# Progressive Inelastic Deformation Characteristics of Cylindrical Structure with Plate-to-Shell Junction Under Moving Temperature Front

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A study on the progressive inelastic deformation behavior of the 316 L stainless steel cylindrical structure with plate-to-shell junction under moving temperature front was carried out by structural test and analysis. The structural test intends to simulate the thermal ratcheting behavior occurring at the reactor baffle of the liquid metal reactor as free surface of hot sodium pool moves up and down under plant transients. The thermal ratchet load that heats the specimen up to 550℃ was applied repeatedly and residual deformation was measured. The thermal ratcheting test was carried out with two types of cylindrical structures, one with plate-to-shell junction and the other without the junction to investigate the effects of the geometric discontinuities on the global ratcheting deformation. The temperature distributions of the test specimens were measured and were used for the ratcheting analysis. The ratchet deformations were analyzed with the constitutive equation of the non-linear combined hardening model. The analysis results were in good agreement with those of the structural tests.

**Key Words :** Thermal Ratcheting, Plat-to-Shell Junction, 316 L Stainless Steel, High Temperature Structure, Liquid Metal Reactor, Combined Hardening Model

## 1. Introduction

For a structure subjected to cyclic variations of mechanical or thermal secondary stresses, it is necessary to evaluate whether it will undergo progressive deformation, so-called ratcheting, or shakedown to a steady state of cyclic strain. The ratcheting due to mechanical secondary stresses usually matters in the case of a pressurized pipe and vessel under bending (Schwertel and Schinke, 1996) or torsion while the ratcheting due to thermal secondary stresses matters in a high temperature liquid metal reactor (LMR). In the LMR, it is well known that only moving axial temperature can cause thermal ratcheting under the null-primary-stress condition (Igari, et. al., 2002 ; Igari, et. al., 2000). Thermal ratcheting in a thin shell structure should be prevented because it can cause dimensional instability due to the excessive deformation. If the thermal ratcheting load exceeds allowable limit (ASME, 2001 ; RCC-MR, 1993 ; Wada, et. al., 1997) in a component, dimensional instability may occur. It was investigated that 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 (Koo and Lee, 2002). In the present study a characteristic thermal ratcheting behavior of the discontinuous structure with plate-to-shell junction has been

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investigated by test and analysis.

Since ratcheting in an austenitic stainless steel component includes the plastic deformation with cyclic hardening, it is necessary to employ a sophisticated non-linear constitutive model to simulate the progressive inelastic behavior realistically (Lemaitre and Chaboche, 1990; Kobayashi and Ohno, 1996; Chaboche and Rousselier, 1983). A nonlinear combined isotropic and kinematic hardening model (Lee, et. al., 2000) was implemented as ABAQUS (ABAQUS, 2001) user subroutine and was used for thermal ratcheting analysis (Lee, et. al., 2002; Yoon, et. al., 2000).

In the present study, a thermal ratchet structural tests with a thin 316 L stainless steel cylinder with plate-to-shell 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. In addition, the ratchet deformation mechanism of contraction or expansion mode was investigated under various cases of load and geometry.

## 2. Thermal Ratcheting Test

### 2.1 Concept of thermal ratchet in LMR

A progressive inelastic strain can occur when the stress range exceeds twice the yield stress ($2\sigma_y$) as shown in Fig. 1(b) while the component is said to be in a shakedown condition if the structure always remains elastic (stress range < $2\sigma_y$) except for the first loading during which plastic strains may occur as shown in Fig. 1(a) for elastic-perfectly plastic material.

