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The ratchetting evaluation methods in japanese demonstration FBR design

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ABSTRACT

In this paper, the ratchetting evaluation method in DDS(Demonstration plant Design Standard; structural design standard at elevated temperature for the Japanese demonstration fast breeder reactor) is introduced .In DDS, ratchet caused only by secondary stresses is considered in addition to the conventional ratchet modes caused by combination of primary and secondary stresses. These evaluation methods cover ratchet mode caused by various combinations of stress possible to be generated in FBR components.

1. Japanese Demonstration Fast Breeder Reactor

Japanese Demonstration Fast Breeder Reactor (DFBR) is under development. At the same time, the design standard at elevated temperature for DFBR has been developed by The Japan Atomic Power Company (JAPC) under the sponsorship from electric power industry. In this project, one of the most important subjects is study on strain limitation.

DFBR is a 660MWe sodium cooling FBR plant. Figure 1 shows the primary coolant system of DFBR. It has a reactor vessel whose diameter is about 10m and three coolant loop systems. Components subjected to relatively high temperature are made of 316FR stainless steel (reducing carbon and adding nitrogen to type 316 stainless steel so as to improve creep fatigue strength) and each vessel is connected with the top-entry piping. The maximum coolant temperature is 550 °C and the maximum pressure is 1.0 Mpa in the primary coolant system at normal operation. The flow between the reactor and an intermediate heat exchanger (IHX) is induced by the principle of siphon and the sodium surface moves when operating conditions change. All vessels are hanged from roof decks, and the decks are cooled at 50 °C to protect mechanical and electrical devices involved. FBR components are subjected to relatively low pressure and high temperature so that high stresses are caused by thermal transition and temperature distribution generated, and secondary stress is exceeding primary stress. Furthermore, the axial temperature gradient makes high secondary membrane stress in the vessel wall. To keep structural integrity in terms of strain limitation, progressive strain due to the secondary stress must be evaluated appropriately.

2. Strain limitation in DDS

To design components of FBR, inelastic strains must be limited to keep their structural integrity. In DDS, elastic analysis and inelastic analysis may be used to evaluate inelastic strains, and several methods to evaluate inelastic strains based on elastic analysis are prepared. The total inelastic strain is limited to 1.0% for membrane and 2.0% for linearized surface strain in the operating condition I, II, III (corresponding to the conditions A,B,C in ASME code Sec.III). In the case of using elastic analysis, if the stress condition is classified as an elastic region (Sa limitation), DDS allows that cumulative inelastic strain can be ignored. In other case, enhanced creep, ratchet and elastic follow-up strains must be calculated and the sum of them to be compared with the limitations above. Figure 2 shows the flow diagram of strain limitation in DDS. Among these strains, ratchet strain is the strain caused by cyclic secondary stress omitting the effect of creep and the details of the evaluation methods in DDS are introduced in the following sections.

3.Ratchet due to Combination of Primary and Secondary Stress

DDS evaluates ratchet strains due to possible combinations of primary and secondary stresses as shown in Table 1. In addition, DDS considers the case that secondary membrane and bending stresses are imposed on the structure simultaneously. For evaluating these, DDS prepares two types of evaluation equations. One is the evaluation equation based on the mechanism of well known Bree type ratchet which is caused by combination of primary membrane and secondary bending stresses [1]. The original theoretical model of Bree type ratchet is based on a flat plate subjected to constant primary membrane stress and alternating secondary bending stress in the same direction. Ratchet strain increment per cycle is given as follows.

$$\Delta\varepsilon = Z(X,Y)\sigma_y / E$$

where Z is a function of X and Y, X is a primary membrane stress parameter and Y is a secondary bending stress parameter. σ_y is yield stress and E is Young's modulus.

