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Interpretation of SOUFFLE experiment : Comparison of the JNC and CEA approaches

(Research Report)

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Interpretation of SOUFFLE experiment : Comparison of the JNC and CEA approaches

(Research Report)

Laurent LE BER * and Naoto Kasahara **)

Abstract

For considering strength reduction of weldments in elevated temperature components, CEA and JNC have developed design evaluation procedures. Both procedures were applied to the same benchmark problems and their results were compared under EJCC contract. One of benchmarks that provided by CEA is creep-fatigue evaluation of plates subjected to cyclic bending. The objective of this problem is comparison of both material data and strength reduction evaluation of welded joints.

When applied to SOUFFLE experiments, JNC and CEA evaluation procedures were clarified to give adequate predictions. Comparison of material data between Japanese 316FR and French 316L(N) showed such similar characteristics as strain hardening of base metal, non-strain hardening of weld metal and approximately the same fatigue strength of weld metal with its base metal. Both fatigue strength approaches were different, since JNC considers material difference between base and weld metal for strength reduction of welded joints and CEA evaluates fatigue strength reduction of weld metal. Concerning creep strength, both of JNC and JEA take strength reduction of weld metal into account.

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SOUFFLEクリープ疲労強度試験解析：JNCとCEAの評価法の比較

（研究報告書）

Laurent LE BER [*)], 笠原 直人[**)]

要 旨

高温構造設計ではクリープ疲労損傷が主要破損モードとして想定される。特に溶接部は繰り返し熱過渡荷重が加わる実機条件下において母材より強度が低下するため留意が必要である。このため、CEAとJNCは高温機器における溶接部の強度低減を考慮するため設計評価法を整備してきている。本研究では両者の評価法をSOUFFLE平板曲げクリープ疲労強度試験解析に適用し、材料データと母材に対する溶接部の強度低減の観点から、評価手法と結果の相互比較を行った。CEAとJNCの最終評価結果は試験結果を精度良く予測出来ることが分かった。材料データに関してはJNCの316FR鋼とCEAの316L(N)鋼を比較したところ、両者とも母材が顕著な繰り返し硬化を示すのに対し溶接金属は硬化を示さず、また母材と溶接金属の疲労強度に大きな差がないことから、類似していた。評価法のアプローチに関しては疲労に関して両者に差が見られた。すなわちJNCは母材と溶接金属の材料特性の差による溶接継手の疲労強度低減を考慮するのに対し、CEAは溶接金属の強度低下を評価する。クリープ強度に関しては、両者とも母材に対する溶接金属の強度低下割合を係数で評価する。

尚、本内容は1999年9月から2000年8月までの期間にCEAカダラッシュ研究所およびサクレー研究所にて実施した業務の一部である。

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Sommaire :

Liste des figures :

Liste des tables :

1. 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 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 [1]. 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.

2. 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 [2] French codified rules for fatigue and creep fatigue of welded joints are still following these historical ways 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.

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

3. Experimental results

3.1 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 ($\Delta\varepsilon$: 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 [3].

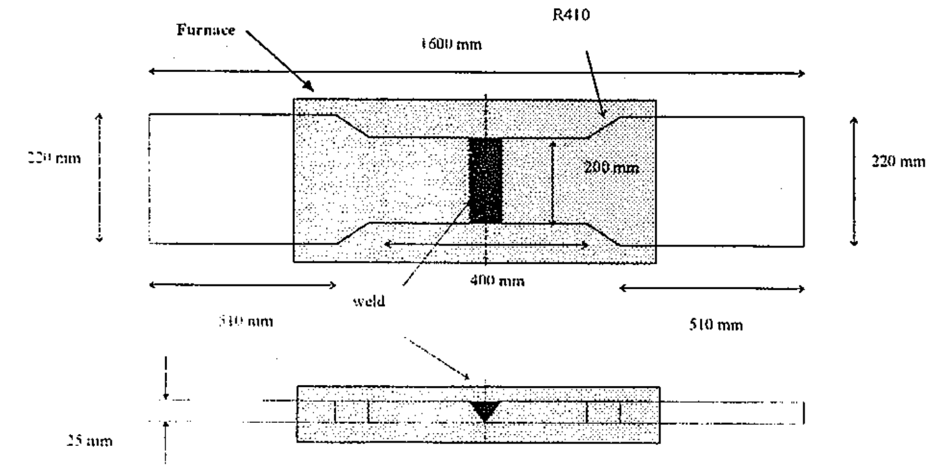

Figure 1 : Schematic of a 25 mm thick plate with transverse butt weld

The experimental device imposes a constant displacement variation (Δd). The strain variation Δε, 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 :

