JNC TN9400 2001-010

Interpretation of TTS Experiment: Comparison of Creep Fatigue Evaluation Methods of Weldment

January 2000

Japan Nuclear Cycle Development Institute
O-arai Engineering Center

JNC TN9400 2001-010
January 2000

Interpretation of TTS experiment :
Comparison of creep fatigue evaluation methods of weldment

(Research Report)

Naoto Kasahara* and Laurent LE BER**)

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 JNC is creep-fatigue evaluation of a welded vessel subjected to cyclic thermal transient loading. The objective of this problem is comparison of total strength evaluation methods of base metal and welded joints against actual loading conditions. This report compared results of the JNC problem evaluated by both procedures from view points of material properties, strength evaluation of base metals, and strength reduction evaluation of welded joints. Main differences of procedures were found in strain concentration evaluation methods of base metal, initial stress evaluation methods of relaxation, fatigue strength reduction factors of weldments, and creep strength reduction factor of weldments. Both of CEA and JNC procedures were confirmed to be conservative for weldments of 316FR.

* Structure and Material Research Group, System Engineering Division, OEC, JNC

** CEA-Saclay DRN/DMT/SEMT/LISN

JNC TN9400 2001-010
２０００年１月

TTS熱過渡強度試験解析：溶接部クリープ疲労強度評価法の比較

（研究報告書）

笠原 直人*), Laurent LE BER**)

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TTSによる溶接容器の熱過渡強度試験解析に適用し、材料データ、母材部評価、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。

この結果、CEAとJNCの評価法の主な違いは、母材部のひずみ集中評価法、緩和初期応力評価法および溶接部の疲労およびクリープ強度低減係数であることが分かった。さらに試験結果と強度評価結果を比較すると、316FR溶接継手に関しては両評価法ともに保守的であり、両者間ではCEAの評価法がJNCに比較して保守的であることが明らかになった。

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。

*) 大洗工学センター システム技術開発部 構造材料技術開発グループ
**) CEA サクレー研究所 構造健全性設計基準研究室

Contents

List of figures

1 INTRODUCTION

Fatigue and creep-fatigue strength of welded joints are lower for the base metal, when applied to elevated temperature components subjected to cyclic thermal transient loading. CEA and JNC have developed design evaluation procedures for considering strength reduction of weldments in elevated temperature components. Both procedures were applied to the same benchmark problems and results were compared in this paper with an associated paper[1] under EJCC contract. Strength evaluation results of welded joints are affected by material data, evaluation methods for base metal, and procedures for considering strength reduction of welded joints. In order to examine these effects separately, two kinds of benchmark problems were planned.

One of benchmarks which was provided by Dr. Laurent LE BER of CEA, is fatigue and creep-fatigue evaluation of welded plates due to reverse bending at 550℃[2]. This problem focuses on comparison of procedures for considering strength reduction of welded joints. Intercomparison of evaluated results of this problem and difference of material data are discussed in the associated paper [1].

Another problem provides by JNC, is creep-fatigue evaluation of a welded vessel due to cyclic thermal transient loading [3]. Point of view of this problem is comparison of total strength evaluation methods of base metal and welded joints on actual loading conditions.

Evaluation procedures of both base metal and welded joints are compared in this paper under the same material data and structural analysis data.

2. BENCHMARK PROBLEM ON A WELDED VESSEL

2.1. THERMAL TRANSIENT STRENGTH TEST

A thermal transient strength test was conducted on a welded vessel model by using a sodium test facility [3]. The test model is a vessel type structure, which has an outer container and an inner vessel as Fig.1. 1055 cycles of thermal transients were applied by alternate flow of hot (600℃) and cold sodium (250℃) which passed though the annulus space between the outside container and the inner vessel. During each cycle, creep damage was accumulated by 2 hours of holding time in 600℃.

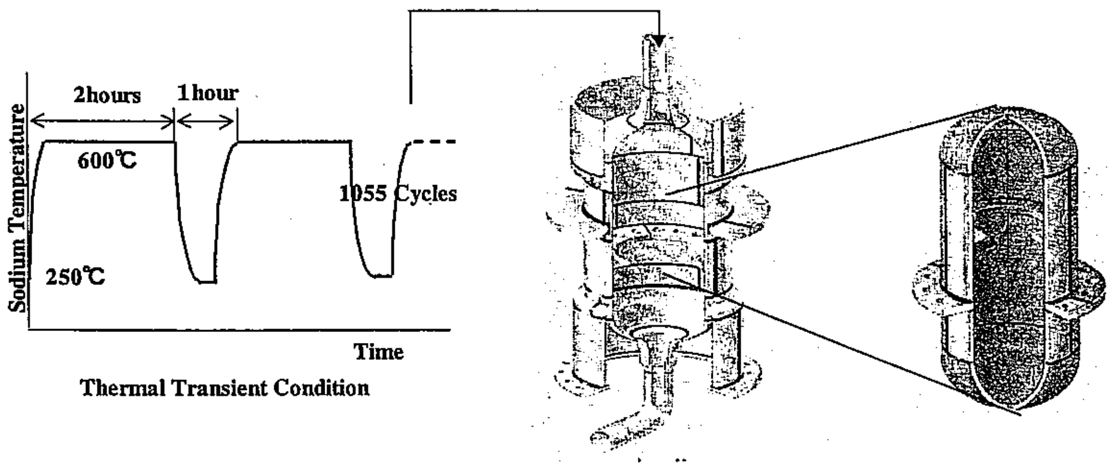

Fig.1 Thermal transient strength test of a welded vessel model

As for materials, the outside container and half of the structure of the inner vessel are made of SUS304 (Japanese TYPE304SS), and the remainder half is made of 316FR (Japanese low carbon medium nitrogen stainless steel for Liquid Metal Fast Reactors). Circumferential and longitudinal welded joints are incorporated in both SUS304SS and 316FR portions. The outside container of the vessel model is 2210mm high and 980mm in diameter with 25mm thickness wall, and the inner vessel is 456 inner diameter with 20 mm thickness wall. The inner vessel has a restraint plate with 25mm wall thickness to make stress gradient on the inner vessel.

Shown in Fig.2 is an example of initiated cracks on the surface of the inner vessel observed by the liquid flaw detection test (PT) after 1055 cycles of thermal transients. In the 316FR division of the inner vessel, micro-cracks were found only at part of welded joints, while many cracks were observed to both of welded joints and base metal in the 304SS parts. Here, the cracks at welded joints were observed to be deeper than that of the nearby base metal.

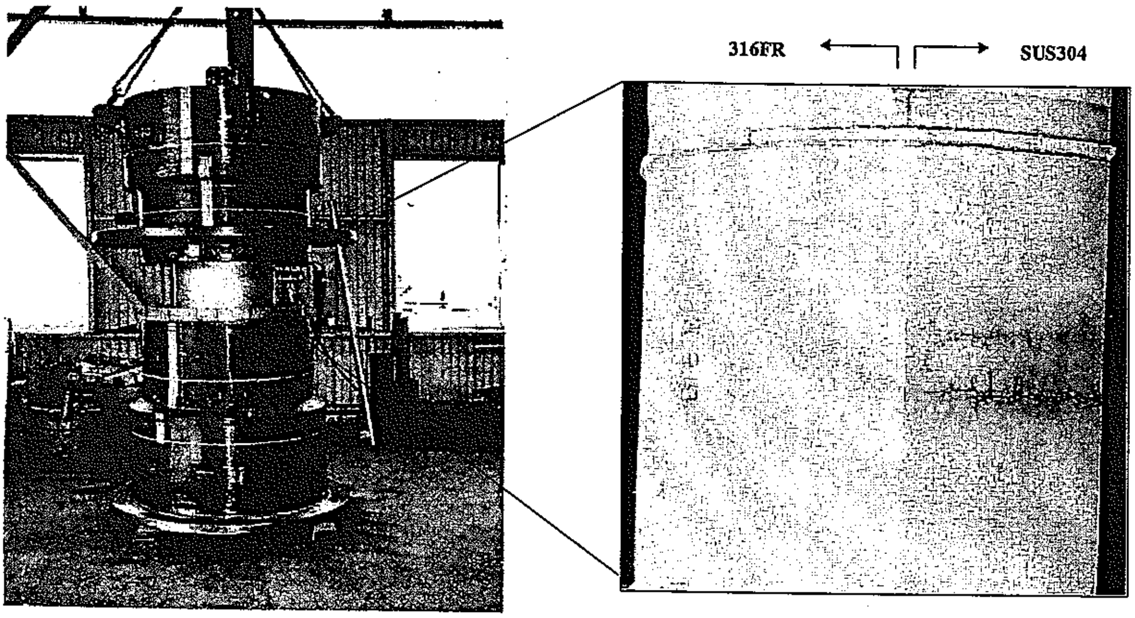

Fig.2 Thermal transient test result of inner vessel

2.2. COMMON MATERIAL DATA AND STRUCTURAL ANALYSIS DATA

In order to compare strength procedures separately from affects of material properties and structural analysis methods, both CEA and JNC have evaluated creep-fatigue strength of the welded vessel based on common material data and structural analysis results.

