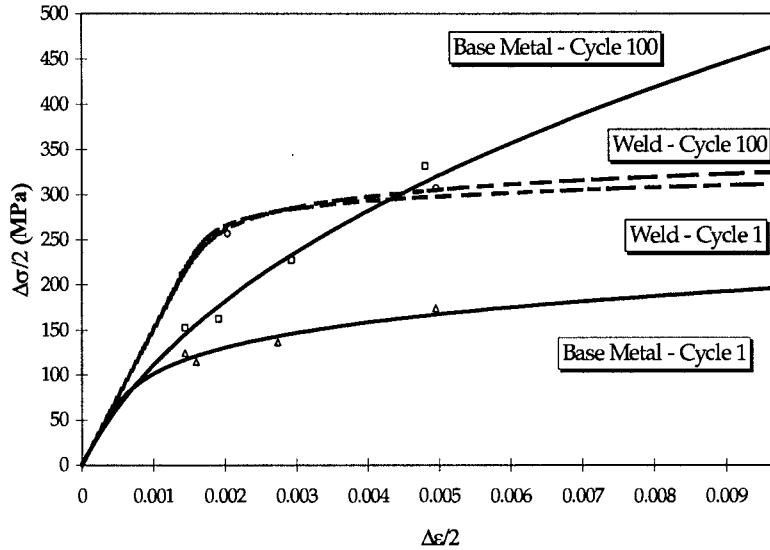


Figure 2 : Cyclic behaviour of both Base Metal and MMA weld

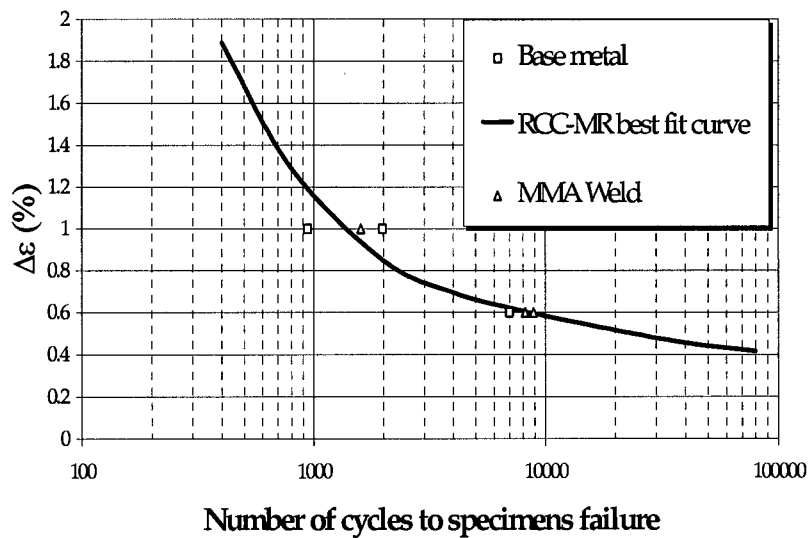


Figure 3 : Fatigue curve of both Base metal and MMA weld

BENCHMARK

The benchmark consisted in the evaluation of the fatigue and creep-fatigue life evaluation according to the CEA and the JNC codified rules. A rapid overview of the fatigue and creep fatigue rules of both countries is first proposed. The purpose of these paragraphs are not to deal with the creep fatigue damage procedure of the codes but to focus on the aspects related to weldments.

Overview of the RCC-MR fatigue and creep fatigue strength evaluation

For fatigue analysis, the RCC-MR French design code [3] provides a method based on the NEUBER rule applied to the elastic stresses calculated on a pure base metal structure. This elastic stress can be enhanced using a n and a f factor to take account of the joint geometry effects, the difficulty in the control phase of the after welding process and other technologic aspect. In the specific case of the SOUFFLE experiment (butt and dressed welded plates, radiographic control examination...) n and f factors had to be taken equal to 1.

