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Division V

FATIGUE DAMAGE IN STRAIGHT PIPES OF NPPS DUE TO DESIGN SEISMIC GROUND MOTION

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ABSTRACT

The failure modes that result in falling of piping are considered. The fatigue damage of elbows and tees is not circumferential crack but axial crack.Thus, the damage does not result in falling. By contrast, the fatigue damage of straight pipe is circumferential crack. Thus, the damage may result in falling. The objective of this study is whether the design seismic ground motion Ss could cause fatigue damage in straight pipes of NPPs. Specifically, a straight pipe is evaluated by using inelastic response analysis and strain-based fatigue criteria based on the Japan Society of Mechanical Engineers Code Case.

INTRODUCTION

In Japan, components and piping in nuclear power plants (NPPs) are classified as Class S, B and C according to their effect on nuclear safety: an earthquake could result in the loss of safety functions and radiation could affect public health. Components and piping are designed based on the seismic classes: Class S components and piping have high-safety-related function and required to be functional for the design seismic ground motion Ss. Class B and C components and piping do not have high-safety-related function, however they are required not to be affect to Class S components and piping due to falling. Figure 1 shows falling of Class B and C piping.

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The purpose of this study is to verify whether the design seismic ground motion Ss could cause fatigue damage in straight pipes and falling to Class S components and piping of NPPs. Specifically, a straight pipe is evaluated by using inelastic response analysis and strain-based fatigue criteria based on the Japan Society of Mechanical Engineers (JSME) Code Case (JSME, 2019).

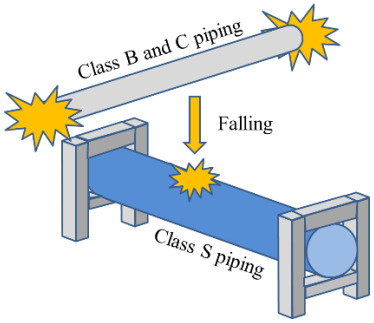


Figure 1. Falling of Class B and C piping

DAMAGE MODE OF PIPING

Previous studies, such as piping system ultimate strength tests, have confirmed that pipes do not collapse plastically due to earthquakes and that the failure mode of pipes during earthquakes is low-cycle ratchet fatigue (Japan Electric Association, 2021). Figure 2 and 3 shows the test equipment and damaged elbow in the in-plane bending test, respectively (Nakamura et al., 2007). Fatigue cracks in elbows and T-pipes, which are the structural weak points of the piping system, due to bending deformation, are axial cracks in the pipe due to their stress distribution and not circumferential cracks in the pipe (Japan Nuclear Energy Safety Organization., 2004), and therefore do not lead to a full-round rupture of the pipe.

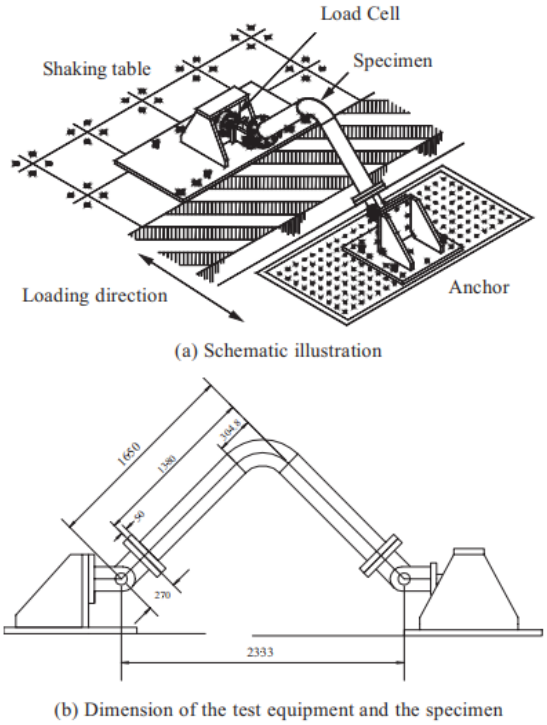


Figure 2. Test equipment for in-plane bending (Nakamura et al., 2007)

Figure 3. Damaged elbow in the in-plane bending test (Nakamura et al., 2007).

