Progressive Inelastic Deformation and Residual Stress Effect for a Welded Cylindrical Structure

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ABSTRACT

An evaluation of the progressive inelastic deformation under moving thermal fronts for the Y-type welded cylindrical structure has been carried out by structural test and inelastic analysis. The behaviour of progressive inelastic deformation was evaluated according to the recently developed Japanese liquid metal reactor design code, DDS and a comparison study for the results by the test and DDS code which accommodates the evaluation procedures of the thermal ratchetting dominated by the secondary hoop membrane stresses with negligible primary stresses were carried out. In addition the influence of the residual stresses at the welded part on the global thermal ratchetting deformation was evaluated according to the R6 procedure of the UK procedure.

The thermal ratchetting load of heating the test cylinder up to 550°C was applied 18 times and deformation was measured. The temperature distribution of the test cylinder in the axial direction was measured and this was used for the ratchetting analysis. The thermal ratchet deformations for the welded structure were analyzed with the constitutive equation of the non-linear combined hardening model which was implemented into ABAQUS by means of a UMAT subroutine and the analysis results were compared with those of the test. The residual displacement after 18 cycles of the thermal load was measured to be 5.7mm. The evaluation results by the DDS code showed that the strain limit due to the thermal ratchetting load reached after 10.9 cycles while that of the structural test was 9.4 cycles, which showed that a good agreement. The contribution of the weld residual stresses at the Y-type weld junction to the strain accumulation when calculated according to R6 procedure was estimated to be less than 0.1%. It was shown that the introduction of Y-type welded structure would be an useful way to reduce the ratchet deformation with the slight increase of the stresses within the allowable limit.

1. Introduction

When a cylinder is subjected to cyclically to axial traveling of a temperature front, circumferential strain is forced to accumulate in the travel region as the number of cycles increase. This type of progressive inelastic strain is known as moving free surface induced thermal ratchetting. The ratcheting due to thermal secondary stresses matters in a high temperature liquid metal reactor(LMR) where only moving axial temperature can cause thermal ratcheting under the null-primary-stress condition[1]. Thermal ratcheting in a thin shell structure should be prevented because it can cause dimensional instability due to the excessive deformation.

Since thermal ratchetting can occur only by secondary stresses, it is in contrast with the classical ratcheting

model of Bree type[2] which is based on the combination of primary membrane stress and alternating secondary bending stress in the same direction. The Japanese LMR design code of DDS[3] has the evaluation module of ratchet strains due to not only possible combinations of primary and secondary stress, but also the case that secondary membrane and bending stresses are imposed on the structure simultaneously. In the present study, the evaluation of thermal ratchetting for the welded cylindrical structure according to the DDS was carried out for comparison purposes with the test results. The conventional study on thermal ratcheting of LMR was carried out for the smooth cylinder[4,5]. However an alternative design with geometric discontinuities for the vessel such as the Y-type cylindrical one can to reduce the progressive inelastic deformation while increasing the stress level within the allowable limits[6,7].

If the thermal ratcheting load exceeds allowable limit[3,8,9] in a component, dimensional instability may occur. All the studies on thermal ratcheting were concentrated on the smooth cylindrical structure because thermal ratcheting has been a problem for such a smooth thin cylindrical vessel as reactor baffle or reactor vessel in LMR. However, a study to relax the steep thermal gradients along the axial direction of the reactor vessel by welding a Y-piece type discontinuous structure near the free sodium surface of the reactor baffle has been carried out[10]. In the present study a characteristic thermal ratcheting behavior of the discontinuous structure with plate-to-shell junction has been investigated by test and analysis.

In the present study, thermal ratchet structural tests with a thin 316L stainless steel cylinder with Y-piece junction as well as smooth cylinder were carried out under an axially moving temperature front. The effect of the weld junction on the global thermal ratcheting behaviors has been investigated. As a constitutive model a nonlinear combined isotropic and kinematic hardening model[4,11] implemented[12] as ABAQUS(ABAQUS, 2001) user subroutine was used for thermal ratcheting analysis[5~7].

The effect of the weld residual stresses at the Y-piece junction on the thermal ratchetting was investigated according to the R6[13] procedure and reviewed the description of R5[14] that the contribution of residual stresses on the cyclic load is about 0.1% level.

