# Nonlinear Seismic Analysis for Pipe Elbow under Sinus Cyclic Loading

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## 1. Introduction

Seismic isolation is one of technologies to increase the seismic safety by reducing the seismic response of structures, systems or components in a nuclear power plant (NPP).

By applying the seismic isolation, components or systems crossing the isolation interface, i.e. piping system, are expected to experience large displacements by relative movement between the isolated structure and the non-isolated foundation during seismic events.

To investigate the behavior of NPP piping systems under large seismic loading, former studies [1,2,3] are conducted on pipe elbows, which is expected to most fragile part of piping systems, based on experiments and computational analyses.

Korea atomic energy research institute (KAERI) also conducted tests with Hybrid Structural Testing Center of Korea Construction Engineering and Transport Development Collaboratory Management Institute (KOCED) on pipe elbows to investigate the behavior of and to define failure mode of piping systems crossing the isolation interface. Using those test result, numerical approach to assess behavior of the pipe elbow has been reported by other researchers. [4] However that study only focused on crack occurrence and propagation at the pipe elbow. In this study, nonlinear numerical analyses of the tested pipe elbows with 3-inch diameter are performed to investigate mechanical behavior of the pipe elbows including ratcheting. Limitation of this study is described with future work.

## 2. Test result

Tests on pipe elbows was performed as shown in Fig. 1. Sinus cyclic loads with amplitude of +/-60 mm, representing large seismic displacement load, are applied to pipe elbows. Comparing with dimension of the 3 inch pipe elbow with total length of about 720 mm, the 60 mm amplitude which yields bending mode of the pipe elbow is extremely large displacement.

2MPa of inner water pressure is always applied to elbows during tests.

The result of the test show the failure of the pipe elbow as shown in Fig. 2. Between 19$^{th}$ and 20$^{th}$ cyclic loading, failure occurred and water leaked out at the crown of the elbow. Two more tests resulted in almost the same failure at the crown.

## 3. Methodology of numerical analysis

For nonlinear numerical analysis, ABAQUS is used. For finite element (FE) modeling, the numerical model of former study [3] was referenced. But there are differences in experimental conditions and hinge design, so that the FE model in this study is developed with consideration of the test conditions. FE model is set as shown at Fig. 3.

Fig. 1. Test set-up


Fig. 2. Failure of pipe elbow

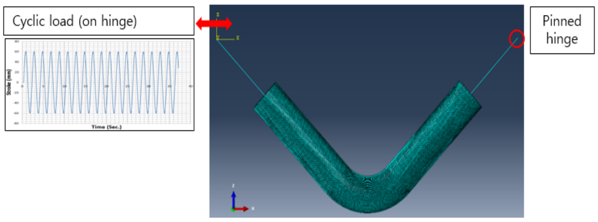


Fig. 3. FE model

Mesh size of the FE model was decided by convergence check relative to the model with over one million degrees of freedom. Cyclic input type is used to apply cyclic load for economic solving time. Implicit dynamic analysis provided by ABAQUS is chosen to solve nonlinear problem.

Bilinear kinematic hardening model is applied as plasticity model. Although former study [1] reported that nonlinear kinematic hardening rule proposed by Chaboche produced the best match to test results, the Chaboche method must require stress-strain hysteresis curves generated from a uniaxial strain cycling test for deciding material parameters and other study [5] shows bilinear kinematic hardening model predicts failure of pipe elbow comparing with test results quite well.

## 4. Analysis results

Nonlinear analysis of 3 inch pipe elbow under cyclic loading results in -0.2167 of maximum principal strain as shown in Fig. 4. Maximum principal strain (ABS) occurs at crown of the pipe elbow inner surface which is blue colored area in Fig. 4. This result does not only predict the elbow failure location, but also predict the through crack is growing from the inside of the pipe elbow and that is the same expectation with former study [4].

Fig. 5 shows the direction of max principal strain of each element. The direction of max principal strain does not same with hoop direction except the crown area. The former studies [1,2,3,5] reviewed its analytic result using hoop strain. The result in Fig. 5 shows that using hoop strain is only acceptable when a research is focused on the crown area or a research is for comparing with experimental data from a strain gage set on the hoop direction.

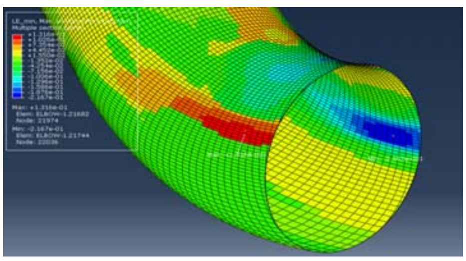

Fig. 4. Max principal strain (ABS)

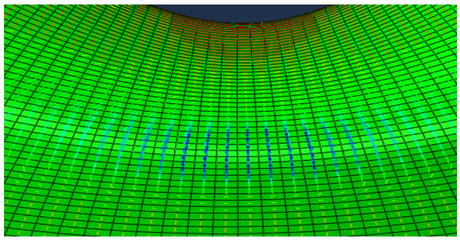

Fig. 5. Direction of max principal strain (ABS)

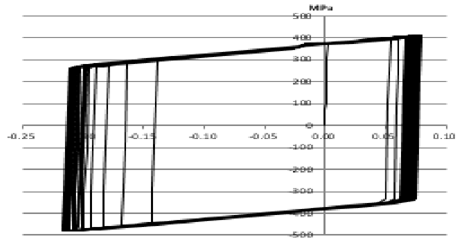


Fig. 6. Stress-strain hysteresis curves (max principal strain)