JNC provided such material properties on Japanese SUS304 and 316FR under various temperatures, as fatigue curves, monotonic stress-strain curves, stress range-strain range relationships, creep strain equations, and creep rupture equations. Fatigue curves of weld metal for SUS304 are the same as base metal and Yield stress of a weld metal for SUS304 is 0.8 times one of base metal after sufficient cyclic loading[4]. As for 316FR weldmetal, fatigue characteristic is the same as base metal and Yield stress of a weld metal is more than 0.9 times of base metal[5].

To define a scope of the program, this benchmark program restricts the evaluation area into the outer surface of the inner vessel as indicated in Fig.3. Materials to be evaluated are SUS304 base metal, flash grained welded joint of SUS304, 316FR base metal, and flash grained welded joint of 316FR. All of these material portions have the same geometry and are subjected to the same loading. Such structural analysis results were provided from thermal elastic analysis based on measured temperature data, that Mises stress range on the surface, tresca stress range from linearized stress components Sn (stress intensity), and a stress classification table as in Fig.4.

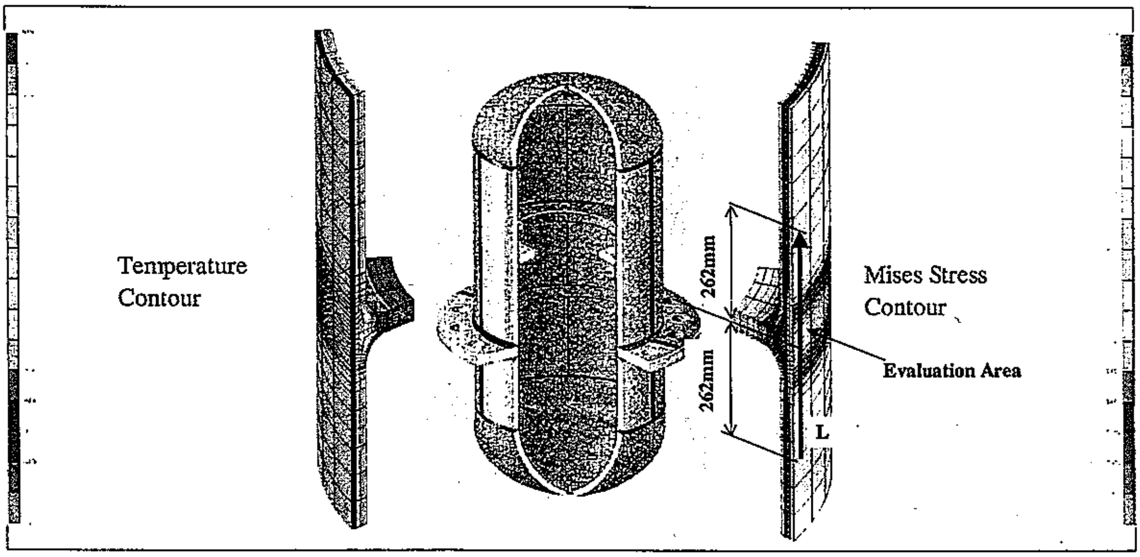

Fig.3 Temperature and Thermal Elastic Analysis Results

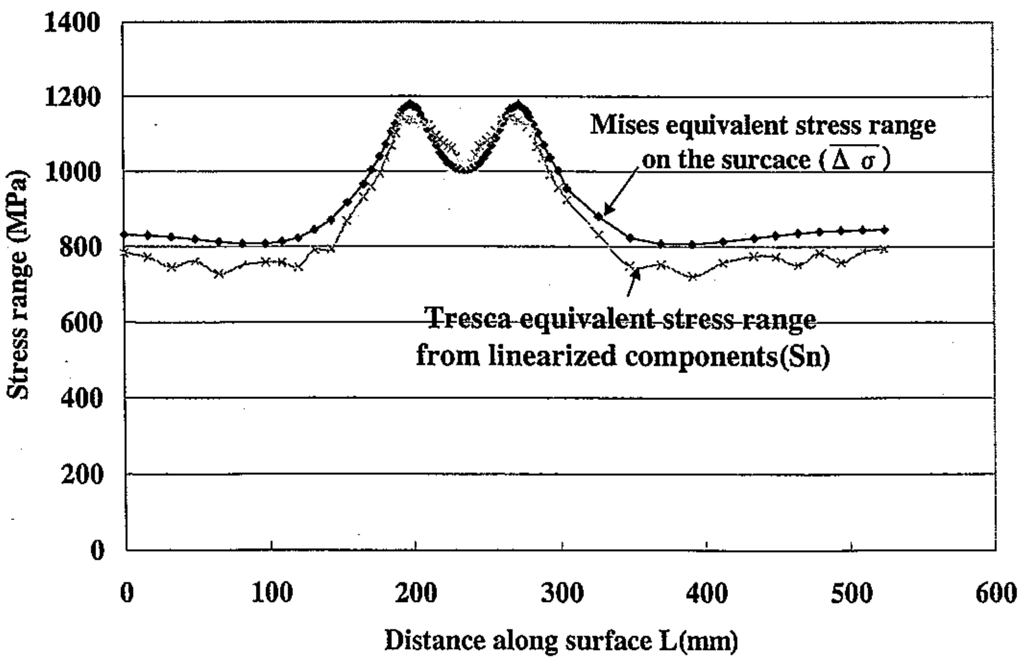

Fig.4 Elastically calculated stress distribution

3. STRENGTH EVALUATION OF BASE METAL

3.1. FATIGUE STRENGTH EVALUATION

Creep-fatigue evaluation procedures for base metals are described in literatures and main difference of fatigue strength evaluation procedure between CEA[6] and JNC[7] is summarized here.

(1) CEA procedure

Total strain range on the surface $\overline{\Delta\varepsilon_{tot}}$ can be estimated from elastically calculated equivalent stress range $\overline{\Delta\sigma}$ by RCC-MR procedure with Neuber's rule and the triaxiality factor as,

$$\overline{\Delta\varepsilon_{tot}} = \overline{\Delta\varepsilon_1} + \overline{\Delta\varepsilon_2} + \overline{\Delta\varepsilon_3} + \overline{\Delta\varepsilon_4}, \tag{1}$$

$$\overline{\Delta\varepsilon_1} = \frac{2(1+\nu)}{3}\frac{\overline{\Delta\sigma}}{E}, \text{ where E is } Young's \text{ modulus.} \tag{2}$$

$\overline{\Delta\varepsilon_2}$ is for consideration of primary stress and is zero when primary stress is absent.

$$\overline{\Delta\varepsilon_3} = \frac{\overline{\Delta\sigma}}{\overline{\Delta\sigma}\left(\overline{\Delta\varepsilon_3}\right)}\left(\overline{\Delta\varepsilon_1} + \overline{\Delta\varepsilon_2}\right), \tag{3}$$

where $\overline{\Delta\sigma}\left(\overline{\Delta\varepsilon_3}\right)$ is stress range of cyclic curve corresponding to $\Delta\varepsilon_3$.

$$\overline{\Delta\varepsilon_4} = (K_\nu - 1)\overline{\Delta\varepsilon_1}, \text{ where } K_\nu \text{ coefficient is provided by RCC-MR A3[6]} \tag{4}$$

(2) JNC procedure

Total strain range $\overline{\Delta\varepsilon_{tot}}$ is estimated from elastically calculated equivalent stress range $\overline{\Delta\sigma}$ and stress intensity Sn from linearized components by JNC procedure with Elastic follow-up model as,

$$\overline{\Delta\varepsilon_{tot}} = KKe'_L\, Ke'_G\, \overline{\Delta\varepsilon_n} \tag{5}$$

$$\overline{\Delta\varepsilon_n} = \frac{S_n}{E} \ , \ K = \max\left\{\frac{\overline{\Delta\sigma}}{S_n}, 1\right\} \tag{6}$$

$$Ke'_L = \{1 + (q_K - 1)(1 - \frac{\overline{3Sm}}{\overline{\Delta\sigma}})\} \ , \ q_k = K^{\frac{n-1}{n+1}} \tag{7}$$

where $\overline{3Sm}$ is modified shakedown limit provided in ETSDG[8] and n is power of cyclic stress strain curve (i.e.n=5 for austenitic stainless steel).

$$Ke'_G = \{1 + (q - 1)(1 - \frac{\overline{3Sm}}{Sn})\} \ , \tag{8}$$

where q is elastic follow-up parameter and can be adjusted to $q = 5/3$ when stress is generated by temperature gradient across wall thickness[9].

