Finite Element Simulation of Hardening Behavior for Nuclear Piping System Under Seismic Loading

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1. Introduction

The elastic stress-based design criteria provided in ASME B&PV Code Sec. III have been typically applied to the design of nuclear components [1]. However, under beyond design basis earthquake condition, it has been revealed that the design assessment based on the stress-based criteria gives unduly conservative results for piping systems, so it is too hard to secure the margin of safety. Therefore, the strain-based assessment is required to mitigate unnecessary conservatism associated with the use of stress-based criteria. For the strain-based assessment, the elastic-plastic analysis should be conducted with the cyclic hardening model of material of interest under seismic loading to produce accurate strain values.

In the present paper, the study to suggest relevant cyclic hardening model for elastic-plastic finite element (FE) cyclic analysis for nuclear piping system are conducted, in which the seismic testing results on pressurized piping system under seismic loading were employed. In terms of cyclic hardening models for the simulation of elastic-plastic behavior of piping systems under cyclic loading, two different kinematic hardening rules, i.e., the bi-linear kinematic hardening (BLKH) model and Chaboche kinematic hardening model, are used. The results from the FE analyses of the piping system under seismic loading are compared with the testing results. Moreover, the fatigue assessment is also made using the FE strain results based on the cumulative fatigue damage concept.

2. Finite Element Analysis

The FE analyses on the piping system test under seismic loading which was performed by Bhabha Atomic Research Center (BARC) in India [2, 3] are carried out. The seismic test was carried out using actual piping system with TP304LN stainless steel (SS) at room temperature (RT).

Fig. 1 shows the present FE model of piping system of seismic test due to BARC. As shown in Fig. 1, the hybrid FE model which has solid elements at elbows and beam elements at straight pipe regions are used. The material properties, such as yield strength and Young's modulus, of TP304LN SS at RT are given in Ref. [2]. The parameters of Chaboche kinematic hardening model are also provided in Ref. [3]. The parameters of BLKH model are calibrated in accordance with JSME code case by using the standard tensile test results [2, 4]. As for loading conditions, the piping systems are subjected to 1.0g ZPA with internal pressure of 12 MPa and 2.5g ZPA with internal pressure of 12 MPa, respectively.

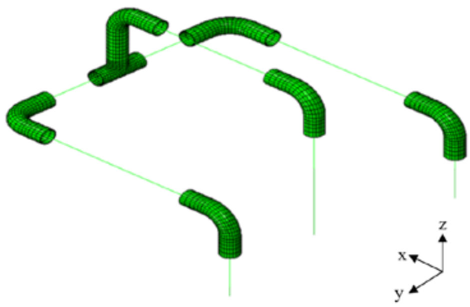


Fig.1 A FE model for piping system under seismic loading

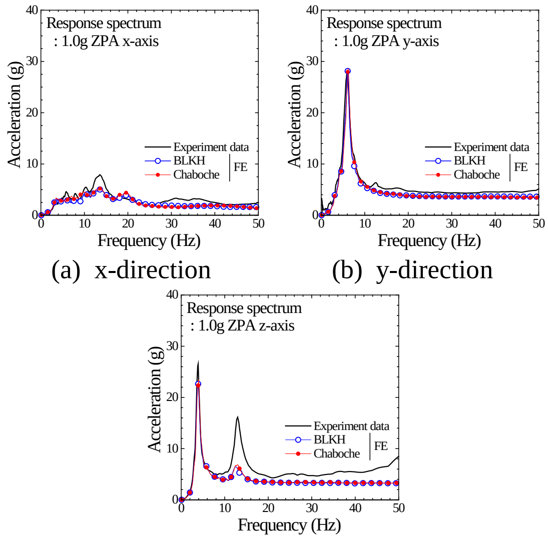
3. Result

Figs. 2 and 3 compare the results from the FE analyses with experiment results for response spectrum worked out at acceleration time history of piping system tests.

As shown in Fig. 2 for 1.0g ZPA, the results of response spectrums from BLKH model and Chaboche kinematic hardening model are similar for all directions, and the FE results from both hardening models agree with the experiment results. In the case of 2.5g ZPA, as shown in Fig. 3, although both hardening models give similar response spectrum for x-direction, for y and z-directions, the results from BLKH model are higher than those from Chaboche kinematic hardening model.

4. Fatigue Assessment for Seismic Loading

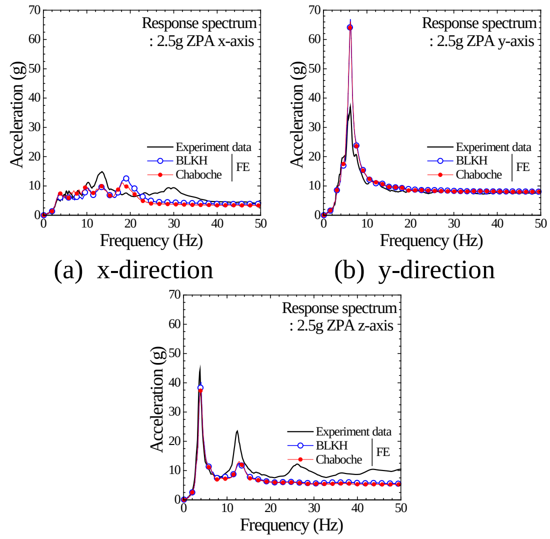
In this study, the FE results are utilized to evaluate fatigue life by using cumulative fatigue damages.



(a) x-direction (b) y-direction

(c) z-direction

Fig.2 Comparisons of acceleration response spectrum under 1.0g ZPA between FE results and experiments



(a) x-direction (b) y-direction

(c) z-direction

Fig.3 Comparisons of acceleration response spectrum under 2.5g ZPA between FE results and experiments

The cumulative fatigue damage is calculated by using fatigue-life curve, in which cumulative fatigue damage is the sum of the fatigue damage during the cycles [5]. Table 1 summarizes the results of fatigue damage assessment and the acceptance criteria of fatigue life is assumed to be 1.0.

As shown in Table 1, regardless of loading conditions and cyclic hardening models, the predicted values of cumulative fatigue damage satisfy the acceptance criteria in all cases. The values predicted by the BLKH model are similar to or higher than those predicted by the Chaboche kinematic hardening model in all cases, which means that the BLKH provides conservative fatigue damage predictions.

5. Conclusion

In this paper, 3-D elastic-plastic FE analyses of pressurized piping system tests under seismic loading are performed to confirm the effects of cyclic hardening models on seismic analysis results. The BLKH model and Chaboche kinematic hardening model are considered in the present analyses as a cyclic hardening rules.

The FE results using two different cyclic hardening models agree with testing results conducted by BARC. In the case of fatigue assessment, although predicted fatigue damages using two cyclic hardening models are less than the fatigue limit, the predictions using the BLKH model give similar or higher fatigue damage than Chaboche kinematic hardening model. Thus, the BLKH model could be used for conservative fatigue life prediction.

Table 1 The results of fatigue assessment according to cyclic hardening models

Loading condition	BLKH	Chaboche
1.0g (12 MPa)	0.00653	0.00654
2.5g (12 MPa)	0.05028	0.04313

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