The elastic stress and strain ranges $\overline{\Delta\sigma_{el}}$ and $\overline{\Delta\epsilon_1}$, obtained from an elastic analysis, do not take into account the plasticity that would be produced if the real behaviour of the material was modeled. The method proposed in the following provides an estimation of the "real" strain range $\overline{\Delta\epsilon}$ from the results of an elastic analysis for cases where creep is negligible, evaluating the amplification of the strain due to plasticity.

For each cycle, the value of the "real" strain range $\overline{\Delta\epsilon}^*$ is the sum of four terms noted $\overline{\Delta\epsilon_1}$, $\overline{\Delta\epsilon_2}$, $\overline{\Delta\epsilon_3}$, $\overline{\Delta\epsilon_4}$. $\overline{\Delta\epsilon_1}$ represents the strain range determined from an elastic analysis. $\overline{\Delta\epsilon_2}$ represents the plastic gain due to the variation of the primary stresses at the point under investigation. $\overline{\Delta\epsilon_3}$ represents the plastic gain in the strains using the NEUBER Hyperbola approach $\left(\overline{\Delta\epsilon_1 + \Delta\epsilon_2 + \Delta\epsilon_3}\right) \overline{\Delta\sigma} = (\overline{\Delta\epsilon_1 + \Delta\epsilon_2}) \overline{\Delta\sigma_{el}}$. $\overline{\Delta\epsilon_4}$ represents the plastic gain in the strains due to triaxiality.

The total strain range $\overline{\Delta\epsilon}^*$ calculated in each point of the structure is associated to a number of cycles to initiation $N_A(\overline{\Delta\epsilon}^*)$ by using the fatigue curve of each material. A life fraction per cycle can then be defined $V_A(\overline{\Delta\epsilon}^*) = 1/N_A(\overline{\Delta\epsilon}^*)$.

In order to take into account of the welded joints, the RCC-MR proposes to apply a reduction factor $J_r = 1.25$ on the strain variation of the associated base metal fatigue curve. To summarise, the RCC-MR does not consider any weld fatigue reduction due to dissimilar cyclic behaviour but an inferior fatigue curve of the weld metal.

According to the RCC-MR code, creep damage during hold time (i.e. relaxation) is evaluated from initial stresses evaluated from elasto-plastic strain range.

At the beginning of each hold time, the stress σ_k is given by the following formula :

$$\sigma_k = K_S \cdot \Delta\sigma^* \quad (1)$$

where K_S is the symmetrisation coefficient

$\Delta\sigma^*$ is determined from the « real » strain range $\Delta\epsilon_{el+pl}$ calculated for the fatigue transients

During the hold time, it is generally admitted that the stress remains constant. A less pessimistic value of σ_k can be obtained if stress relaxation is accounted for during the hold time. This last method is the one chosen for the benchmarks.

For each cycle k considered, the creep rupture usage fraction for time interval k is equal to the ratio of application time t_k to the maximum allowable time T_k . T_k is determined on the basis of the characteristic stress rupture curves S_r given in Appendix A3 (with $S_r = \sigma_k / 0.9$).

For weldments, S_r curves are multiplied by a J_r coefficient to account for the inferior weldments properties under creep loading. For 316L(N) autenitic steel, J_r is temperature and time dependant.

The cumulated creep rupture usage fraction W is the sum over the N intervals of the usage fractions calculated for each interval. W is expressed in the following way : $W_A = \sum \left(\frac{t_k}{T_k} \right)$.

The check on the resistance to the damage resulting from accumulation of the effects of creep and fatigue consists in demonstrating that all points of the structures and for all cycles, the representative points $[V_A(\overline{\Delta\epsilon}), W_A(\sigma^*)]$ are located within an allowable area defined on the creep-fatigue interaction diagrams.