Plate (mm)	Weld orientation(1)	strain variation (%)	Rupture N (cycles)	Rupture 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 1 : Fatigue tests results

Plate (mm)	Weld Orientation(1)	strain variation (%)	hold time (hours)	Rupture N (cycles)	Rupture 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)

Table 2 : Creep fatigue tests

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

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

3.2 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 exhibits 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).

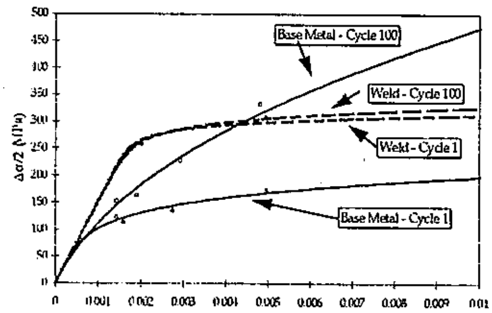

Figure 2 : Cyclic behaviour of both Base Metal and MMA weld

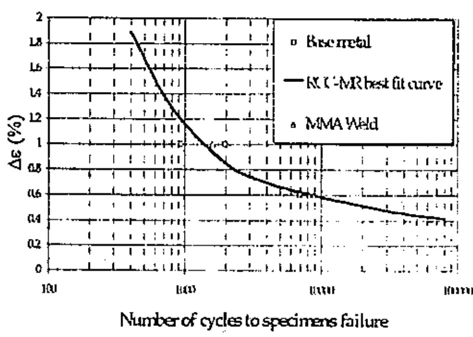

Figure 3 : Fatigue curve of both Base metal and MMA weld

4. 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.

4.1 OVERVIEW OF THE RCC-MR FATIGUE AND CREEP FATIGUE STRENGTH EVALUATION

4.1.1 Fatigue strength evaluation of welded joint

For fatigue analysis, the RCC-MR French design code [2] 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 $\overline{\Delta\varepsilon_1}$, obtained from an elastic analysis, do not take into account the plasticity that would be produced if the real behaviour of the material was modelled. The method proposed in the following provides an estimation of the "real" strain range $\overline{\Delta\varepsilon}$ 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 $\overline{\Delta\varepsilon}^*$ is the sum of four terms noted $\overline{\Delta\varepsilon_1}$, $\overline{\Delta\varepsilon_2}$, $\overline{\Delta\varepsilon_3}$, $\overline{\Delta\varepsilon_4}$. $\overline{\Delta\varepsilon_1}$ represents the strain range determined from an elastic analysis. $\overline{\Delta\varepsilon_2}$ represents the plastic gain due to the variation of the primary stresses at the point under investigation. $\overline{\Delta\varepsilon_3}$ represents the plastic gain in the strains using the NEUBER Hyperbola approach $\left(\overline{\Delta\varepsilon_1}+\overline{\Delta\varepsilon_2}+\overline{\Delta\varepsilon_3}\right).\overline{\Delta\sigma} = (\overline{\Delta\varepsilon_1}+\overline{\Delta\varepsilon_2}).\overline{\Delta\sigma_{el}}$. $\overline{\Delta\varepsilon_4}$ represents the plastic gain in the strains due to triaxiality.

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

In order to take into account of the welded joints, the RCC-MR proposes to apply a reduction factor J_f=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.

4.1.2 Creep fatigue strength of a welded joint

According to the RCC-MR code, creep damage during hod 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 :

$$\boxed{\sigma_k = K_S \cdot \Delta\sigma^*}$$

where K_S is the symmetrisation coefficient

$\Delta\sigma^*$ is determined from the « real » strain range $\Delta\varepsilon_{el+pl}$ 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 Sr given in Appendix A3 (with $Sr=\sigma_k/0.9$).

