Study on a unified criterion for preventing plastic strain accumulation due to long distance travel of temperature distribution

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Abstract
The prevention of excessive deformation by thermal ratcheting is important in the design of high-temperature components of fast breeder reactors (FBR). In an experimental study that simulated a fast breeder reactor vessel near the coolant surface, it was reported that the long distance travel of temperature distribution causes a new type of thermal ratcheting, even in the absence of primary stress. In this paper, we propose a simple screening criterion to prevent continuous accumulation of plastic strain derived from long distance travel of temperature distribution. The major cause of this ratcheting is the lack of residual stress that brings shakedown behavior at the center of yielding area. Because residual stresses are derived from constraint by the neighboring elastic region, we focused on the distance from the center of yielding area to the elastic region. Accordingly, the proposed criterion restricts the axial length of the full-section yield area, which is the double of the above distance. We validated the proposed criterion based on finite element analyses using an elastic-perfectly plastic material. As a result of the validation analyses, we confirmed that the accumulation of plastic strain saturates before second cycles in the cases satisfying the proposed criterion, regardless of the shape of temperature distribution.

Keywords: Ratcheting, Plastic strain, Thermal stress, Traveling temperature distribution, Finite element analysis

1. Introduction

The prevention of excessive deformation due to thermal ratcheting is important in the design of high-temperature components of fast breeder reactors (FBR). In an experimental study (Igari et al., 1990) that simulated a FBR vessel wall near the coolant surface, it was reported that the long distance travel of temperature distribution causes a new type of thermal ratcheting, in the absence of primary stress. Since the current elevated temperature design codes (ASME, 2015) (JSME, 2012) have not considered this ratcheting, development of a design evaluation method to prevent this ratcheting mechanism is desired.

Several studies about this ratcheting mechanism have been conducted. Wada et al. (1989, 1993) proposed an evaluation method for increment in plastic strain due to long distance travel of temperature distribution. Igari et al. (2000) proposed an evaluation method that considered the effect of travel distance. In addition, we have proposed and validated a screening criterion for this ratcheting mechanism (Okajima, 2016a, 2016b). In our previous studies, we assumed a reactor vessel wall near the coolant surface as the target equipment.

Although strength evaluation is required for a large number of FBR equipments, almost all equipments are not subjected to this ratcheting mechanism. Therefore, rather than detailed evaluation method, a simple screening method is required for this ratcheting mechanism. In addition, it is desirable that the screening method can be uniformly applied to various types of temperature distributions.

The major cause of this ratcheting is the lack of residual stress that brings shakedown behavior. In the case with the
long distance travel of axial temperature distribution, the residual stress hardly accumulates at the center of the travel area. Because the residual stresses are derived from constraint by the elastic region, axial distance from the adjoining elastic region to the center of the plastic deformation area is the dominant parameter of this ratcheting. Therefore, we have focused on the axial length of the full-section yield area, which corresponds with double of the above distance. In the case when the full-section yield area is local, the accumulation of plastic strain saturates in the early stage of cycling.

In this paper, we propose a simple screening criterion to prevent continuous accumulation of plastic strain due to the long distance travel of temperature distribution. The proposed criterion restricts the axial length of the full-section yield area, and can be uniformly applied to various types of the traveling temperature distributions. Because the target ratcheting mechanism does not occur when the plastic deformation due to thermal stress is local, we proposed a criterion by considering an analogy to the definition of primary local membrane stress in existing design codes (ASME, 2015)(JSME, 2012).

To validate the proposed criterion, we have carried out a series of finite element analyses (FEAs). In the validation analyses, we have used an elastic-perfectly plastic material. As a result, in the cases satisfying the proposed criterion, we confirmed that the accumulation of plastic strain saturates before the second cycles, regardless of the shape of temperature distribution. In contrast, in the cases exceeding the criterion, the accumulation of plastic strain continues even after the third cycle, and the accumulated plastic strain depends on the shape of temperature distribution.