EVALUATION OF STRAIGHT PIPES

Elbows and T-pipes can crack in the axial direction of the pipe, so that even if they are damaged, the pipe will not fall. On the other hand, straight pipes are subject to circumferential cracking, so circumferential damage at two points on the piping may result in the pipe falling as shown in Fig. 1. Therefore, the evaluation part should be the straight pipe portion of a straight piping system.

Evaluation method

The evaluation is based on the JSME code case, which considers the elastic-plastic properties of the piping. Figure 4 shows the elastic-plastic response analysis evaluation flow for piping (JSME, 2019). It should be noted that this code case covers the evaluation of the piping body (base metal section), excluding weld joints and flange joints.

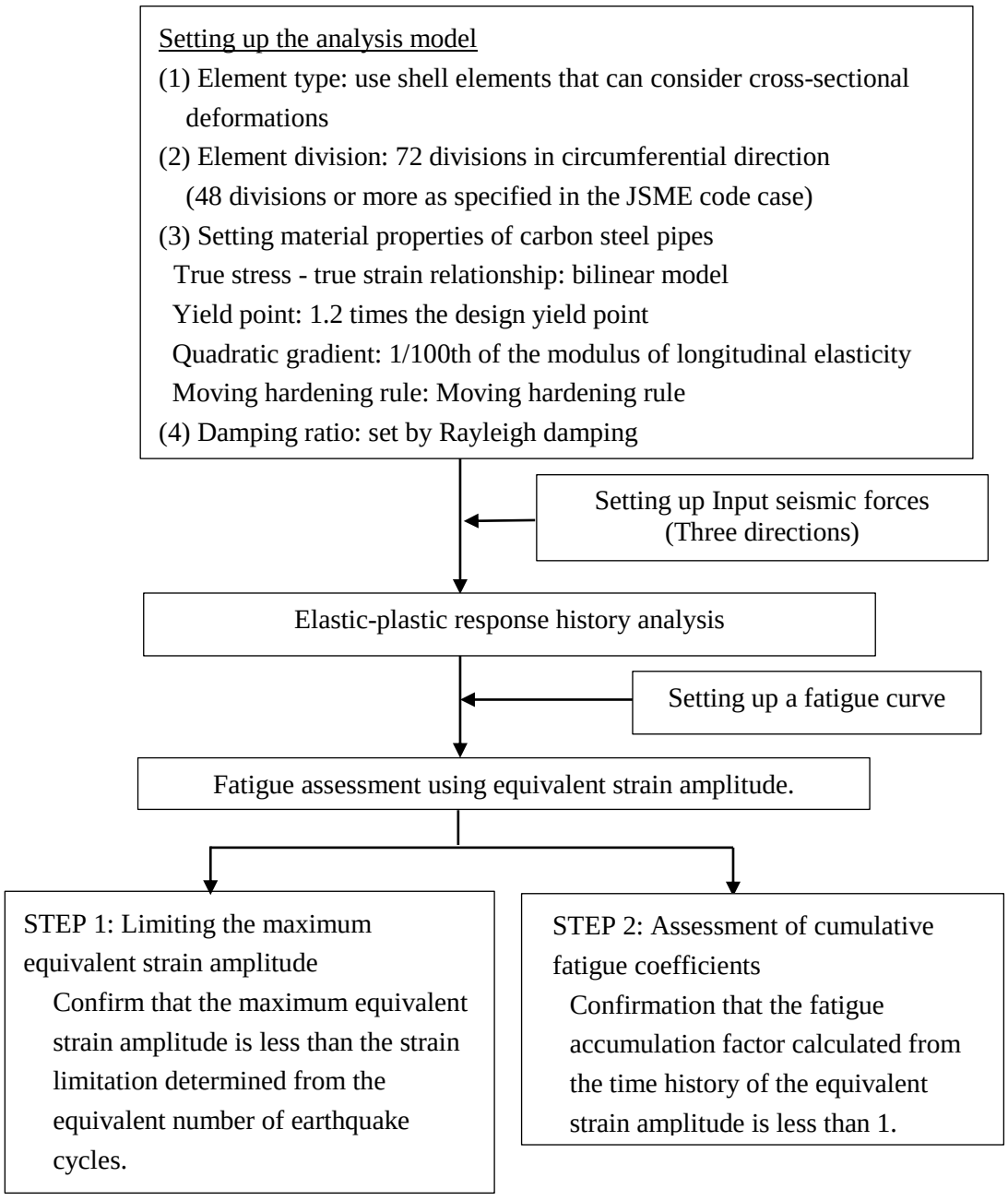


Figure 4 Elastic-plastic response analysis evaluation flow of piping (JSME, 2019).

Seismic forces

As a representative of Japanese nuclear power plants, the time history wave of the floor response with the largest peak value in the acceleration response spectra due to the design seismic motion Ss at the piping system installation floors of Shimane Unit 2 was used for the analysis (Ss-D, reactor building EL51.7 m, North-South (NS) direction). Figures 5 and 6 show the time history waveform of the input acceleration and acceleration response spectrum, respectively.

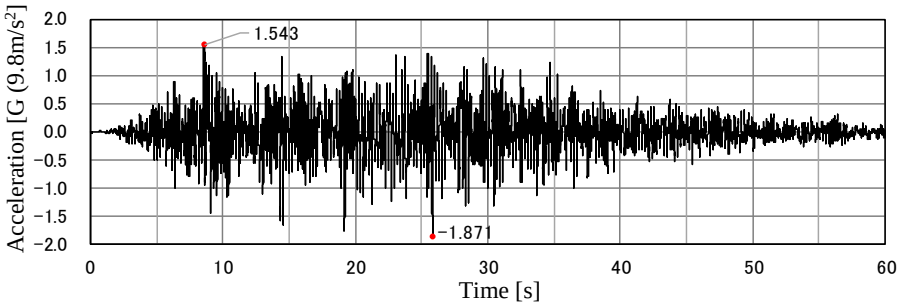


Figure 5. Time history of input acceleration;
Ss-D, Reactor building EL51.7 m, NS direction.