Overview of the JNC fatigue and creep fatigue strength evaluation

The elevated Temperature Structural Design Guide (ETSTG) for the Japanese prototype FBR Monju applied an elastic follow-up concept to estimate both plastic and creep behaviours by introducing the elastic follow up parameter q . The total strain range ε_t is calculated using the elastic stress variation $\Delta\sigma_e$, the elastic strain variation ε_e and the yield stress σ_y :

$$\varepsilon_t = \left\{ 1 + (q-1) \left(1 - \frac{2\sigma_y}{\Delta\sigma_e} \right) \right\} \varepsilon_e \quad (2)$$

For materials that cyclically harden or soften, a « yield stress reduction factor » γ_y correction is also added. Concerning welded joints, this concept is extended [5] by the addition of a q_w factor that accounts for the elastic follow-up due to the presence of a welded joint :

$$\varepsilon_t = \left\{ 1 + (q \cdot q_w - 1) \left(1 - \gamma_y \frac{2\sigma_y}{\Delta\sigma_e} \right) \right\} \varepsilon_e \quad (3)$$

As the last equation accounts strain concentration in inelastic region only, an additional factor K_{ε_0} is introduced in order to take into account the weld inferior fatigue performance at low strain variation due to degradation, ageing, environmental effects, residual stresses :

$$\varepsilon_t = \text{Max} \left[\left\{ 1 + (q \cdot q_w - 1) \left(1 - \gamma_y \frac{2\sigma_y}{\Delta\sigma_e} \right) \right\} \varepsilon_e, K_{\varepsilon_0} \cdot \varepsilon_0 \right] \quad (4)$$

The fatigue damage evaluation is very similar to the RCC-MR one presented. Concerning the material fatigue curve, it is supposed to be the same as the base metal fatigue one. To summarise, in exception to low strain variation, the JNC procedure assumes that the observed inferior fatigue properties of welded joints are not linked to an inferior fatigue weld performance but to a strain enhancement due to dissimilar cyclic behaviour.

The initial relaxation stress σ_i is calculated by the JNC procedure considering, for mechanical loading :

$\sigma_i = \frac{1}{2} \Delta\sigma (\Delta\varepsilon_{el+pl})$ where $\Delta\varepsilon_{el+pl}$ is the total elastic plastic strain range and $\Delta\sigma$ the associate cyclic stress variation.

Concerning the creep material data, in order to take into account the observed inferior creep fatigue properties of the welded joint, an α_R coefficient is added to the base metal creep rupture time curve and an α_C coefficient is added to modify the creep curve. For the 316L(N) French steel which is close to the 316FR Japanese steel, the α_R is assumed constant and equal to 10. The α_C coefficient is taken to 1, that is the weld metal creep curve is the same as the base metal one.

Benchmark Results : Fatigue

The results of rules application for both CEA and JNC are presented in the next tables and compared to the experimental results :

Table 3 : JNC evaluation of fatigue tests

$\Delta\varepsilon$ (%)	K_ε	ε_t (%)	calculated number of cycles to plate initiation	experimental number of cycles to plate rupture
1.	1.4	1.396	692	1295
0.6	1.33	0.796	2502	3932
0.3	1.2	0.36	236461	114670
0.60	1.33	0.796	2502	8480

Table 4 : CEA evaluation of fatigue tests

$\Delta\varepsilon$ (%)	J_f	calculated number of cycles to plate initiation	experimental number of cycles to plate rupture
1.	1.25	889	1295
0.6	1.25	3079	3932
0.3	1.25	173700	114670
0.6	1.25	3079	8480

The next figure presents a Manson Coffin fatigue curve of the base metal and the dots represents the experimental and calculated data :