2. Previous study

2.1 Experimental study

Igari et al. (1990) experimentally studied the ratcheting due to traveling temperature distribution. In their study, an axial temperature distribution was generated on hollow cylindrical specimens by using a combination of cooling water and a high-frequency-induction heating coil. This temperature distribution traveled because of the movement of the cylindrical specimen along the axial direction.

As a result of their experiment, long distance travel (travel distance \( t \approx 5 \sqrt{r \cdot t} \), where \( r \) and \( t \) are inner radius and thickness of the cylinder, respectively) led to continuous accumulation of the plastic deformation through dozens of cycles. In contrast, in the case with short distance travel (travel distance \( t \approx 0.85 \sqrt{r \cdot t} \)), the accumulation of plastic deformation saturated in the early stage of cycling.

2.2 Formulation of the accumulated plastic strain

Wada et al. (1989, 1993) proposed a method for evaluating the plastic strain increment due to long distance travel of temperature distribution. In their formulation, they used the step-shape temperature distribution to simply simulate temperature distribution on the vessel wall near the coolant surface. In addition, they considered acceleration effects due to axial bending and primary stresses in their formulation. However, the effect of travel distance was not introduced into their method.

To consider the effect of travel distance, Igari et al. (2000) proposed the mechanism-based evaluation method. They formulated the accumulated plastic strain and residual stress based on Timoshenko’s shell theory (Timoshenko and Krieger, 1959). In this formulation, they used a hot-spot model as the traveling temperature model. The hot-spot model consisted of a very short region on the cylinder with high temperature and a residual cold region.

In the case where this hot-spot travels in the axial direction, plastic strain is accumulated in the entire region experiencing the temperature travel. When the residual membrane stress in the adjoining region of the temperature travel reaches the yield strength, the full section yield area expands and the constraint by the elastic region is reduced. Because of this reason, Igari et al. explained that shakedown occurs when yielding does not occur at the start and the end points of the temperature travel.

2.3 Screening criterion for reactor vessel wall nearby coolant surface

In our previous paper (Okajima et al., 2016a), we proposed a screening method of thermal ratcheting strain for the practical component design. The proposed method initially determines whether plastic strain is generated at all points
throughout the wall thickness. If all points of a certain cross-section are in the plastic state, the proposed method
determines whether or not plastic strain saturates based on the axial length of the full-section yield area, $l_p$. To prevent
continuous accumulation of plastic strain, Eq. (1) should be required as shown in the previous paper.

$$\beta l_p \leq 0.93$$ \hspace{1cm} (1)

where $\beta$ is the Timoshenko’s shell parameter (Timoshenko and Krieger, 1959), which can be obtained by Eq. (2).

$$\beta = \frac{\sqrt{3(1-\nu^2)}}{\sqrt{r^2-t}}$$ \hspace{1cm} (2)

where $r$ and $t$ are inner radius and thickness of the cylinder, respectively. $\nu$ is Poisson’s ratio of the cylinder material.

The proposed criterion, Eq. (1), was validated by a set of FEA using elastic perfectly-plastic material and a
ramp-shaped temperature distribution. We also validated the applicability of this criterion to the more detailed
temperature model simulating the thermal transients nearby the coolant surface of the vessel (Okajima, 2016b). This
temperature model had the feature that the increasing of the coolant level was synchronized with the increasing of the
coolant temperature, and so we called this model the synchronizing model. Through the above validation studies, we
have confirmed that the proposed criterion, Eq. (1), prevents the continuous accumulation of plastic strain with
sufficient margin.

3. Proposal of the screening criterion

3.1 Consideration of ratcheting mechanism

Before proposing the screening criterion, we considered the target ratcheting mechanism. In the previous study
(Okajima et al., 2016a), we focused on the axial length of the full-section yield area as the dominant parameter of the
ratcheting mechanism in this paper. Figure 1 illustrates the effect of this parameter.