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 defor-

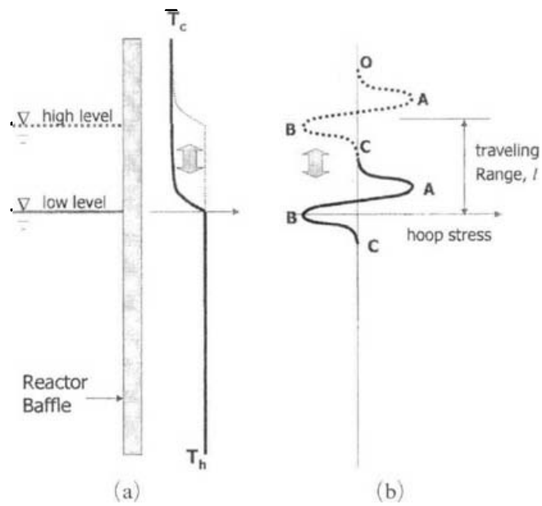



**Fig. 2** Concept of moving temperature front and corresponding hoop stress distribution

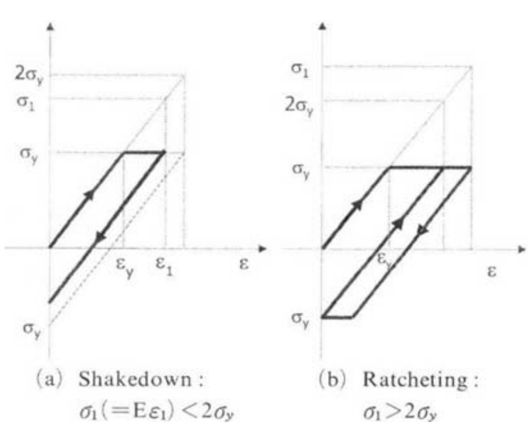



**Fig. 1** Concept of thermal ratchet phenomenon

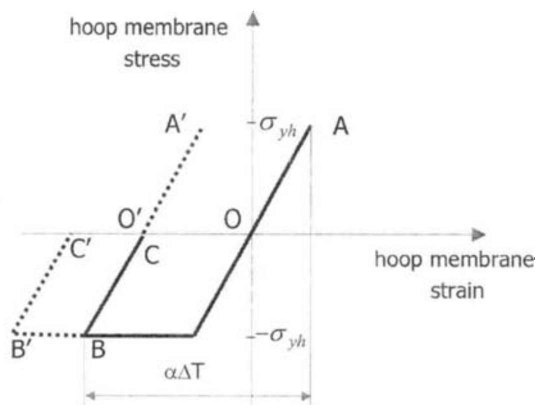



**Fig. 3** Stress-strain loci in shrinkage region

mation 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 3. Assuming the yield stresses remain constant, the inelastic ratchet strain in circumferential direction per one ratcheting cycle is given as (Igari, et al., 2002)

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

where $\sigma_y$ 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.

## 2.2 Thermal ratcheting test

In the present study, the thermal ratcheting structural test was carried out using the structural test facility shown in Fig. 4. 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. 4.

So far all the 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. 5, 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 as shown in Fig. 5(a) was

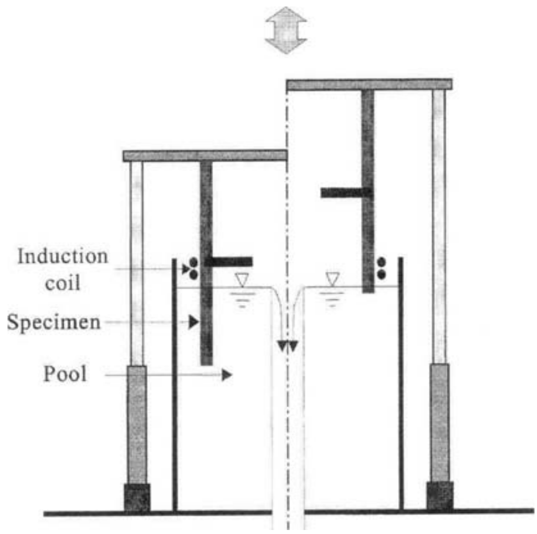



Fig. 4 Schematic diagram of thermal ratcheting test facility

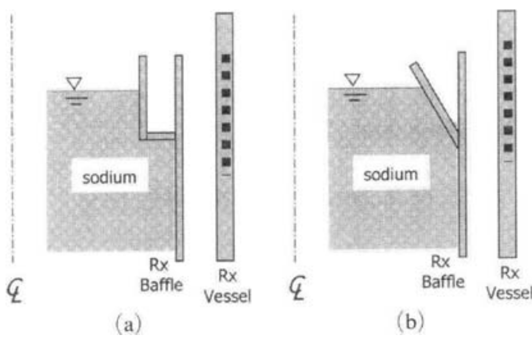
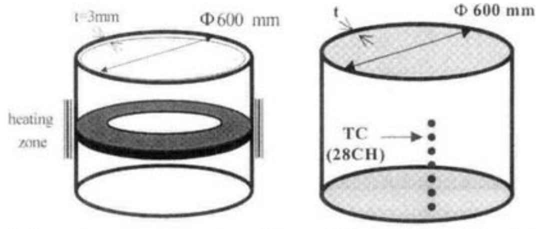