JNC procedure also takes strain rate effect into account to fatigue damage.

Calculated total strain ranges and fatigue damage factors were compared as in Fig.5 and Fig.6.

In spite that strain ranges of CEA are larger than one of JNC, fatigue damage is approximately the same. The reason is that JNC evaluates fatigue damage factors based on lower strain rate than one of CEA.

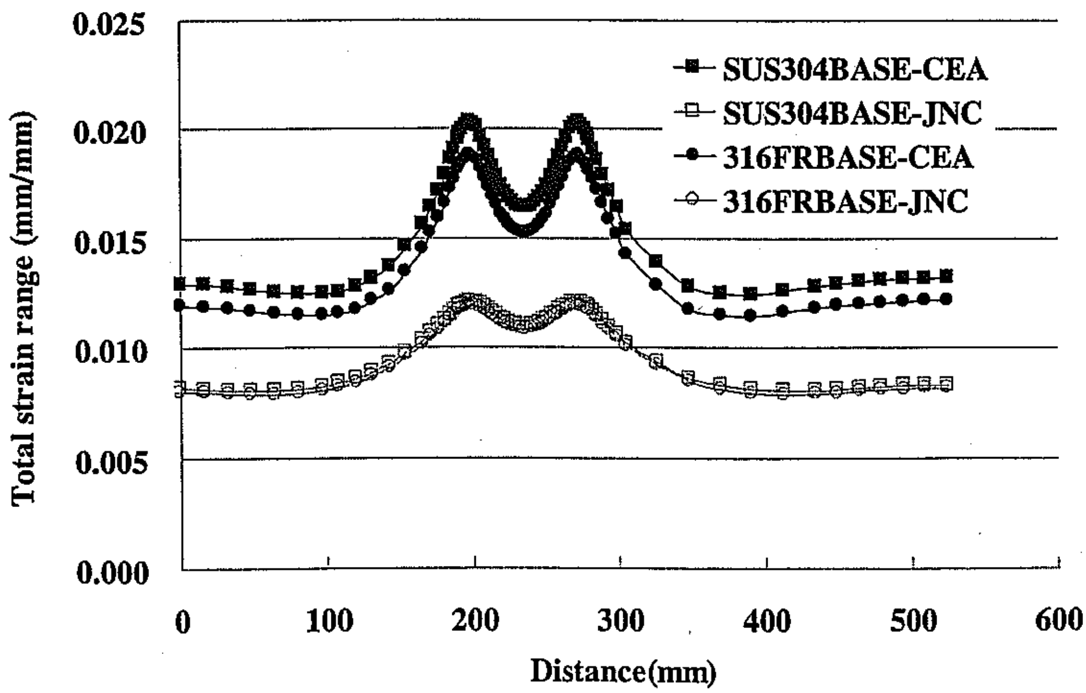

Fig.5 Comparison of total strain range

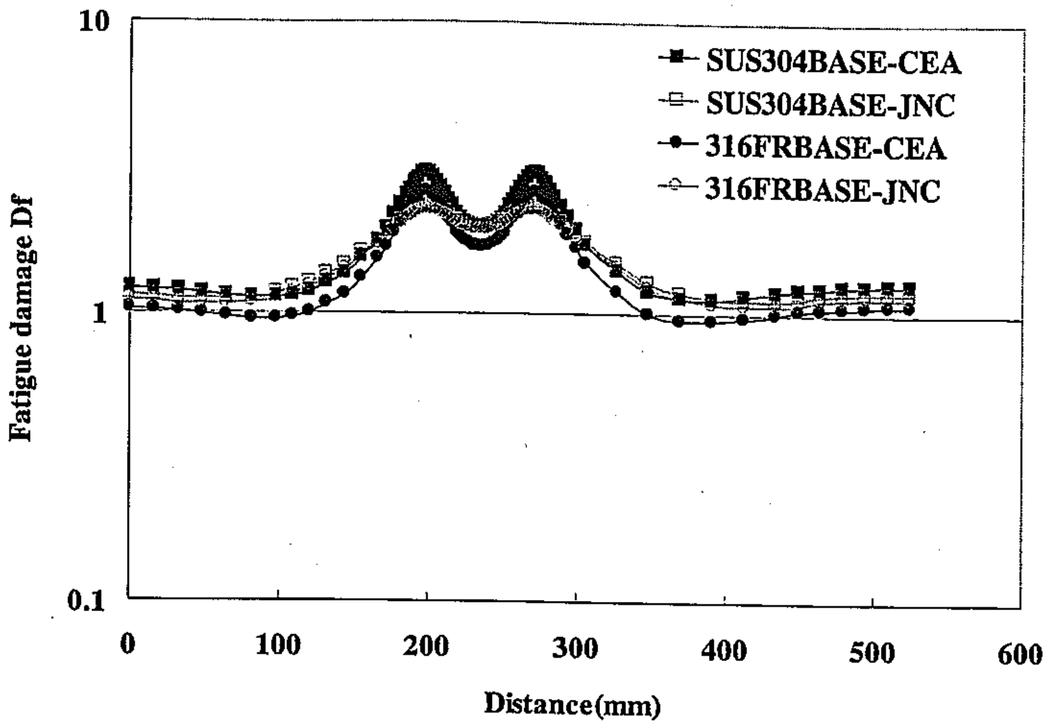

Fig.6 Comparison of fatigue damage

3.2. CREEP STRENGTH EVALUATION

Main differences of creep strength evaluation procedure between CEA and JNC are summarized here.

(1) CEA procedure

Initial value of stress relaxation σ_i is calculated by RCC-MR procedure with symmetry factor as,

$$\sigma_i = K_s \Delta\sigma(\Delta\varepsilon_{el+pl}), \tag{9}$$

where $\Delta\sigma(\Delta\varepsilon_{el+pl})$ is stress range of cyclic curve corresponding to $\Delta\varepsilon_{el+pl}$ and Ks is symmetry factor provided by RCC-MR[6]. $\Delta\varepsilon_{el+pl}$ is evaluated from an equation $\overline{\Delta\varepsilon_{tot}} = \Delta\varepsilon_{el+pl} + \Delta\varepsilon_c$, where $\Delta\varepsilon_c$ is creep strain from primary stress and is zero in the case of TTS experiment.

Stress relaxation rate is estimated by RCC-MR procedure with the Cr factor as,

$$\dot{\sigma}(t) = -\frac{1}{C_r} E\dot{\varepsilon}_c, \tag{10}$$

where C_r is elastic follow-up and triaxiality coefficient and is equal to 3 or a lower value if justified by the designer.

(2) JNC procedure

Initial value of stress relaxation σ_i is calculated by JNC procedure considering combination of thermal transients as,

$$\sigma_i = \frac{1}{2}\Delta\sigma\left(\Delta\varepsilon_{el+pl}\right),\ \ \Delta\varepsilon_{el+pl} = \max\left(\Delta\varepsilon_{el+pl}{}^1, \Delta\varepsilon_{el+pl}{}^2\right), \tag{11}$$

where $\Delta\sigma\left(\Delta\varepsilon_{el+pl}\right)$ is stress range of cyclic curve corresponding to $\Delta\varepsilon_{el+pl}$ and $\Delta\varepsilon_{el+pl}{}^i$ is elastic plastic strain range defined between peak time i and no loading condition.