2. Thermal ratchetting test for the welded cylindrical structure

2.1 Concept of thermal ratchet in pool type LMR

In the present study, the thermal ratcheting structural test was carried out using the structural test facility shown in Fig. 1. In this test facility, the cyclic thermal gradients along the axial direction was simulated by moving the test specimen up and down across the fixed induction heating coil and cooling water whose level maintains constant with an overflow hole at the center as shown in Fig. 1. The schematic diagram of thermal ratchetting test facility with specimen of welded cylindrical structure is shown in Fig.1. The usual ratcheting in light water reactor and industry occurs due to the cyclic variation of mechanical or thermal secondary stress in presence of steady primary stress. In LMR, however ratcheting can occur near the free sodium surface in a reactor baffle as hot sodium moves up and down as shown in Fig. 2(a). This is the typical thermal ratcheting phenomenon which can occur in LMR due to hoop membrane stresses under moving thermal gradients.

The deriving stress of progressive plastic deformation in thermal ratcheting is hoop membrane stress. The distribution of hoop membrane stress along the axial direction of the cylinder moves up and down as hot free sodium surface goes up and down as shown in Fig. 2(b). A point in the traveling range of Fig. 2(b) will experience the stress history of O-A-B-C as shown in Fig. 2(b) and the hysteresis curve of stress-strain relation would be drawn as in Fig 2(c). Assuming the yield stresses remain constant, the inelastic ratchet

strain in circumferential direction per one ratcheting cycle is given as[1].

$$\Delta\varepsilon_\theta^R = \alpha\,\Delta T - 2\sigma_y/E = 2(\sigma_{\theta m} - \sigma_y)/E \tag{1}$$
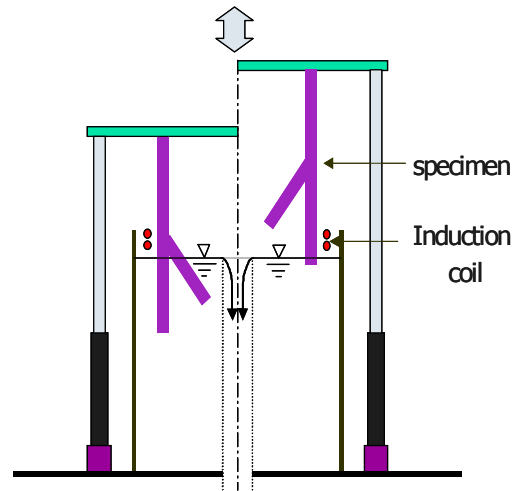

Fig. 1. Schematic diagram of thermal ratchetting test facility

where σ_y and E are yield strength and Young's modulus, respectively. After first cycle, the stress-strain locus will follow O'-A'-B'-C' in a form of progressively increasing inelastic strain as shown in Fig. 3. However, the amount of inelastic deformation usually tends to decrease after first cycle.

The cyclic moving temperature gradients in axial direction can induce inward or outward deformation depending on the geometry of the test specimen and load conditions.
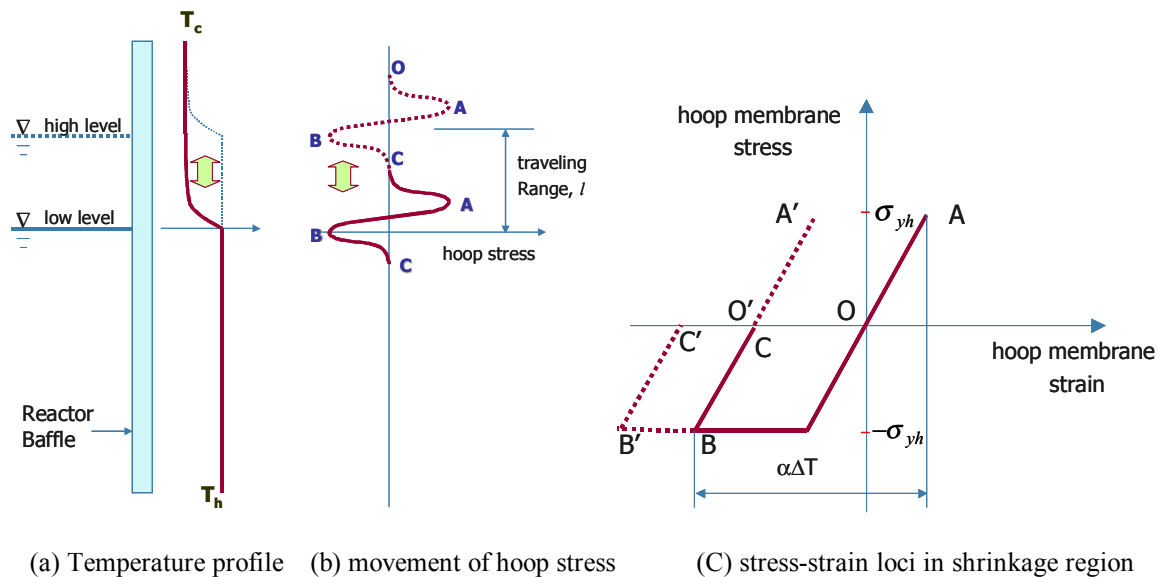