Fig. 5 Thermal ratcheting near hot free surface at reactor baffle with plate-to-shell junction

investigated (Koo and Lee, 2002). Therefore, it is necessary to carry out thermal ratchet study for the plate-to-shell junction.

In the present study thermal ratcheting behavior of plate-to-shell junction shape shown in Fig. 6(a) has been compared with that of the smooth cylinder shown in Fig. 6(b). All of the test specimens were made of Type 316 L stainless steel and the shell part of the structural specimen has a diameter of 600 mm and height of 500 mm. The four specimens were used in the present study ; two specimens with junction have the plate thickness of 3 mm and 6 mm, respectively in plate-to-shell junction. Another two smooth specimens have the thickness of 1.5 mm and 3 mm, respec-




(a) cylindrical shell with plate-to-shell junction (2EA)

(b) smooth cylinder (2EA)

**Fig. 6** Schematic diagram of the test cylinders

tively. The width of the plate for the welded structure is 120 mm. The heating zone of the specimen for all cases is 15 cm over the mid part of the specimen as shown in Fig, 6(a). The heating zone of the specimen would be subjected to moving temperature front.

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 (R5, 1998) 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 10 mm from 135 mm to 365 mm from the bottom edge of the shell, and 4 thermocouples were welded at the locations of 10 mm, 20 mm, 50 mm and 100 mm on the lower surface of the plate as shown in Fig. 7 for the data acquisition of transient temperature profiles. The residual displacement of the specimen was measured by a laser displacement sensor and two LVDTs (Linear variable displacement transducers) arranged every 120° in circumferential direction were used to measure the ratcheting deformation.

## 3. Ratcheting Test Results

### 3.1 Temperature profiles

The thermal ratcheting load was applied repeatedly more than 7 times for the four specimens. The transient temperature data acquired at 28 channels of the thermocouples attached on the test

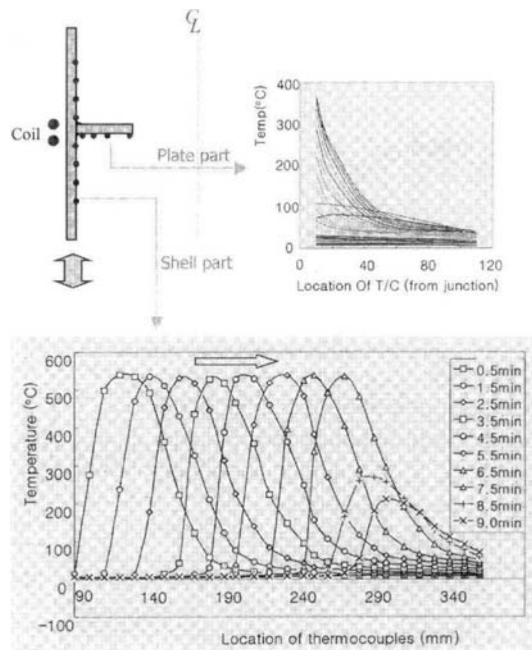



**Fig. 7** Temperature profiles measured by 28 channel thermocouples

specimen are shown in Fig. 7. The transient temperature distribution at the shell part moves gradually to the right as the cylindrical specimen moves down into the pool in Fig. 4 while the temperature profile in radial direction of the plate part decreases very steeply as shown in Fig. 7. Each pattern curve in Fig. 7 was plotted every 30 seconds.