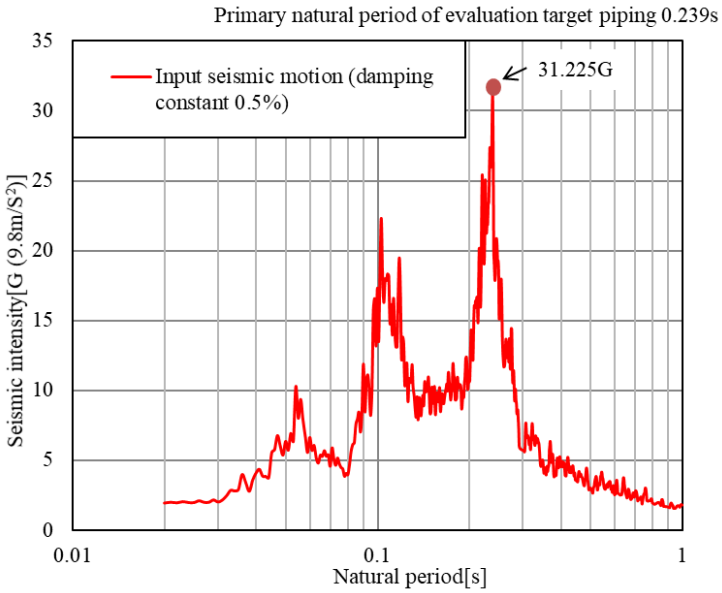


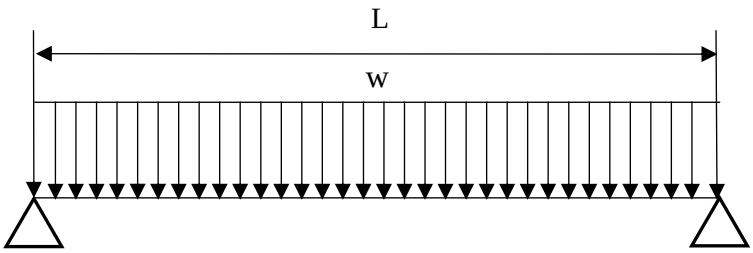
Figure 6. Acceleration response spectrum of input acceleration;
Ss-D, Reactor building EL51.7 m, NS direction, damping ratio 0.005.

Analysis model

A both ends simply supported one span piping system is analysed. The pipe length is set to be the primary natural period of the piping system coincides with the natural period of the peak value of the acceleration response spectrum, as shown in Fig. 6, to maximise the seismic force. To determine the specification of the piping system to be analysed, the bending stresses due to an equally distributed load at one gravitational acceleration (9.8 m/s^2) are calculated for the piping systems whose pipe lengths are set as mentioned above

using the formula of both ends simply supported beams, as shown in Fig. 7. Figure 8 shows the relationship between piping diameter, plate thickness and bending stress calculated from the formula for beam bending stress. Since the stresses generated tend to be higher in thin-walled, large-diameter piping, the following specifications for turbine auxiliary seawater system piping were used in the analysis.

<Piping specifications>
Piping diameter: 750 A
Thickness: 9.5 mm
Material: SM400A
Internal fluid: Seawater (density: 1.0 × 10^{-3} g/mm^3)
Internal pressure: 0.54 MPa



$$L = \sqrt{\frac{\pi}{2f}\sqrt{\frac{EI}{\rho A}}} \text{ [mm]}$$

$$w = \frac{m \cdot a}{L} \text{ [N/mm]}$$

where.
L: Pipe length [mm]
w: Equally distributed load [N/mm]
m: Piping mass [kg]
a: Acceleration due to input seismic force [m/s^2]
f: Primary natural frequency (= 4.184[1/s])
E: Modulus of longitudinal elasticity[MPa]
I: Moment of inertia[mm^4]
ρ: Mass density[kg/mm^3]
A: Cross-sectional area[mm^2]

Figure 7 Overview of model with simple support at both ends subject to equally distributed load .

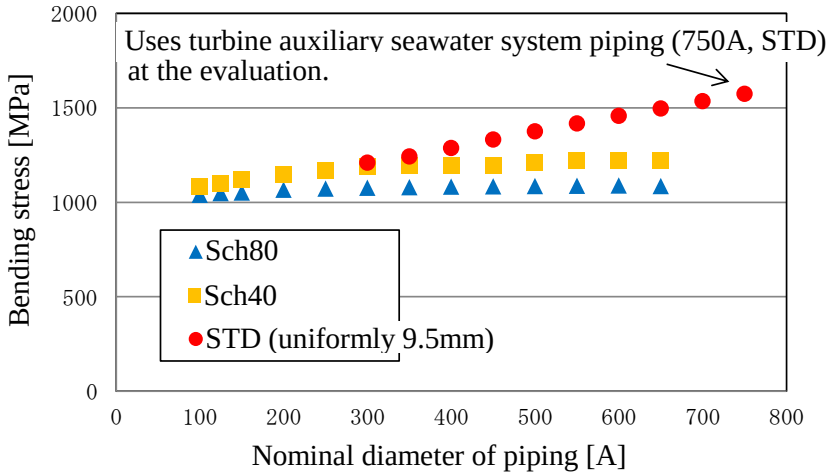
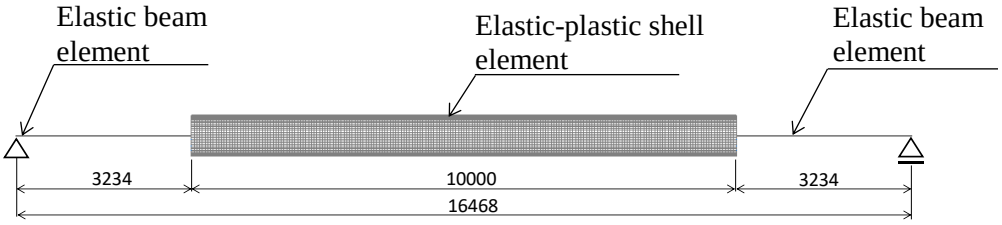