(a) Temperature profile   (b) movement of hoop stress   (C) stress-strain loci in shrinkage region

Fig. 2 Mechanism of thermal ratcheting under moving temperature gradients

2.2 Thermal ratcheting test with welded cylindrical structure

So far all studies on the thermal ratcheting in LMR have dealt with only smooth cylindrical structure without weld junction because there is no discontinuity in the cylindrical structure subjected to thermal

ratchet load. Since a steep temperature gradient along the axial direction of the reactor vessel would induce a severe thermal stresses at the dotted part of the RV in Fig. 3, an alternative design concept of introducing plate-to-shell junction in the reactor baffle structure in order to reduce the thermal gradients in RV along the axial direction was investigated Therefore, it is necessary to carry out thermal ratchet study for the Y-type cylindrical structure.
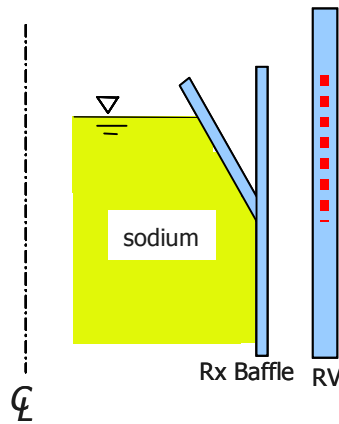

Fig. 3. An alternative design concept of reactor baffle with weld junction to reduce thermal stress at reactor vessel

In the present study thermal ratcheting behavior of welded cylindrical specimen shown in Fig. 4(a) has been compared with that of the smooth cylinder shown in Fig. 4(b). All of the test specimens were made of Type 316L stainless steel and the shell part of the structural specimen has a diameter of 600mm and height of 500mm.

The influence of the weld junction on the ratcheting deformation is to be investigated in this study. The effect of residual stresses generated during weld fabrication is not important in ratchet condition. R5[14] says that the maximum contribution of the weld residual stress is of 0.1% order in strain and its effect would   be negligible as the ratchet load is applied cyclically.

A series of thermocouples were welded on the inner surface along the axial direction every 10mm from 135mm to 365mm from the bottom edge of the shell, and 4 thermocouples were welded at the locations of 10mm, 20mm, 50mm and 100mm on the lower surface of the plate as shown in Fig. 4(b) for the data acquisition of transient temperature profiles.