### 3.2 Residual deformation

The progressive residual deformation for each cycle of thermal ratchet loading was measured after cooling down the specimen to room temperature. Fig. 8 shows the accumulation feature of radial ratchet deformation measured by laser sensor for the specimen with plate thickness of 3 mm. The deformation profile of the specimen with junction in axial direction is quite different from that of the smooth cylinder whose feature shows a smooth accumulation as shown in Fig. 9.

It is shown that the presence of plate-to-shell junction decreases the amount of ratchet deformation and induces different deformation shapes from that of the smooth cylinder as shown in

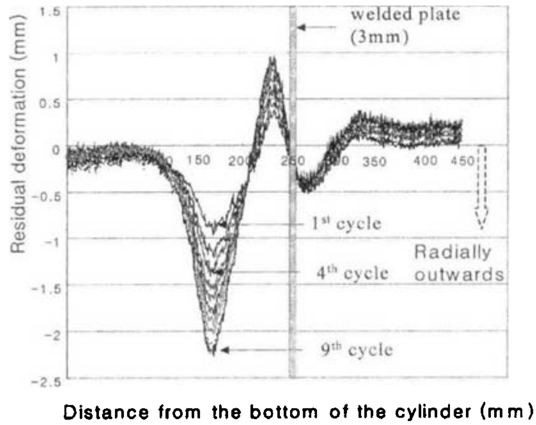



**Fig. 8** Accumulation feature of residual deformation in axial direction for specimen with plate-to-shell junction

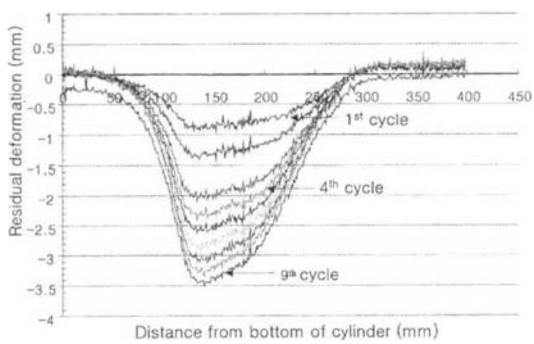



**Fig.9** Accumulation feature of residual deformation in axial direction for smooth specimen

Fig. 8 and Fig. 9. As for the specimen with weld junction the progressive deformation mainly occurred near the location of 170 mm from the bottom edge of the shell and the deformations were accumulated outward. However, the deformation at the location near 220 mm is inward and the amount of accumulation was less than outward deformation. The maximum residual deformation after the 7$^{th}$ cycle was measured to be 1.91 mm.

The test results for the smooth cylinder showed that the deformation for the thickness of 3 mm was 2.88 mm after 7$^{th}$ cycle while that for the thickness of 1.5 mm was 3.95 mm as shown in Table 1. This test results corresponds with the physical concept that as the thickness decreases the deformation increases while the stress decreases.

**Table 1** Maximum residual deformations measyred by laser sensor for various specimen geometries

| specimen | thickness (mm) | $\lvert u_r \rvert_{max}$ after 7th cycle (mm) |
|---|---|---|
| Cylinder with junction | 3 (plate part) | 1.91 |
| | 6 (plate part) | 1.85 |
| Smooth cylinder | 1.5 (shell) | 3.95 |
| | 3 (shell) | 2.88 |

The test results for the cylindrical structure with plate-to-shell junction show that the deformation for plate thickness of 3mm is 1.91 mm while that for the plate thickness of 6 mm was 1.85 mm after 7$^{th}$ cycle as shown in Table 1. These results indicate that the ratchet deformations for the cylinders with junction were similar but quite smaller than those of the smooth cylinders. It is to be noted that the plate welded to the shell acts as a constraint to the structure so that it decreases the deformation as shown in Table 1 and increases the stresses as explained in section 4.3.

## 4. Analysis of Thermal Ratcheting

### 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 6 mm, 256 elements with 1027 nodes for the case of plate thickness 3 mm and 300 elements with 987 nodes for the smooth cylinders. As a boundary condition, the top surface was fixed in the axial direction.

The loads acting in the specimen are the thermal transient loads as well as the dead weight. However, the deadweight induces an axial stress of 0.01 MPa order. So the deadweight was neglected in the analysis.