Another equation which DDS prepares is the equation for membrane-membrane type ratchet due to combination of primary and secondary membrane stresses. The original theoretical model of membrane-membrane type ratchet is based on a flat plate to which constant primary membrane stress and alternating secondary membrane stress are applied in the orthogonal direction. The mechanism of ratchet of this type is illustrated in Fig.3. Cyclic secondary stress moves on the line between points, A and B in the stress plane. When stress exceeds the elastic range A-B, plastic strain corresponding to intensity of the stress and the flow theory. Then, the plastic strain in the direction of secondary stress canceled because the same strain is produced during loading and unloading. But, the plastic strain in the direction of primary stress cannot be canceled and is cumulated cycle by cycle.

The stress condition in a real component cannot be sufficiently expressed as such a simple model. Therefore DDS modifies the evaluation procedure as is mentioned above to keep evaluations conservative. Stress parameters in an evaluation equation is expressed as stress intensity so that the discrepancy of stress direction is ignored. Some stress components that are not considered in those theoretical models are added to the original parameter. The primary membrane stress parameter X includes primary bending stress (modified to be equivalent to membrane stress) and the secondary bending stress parameter Y includes secondary membrane stress in the Bree type ratchetting evaluation method. On the other hand, the primary membrane stress parameter is replaced with core stress considering the effect of secondary bending stress in the membrane-membrane type ratchetting evaluation. Finally, values got from two types of evaluation equations are added up. The applicability of the evaluation method to relatively complex stress conditions simulating real components are confirmed by inelastic finite element analyses assuming perfectly plastic elastic material. As an example of the ratchet whose mechanism is not taken into consideration in DDS, a cylindrical vessel subjected to both of inner pressure and axial temperature distribution was considered. In this case, primary and secondary membrane stresses are generated in hoop direction. DDS evaluates ratchet strain for this with the membrane-membrane type ratchet evaluation equation based on the combination of membrane stresses orthogonal each other and the inelastic strain increment is evaluated conservatively as shown in Fig.4. For the case that both bending and membrane secondary stresses act on structures, conservativeness of the evaluation method was verified by carrying out the inelastic analysis with an one shell element model as shown in Fig.5. In this evaluation method, elastic follow-up is not considered in the ratchet strain evaluation and it may increase ratchet strain. The model simulating a cylindrical shell with a tube sheet which causes relatively large elastic follow-up at a structural discontinuity was employed in inelastic analysis. Also in this case, inelastic strain increment can be evaluated conservatively by DDS (Fig.6).

4.Ratchet caused only by Secondary Stresses

DDS prepares the evaluation method for ratchet strains produced only by secondary stresses. The evaluation method for moving temperature distribution is applied to a cylindrical part subjected significant temperature distribution, a vessel wall for example. And the Sn' limitation (limitation of stress intensity of primary and secondary membrane stresses) or the secondary membrane ratchetting evaluation method is employed for other parts. Furthermore, DDS limits primary plus secondary stress range Sn under $2.5(3\overline{Sm})$ (where $3\overline{Sm}$ is a shake down range). This means that the excessive secondary stress is not allowable unconditionally, and this limitation originates from the results of the ratchetting test of elbows.

4.1 Ratchet due to Moving Temperature Distribution

In the condition without primary stress, it is known that the ratchet may occur with moving of temperature distribution. In DFBR, sodium surface moves, when operating conditions change. Then the temperature distribution moves and may cause ratchetting. Based on the rigid-plastic cylinder model, the following equation is introduced [2].

$$\Delta\varepsilon = 2(\sigma_\theta - \sigma_y)/E$$

where σ_θ is elastic hoop stress.

This basic equation is modified to consider the bending stress and moving distance. The bending stress decreases the yield against membrane stress seemingly and increases ratchet strain, thus σ_y is replaced by $\bar{\sigma}_y$ which is the reduced yield stress in consideration of the effect of bending stress [2]. On the other hand, the ratchet strain is decreased by residual stress around deformed area in the case of short moving distance. If the residual stress does not reach yield stress, ratchet strain decreases cycle by cycle in a geometric series [3]. Then, DDS specifies the applicable region (Fig.7) where this effect is valid and the total strain is given as a sum of a geometric series. Finally, the equations below are adopted in DDS.