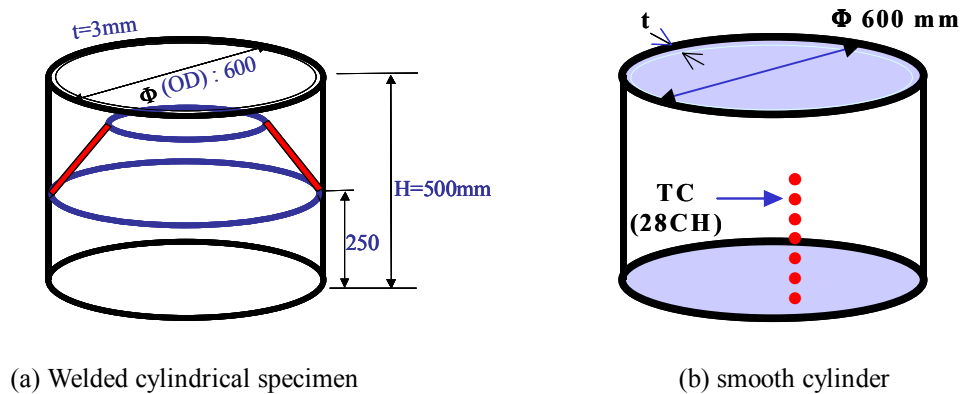(a) Welded cylindrical specimen   (b) smooth cylinder
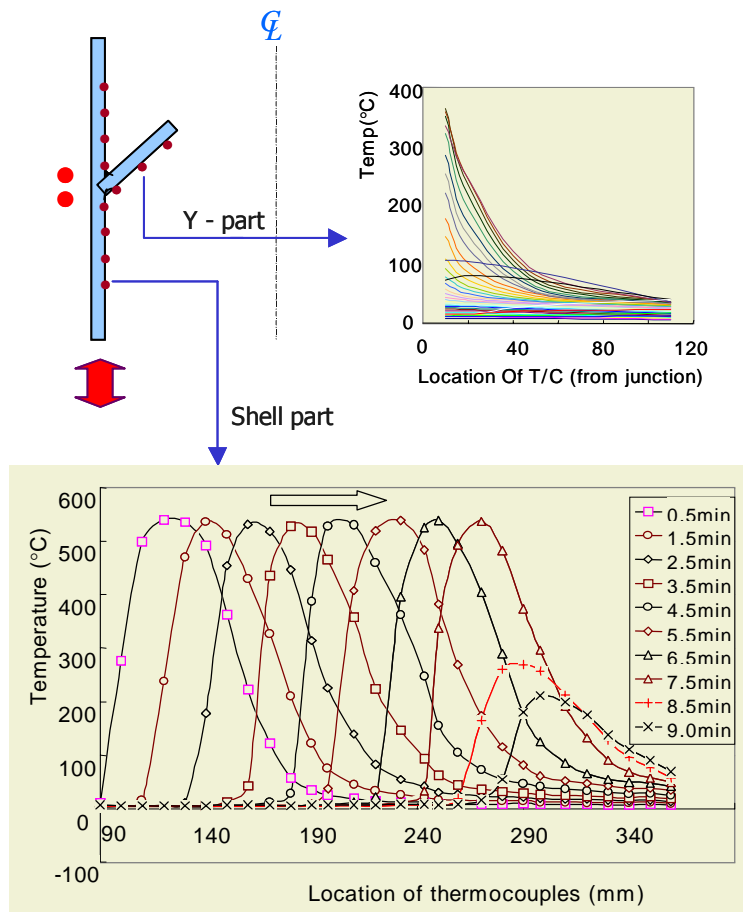Fig. 4 Schematic diagram of the test cylinders
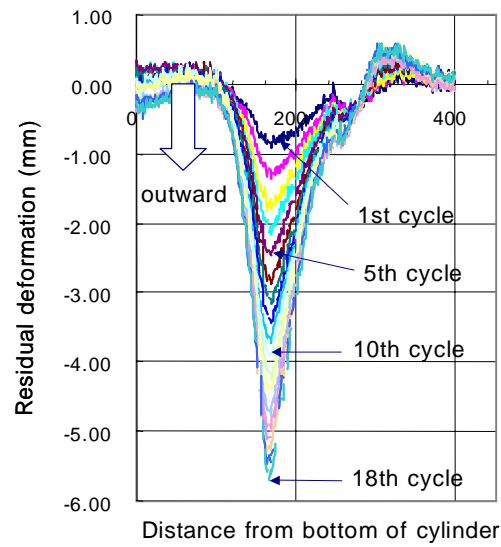
Fig. 5. Moving temperature profile

Fig. 6. Accumulation of residual deformation for welded cylindrical structure

The temperature profile measured by the thermocouples along the axial direction is shown in Fig. 5 which shows that a pattern of heating and cooling is shifted as the cylinder moves downward into the pool at the shell part. At the right part of weldment the temperature decays steeply as the location goes farther from the shell. The transient temperature data acquired at 28 channels of the thermocouples attached on the test specimen are shown in Fig. 5. Each pattern curve in Fig. 5 was plotted every 30 seconds.

The measured ratchet deformations show that the deformation is accumulated cycle by cycle. The progressive deformation after 18cycles was measured to be 5.7mm outwardly. It should be noted that the biggest deformation under thermal ratcheting load occurs at the first cycle.