Stress relaxation rate is estimated by JNC procedure with elastic follow-up parameter as,

$$\dot{\sigma}(t) = -\frac{1}{q_{eff}(q_k, q)}E\dot{\varepsilon}_c, \tag{12}$$

where $q_{eff}(q_k, q)$ is elastic follow-up parameter and is qual to $q_k \cdot q$ or a lower value if calculated by the precious equation[7].

Initial stress of relaxation and creep damage factors were compared as in Fig.7 and Fig.8

Estimated creep fatigue damages were also compared with distribution of initiated cracks on the surface of the inner vessel as in Fig.9,Fig.10 and Fig.11.

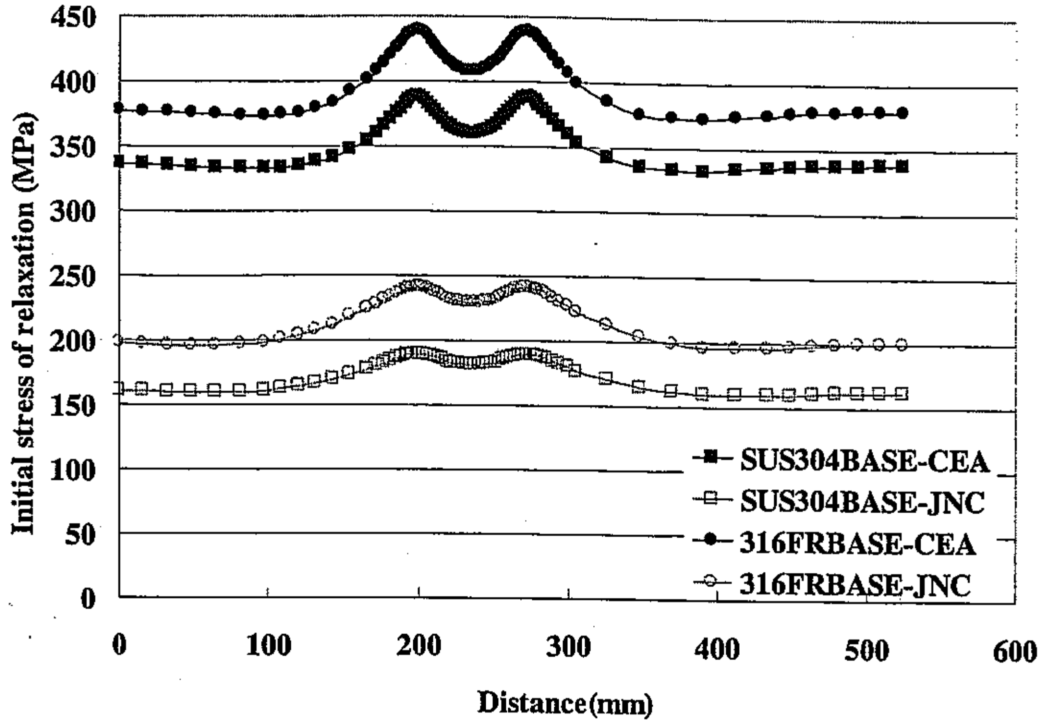

Fig.7 Comparison of initial stress

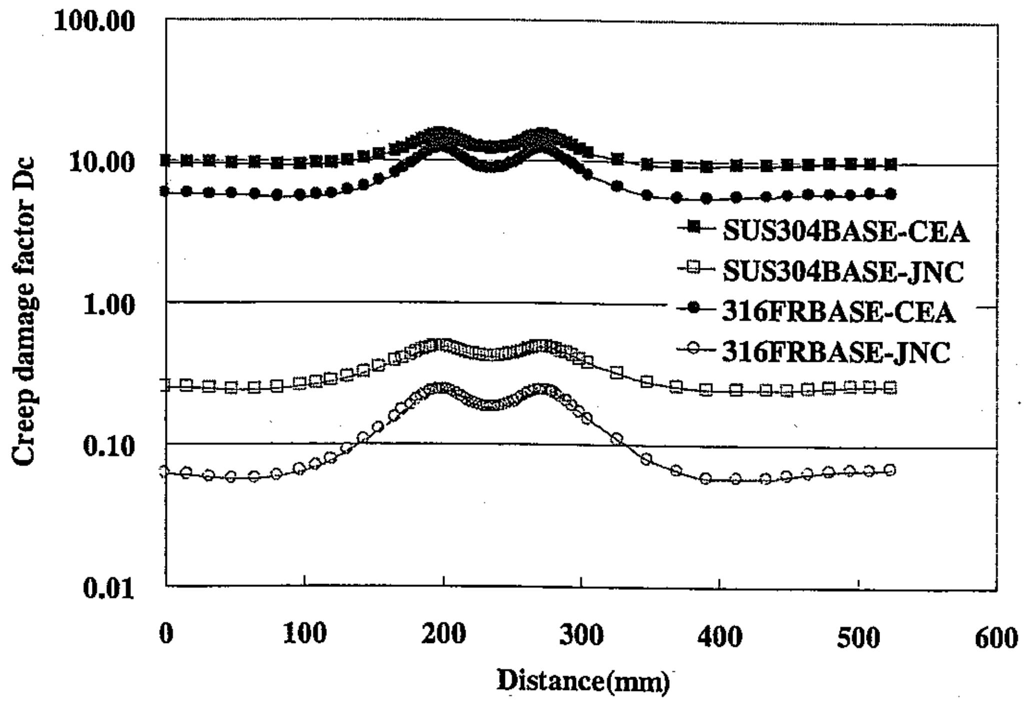

Fig.8 Comparison of creep damage factors

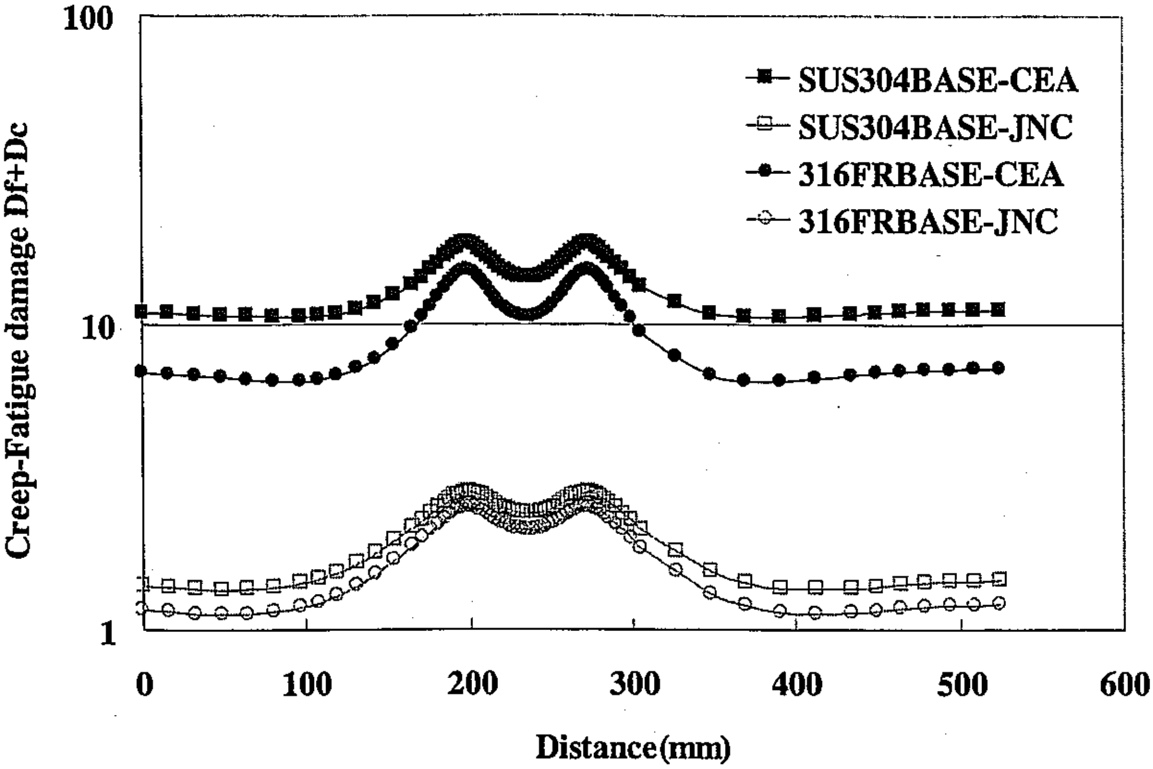

Fig.9 Comparison of creep-fatigue damage factors

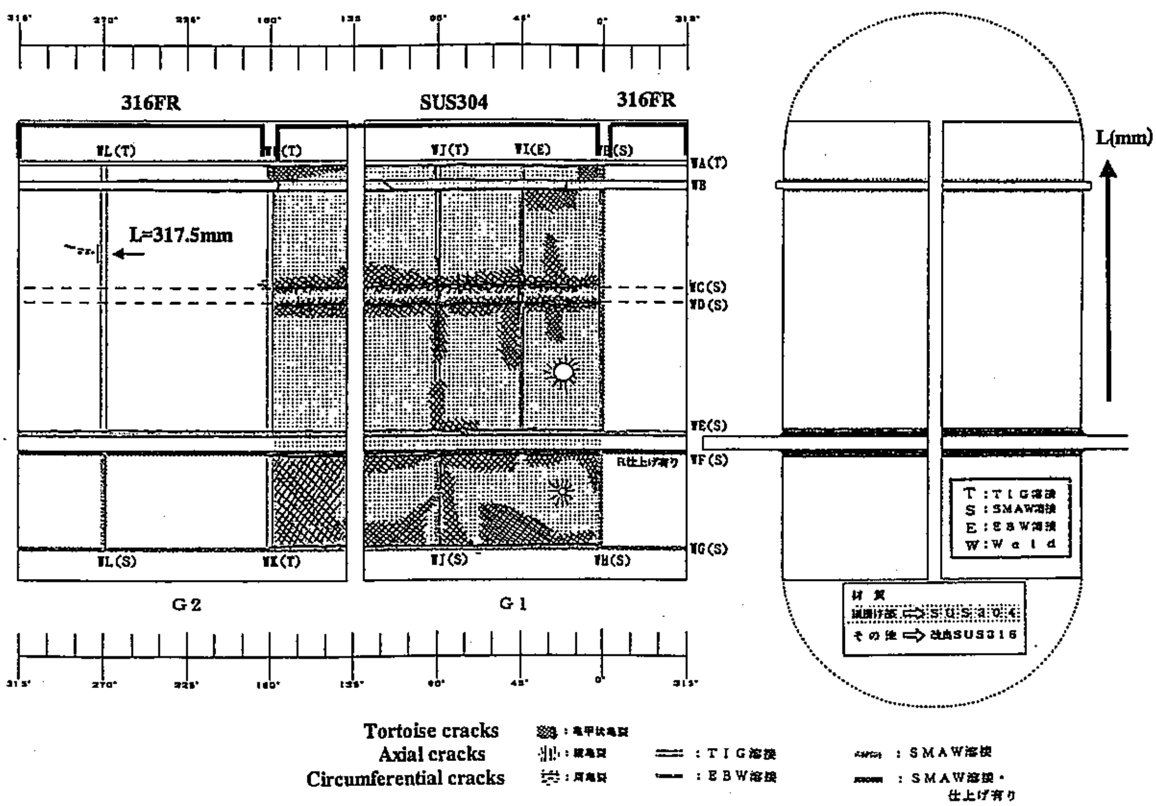

Fig.10 Distribution of initiated cracks on the surface of the inner vessel

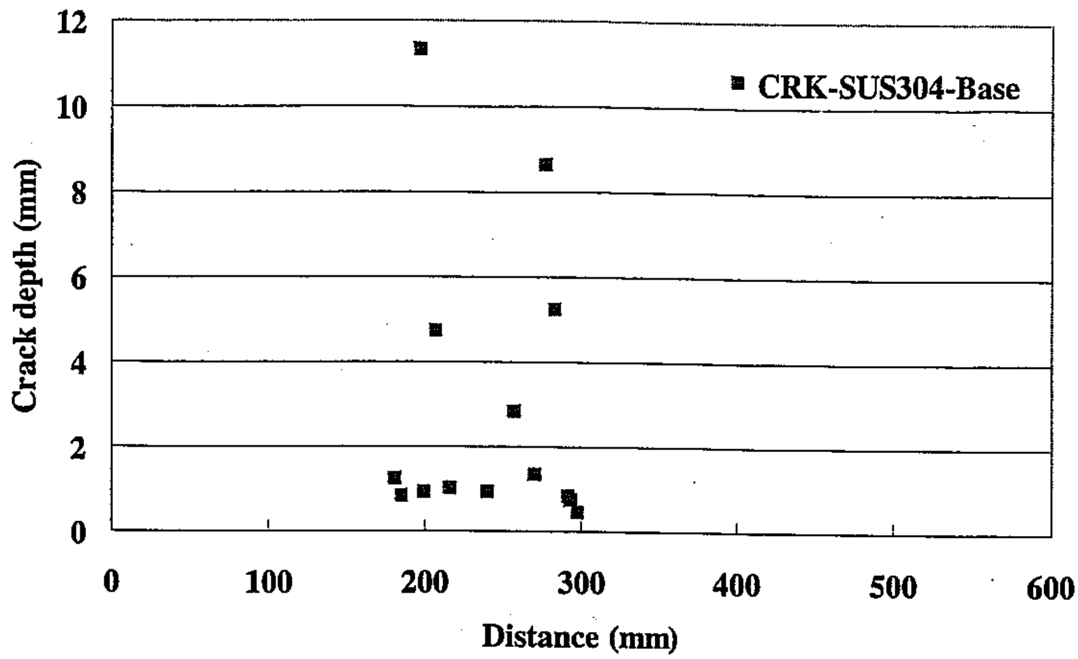

Fig.11 Distribution of crack depth at base metal

4. STRENGTH EVALUATION OF WELDED JOINTS

4.1. FATIGUE STRENGTH EVALUATION

Creep-fatigue evaluation procedures for welded joints are described in literatures [5][6][10] and main differences of fatigue strength evaluation procedure between CEA and JNC are summarized here.

(1) CEA procedure

The last version of RCC-MR[6] has proposed a strength reduction factor J_f on fatigue curves as $J_f = 1.25$ for 316L(N) steel. This value was determined by

$$J_f = \frac{\Delta\varepsilon(N_r)}{\Delta\varepsilon_{ap}}, \tag{13}$$

