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Structural Evaluation Method for Protection against Failures of Safety Class 1 Components under Large Seismic Load

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1. Introduction

Since the accident in the Fukushima nuclear power plant, enhancing the safety of facilities in nuclear power plants against external events such as earthquakes and tsunamis that exceed design basis has been emerging as an important technical issue in both domestic and foreign country. The major event among several beyond design basis events is the occurrence of a large earthquake. Some probabilistic evaluation means has been prepared and implemented to ensure the safety of the plants against the beyond design basis earthquake. However, any means for deterministically evaluating the structural integrity of the safety class 1 components has not been prepared yet. This paper presents acceptance criteria for each failure mode due to the large earthquake in order to evaluate deterministically the structural integrity of the components and proposes damage evaluation methods in outline.

2. Failure Modes under Large Seismic Load

The ASME B&PV Code, which is applied to the structural design of the safety class 1 components under the design basis loads, includes implicitly the design concept of maintaining the structural integrity of pressure boundaries and preventing leak by ensuring the load-carrying capacity. The ASME B&PV Code, Section III, Appendix FF and Section VIII, Part 5 follow this design concept and the acceptance criteria are presented as strain limits [1]. If applying the above design concept of the ASME B&PV Code, in order to ensure the load carrying capacity in the pressure boundaries even in case of the beyond design basis earthquake, the maintenance of the pressure boundaries can be divided into the aspect to prevent the plastic collapse which is the damage through the cross section of the pressure boundary, and the aspect to prevent the local failure which is the damage at a local point of the cross section.

The plastic collapse is the failure mode which occurs as the structural material loses its load-carrying capacity due to the plastic deformation that occurs over the entire cross-section to which a single load is applied. On the other hand, the local failure is the failure mode in which cracks are generated by large amount of the plastic deformation in the localized region of the cross section where a single load acts. In addition, the fatigue due to the cyclic load was confirmed to be a major failure mode through the results of seismic tests for piping, it is considered that the failure due to the ratcheting is not likely to occur actually in the pressure vessel or piping because the ratcheting strain is small as compared with the test conditions in which the pressure is one to three times higher than the nominal pressure [2~4].

3. Structural Evaluation Method in Each Failure Mode

3.1 Nonlinear Finite Element Analysis

In order to simulate the behavior of structures by the large earthquake, the total time history of the seismic load is required for a finite element analysis. The analysis should be performed dynamically with the large deformation option to take account of the characteristics of the seismic load with large acceleration. Also, it is necessary to use cyclic material properties considering both isotropic hardening and kinematic hardening for accurate results because tension and compression loads are repeatedly applied to the structures under reversing dynamic loading such as the seismic load.

3.2 Evaluation against Plastic Collapse

The acceptance criteria to prevent the plastic collapse refer to the ASME B&PV Code, Section III, Appendix FF. The mean value of the equivalent plastic strains (ε_{peq}) multiplied by the stress triaxiality (ST) at the section where the load is applied is compared with the acceptance criteria. The outline evaluation procedure is as follows.

- Select the region of interest in the analysis model
- Identify a cycle with the largest strain amplitude in the complete cycles
- Calculate the maximum equivalent strain range and the maximum stress triaxiality
- Substitute the equivalent plastic strain (ε_{peq}) with the maximum equivalent strain range
- Compared with the acceptance criteria according to Equation (1)

$$[(\mathrm{ST})(\varepsilon_{\mathrm{peq}})]_{\mathrm{avg}} \leq \frac{\mathrm{SF}\cdot\varepsilon_{\mathrm{uniform}}}{3} \quad (1)$$

where $\varepsilon_{\mathrm{uniform}}$ = uniform strain, SF = safety factor

The safety factor is 0.67 in the region farther than three times the nominal thickness from discontinuities and 0.85 in the region of discontinuities.

3.3 Evaluation against Local Failure

The acceptance criteria to prevent the local failure refer to the ASME B&PV Code, Section III, Appendix FF and Section VIII, Part 5. When referring to the evaluation method of the Section III, Appendix FF, the maximum value of the equivalent plastic strain (ε_{peq}) multiplied by the stress triaxiality (ST) at the section which the load is applied to is compared with the acceptance criteria. When referring to the evaluation method of the Section VIII, Part 5, the maximum value of the equivalent plastic strain (ε_{peq}) at the section where the load is applied is compared with the acceptance criteria. The outline evaluation procedure is as follows.

- Select the region of interest in the analysis model
- Identify a cycle with the largest strain amplitude in the complete cycles
- Calculate the maximum equivalent strain range and the maximum stress triaxiality
- Substitute the equivalent plastic strain (ε_{peq}) with the maximum equivalent strain range
- Compared with the acceptance criteria according to Equation (2) and Equation (3) respectively

$$[(\mathrm{ST})(\varepsilon_{\mathrm{peq}})]_{\max} \le \frac{[\varepsilon_{\mathrm{uniform}} + \mathrm{SF}\cdot(\varepsilon_{\mathrm{fracture}} - \varepsilon_{\mathrm{uniform}})]}{3} \quad (2)$$

where $\varepsilon_{\mathrm{fracture}}$ = fracture strain

$$\varepsilon_{\mathrm{peq}} \le \varepsilon_{\mathrm{Lu}} \cdot \exp[-(\frac{\alpha_{\mathrm{sl}}}{1+m_2})\{\left(\frac{\sigma_1+\sigma_2+\sigma_3}{3\sigma_{\mathrm{e}}}\right) - \frac{1}{3}\}] \quad (3)$$

where $\varepsilon_{\mathrm{Lu}}$, α_{sl}, and m_2 as material properties are determined from the ASME B&PV Code, Section VIII, Part 5.