3. EVALUATION OF THERMAL RATCHETING PER JAPANESE DDS DESIGN CODE

3.1 Thermal ratcheting strain for pool type reactor (ε_{mR1})

For actual pool type LMR where temperature gradients are moving axially, a large secondary membrane stresses are induced and the primary stresses are negligible. In order to calculate the ratcheting strain for the shell part, the value of L, W should be determined first.

$$L = \frac{\sqrt[4]{3(1-v^2)}}{\sqrt{D_i t / 2}} \cdot l$$

$$(2)$$

$$W = \frac{X}{X - 0.5Z} - 1$$

where

$$X = \left\langle P_L + P_L^* + P_b / K_t + P_b^* / K_t + Q_m + Q_m^* \right\rangle_{max} / S_y$$

$$Y = \left\langle Q + Q^* - Q_m - Q_m^* \right\rangle_R / S_y$$

$$(3)$$

The ratcheting factor of Z is determined as follows

$$Z = 2\left[X - \frac{\sqrt{3}X}{2(1-v^2)Y} \ln\left(\frac{\sqrt{3X^2 + (1-v^2)Y^2} + (1-v^2)Y}{\sqrt{3X^2 + (1-v^2)Y^2} - (1-v^2)Y} \right) \right]$$

$$(4)$$

If the calculated point of (L,W) is inside O, formula (5) is to be applied while inside I, formula (6) is to be applied.

$$\varepsilon_{mR1} = \sum_i \left(\frac{Z_i S_y}{E} \right)$$

$$(5)$$

$$\varepsilon_{mR1} = A \cdot Z \cdot \frac{S_y}{E}$$

$$(6)$$

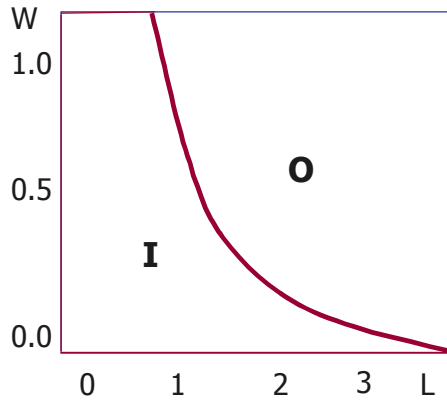where the constant of A in eqn (6) is determined from L in Fig. 8.
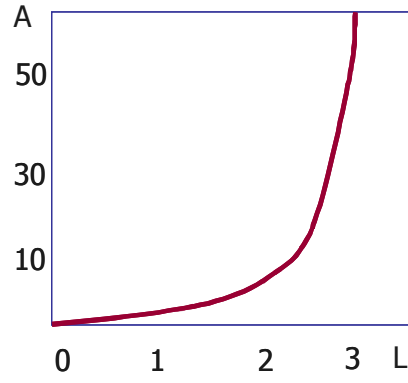
Fig. 7 Ratchetting region   Fig. 8 A's curve

3.2 Determination of ε_{mR1}

ε_{mR1} due to the movement of temperature distribution per DDS is calculated as follows; The following values are determined using linear elastic evaluation procedure of DDS rule

$$P_L, P_L^*, P_b, P_b^* \approx 0$$

$$Q = 270\,(\text{Mpa}), \quad Q_m = 213.33\,(\text{Mpa}), \quad \sigma_y = 135.8$$

$$X = \left\langle P_L + P_L^* + P_b/K_t + P_b^*/K_t + Q_m + Q_m^* \right\rangle_{max} / \sigma_y = \frac{213.33}{135.8} = 1.57 \tag{7}$$

$$Y = \left\langle Q + Q^* - Q_m - Q_m^* \right\rangle_R / \sigma_y = \frac{56.67}{135.8} = 0.417$$

Then the ratcheting factor of Z is determined as follows

$$Z = 2\left[X - \frac{\sqrt{3}X}{2(1-v^2)Y} \ln\left(\frac{\sqrt{3X^2 + (1-v^2)Y^2} + (1-v^2)Y}{\sqrt{3X^2 + (1-v^2)Y^2} - (1-v^2)Y} \right) \right] \tag{8}$$

$$= 0.885$$

Calculating the Z values according to eqn (8) in axial direction, the traveling zone of Z>0 was evaluated to be about 45mm.