where, $\Delta\varepsilon_{ap}$ is the applied strain range, and $\Delta\varepsilon(N_r)$ is the strain range corresponding to the experimental number of cycles to rupture N_r and derived from the base metal best fit fatigue curves.

(2) JNC procedure

JNC procedure provides a strain concentration factor for welded joints based on mechanical models as

$$\overline{\Delta\varepsilon_{tot}} = \max\ \{KKe'_L\ Ke'_G\ , K_{\varepsilon 0}\}\overline{\Delta\varepsilon_e}\ , \tag{14}$$

$$Ke'_L = \{1 + (q_K - 1)(1 - \gamma_y \frac{\overline{3Sm}}{\Delta\sigma})\}\ , \tag{15}$$

where $K_{\varepsilon 0} = 1.2$ is a factor for considering material degradation, and γ_y is a reduction ratio of yield stress in weld metal to one of base metal, value of which is 0.8 for SUS304 and is 0.9 for 316FR.

$$Ke'_G = \{1 + (q_w q - 1)(1 - \gamma_y \frac{\overline{3Sm}}{Sn})\}\ , \tag{16}$$

where q_w is elastic follow-up parameter for considering strain redistribution between weld metal and base metal. Its value is 1.5 for both SUS304 and 316FR.

The JNC procedure can be reduced to the same fatigue strength reduction factor as J_f by

$$J_f = \frac{\left(\overline{\Delta\varepsilon_{tot}}\right)_{weld}}{\left(\Delta\varepsilon_{tot}\right)_{base}} \quad (17)$$

Fatigue strength reduction factors, fatigue damage ratio of welded joints to base metal $(D_f)_{weld}/(D_f)_{base}$, and fatigue damage factor of welded joints $(D_f)_{weld}$ were compared as in Fig.12, Fig.13 and Fig.14.