![Diagram of ratcheting mechanism](image)

The axial length of the area with full-section yield state is…

(a) Small (Yielding area is local) (b) Large (Yielding area is global)

When the travel distance of the temperature distribution is short, a full-section yield area is generated within a local
region. In this case, although the plastic strain is generated at the full-section yield region, the total strain, $\varepsilon_t$, is nearly
equal to 0 due to the constraint by the adjoining elastic region. As a result, when the temperature distribution flattens, or
thermal strain $\varepsilon_{th}$ is removed, the elastic strain, $\varepsilon_e$, is generated, which corresponds to the residual stress and has an
opposite direction to the plastic strain, $\varepsilon_p$. Because of this residual stress, further plastic strain does not generate in the
subsequent thermal cycles, that is, elastic shakedown is achieved.

In contrast to the short distance travel, the long distance travel of the temperature distribution can generate
continuous accumulation of the plastic strain, due to the large full-section yield area. Since the constraint by the
adjoining elastic region affects only both ends of this yielding area, the diameter at the center of this area may change.
As a result, at the center of this yielding area, the total strain, $\varepsilon_t$, is not equal to 0 even when the thermal strain $\varepsilon_{th}$ is
removed. Therefore, the elastic strain, $e_e$, corresponding to the residual stress becomes smaller than the plastic strain. Therefore, plastic strain generates also at subsequent thermal transient. This accumulation of plastic strain continues until the residual stress reaches an adequate level.

Since the residual stresses are derived from the constraint by the adjoining elastic region, the axial distance from the elastic region to the center of the yielding area is the dominant parameter of this ratcheting mechanism. We have focused on the axial length of the full-section yield area, which corresponds with double of the above distance. In the previous study (Okajima, 2016b), we confirmed that the saturation of the plastic strain accumulation depends not on the travel distance of the temperature distribution but on the axial length of the full-section yield area, which was predicted by the elastic analysis.

### 3.2 Definition of local stress in existing design codes

As mentioned in the above section, when the yielding area due to thermal stress is within local region, the ratcheting mechanism accompanying the large full-section yield area does not occur. In other words, local thermal stress does not bring this mechanism. In order to consider the consistency with the existing design code, we employed the definition of “local stress” in ASME Boiler &Pressure Vessel Code (ASME, 2015) and JSME Rules on Design and Construction for Nuclear Power Plants (JSME, 2012).

In both codes, primary local membrane stress is defined based on the distance over which the membrane stress intensity exceeds $1.1S_m$. For austenitic stainless steel, the stress criterion $1.1S_m$ is equal to the yielding strength, $S_y$. According to the ASME Companion Guide (Rao, 2012), primary local stresses are described as follows: “Such stresses are sufficiently localized to have the ability to redistribute to the adjoining areas that have lower stresses.” The definition of the primary local stress is related to the distance from the adjoining areas with the stress below the yielding strength; this definition is considered to have an analogy to the above-mentioned ratcheting mechanism. Therefore, we considered that the thermal membrane stress by the short and long distance travel is classified respectively to the local and the global stresses referring to the definition of primary local membrane stress.

### 3.3 Proposal of the screening criterion

In this section, we propose a simple screening criterion that can be uniformly applied to various types of the traveling temperature distributions. JSME ETD code (2012) already regulates the range of primary plus secondary membrane stress within the shakedown range, $3S_m$. Accordingly, not only in the previous papers but also in this paper, we have assumed the precondition that the membrane stress range is below the shakedown range. In other words, the plastic strain in the first cycle can be generated in either along the compressive or the tensile direction.