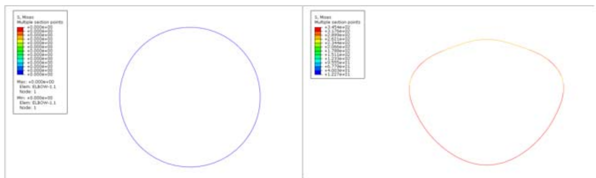

Fig. 7. Shape of cross section (before/after)

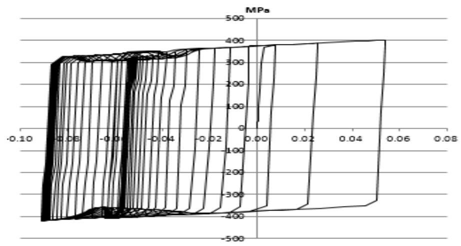


Fig. 8. Stress-strain hysteresis curve (neutral axis)

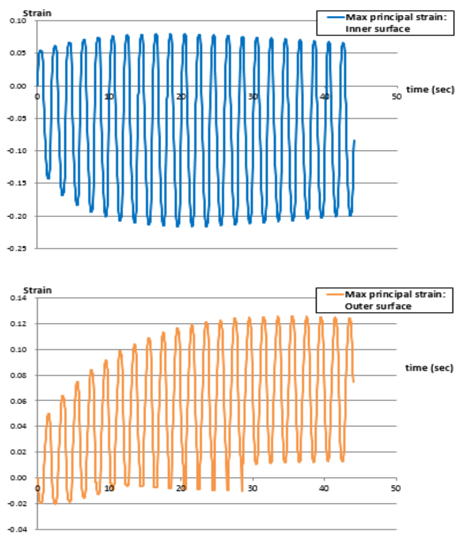


Fig. 9. Strain curves (inner / outer surface)

Fig. 6 shows stress-strain hysteresis curves of the element with absolute maximum principal strain value under cyclic loading. The stress-strain curve is plotted using maximum principal stress and strain on the pipe inner surface. The hysteresis curves reveal expansions in strain axis after each cycle ends while one dimensional uniaxial case must result in hysteresis curves with uniform shape. The stress-strain curves shows the element experiences varied load though we applied displacement load with fixed amplitude. Change of geometry of the pipe elbow during cyclic loading is considered as a contributory factor to the expansion of hysteresis curves. The cross section of the pipe elbow at the failed area is plastically deformed as shown in Fig. 7. Plastic deformation appears on overall area of the cross section, then stress-strain hysteresis curves of the element at the center of the pipe elbow in neutral axis also reveal shrink and translation in strain axis after each cycle as shown in Fig. 8.

Fig. 9 shows strain curves of the element with absolute maximum principal strain value under cyclic loading. Curves are plotted using maximum principal strain. Upper graph is the strain curve on the pipe inner surface and lower one is that on the pipe outer surface. As applied displacement load is relatively large, ratcheting behavior does appear but not clearly appear as shown in the study conducted by BNL [1]. Both strain curves achieved shakedown in ten to fifteen cycles and that is similar phenomenon with the numerical result using ANSYS with bilinear kinematic hardening model [1].

## 5. Summary and future work

Nonlinear numerical analyses using ABAQUS are conducted to investigate mechanical behavior of the pipe elbows including ratcheting. Bilinear kinematic hardening model is applied as plasticity model.

Analysis result showed maximum principal strain appeared at the actual failure location in experiments and predicted the through crack grew from the inner surface of the pipe elbow. At the crown where the failure observed, the direction of max principal strain is coincident with with hoop direction but in the other area the coincidence is not guaranteed. The nonlinear analysis provides stress-strain hysteresis curves during the cyclic loading, and the curves reveal variations in strain axis after each cycle ends because of plastic deformation of the pipe. The strain curves shows ratcheting behavior and shakedown.

From the strain curves strain rate, of which pipe material is experienced, is yielded and maximum strain rate is about 1 (1/s). The tests cannot be considered as quasi-static, therefore future work would be to conduct uniaxial strain test with variant strain rate and numerical analysis implementing the uniaxial strain test result.

## Acknowledgements

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## REFERENCES

[1] G. DeGrassi et al, BNL Nonlinear Pre-Test Seismic Analysis for the NUPEC Ultimate Strength Piping Test Program, BNL-NUREG-71119-2003-CP, 2003

[2] G. DeGrassi et al, Seismic Analysis of Large-Scale Piping System for the JNES/NUPEC Ultimate Strength Piping Test Program, NUREG/CR-6983, 2008

[3] Seismic Performance Assessment of Seismic Isolation System for Nuclear Power Plants - Seismic Fragility Evaluation of Base Isolated Nuclear Power Plant Piping System, KAERI/CM-2324/2017, 2017

[4] H.W. Jang et al, Effective numerical approach to assess low-cycle fatigue behavior of pipe elbows, Nuclear Engineering and Technology, 50, 758-766, 2018

[5] E. S. Firoozabad et al, Failure criterion for steel pipe elbows under cyclic loading, Engineering Failure Analysis, 66, 515-525, 2016