Figure 8 Relationship between piping diameter, plate thickness and bending stress (piping under simply supported conditions at both ends)

Elastic-plastic shell elements are used for the areas of the analytical model that are of interest for evaluation, and elastic-beam elements are used for the areas that are not affected by the shell elements. To simulate the actual piping and to avoid local stresses caused by axial deformation due to internal pressure, one end is pin-fixed, and the other end is slide-fixed as a condition where axial deformation is not constrained, and the connection between shell and beam elements is a rigid body connection. Figure 9 shows an overview of the analytical model, and Table 1 shows the physical properties of the analytical model. The stress-strain relationship is assumed to be bilinear, as shown in Fig. 10. The yield stress and quadratic gradient were set to 1.2 times the design yield point and gradient of 1/100th of the modulus of longitudinal elasticity at each temperature specified in the material standard (JSME, 2012).

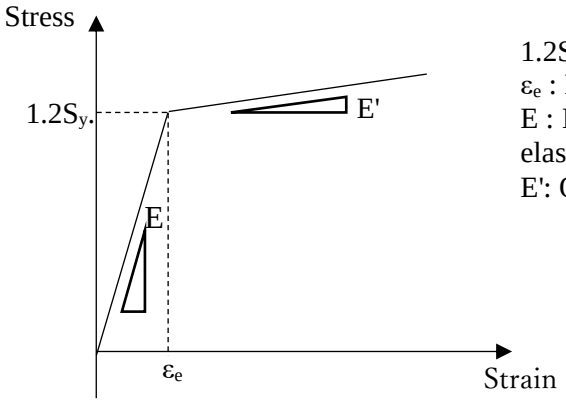


Unit: mm

Figure 9 Analysis model overview.

Table 1: Physical properties of the analysis model

Item	Physical property	Basis for setting
Temperature T [°C]	40	Design condition
Elastic limit strain ε_e [%]	0.14	1.2 Sy/E
Modulus of longitudinal elasticity E [MPa]	2.02×10^5	Based on JSME (2005/2007)
Poisson's ratio ν [-]	0.3	Based on JSME (1986)
Yield stress (true stress) 1.2 Sy [MPa]	294	1.2 Sy based on JSME (2019)
		Sy value based on JSME (2005/2007)
Quadratic gradient E' [MPa] (=E/100)	2.02×10^3	Based on JSME (2019)
Mass density considering internal fluid ρ [g/mm^3]	2.72×10^{-2}	Based on Japanese Standards Association (2019)



$1.2S_y$: Yield stress.
ε_e : Elastic limit strain
E : Modulus of longitudinal elasticity
E': Quadratic gradient

Figure 10. Image of stress-strain relationship

Analytical methods

The seismic force, internal pressure and gravity were applied to the analysis model. To account for simultaneous seismic force from two directions perpendicular to the piping, $\sqrt{2}$ times the input seismic force was applied in the vertical direction, the direction in which gravity acts. The response history analysis is performed using the ABAQUS finite element method, considering geometrical (large-form) and material (elastic-plastic) non-linearity. The time steps are set to 1/1000 s, the damping ratio is set to 0.5% and Rayleigh damping is used; the representative frequencies of Rayleigh damping are 0.9 times the first-order natural frequency of the pipe (4.18 Hz) and 20 Hz.