Height*	Z
365mm	-0.637
350	0.784
355	1.146
315	0.244
310	-0.328

＊：Distance from bottom

Inserting this *L* value into eqn (9).

$$L = \frac{\sqrt[4]{3(1-v^2)}}{\sqrt{D_i t/2}} \cdot l = 1.935 \tag{9}$$

$$W = \frac{X}{X - 0.5Z} - 1 = = 0.574$$

Since this (*L,W*) point is inside I in Fig. 5, eqn (9) should be applied. Therefore the amount of accumulation per cycle is 0.0917% as shown in eqn (10).

$$\varepsilon_{R2} = \sum_i^N \left(\frac{Z_i S_y}{E} \right) = \sum_i^N \left(\frac{1.1484 \times 135.8 \times 10^6}{170 \times 10^9} \right) \tag{10}$$

$$= 0.0917\% \times N$$

In the meantime assuming the strain is wholly induced by thermal ratcheting, the limit number of cycles reaching the limit strain (1% for base metal and 0.5% for weld metal) is calculated as 10.9 cycles for the base metal while the maximum strain for the welded part was less limiting. Therefore, the stain limit of DDS rule will be exceeded if ratcheting cycles are applied greater than 11 cycles. Comparing the results by the test and evaluation per DDS code, the two results are in good agreement, which shows that DDS procedure yields quite realistic results.

4. ASSESSMENT OF RESIDUAL STRESS EFFECT PER R6

The UK assessment code R6[13] "Assessment of the integrity of structures containing defects" code suggests the evaluation procedure for residual stresses at section II.27 of Chapter 2. The R6 gives three evaluation procedures of Level I(Simple Estimate), Level II(Bounding Profile) and Level III(Detailed Evaluation).

In Level I procedure, the transverse and longitudinal(welding line direction) residual stresses are set to 1% proof stress of the materials uniformly because it is less variable than 0.2% proof stress for austenitic steels. In the present analysis the residual stress is assumed to be short range stress where no elastic follow-up is accompanied.
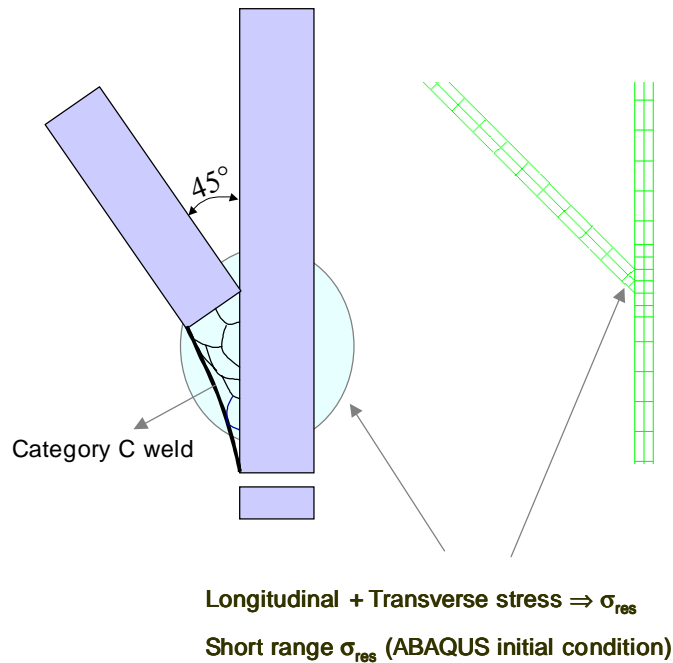

Fig. 9. Finite element analysis model for the welded structure

4.1 Finite element modeling

For the finite element analysis using ABAQUS axisymmetric 8-node 310 elements with 1173 nodes were used for the case of plate thickness 6mm, 256 elements with 1027 nodes for the case of plate thickness 3mm and 300 elements with 987 nodes for the smooth cylinders. As a boundary condition, the top surface was fixed in the axial direction. Fig. 9 shows the finite element model for the present analysis.

Since the moving speed of the specimen is as low as 19mm/min and the stress induced by the buoyancy force is very small compared with the thermal stress the buoyancy force was neglected. In the present analysis, the transient axial temperature distributions acquired from the ratcheting test were used as thermal ratchet load.

4.2. Constitutive model

The classical constitutive models can not predict realistically the progressive inelastic behavior of the cyclic hardening for stainless steel components. In this study, the Chaboche-Rousselier non-linear combined hardening model[15-16] of isotropic and kinematic hardening which is known to predict the behavior of ratcheting more realistically was implemented into ABAQUS as a UMAT subroutine.

For the assessment per R6, the elastic-plastic analysis with combined hardening model was carried out and the effect of the residual stresses on the progressive inelastic deformation was investigated.