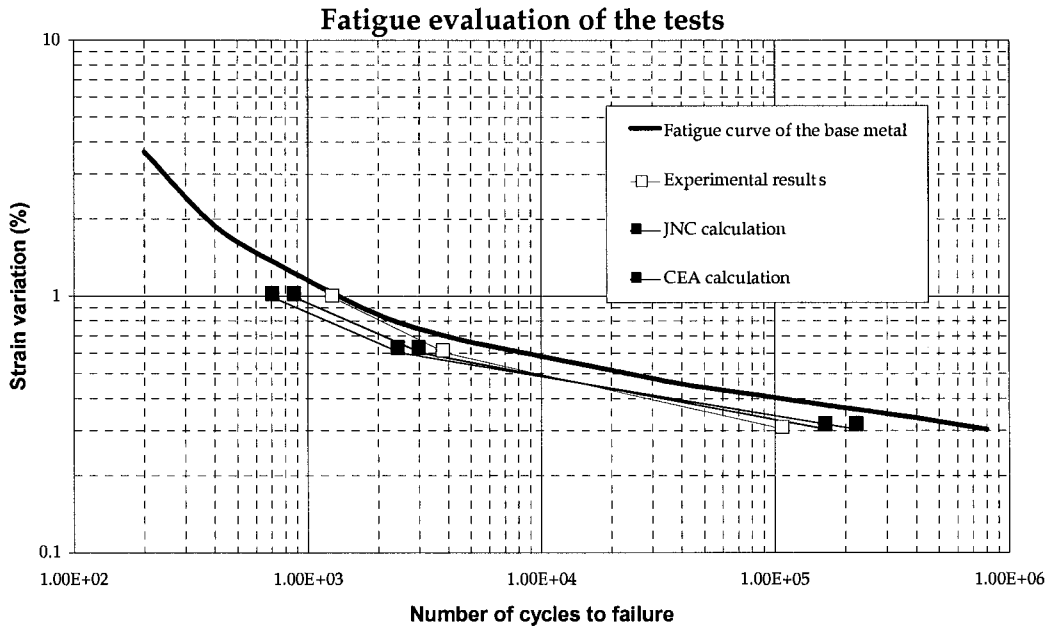


Figure 4 : JNC and CEA fatigue calculation compared to the experimental datas

Benchmark Results : creep fatigue

The results of rules application for both CEA and JNC are presented in the next tables and compared to the experimental results :

Table 5 : JNC and CEA evaluation of creep fatigue tests

$\Delta\varepsilon$ (%)	Hold time	JNC results $\alpha_R=10$ (cycles)	JNC results $\alpha_R=20$ (cycles)	CEA results (cycles)	Experimental results (cycles)
0.98	1	390	269	191	723
0.6	1	1923	1620	1114	3593
0.595	5	1420	896	621	1739
0.396	1	16753	13108	7215	8833
0.596	1	1988	1676	1146	6833

The next figure presents a Manson Coffin fatigue curve of the base metal and the dots represents the experimental and calculated creep fatigue data :