$\Delta\varepsilon = 2(\sigma_\theta - \bar{\sigma}_y)/E$; if the effect of moving distance is not considered

$\varepsilon = \sum \Delta\varepsilon = A(\sigma_\theta - \bar{\sigma}_y)/E$; if the effect of moving distance is considered

where A is the coefficient to get a sum of the series and given as a function of βl (β: shell parameter, l: moving distance).

Figure 8 shows the evaluation results of ratchetting tests with cylindrical specimens subjected to cyclic thermal loads. DDS's evaluation method estimates these experimental strains conservatively.

4.2 Prevention of Excessive Secondary Membrane Stress

Even in the case that ratchet due to moving temperature distribution does not occur, it is also possible that only secondary membrane stresses cause ratchet. For this phenomenon, DDS prepares the conservative strain evaluation equation for the case that primary plus secondary stress exceeds shake down range.

$$\Delta\varepsilon = 2(Sn' - 3\overline{Sm})/E$$

where Sn' is primary plus secondary membrane stress intensity range.

This equation does not have a mechanical basis, but calculates strain in the manner that plastic strain while loading and unloading is added up without cancellation. The adoption of this equation means that secondary membrane stress can exceed shake down range for limited number of cycles.

5. Conclusion

The ratchetting evaluation methods in DDS were introduced. The whole procedure is shown in Fig.9. In DFBR design, the secondary membrane stress must be evaluated, and

DDS prepares for the evaluation methods for it. Validity of the procedure has been confirmed by inelastic analyses and experiments.

Acknowledgment

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Reference

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Table.1 Ratchet Evaluation for Combinations of Primary and Secondary Stress in DDS

Secondary Stress Primary Stress		membrane		bending	
		axial	hoop	axial	hoop
membrane	axial	—	○	○	△-1
	hoop	○	—	△-1	○
bending	axial	—	△-2	△-2	△-3
	hoop	△-2	—	△-3	△-2

○ : The theoretical ratchet model is considered in DDS
△ : The stress is transformed into other stress classification for conservative evaluation
-1 Direction of secondary stress is considered to be the same as that of primary stress
-2 Primary bending stress is transformed into equiverent membrane stress
-3 Both of 1 and 2
— : The ratchet model is not considered in DDS
The conservative evaluation method for the other ratchet models calculate strain also for this combination. The varidity is confirmed by inelastic analysis.