For weldments, Sr curves are multiplied by a Jr coefficient to account for the inferior weldments properties under creep loading. For 316L(N) autenitic steel, Jr 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 : $W_A = \sum_k \left(\frac{t_k}{T_k}\right)$.

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 $[V_A(\overline{\Delta\varepsilon}), W_A(\sigma^*)]$ are located within an allowable area defined on the creep-fatigue interaction diagrams.

4.2 OVERVIEW OF THE JNC FATIGUE AND CREEP FATIGUE STRENGTH EVALUATION

4.2.1 Fatigue strength of a welded joint

The elevated Temperature Structural Design Guide (ETSDG) 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 :

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

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 [4] by the addition of a q_w factor that accounts for the elastic follow-up due to the presence of a welded joint :

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

As the last equation accounts strain concentration in inelastic region only, an additional factor $K\varepsilon_0$ 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 :

$$\varepsilon_t = \mathrm{Max}\left[\left\{1 + (q.q_W - 1)\left(1 - \gamma_y \frac{2\sigma_y}{\Delta\sigma_e}\right)\right\}\varepsilon_e, K_{\varepsilon 0}.\varepsilon_0\right]$$

The fatigue damage evaluation is very similar to the RCC-MR one presented in paragraph 4.1.1. 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.

4.2.2 Creep fatigue strength of a welded joint

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

$\sigma_i = \frac{1}{2}\Delta\sigma\left(\Delta\varepsilon_{el+pl}\right)$ where $\Delta\varepsilon_{el+pl}$ is the total elastic plastic strain range and $\Delta\sigma$ the associated 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.

4.3 Benchmark Results

4.3.1 Fatigue results

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

Δε (%)	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 3 : JNC evaluation of fatigue tests

Δε (%)	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

Table 4 : CEA evaluation of fatigue tests

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

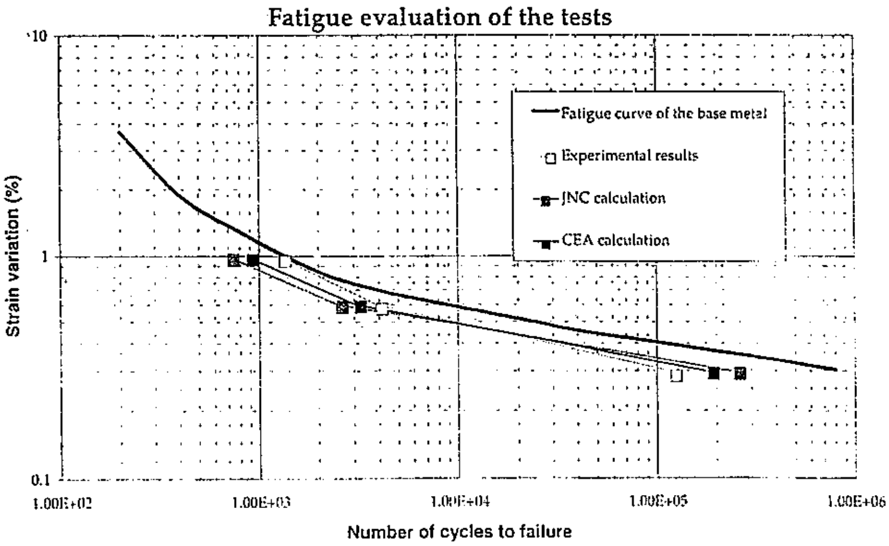

Figure 4 : JNC and CEA fatigue calculation compared to the experimental datas

4.3.2 Creep fatigue results

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

Δε (%)	Hold time	JNC results α_R=10 (cycles)	JNC results α_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