4.3 Analysis results
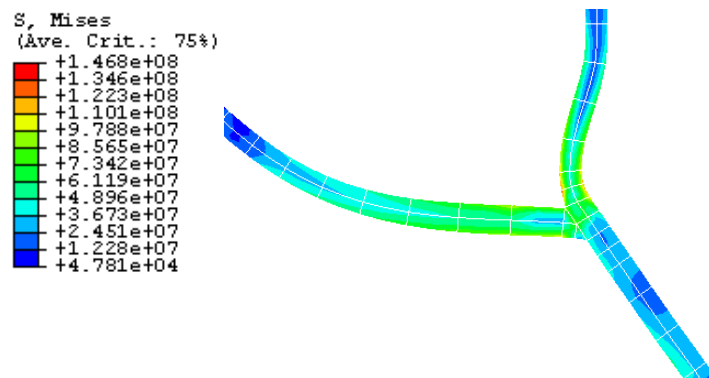### 4.3.1 When residual stress not considered (7th cycle)

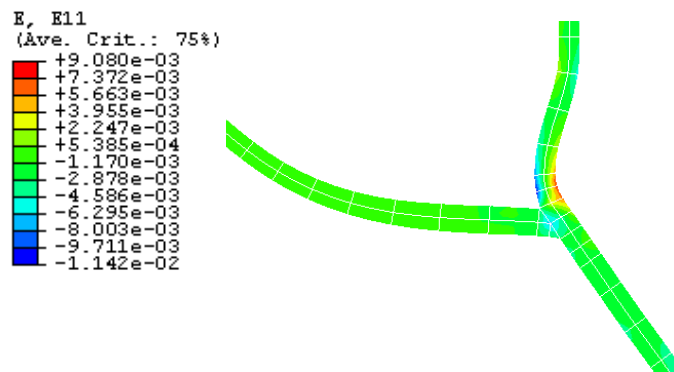Fig. 10. Computed Mises stresses for the welded structure when residual stresses not considered

Fig. 11. Computed radial strains for the welded structure when residual stresses not considered
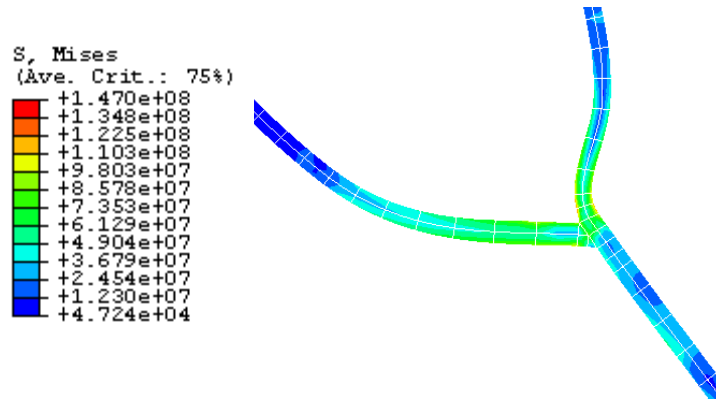
4.3.2 When residual stress considered (7th cycle)

S, Mises
(Ave. Crit.: 75%)
+1.470e+08
+1.348e+08
+1.225e+08
+1.103e+08
+9.803e+07
+8.578e+07
+7.353e+07
+6.129e+07
+4.904e+07
+3.679e+07
+2.454e+07
+1.230e+07
+4.724e+04

Fig. 12. Computed Mises stresses for the welded structure when residual stresses considered

E, E11
(Ave. Crit.: 75%)
+9.354e-03
+7.571e-03
+5.789e-03
+4.007e-03
+2.225e-03
+4.431e-04
-1.339e-03
-3.121e-03
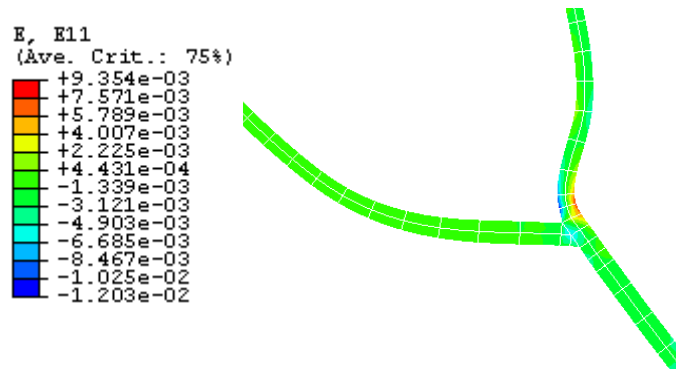-4.903e-03
-6.685e-03
-8.467e-03
-1.025e-02
-1.203e-02