Since the moving speed of the specimen is as low as 19 mm/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 (Lemaitre and Chaboche, 1990) of isotropic and kinematic hardening which is known to predict the behavior of ratcheting more realistically was implemented into ABAQUS as a UMAT subroutine.

The non-linear combined hardening model has a yield condition with internal state variables and utilizes the normality hypothesis with the associated flow rule:

$$d\varepsilon^{p}=\frac{3}{2}d\lambda\frac{\sigma'-X'}{J_2(\sigma-X)} \tag{2}$$

$$d\lambda=\frac{H(f)}{h}\left\langle\frac{3}{2}\frac{\sigma'-X'}{J_2(\sigma-X)}d\sigma\right\rangle \tag{3}$$

$$J_2(\sigma-X)=\sqrt{\frac{3}{2}(\sigma-X):(\sigma-X)} \tag{4}$$

$$f=J_2(\sigma-X)-R-\kappa \tag{5}$$

$$h=C=\frac{3}{2}\gamma X\frac{\sigma'-X'}{J_2(\sigma-X)}+b(Q-R) \tag{6}$$

where $d\lambda$ : plastic multiplier
$\sigma$ : deviatoric stress tensor
$X'$ : deviatoric back stress tensor
$X$ : back stress
$J_2(\sigma-X)$: the second invariant of the deviatoric stresses
$R$ : drag stress in isotropic hardening
$p$ : accumulated plastic strain
$d\varepsilon^p$ : plastic strain increment
$f$ : yield condition
$h$ : hardening modulus
$H(f)$ : Heaviside step function
$\kappa$ : initial yield stress

$$\langle x\rangle=\begin{cases}x \text{ if } x>0\\ 0 \text{ if } x<0\end{cases}$$

The rate of back stress describing kinematic hardening is

**Table 2** Material parameters for the non-linear combined hardening model

| parameters | value |
|---|---|
| C | 92400 (MPa) |
| $\sigma$ | 1390 |
| b | 14.6 |
| Q | 51.1 (MPa) |
| $\kappa$ | 59.4 (MPa) |

$$\dot{X}=\frac{2}{3}Cd\varepsilon^{p}-\gamma X\dot{p} \tag{7}$$

where $C$ and $\gamma$ are material parameters describing the kinematic hardening, respectively and $\dot{p}$ is accumulated plastic strain rate.

Eq. (7) describes the evolution of the back stress in kinematic hardening based on Prager hardening law and the recall term is included to introduce nonlinear relationship between back stress and plastic strain increment.

The evolution of isotropic hardening variable is

$$\dot{R}=b(Q-R)\dot{p} \tag{8}$$

where $Q$ is the asymptotic value which corresponds to a regime of stabilized cycles and $b$ indicates the speed of the stabilization. There are five material constants in the present model besides Young's modulus and Poisson's ratio, $C$, $\gamma$, $b$, $Q$ and $\kappa$ whose procedure values (Schwertel and Schinke, 1996; Yoon, et al., 2000) are given in Table 1.

Chaboche has suggested different versions of time-independent constitutive models (Lemaitre and Chaboche, 1990; Chaboche and Rousselier, 1983). The kinematic hardening term in the above constitutive model is based on the Prager hardening law, which is different from that of the ABAQUS combined hardening model based on Ziegler hardening law (Lemaitre and Chaboche, 1990).

The formulation from Eqs. (2) to (8) has been implemented into ABAQUS by means of a UMAT subroutine. The solution of the non-linear algebraic differential equations arising from time discretization with the generalized mid-point rule is determined by using the line-search technique in combination with the Broyden method.