As discussed in the above section, we propose a method to classify thermal stress as the local or global stresses as follows. This method can be used as a screening criterion to prevent the continuous accumulation of plastic strain. Referring to the existing definition of local membrane stress, we propose the following screening criterion, Eq. (3).

$$ l_p \leq \sqrt{r \cdot l}, \quad (3) $$

where $l_p$ is the axial length of the area in which Eq. (4) is not satisfied. In other words, $l_p$ is the evaluated value of the axial length of the full-section yield area based on an elastic analysis.

$$ \langle P_m + Q_m \rangle_{\text{max}} \leq S_y, \quad (4) $$

where $P_m$ is primary membrane stress, $Q_m$ is secondary membrane stress, and $S_y$ is yielding strength. $\langle >_{\text{max}}$ denotes maximum value of stress intensity.

### 4. Validation of the proposed criterion

#### 4.1 Analyses conditions

To validate the proposed criterion, we performed a series of FEAs. The analyzed model was a simple cylinder
subjected to traveling temperature distribution. The FEM code FINAS (Iwata et al., 1982) Ver.21 and the 8-node axisymmetric solid element were used in these analyses. In this paper, we assumed elastic perfectly-plastic material, which is simple and conservative constitutive model. In other words, we ignored strain hardening effect. The reasons are as follows: i) Although the significant increase of yielding strength due to the strain-hardening may mitigate the continuous accumulation of plastic strain, it requires significant magnitude of plastic strain, which should be prohibited by the proposed screening criterion. We thought that the consideration about the strain-hardening provides insignificant effect for the validation of the screening criterion. ii) The strain-hardening may mitigate also continuous accumulations of plastic strain due to the Bree ratcheting mechanism. Although both of the ASME(2015) and JSME(2012) codes provide rules for prevention of excessive deformation due to the Bree ratcheting, these prevention rules don’t consider the mitigation effect due to the strain-hardening. Therefore, the assumption of the elastic perfectly-plastic material is consistent with the existing codes.

In addition to the reactor vessel wall near the coolant surface, the travel of the axial temperature distribution may occur on the various types of cylindrical equipments. Therefore, the proposed criterion should be uniformly applicable to the various types of traveling temperature distributions. Accordingly, for the validation analyses, we used several types of temperature travel models, as shown in Fig. 2. Excepting (c) Synchronizing model, we assumed the uniform temperature distribution on the radial and the circumferential directions in the temperature traveling models shown in Fig. 2.

(a) Ramp-shaped temperature distribution is the most used simple model for simulating the reactor vessel walls near the coolant surface (Wada et al., 1993) (Okajima et al., 2016a). We also used (b) Polyline-shaped temperature distribution, which has lower tensile thermal stress than Ramp-shaped distribution. Furthermore, we used (c) Synchronizing model (Okajima, 2016b), which is a more detailed model of the reactor vessel wall nearby the coolant surface. In the synchronizing model, the temperature distributions were evaluated based on the heat transfer analyses.

In addition, we also have used two models different from those for the reactor vessel wall near the coolant surface. To reproduce the hot-spot model used in the formulation by Igari et al. (2000) in the validation study, we used (d) Triangle-shaped models. In (e) Double-Ramp-shaped model, temperature distribution expands spatially with time. The temperature distributions used in these two models do not generate compressive thermal stress on the adjoining elastic area.

For the cases based on (a) Ramp shape temperature distribution and (c) Synchronizing model, detailed conditions of the analyses were shown in our previous papers (Okajima et al., 2016a)(Okajima, 2016b). For the other cases, the conditions of the analyzed cylinder are shown in Fig. 3, and the conditions of the traveling temperature distributions are
shown in Table 1. The material properties given in Fig. 3 were based on the values of 316FR stainless steel at 550°C.

![Figure 3: The model of the analyzed cylinder used in the validation study.](image)

**Table 1: Conditions of the traveling temperature distributions.**

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<tr>
<th>Case</th>
<th>$l_e$ [mm]</th>
<th>$\Delta T$ [°C]</th>
<th>$(P_m + Q_m)<em>{max}$ [x$S</em>{yc}$] (target value)</th>
<th>$l_m$ [mm]</th>
<th>$l_p$ [mm] (target value)</th>
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<th>$l_m$ [mm]</th>
<th>$l_p$ [mm] (target value)</th>
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* In these cases, the magnitude of the membrane stress depends on the location. At the starting point of the temperature travel, the membrane stress is double of the value shown in this table.
4.2 Analyses results for the reference case

In this section, we show the example result of the FEA for a “reference case” in which \( l_p \) is nearly equal to the proposed criterion, Eq. (3). The reference case is shown as Case (b)-1 in Table 1.