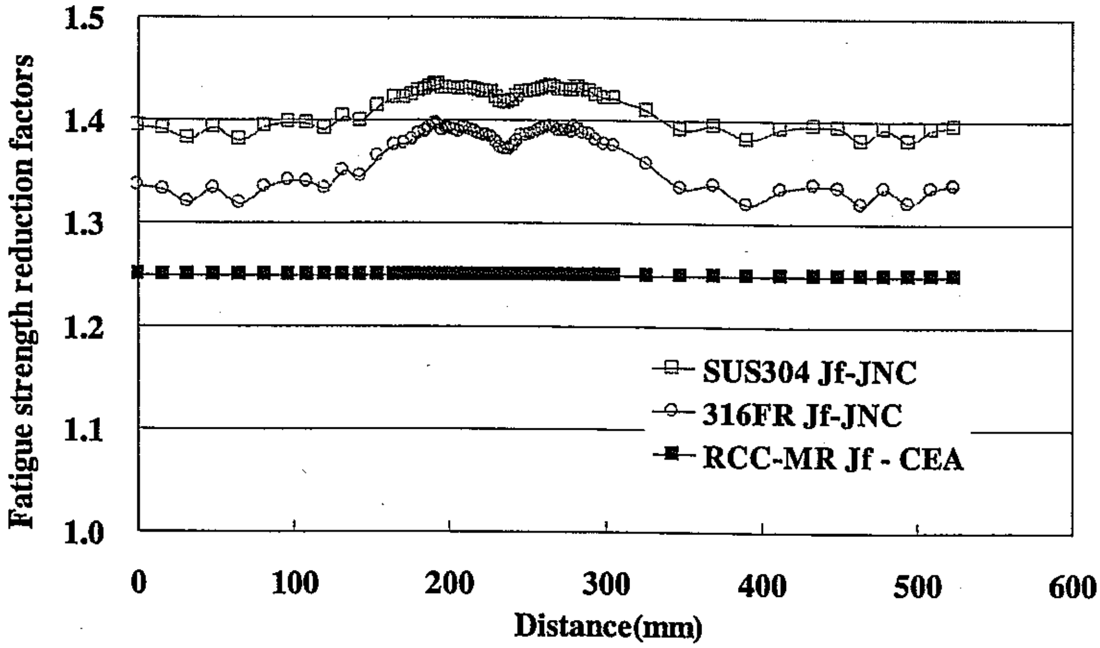

Fig.12 Comparison of fatigue strength reduction factors

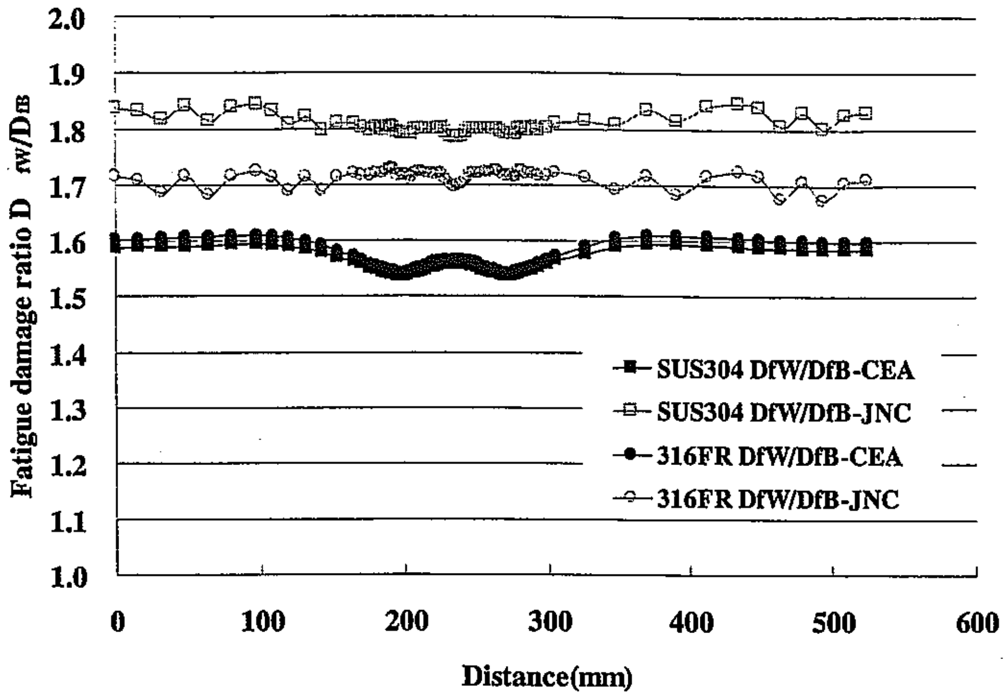

Fig.13 Comparison of fatigue damage ratio of welded joints to base metal

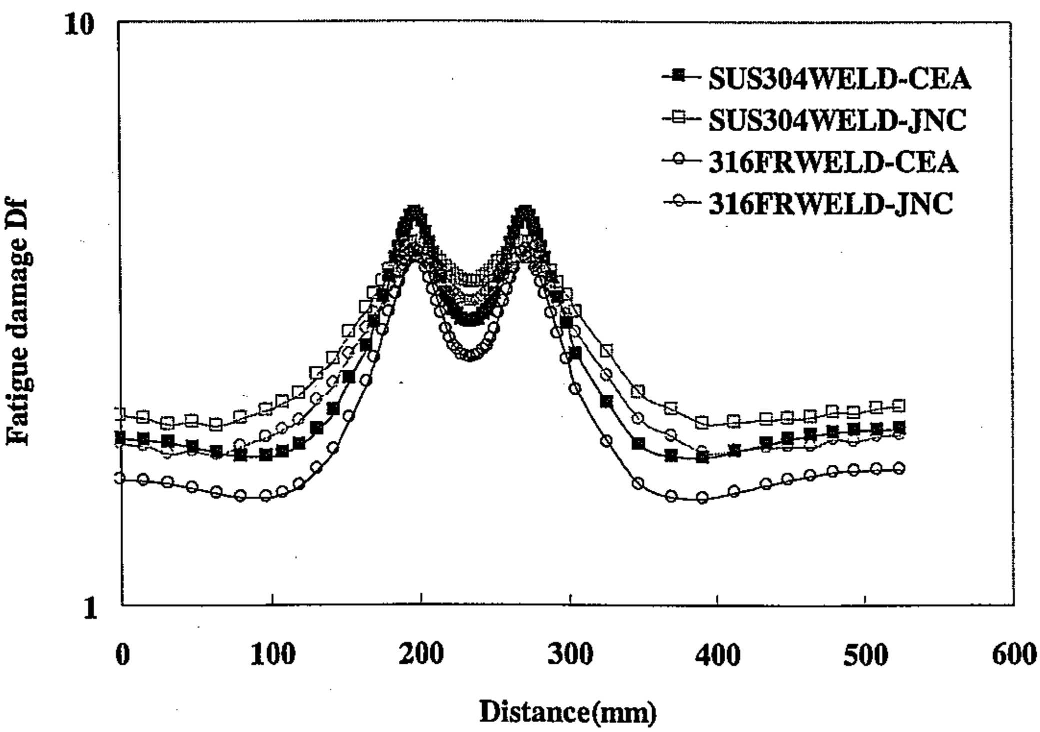

Fig.14 Comparison of fatigue damage factors

4.2. CREEP STRENGTH EVALUATION

Main differences of creep strength evaluation procedure between CEA and JNC are summarized here.

(1) CEA procedure

The time to rupture per cycle is calculated with the real creep rupture stress of the base metal multiplied by the Jr coefficient that depends on time and temperature. This value is provided by RCC-MR as Jr=0.85(550℃ 1hr.), 0.78(600℃ 2hr) for316L(N).

