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A Round Robin Analysis for Developing Strain-Based Structural Integrity Assessment Procedure of Nuclear Components under Beyond Design Basis Earthquake

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1. Introduction

It has been reported that seismic events such as beyond design basis earthquake (BDBE) or cyclic design basis earthquake (DBE) have occurred in nuclear power plants. In safety class 1 nuclear component design, structural failures due to material rupture in level D service loads such as safety shutdown earthquake (SSE) are prevented by the application of stress limits, which are specified in the American Society of Mechanical Engineers (ASME) boiler and pressure vessels (B&PV) Code, Sec.III [1]. However, the stress-based acceptance criteria are often excessively conservative for the level D service loads because the criteria cannot consider energy absorption during plastic deformation. Strain-based methodology, on the other hand, is directly related to the material damage mechanisms in multi-axial stresses. Also, unlike the stress-based criteria, the strain-based acceptance criteria are applicable to the evaluation of cumulative damage caused by sequential loads. But, it is difficult to perform dynamic finite element time history seismic analysis considering cyclic elastic-plastic material behavior reliably and efficiently.

So, in this study, a RR (round robin) analysis was performed on the previous Battelle's test to establish the optimal dynamic finite element cyclic elastic-plastic stress analysis procedure to ensure both reliability and efficiency.

2. Round Robin Analysis

2.1 Target Model

Fig.1 is a finite element analysis model. The IPIRG-2 piping system experiment program included in Battelle's Pipe fracture encyclopedia was selected for the test assessment for damage analysis. The shape of the pipe is constant except for Elbow 4, with an outer diameter of 406 mm and a thickness of 26 mm. Elbow 4 has an outer diameter of 406 mm and a thickness of 41 mm [2] The excitation history of the through cracks used in the IPIRG-2 experiment was selected. In addition, the experiment gave the same internal pressure of 15.5 MPa, which is the same as the operating condition of the pressurized water reactor and consider self-weight.

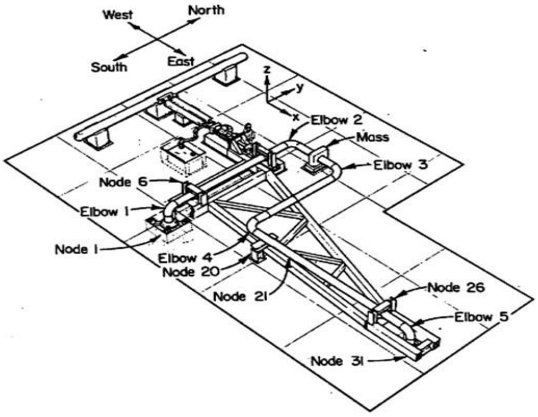

Fig.1 Battelle IPIRG-2 Piping System Geometry

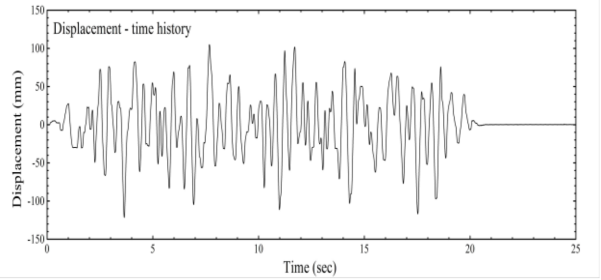

Fig.2 Displacement–Time History of Used FEA

2.2 FEA Model

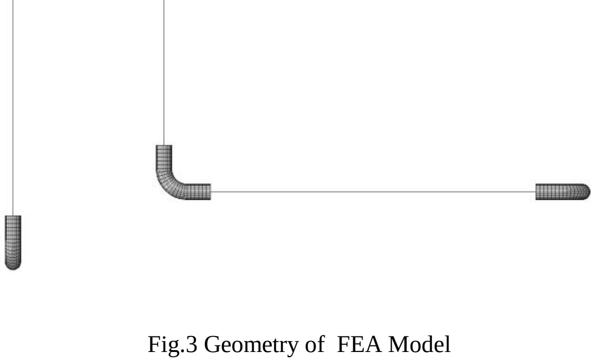

Fig.3 Geometry of FEA Model

The information of the finite element analysis model of three research organization participating in the round robin is shown in Table I.

Fig.3 shows the model geometry used in FEA. The element type of the three institutions are the same, but the number of elements and the transition length are slightly different. In this case transition length means the length of a solid element added to the elbow.