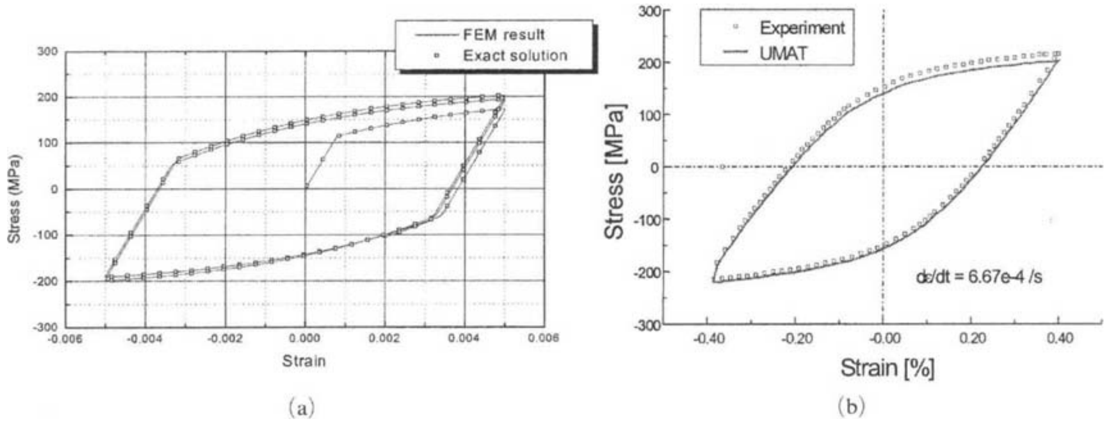



**Fig. 10** Validation of ABAQUS subroutine UMAT

For validation of the UMAT, a uniaxial cyclic hardening test with material specimen was carried out and also a uniaxial cyclic hardening problem was solved by this exact solution using the DREBS subroutine of IMSL (IMSL, 2000). It was shown that the analysis results with the ABAQUS UMAT are in good agreement with the experimental result and the exact solution result as shown in Fig. 10(a) and 10(b), respectively.

### 4.3 Deformation modes under ratcheting load

It is interesting to see that the ratchet deformation can occur inward or outward according to the load condition or geometric shapes as shown in Fig. 11. Fig. 11(a) shows that when the traveling speed for the smooth cylinder increases 2, 4 or 8 times against the reference thermal load (geometry fixed), the ratchet deformation is gradually changed from outward to inward.

In addition, when the thickness of the shell changed from 3 mm to 2 cm, 3 cm, 4 cm or 5 cm under fixed load condition, it was shown that the ratchet deformation gradually changed from outward to inward direction as shown in Fig. 11(b).

It was shown that the factor which affects the deformation of inward or outward direction was the temperature gradients along the thickness direction. When the temperature distribution maintains uniform over the thickness as the thickness is changed, the deformation mode does not change while the deformation mode can be changed if

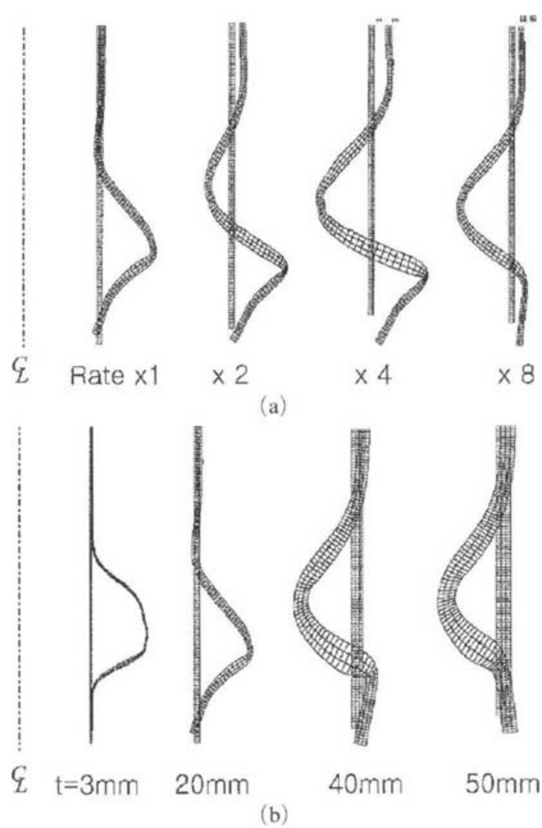



**Fig. 11** Change of ratchet deformation from outward to inward depending on various load conditions and geometries

there is temperature gradient over the thickness as shown in Fig. 11(b) and Table 3. Table 3 shows that as the thickness of the cylinder increases, the deformation decreases while the