Creep damage factor of welded joints is calculated with Jr as

$$D_c = \frac{t}{t_R(\sigma_c / J_r)}, \text{ where t is holding time and } t_R \text{ is rupture time.} \tag{18}$$

(2) JNC procedure

The time to rupture per cycle is calculated with the real creep rupture time of the base metal multiplied by the α_R coefficient. This value is 10 for both SUS304 and 316FR. Since the same value of α_R is applied to base metal in the JNC procedure, effect of this value to strength reduction factors is canceled.

$$D_c = \frac{t}{\alpha_R t_R(\sigma_c)}, \text{ where t is holding time and } t_R \text{ is rupture time.} \tag{19}$$

Initial stress of relaxation is evaluated based on strain range of welded joints.

$$\sigma_i = \frac{1}{2}\Delta\sigma\left(\left(\Delta\varepsilon_{el+pl}\right)_{weld}\right), \quad \left(\Delta\varepsilon_{el+pl}\right)_{weld} = \max\left(\left(\Delta\varepsilon_{el+pl}\right)_{weld}{}^{1}, \left(\Delta\varepsilon_{el+pl}\right)_{weld}{}^{2}\right) \tag{20}$$

Stress relaxation rate is estimated by JNC procedure with the elastic follow-up parameter as,

$$\dot{\sigma}(t) = -\frac{1}{q_{eff}\left(q_k, q_w q\right)} E\dot{\varepsilon}_c, \tag{21}$$

Since direct comparison of both methods for considering creep strength reduction is difficult, creep damage ratio of welded joints to base metal and creep damage factors were compared as in Fig.15 and Fig.16.

Estimated creep fatigue damages were also compared with distribution of initiated cracks on the surface of the inner vessel as in Fig.17 and Fig.18.