Table I: FEA Model Input Information of Three Institutions

	Korea University	KHNP CRI	SeJong University
Element type	Pipe31 + C3D8I	Pipe31 + C3D8I	Pipe31 + C3D8I
Number of element (circumference/ thickness)	20 / 5	24 / 4	24 / 6
Transition length	500(mm)	300(mm)	610(mm)
Maximum Time Increment	0.005(sec)	0.01(sec)	0.005(sec)
Natural Frequency (Mode1,2)	4.586(Hz) 13.821(Hz)	4.549(Hz) 13.915(Hz)	4.323(Hz) 13.842(Hz)
Rayleigh Damping (α ,β)	2.164 0.000865	2.154 0.000862	2.069 0.000876

2.3 Assessment equation

$$[(ST)(\varepsilon_{eq})]_{avg} = [\varepsilon_{uniform} + SF(\varepsilon_{fracture}) - \varepsilon_{uniform}]/3 \quad (1)$$

$$[(ST)(\varepsilon_{eq})]_{\max} = [\varepsilon_{uniform} + SF(\varepsilon_{fracture}) - \varepsilon_{uniform}]/3 \quad (2)$$

Equation 1 plastic collapse and Equation 2 local failure. The cumulative effect of cyclic loading can’t be considered in this equation, so it is not applicable to fatigue assessment.

$$\varepsilon_{an} = \frac{S_{a10}}{E\sqrt{N}} \quad (3) \qquad \varepsilon_a \le \varepsilon_{an} \quad (4)$$

$$D_\varepsilon = \frac{\Delta\varepsilon_{peq,k}}{\varepsilon_{L,k}} \quad (5) \qquad D_\varepsilon = \sum_{k=1}^{M} D_{\varepsilon,k} \le 1.0 \quad (6)$$

$$UF_k = \frac{n_k}{N_k(\varepsilon_\alpha)} \quad (7) \qquad CUF = \sum_{k=1}^{M} UF_k \le 1.0 \quad (8)$$

In this study, three methods were selected for the assessment of the fatigue damage mode: peak strain amplitude (Tim Adams) (3,4), cumulative plastic damage (6,8), and cumulative fatigue damage (7,8). The cumulative plastic damage assessment method refers to the allowance criteria for successive loads among the local failure breakage criterion given in ASME B & PV Code, Sec. VIII, Div. 2, Part 5. [3]

2.4 Compare Results

The finite element analysis was performed using Abaqus 6.13v [4]. Assessment was carried out using the equations mentioned in Section 2.3, and the results of the three research organizations are summarized as Table II.

Table II: Strain-based Finite Element Analysis Results

	Korea University	KHNP CRI	Sejong University	Failure Criteria
Plastic Collapse	0.00124 (98.68%)	0.000141 (99.85%)	0.000138 (99.85%)	0.09438
Local Failure	0.00228 (98.96%)	0.00253 (98.85%)	0.00229 (98.96%)	0.2202
Tim Adams	0.00259 (73.38%)	0.00244 (74.92%)	0.00237 (75.64%)	0.00973
Cumulative Plastic Damage	0.0298 (97.02%)	0.0286 (97.14%)	0.0292 (97.08%)	1
CUF	9.27 (90.73%)	8.62 (91.38%)	9.53 (90.47%)	100

※ The parentheses are design margin.

In the results excluding Tim Adams [5], over 90% design margin was calculated, and all three organizations derived similar calculation results. It is thought that this results in reliability.

2.5 Stress-based Assessment

We used the existing stress-based assessment method. The following equations are stress-based and refer to ASME code sec III. Equation 9 is the self-weighting equation, Equation 10 is the assessment of the inertial load, and Equations 11 and 12 are the Seismic Anchor Motion(SAM) assessment. The assessment results are shown in Table III.

$$B_2 \frac{D_0}{2I} M_W \le 0.5S_m \quad (9)$$

$$B_1 \frac{P_D D_O}{2t} + B_{2'} \frac{D_O}{2I} M_E \le 3S_m \qquad (10)$$

$$C_2 \frac{M_{AM} D_O}{2I} < 6.0 S_m \quad (11) \qquad \frac{F_{AM}}{A_M} < S_m \quad (12)$$

Table III: Stress-based Finite Element Analysis Results

	Stress-based	Failure Criteria	Design Margin
Self-Weighting	2.51MPa	57.5MPa	95.6%
Inertia	481.4MPa	345MPa	-39.5%
SAM (11)	411.83MPa	690MPa	40.3%
SAM (12)	8.98MPa	115MPa	92.2%

Satisfaction with self-weight and SAM and dissatisfaction with inertia were found. Also, design margin is lower than strain - based assessment method.

3. Conclusions

The following conclusions were drawn through the RR analysis for the development of the optimal finite element seismic analysis procedure.

- All three institutions involved in the RR analysis produced similar results.
- The strain-based assessment had a much higher safety margin than the stress-based assessment.
- Excessive conservativeness of the stress-based assessment was confirmed.

REFERENCES

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[5] T.M. Adams, Basis of the Upcoming Changes to Piping Seismic Design Rules in the ASME BPVC Section III, Division 1, Article NB-3200, Proceedings of ASME PVP 2015, PVP2015-45697.