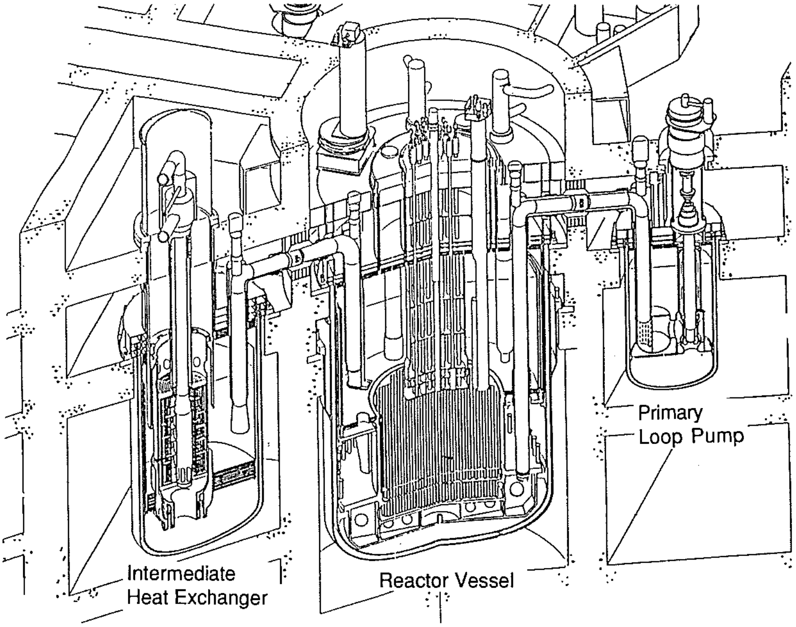


Fig.1 Bird View of DFBR

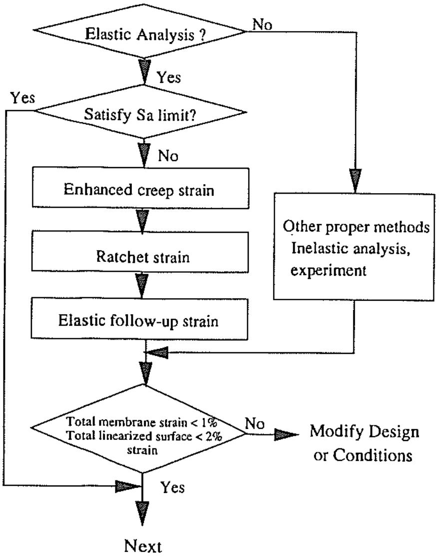
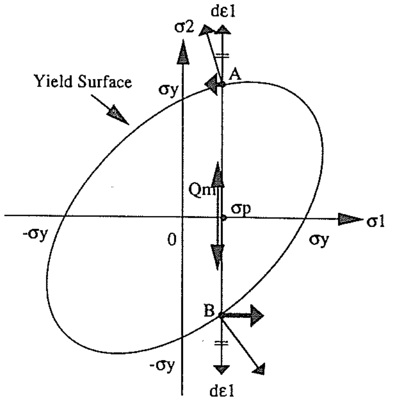
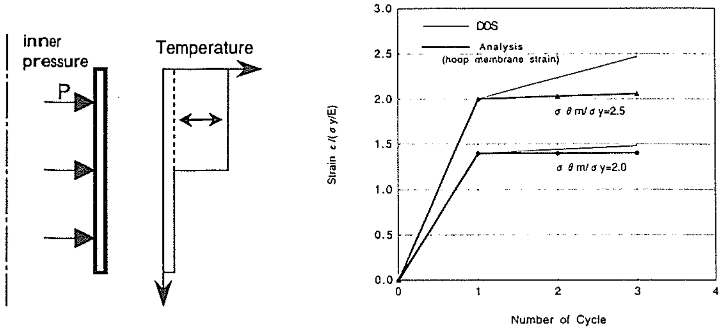


Fig.2 Flow Diagram of Evaluation of Strain Limtaion in DDS



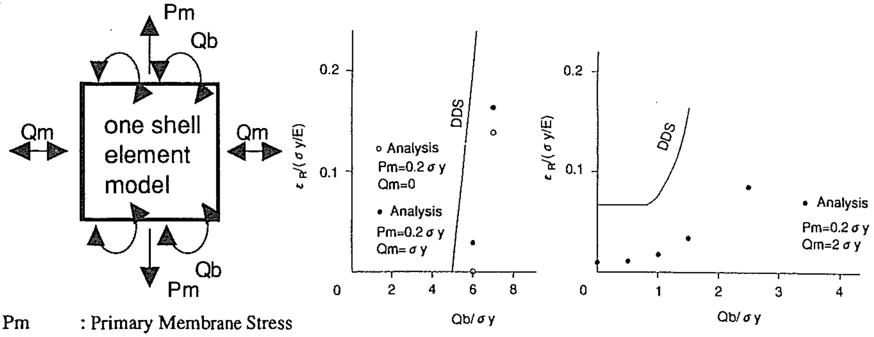
The strain represented with thick arrows is cumulated