Figure 4 shows the accumulated plastic membrane strain in the reference case. At the end of first cycle, the peak position of plastic strain was at the terminal point of temperature travel. With repetition of the thermal transient, the increment of the plastic strain was reduced, and the peak position moved to the center of the travel area. After the third cycle, the increment of the plastic strain became nearly equal to 0; in other words, the elastic shakedown was achieved. Figure 5 shows the circumferential membrane residual stress in the reference case. In the travel range, the residual stress reached about 17 MPa in the third cycle. This residual stress was nearly equal to difference between the maximum thermal membrane stress (121 MPa) derived from temperature distribution and the yielding strength (105 MPa). Therefore, in the reference case, it was shown that the accumulated residual stress led to elastic shakedown in the third cycle.

Fig. 4 Spatial distribution of the accumulated plastic strain. After the third cycle, the increment of the plastic strain became sufficiently small.

Fig. 5 Spatial distribution of the residual stress. Residual stress sufficient for causing shakedown was accumulated in the third cycle.

4.3 Summary of the validation

To judge whether plastic strain accumulates continuously, we focused on the ratio of plastic strain in the tenth cycle to that in the second cycle. In the case where this ratio is nearly equal to 1, the accumulation of plastic strain saturates, that is, shakedown is achieved in the early stage of cycling. In other cases, plastic strain accumulates even after the third cycle. Figure 6 shows relationship between this ratio of circumferential plastic strain and normalized axial length of the full-section yield area, \( l_p / \sqrt{R - t} \). The cases in which the normalized axial length is lower than 1 satisfy the proposed criterion, Eq. (3).
Fig. 6 Relationship between ratio of accumulated plastic strain and axial length of the full-section yield area. In the case where the horizontal axis was lower than 1, in other words the proposed criterion was satisfied, significant accumulation of the plastic strain did not generate after the third cycle.

Because the screening criterion is based on the definition of local membrane stress, we can classify thermal stress that satisfies the screening criterion, Eq. (3), as thermal local membrane stress. As shown in Fig. 6, regardless of the type of temperature distribution, the accumulation of plastic strain derived from the thermal local membrane stress saturated before the second cycles. Therefore, we confirmed that the proposed criterion in Eq. (3) can be uniformly applied to the various types of temperature distributions.

By contrast, we can classify thermal stress that exceeds the screening criterion, Eq. (3), as thermal global membrane stress. In this case, as shown in Fig. 6, plastic strain accumulated even after the third cycles. Therefore, we can say that the thermal global membrane stress has the characteristic that is hard to shakedown. The magnitude of the accumulated plastic strain depended on the analyses conditions such as type of temperature distribution. Therefore, it would be desired that the evaluation method for the accumulated plastic strain due to thermal global membrane stress is developed in future.

The above tendency is consistent with the experimental results (Igari et al., 1990). In the case where the travel distance was about $0.85 \sqrt{R \cdot t}$, which satisfies the criterion, the accumulation of plastic strain saturated in the early stages of cycling. In contrast, in the case where the travel distance was about $5 \sqrt{R \cdot t}$, that exceeds the criterion, the accumulation of plastic strain continued for dozens of cycles.

4.4 Discussion: effect of the shape of the traveling temperature distribution

In this section, we discuss the reason why the accumulated plastic strain depends on the temperature distribution in the case exceeding the proposed criterion. For this purpose, we show the result of the FEA for a “long distance travel case,” where $l_p$ was considerably larger than the proposed criterion, Eq. (3). This case is shown as Case (b)-6 in Table 1. As the result of this travel, $l_p$ was evaluated as nearly equal to $3.3 \sqrt{R \cdot t}$ by elastic FEA.