The equation relating the Rayleigh damping constant ζ to the angular natural frequency ω_n is given by the following equation using the coefficients α and β.

$$\zeta = \frac{1}{2}\left(\frac{\alpha}{\omega_n} + \omega_n \cdot \beta\right) \quad (1)$$

Where the coefficients α and β are 1.989×10^{-1} and 6.697×10^{-5}, respectively.

Evaluation results

The design fatigue curve used for the evaluation is specified in the rules on design and construction of the JSME (2005/2007), and is shown in Fig.11 (gray dashed line). This figure also shows the test result average curve of fatigue life obtained from tests of piping elements (elbows, tees and reducers; green curve) and the test result -3σ curve (purple curve). The permissible value of the maximum equivalent strain amplitude, assuming the equivalent number of earthquake repetitions to be 150 (setting the equivalent number of repetitions of the design seismic motion Ss), is 5.97×10^{-3} from the design fatigue curve. The evaluation results for the maximum equivalent strain amplitude (STEP1 evaluation) and the fatigue accumulation factor (STEP2 evaluation) with the equivalent number of earthquake repetitions set to 150 are shown in Table 2. The contour plot of the maximum equivalent plastic strain is shown in Fig. 12. Even under conservative evaluation conditions, the maximum equivalent strain amplitude is less than the permissible value and the fatigue accumulation factor is 9.43×10^{-2}, which is a large margin to the permissible value of 1, thus no fatigue cracks are generated. The design fatigue curve has a sufficient margin of more than twice the strain range obtained from the test result average curve in Fig 11. Therefore, no circumferential fatigue cracks will occur in the straight pipes (base metal sections) due to the design seismic motion Ss, and the pipes will not fall.

Table 2: Fatigue assessment results

		Generated value	Permissible value
STEP1.	Maximum equivalent strain amplitude	4.20×10^{-3}	5.97×10^{-3}
STEP2.	Fatigue accumulation factor	9.43×10^{-2}	1