Fig.3 Mechanism of Membrane-membrane Type Ratchet



(a) Model (b) Results of Analysis and Evaluation

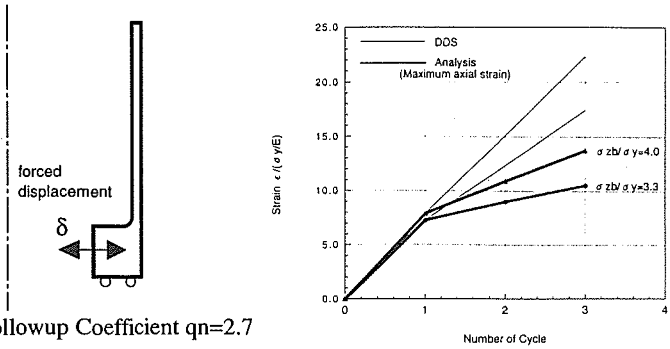
Fig.4 The Ratchet due to the Combination of Stress in the Same Direction



Pm : Primary Membrane Stress
Qm : Secondary Membrane Stress
Qb : Secondary Bending Stress

(a) Model (b) Results of Analysis and Evaluation

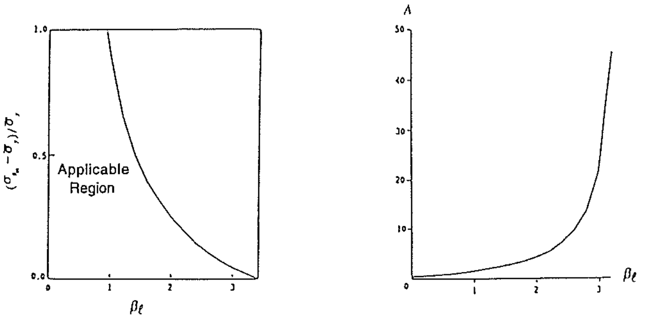
Fig.5 The Ratchet due to Membrane and Bending Secondary Stress



Elastic Followup Coefficient qn=2.7

(a) Model (b) Results of Analysis and Evaluation

Fig.6 The Ratchet with Relatively Large Elastic Follow-up



(1) Applicable Region

(2) Coefficient A

Fig.7 Evaluation Method of Ratchet due to Moving Temperature Distribution in Consideration of Moving Distance

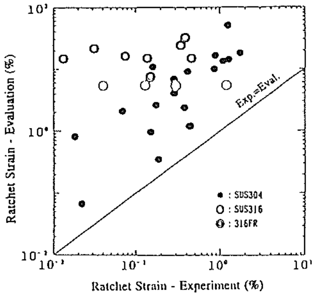


Fig.8 Evaluation of Experimental Result
Ratchet due to Moving Temperature Distribution

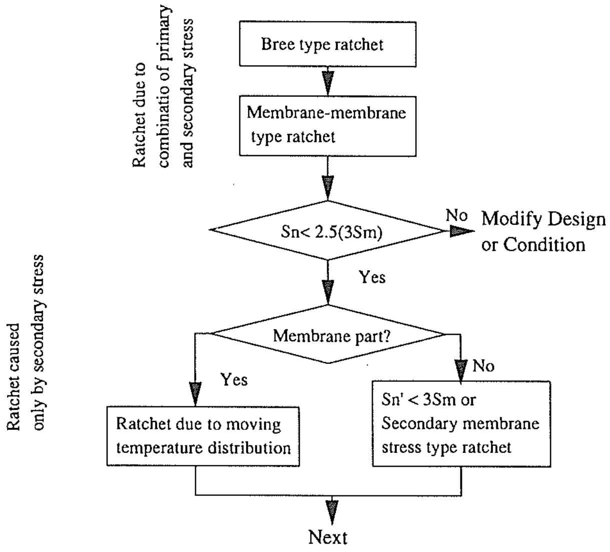


Fig.9 Flow Diagram of Assesment of Ratchet Strain Using Elastic Analysis in DDS