Table 5 : JNC and CEA evaluation of creep fatigue tests

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

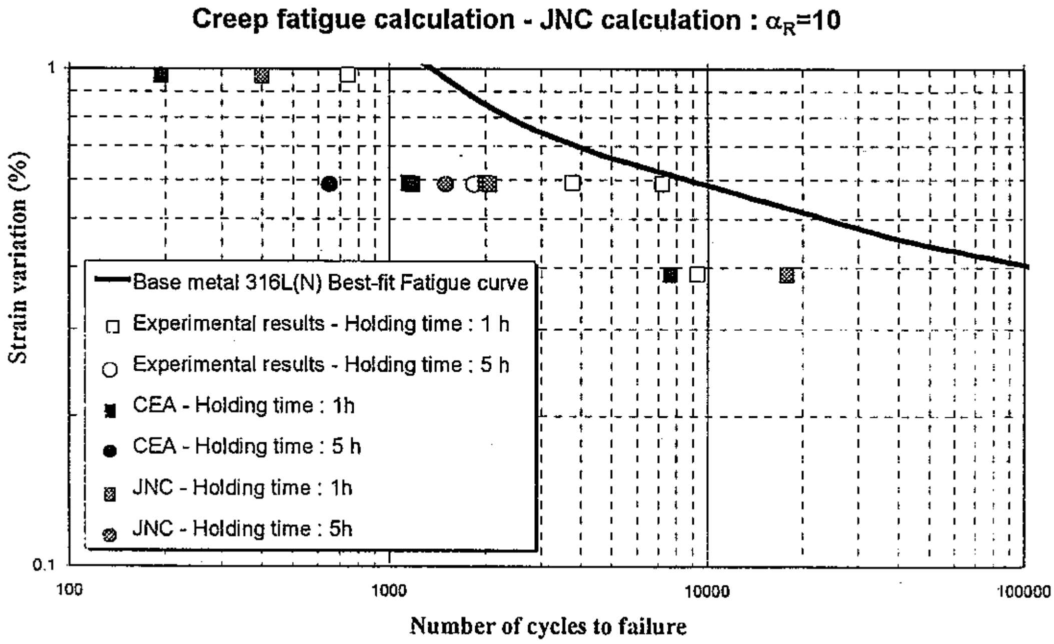

Figure 5 : Creep fatigue calculation - JNC α_R coefficient is equal to 10

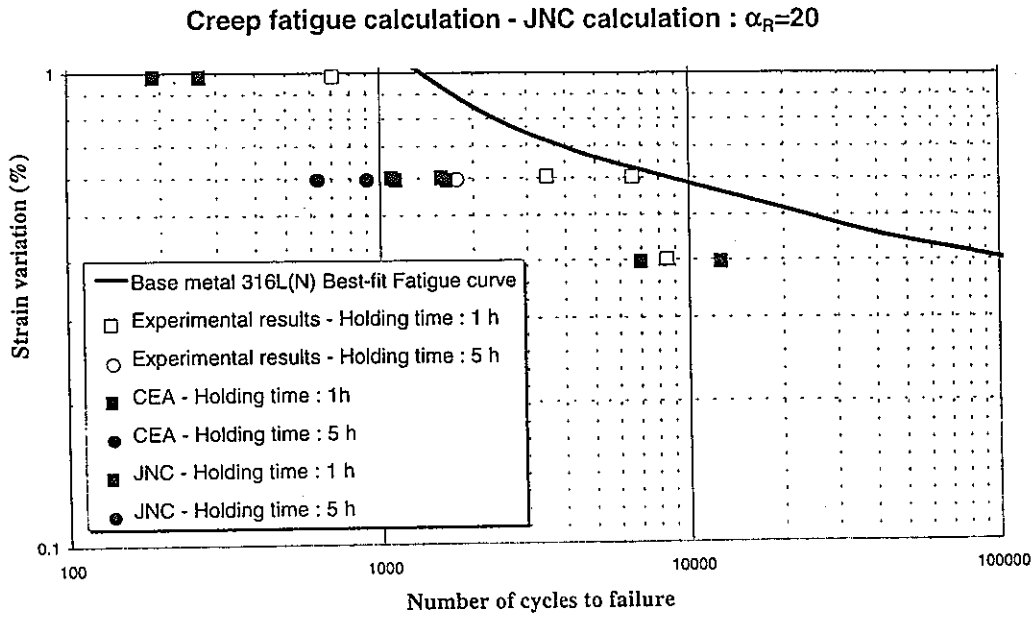

Figure 6 : Creep fatigue calculation - JNC α_R coefficient is equal to 20

5. 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 make 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 Jr (depending on time and temperature) is available to determine the creep rupture strength by multiplying the creep rupture strength of parent material by the Jr value. The Japanese rules makes use of a α_R reduction factor, temperature and stress level independent.

6. References

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