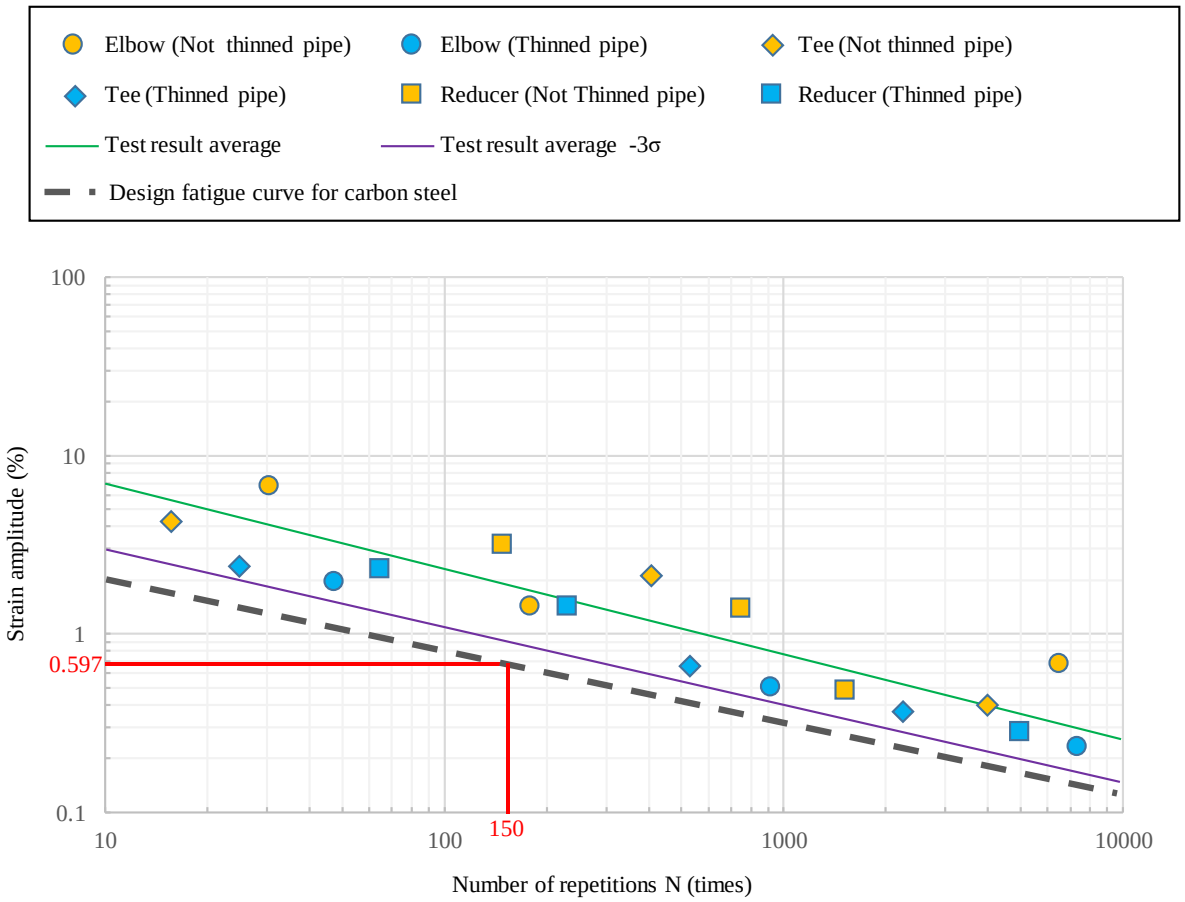


Figure 11. Fatigue test data of various piping element and design fatigue curve for carbon steel (JSME, 2019)

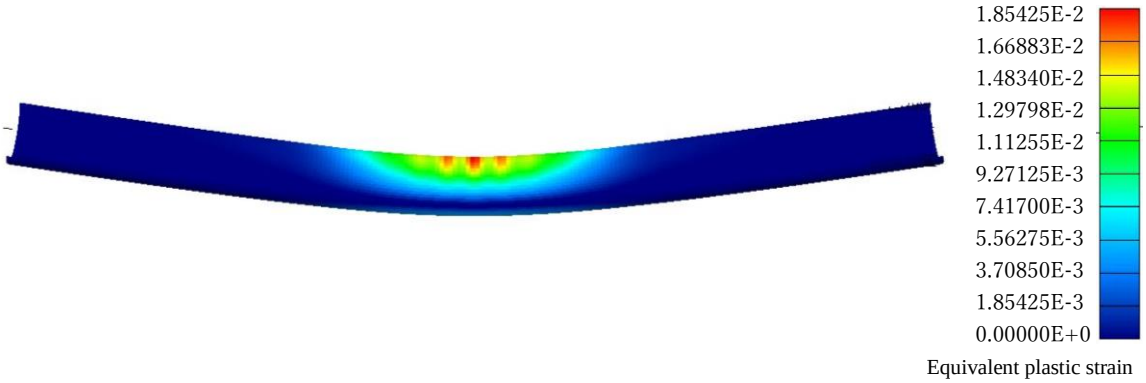


Figure 12 Contour diagram of maximum equivalent plastic strain

CONCLUSION

The failure mode of piping during earthquakes is low-cycle ratchet fatigue, and fatigue cracks in elbows and T-pipes, which are structural weak points of the piping system, will be axial cracks in the pipe due to their stress distribution and not circumferential cracks. Thus, they will not result in a full-round rupture of the pipe. Fatigue cracks in straight pipes are circumferential cracks and may lead to a circumferential damage of the pipe, but at the design seismic motion Ss, as a result of the evaluation based on the JSME Code Case, fatigue cracks do not occur even in the lower class pipes, so the possibility of a falling due to pipe rupture is sufficiently small.

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