The safety factor of 0.25 is applied to any region.

3.4 Evaluation against Fatigue

Strain-based evaluations to protect against the fatigue failure are described referring to the method of the ASME B&PV Code, Section VIII, Part 5 and Section III, NB-320 in the following three independent methods.

3.4.1 Cumulative Plastic Damage

The cumulative plastic damage is evaluated referring to the acceptance criteria of the ASME B&PV Code, Section VIII, Part 5 for the local failure under consecutive loads. This quantifies the cumulative plastic damage resulted from the earthquake by calculating and accumulating plastic damages caused by the seismic load in the local region. The outline evaluation procedure is as follows.

- Select the region of interest in the analysis model
- Calculate the limiting triaxial strain ($\varepsilon_{\mathrm{L,k}}$) of Equation (4) at each loading point k
- Calculate the increment of the equivalent plastic strain ($\Delta\varepsilon_{\mathrm{peq,k}}$) of Equation (5) at each loading point k
- Calculate the plastic damage ($D_{\varepsilon,k}$) of Equation (6) at each loading point k
- Calculate the cumulative plastic damage (D_{ε}) and compare with the acceptance criteria according to Equation (7)

$$\varepsilon_{\mathrm{L}} = \varepsilon_{\mathrm{Lu}} \cdot \exp[-(\frac{\alpha_{\mathrm{sl}}}{1+m_2})\{\left(\frac{\sigma_1+\sigma_2+\sigma_3}{3\sigma_{\mathrm{e}}}\right) - \frac{1}{3}\}] \quad (4)$$

$$\Delta\varepsilon_{\mathrm{peq,k}} = \varepsilon_{\mathrm{peq,k}} - \varepsilon_{\mathrm{peq,k-1}} \quad (5)$$

$$D_{\varepsilon,k} = \frac{\Delta\varepsilon_{peq,k}}{\varepsilon_{L,k}} \quad (6)$$

$$D_{\varepsilon} = \sum_{k=1}^{M} D_{\varepsilon,k} \le 1.0 \quad (7)$$

3.4.2 Cumulative Fatigue Damage

The cumulative fatigue damage is evaluated referring to the acceptance criteria of the ASME B&PV Code, Section III, NB-3200. This evaluation method is a same concept to the conventional stress-based evaluation method for the cumulative fatigue damage, which uses the strain-life fatigue curve instead of the stress-life fatigue curve. It quantifies the cumulative fatigue damage of the structural materials resulted from the earthquake by calculating and accumulating the fatigue damages occurring in each cycle using the strain-life fatigue curve. The outline evaluation procedure is as follows.

- Select the region of interest in the analysis model
- Calculate the equivalent strain ($\varepsilon_{\mathrm{eq}}$) of Equation (8) from the complete cycles
- Count all cycles using the rainflow counting algorithm
- Calculate the fatigue damage ($D_{f,k}$) of Equation (9) at each cycle k using the strain-life fatigue curve
- Calculate the cumulative fatigue damage (D_f) and compare with the acceptance criteria according to Equation (10)

$$\varepsilon_{\mathrm{eq}} = \mathrm{Maximum}[(\varepsilon_1 - \varepsilon_2), (\varepsilon_2 - \varepsilon_3), (\varepsilon_3 - \varepsilon_1)] \quad (8)$$

$$D_{f,k} = \frac{n_k}{N_k} \quad (9)$$

$$D_f = \sum_{k=1}^{M} D_{f,k} \le 1.0 \quad (10)$$

3.4.3 Peak Stain Amplitude

The peak strain amplitude is evaluated referring to Equation (11) proposed as the piping seismic design requirements in the ASME B&PV Code, Section III, NB-3200 by T. Adams [5].

This means that the effective local peak cyclic single-amplitude strain (ε_{an}) due to the seismic load shall not exceed 0.316 times the strain amplitude corresponding to the alternating stress intensity at 10 cycles from the stress-life fatigue curve. The outline evaluation procedure is as follows.

- Select the region of interest in the analysis model
- Identify a cycle with the largest strain amplitude in the complete cycles
- Calculate the maximum equivalent strain range

- The effective local peak cyclic single-amplitude strain (ε_{an}) is half the equivalent strain range.
- Compared with the acceptance criteria according to Equation (11)

$$\varepsilon_{an} \le \frac{S_{a10}}{E\sqrt{10}} \qquad (11)$$

where S_{a10} = the alternating stress intensity at 10 cycles from the stress-life fatigue curve of the ASME B&PV Code, Section III, NB-3200

4. Conclusions

The plastic collapse, local failure and fatigue were taken into account as the failure modes of the safety class 1 components due to the large seismic load in the nuclear power plants. The strain-based acceptance criteria and the brief evaluation procedure were presented to quantitatively ensure the structural integrity of the components in each failure mode. This structural evaluation method was drafted based on the ASME B&PV Code and the previous research results, and will be revised and supplemented in detail through the applications for validation.

REFERENCES

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