Fig. 13. Computed radial strains for the welded structure when residual stresses considered

It was shown from Fig. 10~13, the weld residual stresses has small effect on the stresses and deformations. The two results with and without residual stresses for radial strains, residual deformation and Mises stresses are shown in Fig. 14 and Fig. 15.
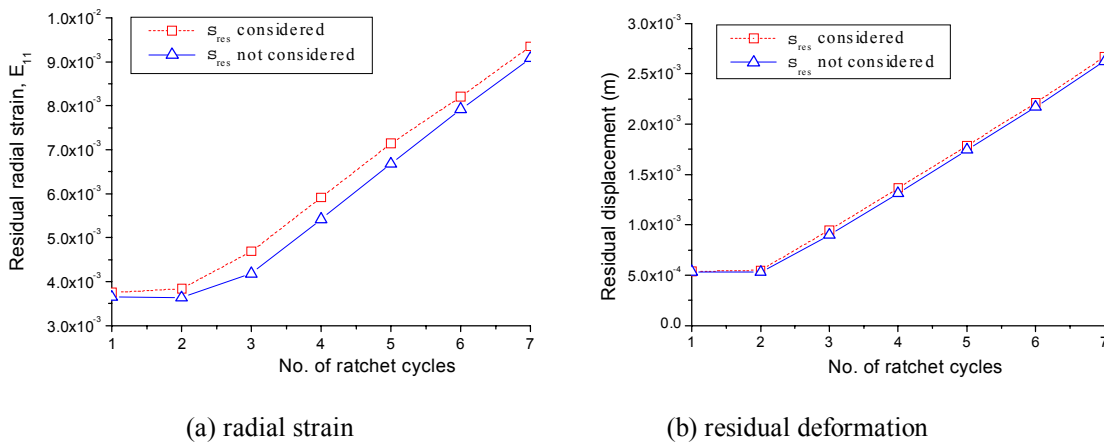

(a) radial strain

(b) residual deformation

Fig. 14. Comparing the analysis results for the cases with and without residual stresses
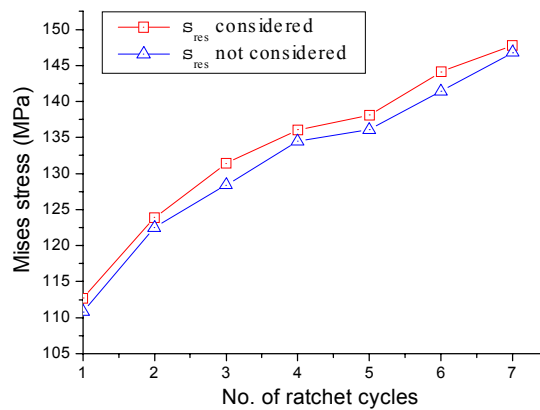
Fig. 15. Comparing the Mises stresses for the cases with and without residual stresses

From the above analysis results, it is shown that the final evaluation results per the Level I procedure of R6 has shown that the overall contribution of the weld residual stress was less than 0.1% to the global ratcheting strain. This corresponds to the statement of R5 which says that the weld residual stress would have less than 0.1%(which is about the order of σ_y/E).

5. Conclusions

In this study, the progressive inelastic deformation of 316L stainless steel cylinder with weld junction under moving temperature front was investigated by a thermal ratcheting test and the corresponding analysis. The evaluation of the test results using the Japanese DDS code was carried out and comparison between the structural test results and DDS code rule was carried out. The effect of weld residual stresses was evaluated according to the UK assessment rule Chapter 2, Section II.7 of R6. The test results and the evaluation results be per DDS rule were in good agreement.

Since the weld junction attached on a reactor baffle structure can reduce the ratchet deformation, cylindrical structure with Y-junction can be a promising design alternative within the limit of load controlled stresses because thermal stress would increases while deformation decreases.

From the evaluation of the residual stresses according to R6 procedure has shown that the overall contribution of the weld residual stress was less than 0.1% to the global ratcheting strain. This corresponds to the statements of R5 which says that the weld residual stress would have less than 0.1% which is the level of σ_y/E for the material.

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