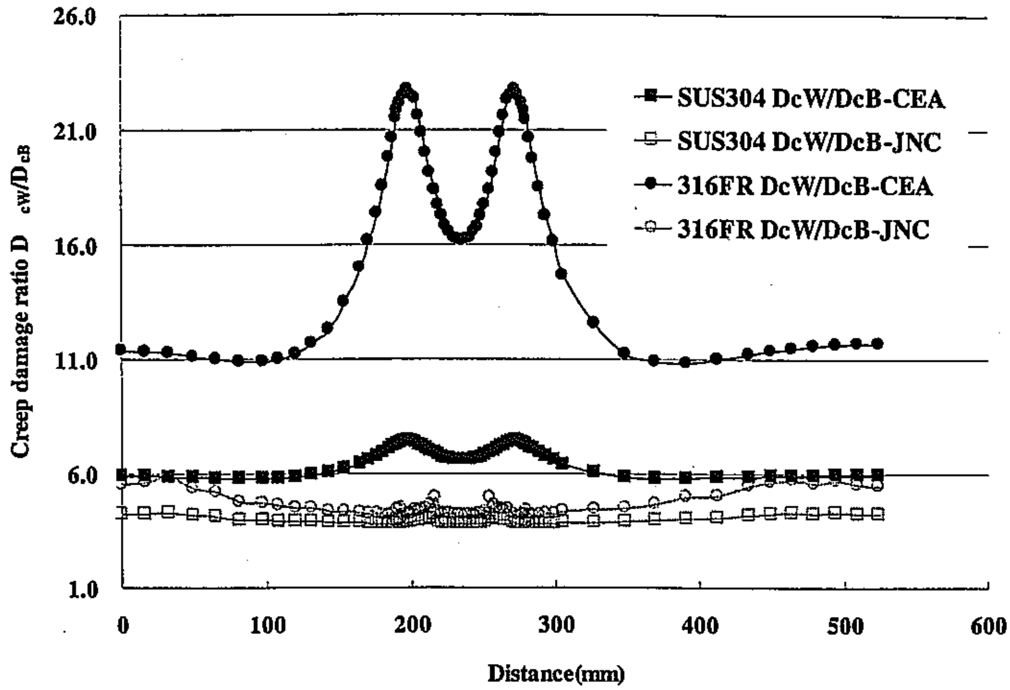

Fig.15 Comparison of creep damage ratio of welded joints to base metal

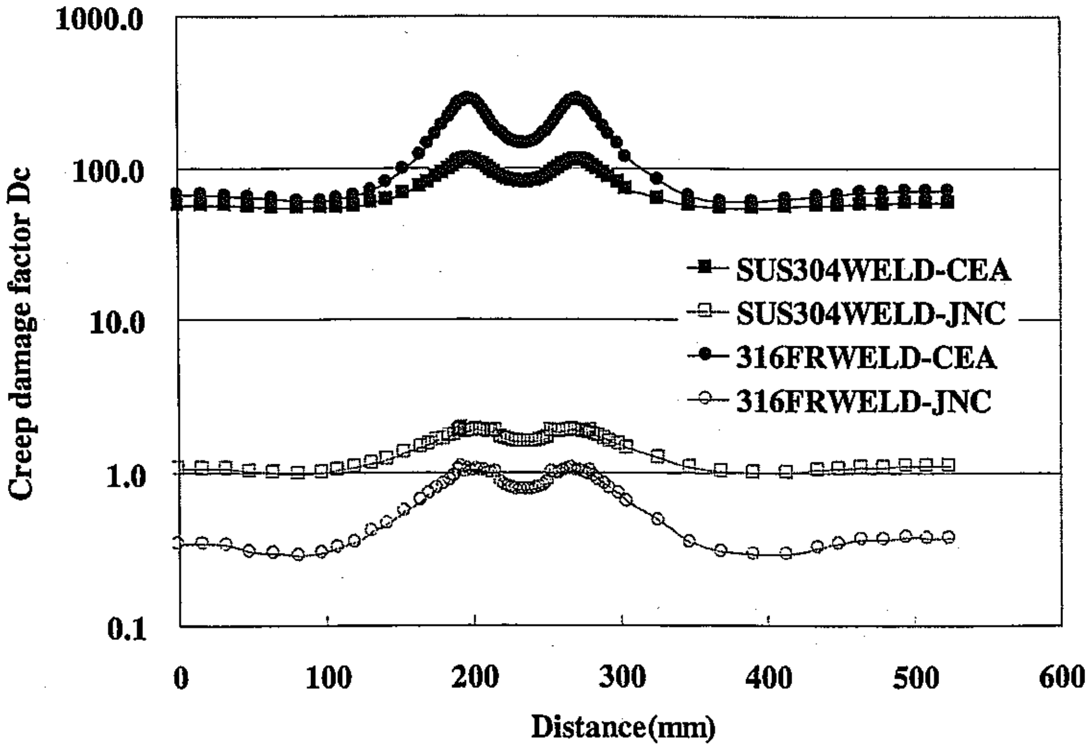

Fig.16 Comparison of creep damage factors

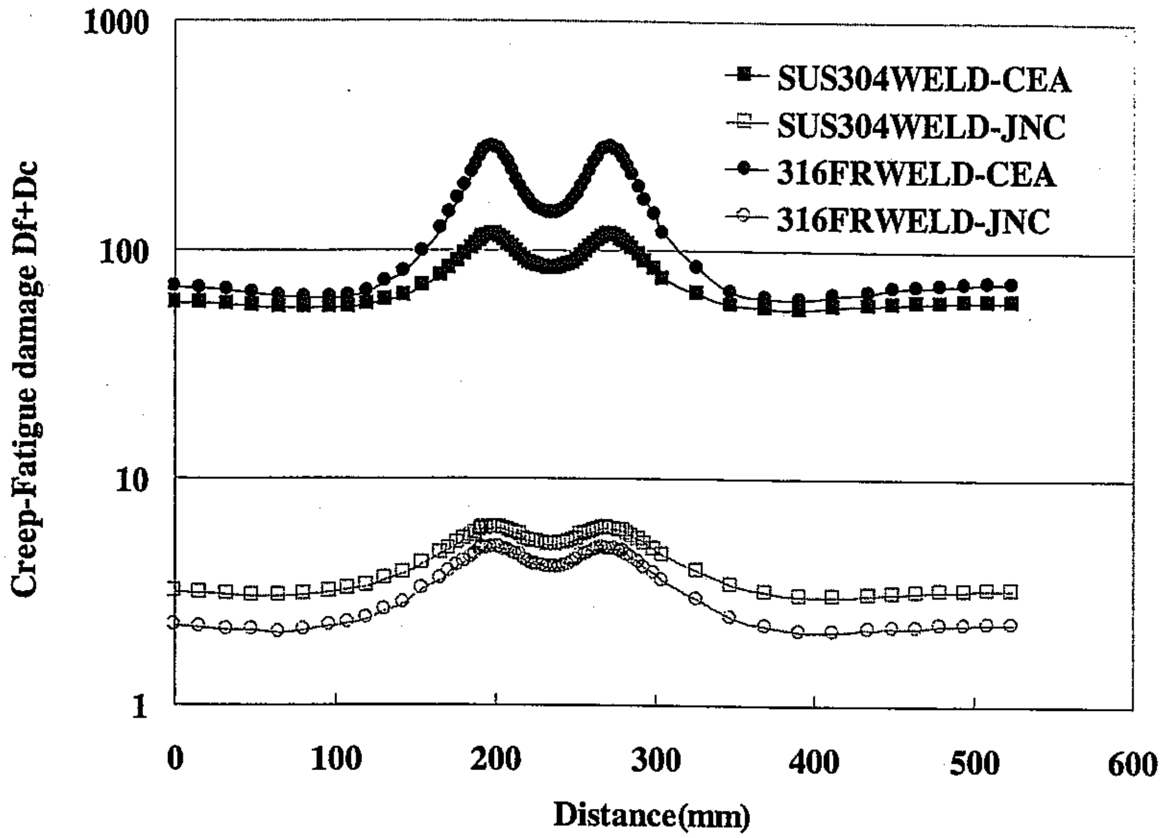

Fig.17 Comparison of creep-fatigue damage factors

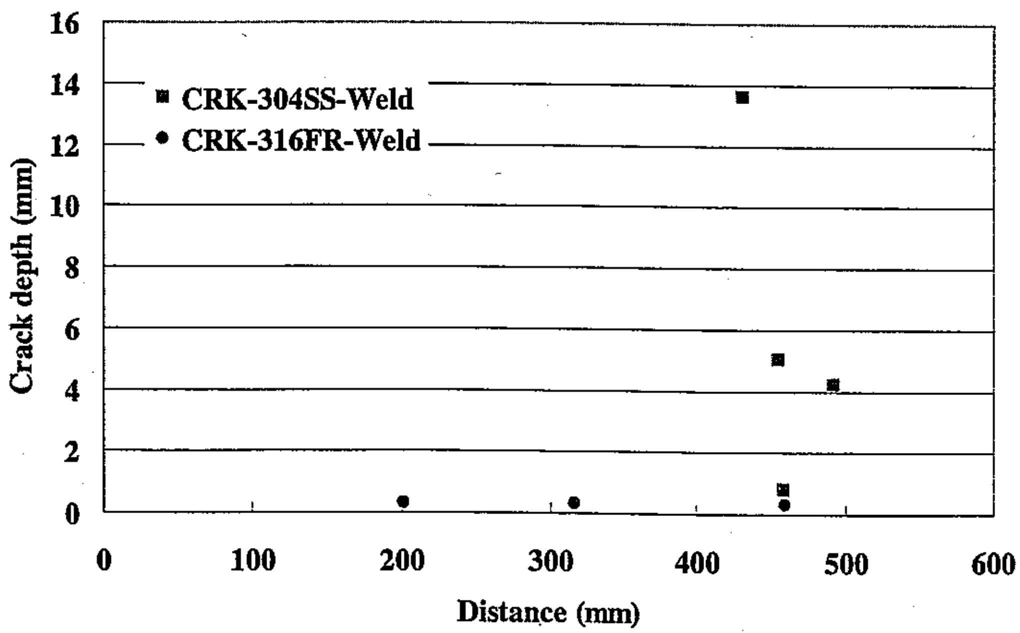

Fig.18 Distribution of crack depth at welded joints

5. CONCLUSIONS

(1) Material properties

- Both CEA and JNC base metals exhibit remarkable strain hardening, however, weld metal does not.
- Fatigue strength of both CEA and JNC weld metal is close to their base metal .
- CEA creep strength reduction factor of welded joints obtained from weld metal data depends on stress and temperature. On the other hand, JNC creep strength reduction factor of weld metal is almost constant.

(2) Strength evaluation of base metal

- CEA strain range is larger than JNC one since difference of strain concentration evaluation methods. However fatigue damage factor is approximately the same between CEA and JNC, since JNC takes strain rate effects into consideration.
- CEA creep damage factor is larger than JNC one since difference of initial stress evaluation methods and elastic follow-up parameters.
- Both of CEA and JNC procedures of creep-fatigue damage are conservative for 316FR.

(3) Strength evaluation of welded joints

- CEA fatigue strength reduction factor of welded joints to base metal is smaller than one of JNC which is estimated from strain concentration factor.
- CEA creep strength reduction factor of welded joints to base metal is approximately equivalent to one of JNC for SUS304 and is larger than one of JNC for 316FR.
- CEA creep fatigue damages of welded joints are larger than one of JNC, mainly since difference of procedures for base metals.
- Both of CEA and JNC procedures of creep-fatigue damage are conservative for 316FR.

6. DISCUSSIONS

(1) One of main factors of fatigue strength reduction in welded joints is difference of cyclic stress-strain curves between base and weld metals. From above point of view, benchmark with different width of welded joints and loading conditions are requested.

(2) Adoption of Jr coefficient of 316L(N) in RCC-MR to 316FR is too conservative since Jr depends on material properties. Intercomparison of creep strength reduction trend such as time and temperature dependencies is necessary.

(3) Procedures for base metal show larger difference than one for strength reduction of welded joints. Benchmark problems for structural discontinuities with base metal are desirable.

(4) Comparison with absolute values of damage factors is not sufficient, since those values are affected from both procedures of base metal and welded joints. In order to distinguish both effects, it is recommended that comparison by strength reduction factors of welded joints from base metals.

(5) What strength reduction factors should be explicitly considered in design codes ?
- Metallurgical discontinuity between base and weld metal
- Structural discontinuity of unfinished welded joints
- Degradation of weld metal
- Residual stress
- Scale factors, etc.

(6) Possibility of data sharing and further benchmark
- Metallurgical discontinuity between base and weld metal
  Uniaxial material tests, Bending plate tests, FFAST
- Structural discontinuity of base metal
  FORTUNA, TERMINA, TTS
- Structural discontinuity of unfinished welded joints
  TTS reactor vessel model
- Degradation of weld metal
  Long term material tests
- Scale factors, etc.
  SPTT, STST, TTS

ACKNOWLEDGEMENT

Several helpful discussions in interpretation of material tests with Dr. T. Asayama of OEC/JNC are gratefully acknowledged. Thanks are due to Dr. J.Devos, Dr. F.Touboul and Dr.D.Moulin of CEA-Sacly, and Dr. Y.Wada and Dr.M.Morishita of OEC/JNC, for their kindness to make a chance of cooperative work under the EJCC contract. The author is also deeply indebted to Dr. M.N. Berton for her comments to and correction of documentation.

REFERENCES

[1] Laurent LE BER and Naoto KASAHARA, Interpretation of SOUFFLES experiment: Comparison of the JNC and CEA approaches, JNC TN9400 2001-011,(2000)

[2] Laurent LE BER, et.al., Fatigue and Creep Fatigue of 316L(N) high temperature welded plates submitted to reverse bending, Int. Conf. on integrity of high temperature welds, Nottingham, UK (1998)

[3] Naoto KASAHARA, JNC Benchmark Problem on Creep-Fatigue Evaluation Method for Weldments, EJCC report, (1999)

[4] Y.Wada et al.,'Study on Mechanical Behavior of Weldments of Type 304SSS under Creep-fatigue Loading', ASME PVP-Vol.313-2, pp487/492, (1995)

[5] Asayama,T., 'Creep-fatigue evaluation of welded joints in FBR Class 1 components', 7th Japanese-German Joint International Seminar on Research on Structural strength and NDE Problems in Nuclear Engineering, (1997)

[6] RCC-MR, Design and Construction rules for mechanical components of FBR nuclear islands, AFCEN, (1993)

[7] Kasahara, N. et al., 'Advanced Creep-fatigue Evaluation Rule for Fast Breeder Reactor Components : Generalization of Elastic Follow-up Model', NED 155, pp499/518, (1995)

[8] Iida, K. et al.,'Simplified analysis and design for elevated temperature components of MONJU',NED98, pp305/317., (1987)

[9] Kasahara,N. et al.,'Strain Concentration Evaluation of Smooth Structures Subjected to Thermal Stress', JSME, Proc.of Annual Meeting of JSME/MMD,315 In Japanese,(1993)

[10] Kasahara,N. and Kikuchi,M.,'Proposal of a Strain Concentration Model of Welded Joints for Creep-Fatigue Evaluation of Welded Structures', JSME Int.J.,Series A, Vol.40,No.3 pp247-254,(1997)