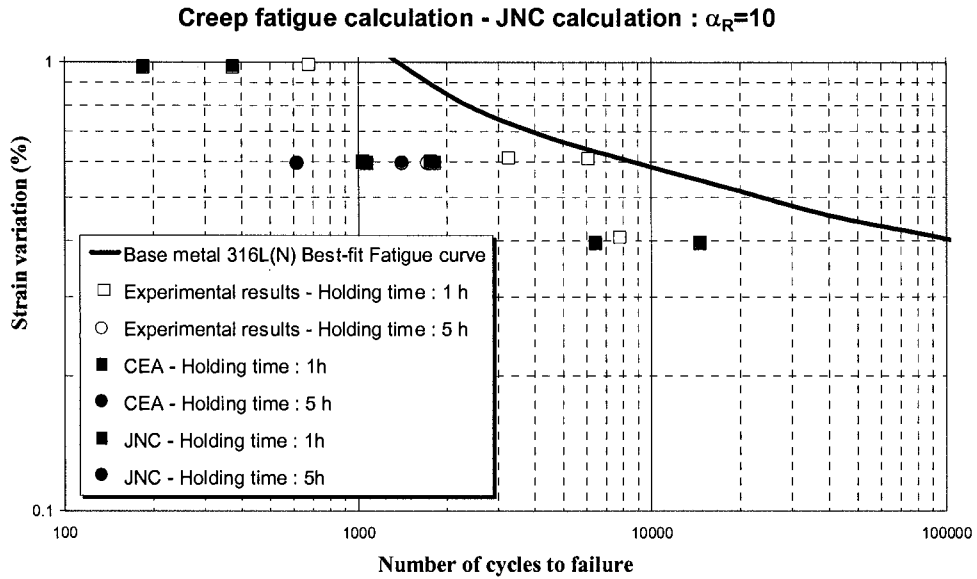


Figure 5 : Creep fatigue calculation - JNC α_R coefficient is equal to 10

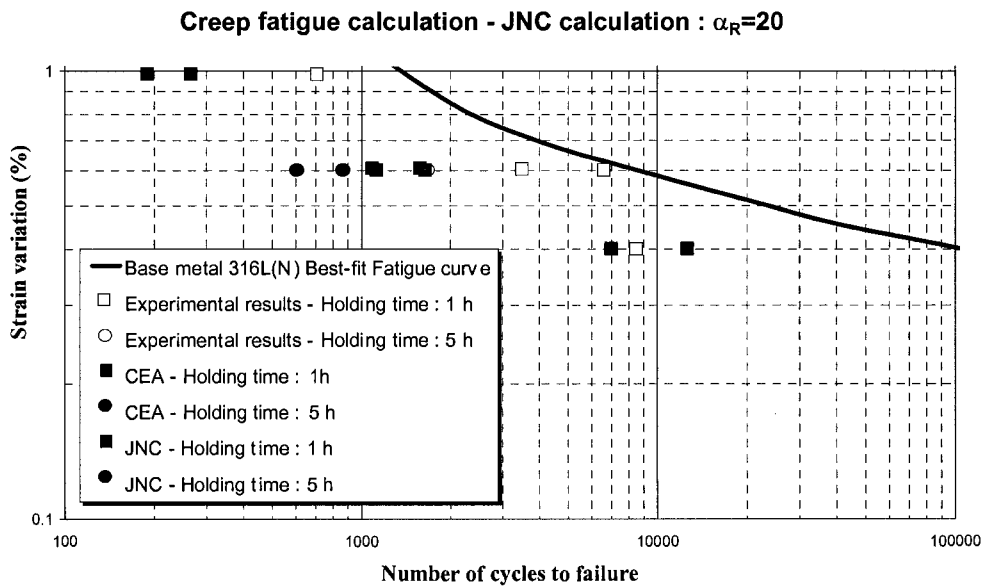


Figure 6 : Creep fatigue calculation - JNC α_R coefficient is equal to 20

CONCLUSIONS

Both JNC and CEA calculations give good results in term of number of cycles to failure either for fatigue calculations or creep-fatigue calculations. Nevertheless, at low strain ranges, some calculations happen to be non-conservative in respect to the experimental results. One should remember that the proposed material data do not take into account the safety margins usually added in a design code analysis.

Concerning the material data, both 316L(N) French and 316FR Japanese base metal exhibit a rather huge cyclic hardening as the associated weld material does not cyclically harden. Moreover, the fatigue curve of both 316FR base material and weld material are very similar. Concerning fatigue codification, the major differences between the JNC and CEA rules is that the RCC-MR does not consider any weld fatigue reduction due to dissimilar cyclic behaviour but to an inferior fatigue performance of the weld metal using a lower fatigue curve. The JNC method takes into account the dissimilar cyclic behaviour but the fatigue curve of the base metal is similar to the weld metal one.

Concerning creep analysis, the difference between the JNC and the CEA rules is more related to the material data reduction factors than to the codification. In fact, both codes makes use of reduction factors related to the inferior weld creep properties. Concerning creep rupture strength of welded joint in the RCC-MR, a set of coefficients values J_r (depending on time and temperature) is available to determine the creep rupture strength by multiplying the creep rupture strength of parent material by the J_r value. The Japanese rules makes use of a α_R reduction factor, temperature and stress level independent.

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