Figure 7 shows the spatial distribution of plastic membrane strain in the long distance travel case. As shown in Fig. 7, with repetition of the thermal transient, the plastic deformation region expanded near the initial location of temperature travel (i.e., the horizontal axis $< 0$mm). In other words, “actual” value of the axial length of the full-section yield area became larger than $l_p$, which is evaluated using the elastic analysis. As a result of this expansion of the yielding region, the accumulation of plastic strain was accelerated. In contrast, the plastic deformation region did not expand near the terminal location of temperature travel.
Fig. 7 Spatial distribution of the accumulated plastic strain. The plastic strain accumulated continuously. In addition, the plastic deformation region expanded near the initial location of temperature travel.

Figure 8 shows the accumulated circumferential membrane residual stress at the end of each cycle in the long distance travel case. This stress distribution was derived from the spatial distribution of the accumulated plastic strain. Figure 9 shows the maximum and the minimum values of circumferential membrane stress evaluated by elastic FEA. This stress distribution was derived from the traveling temperature distribution.

In the terminal location side of the adjoining region (i.e., the horizontal axis > 1740mm), the residual stress was generated on the compressive direction as shown in Fig. 8, while significant thermal stress was not generated on the compressive direction due to the temperature distribution as shown in Fig. 9. As the result, the sum of these compressive stresses did not exceed the yielding strength (105 MPa). Therefore, as shown in Fig. 7, the plastic membrane strain did not accumulate on this region.

In contrast, in the initial location side of the adjoining region (i.e., the horizontal axis < 0mm), compressive stress...
generated in the both of Fig. 8 and Fig. 9. While each of the above compressive stresses was smaller, the sum of these stresses was nearly equal to the yielding strength (105 MPa). Therefore, it was revealed that the expansion of the yielding region shown in Fig. 7, which accelerated the accumulation of plastic strain, was brought by the combination of the accumulated residual stress and the thermal stress. Accordingly, the expansion of the yielding region depends strongly on the thermal stress, i.e. the magnitude and the shape of temperature distribution. The above mechanism is consistent with the tendency of the results shown in Fig. 6. The synchronizing model, which induced compressive thermal stress over a wide area in the adjoining elastic region, showed larger ratio of the accumulated plastic strain than others in Fig. 6.

When the yielding region expanded, because the constraint by adjoining elastic region was weakened, the accumulation of plastic strain was accelerated at the center of this region. Then, the increase of plastic strain made the residual stress on the adjoining elastic region larger. As the result, the yielding region was expanded again. These sequences were caused each time the temperature distribution traveled. Because of complexity of these sequences, in the case exceeding the proposed criterion in Eq. (3), prediction whether the accumulation of plastic strain saturates or not is difficult without inelastic FEAs. In order to design a cylinder that exceeds the criterion proposed in this paper, it is desired to develop not a screening method but more detailed evaluation method for the accumulated plastic strain. In the detailed evaluation of the accumulated plastic strain, the effect of strain hardening, which is ignored in this paper, should be considered.

5. Conclusion

We proposed a screening criterion to prevent the continuous accumulation of plastic strain due to a traveling temperature distribution. This criterion restricts axial length of the full-section yield area. Because of the ratcheting mechanism, we proposed this criterion by referring to the definition of local membrane stress in existing design codes.

To validate the proposed screening criterion, we carried out a series of FEAs. In the validation analyses, we used an elastic-perfectly plastic material. The analytical results show that the accumulation of plastic strain saturated before the second cycles in the cases satisfying the proposed criterion, regardless of the shape of temperature distribution. In contrast, in the cases exceeding the criterion, the plastic strain accumulated depending on the shape of the traveling temperature distribution.

References

American Society of Mechanical Engineers, Boiler and Pressure Vessel Code Section III, Division 1 Subsection NB, 2015 Edition