**Table 2** Thermal ratchet analysis results for the smooth specimen

| Thickness (mm) | Mises stress (MPa) | Deformation (mm) |
|---|---|---|
| 0.3 | 93.5 | 4.0 |
| 2 | 101 | 1.72 |
| 3 | 103 | 0.9 |
| 4 | 107 | −2.2 |
| 5 | 118 | −1.5 |

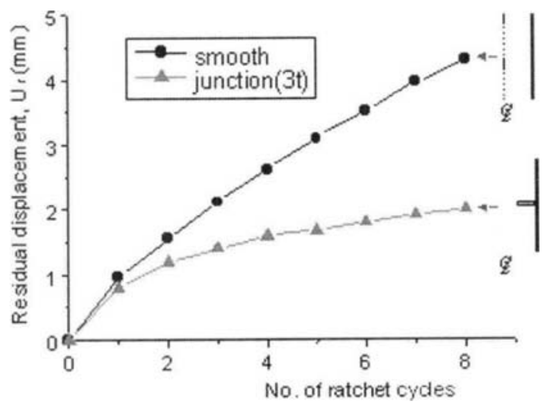



**Fig. 12** Comparison of test results for smooth cylinder and cylinder with plate-to-shell junction

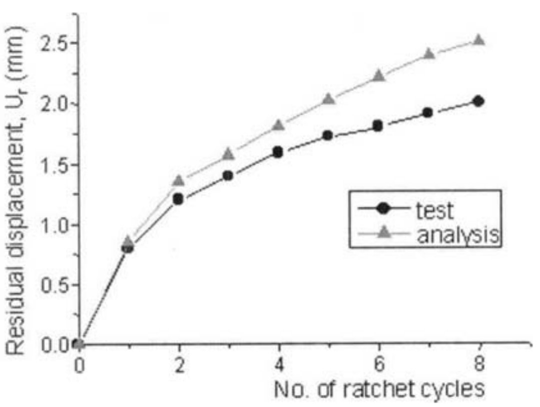



**Fig. 13** Comparison of ratchet deformation for the test and analysis for cylinder with plate-to-shell junction

stress level increases.

### 4.4 Comparison of the results between test and analysis

The ratchet deformation for the smooth cylinder increased rather more steeply than that of the cylindrical shell with plate-to-shell junction as the cyclic load increases as shown in Fig 12. The von Mises stress computed for the smooth cylinder and cylindrical structure with junction were 78.4 MPa and 155 MPa, respectively, which means that the junction reduces the ratchet deformation and increases the stress. The junction structure in the shell acts as a constraint in deformation so that it induces less deformation and high stresses.

Comparing the results by the test and analyses for the cylinder with plate-to-shell junction with thickness of 3 mm, the results by the analysis tend to overestimate slightly those of the tests as shown in Fig. 13. The inelastic strains due to creep and elastic follow-up (ASEM-NH, 2001, RCC-MR, 1993) can occur at high temperature in this cylinder with junction. However, as no creep load or hold time was applied, this effect can be neglected. This means that the measured inelastic deformation would be used to determine ratchet strain.

## 5. Conclusions

In this study, the progressive inelastic deformation of 316 L stainless steel cylinder with plate-to-shell junction under moving temperature front was investigated by a thermal ratcheting test and the corresponding analysis. Thermal ratcheting tests with four structural specimens having different plate thickness in plate-to-shell junction and different shell thickness were carried out. A case study showed that the deformation can be changed from inward to outward direction depending on the load and geometry conditions. As the plate thickness increases the deformation decreased and the stresses increased. However, the global accumulation features of residual deformation were similar. The ratcheting analysis results with nonlinear combined hardening model showed that the analyses results slightly overestimate those of the tests. The effect of changing plate thickness in the plate-to-shell junction on ratcheting behavior was relatively small and the amount of deformations were almost the same.

Since the plate-to-shell junction attached on a reactor baffle structure can reduce the ratchet deformation, cylindrical structure with junction can be a promising design alternative.

## Acknowledgment

This work was performed under the long term nuclear R&D program sponsored by the Ministry of Science and Technology of Korea.

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