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APPROACHES TO ESTABLISH A SEISMIC SAFETY EVALUATION PROCEDURE BASED ON THE INELASTIC RESPONSE ANALYSES

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ABSTRACT

After the accident of Fukushima Dai-ichi Nuclear Power Plant (NPP) at the 2011 Great East Japan Earthquake disaster, the regulatory requirements on design seismic ground motion have tended to increase to a large extent. Piping systems used in the existing NPPs are also re-examined under the reassessed seismic motion, and if they do not comply with the allowable stress level of the current seismic design code, which is essentially based upon the elastic stress analysis, seismic retrofitting is required. On the other hand, it is recognized that piping systems have a large amount of safety margin until boundary failure even when the input seismic load exceeds the design basis level. The reason is attributed to the large strength capacity of piping systems due to the plastic deformation.

In order to establish an evaluation procedure in which the elastic-plastic behaviour of piping systems is taken into account in a rational way, a Task Group (TG) activity under the Japan Society of Mechanical Engineers (JSME) has been conducted. As a deliverable of this activity, a Code Case in the framework of the JSME Nuclear Codes and Standards is now on the way to be developed. The Code Case provides a strain-based criteria, an evaluation procedure by response-spectrum based elastic-plastic analysis and by detailed inelastic response analysis with FEM model. In developing the Code Case, benchmark analyses and parametric analyses have been conducted to evaluate and verify the applicability of the proposed procedure based upon the elastic-plastic analyses.

In this paper, a brief summary of the TG activity and the Code Case are introduced.

INTRODUCTION

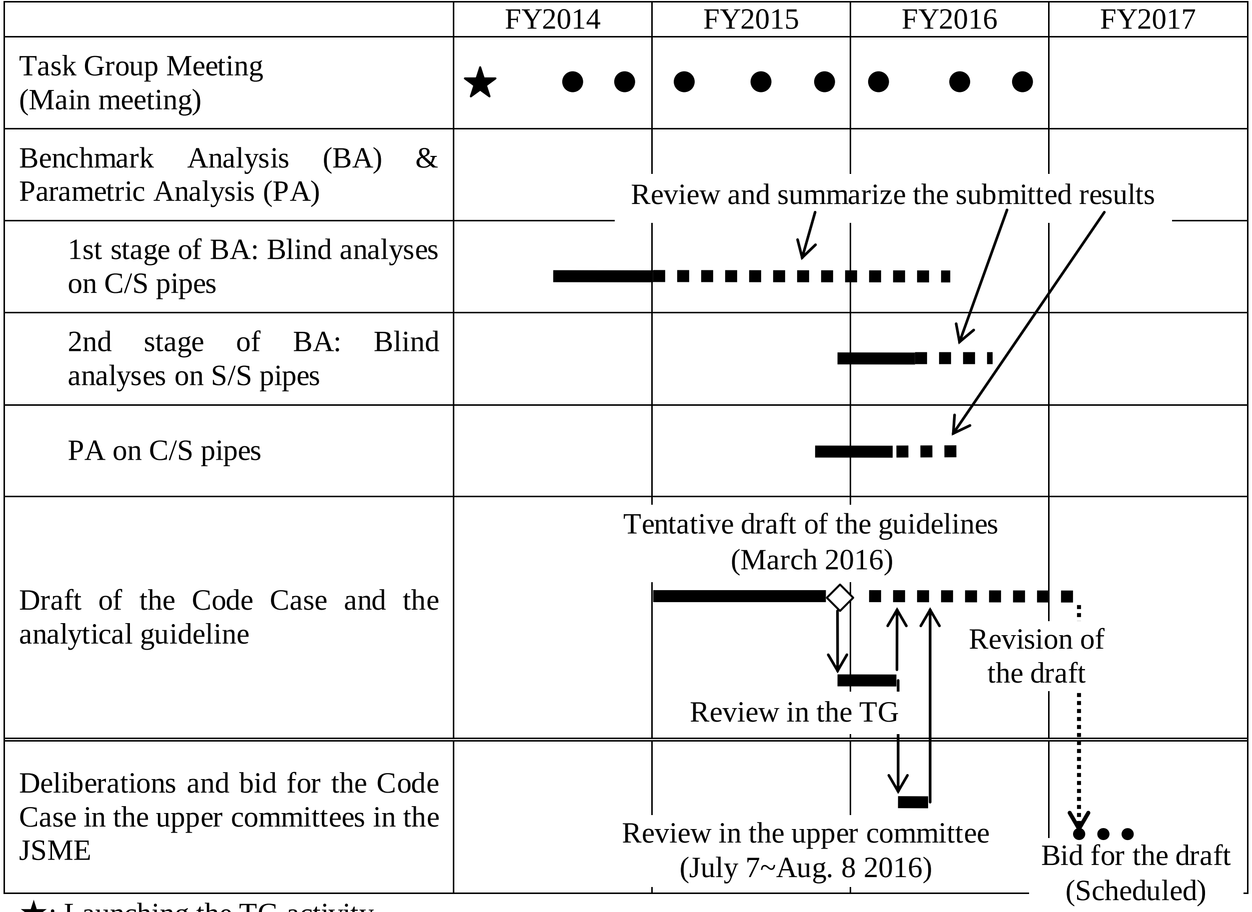
Piping systems used in nuclear power plants (NPPs) are designed on the basis of an elastic stress analysis and it is assumed to use linear elastic response analysis in the current seismic design code in Japan (hereinafter, JEAC4601-2008) (The Japan Electric Association, (2009)). The design basis seismic motions of existing NPPs have been re-examined after the accident of Fukushima Dai-ichi NPP at the 2011 Great East Japan Earthquake disaster, and they have been increased to a large extent in many NPPs. In case they would not comply with the allowable stress limit determined in JEAC4601-2008 under the re-examined seismic motions, additional countermeasures to reduce the maximum stress caused on piping systems should be taken.

Conversely, from several investigations of NPPs hit by actual seismic events (Nagasawa and Narabayashi (2016), Nagasawa and Narabayashi (2017)) and also from a lot of experimental researches (Tagart et al (1990), Suzuki et al (2002), Nakamura et al (2004), Varelis et al (2013), Ravikiran et al (2015)), it is recognized that piping systems used in NPPs have a large seismic safety margin until the point of boundary failure even when the input seismic load exceeds the allowable design level. Such seismic margin is attributed to the large strength capacity of the piping systems due to the plastic deformation, which is not taken into account in the current seismic design code explicitly. Moreover, the dominant failure mode confirmed in the experiments is the low cycle fatigue failure, not the plastic instability that is a primary failure mode postulated by design codes in various countries. Such seismic margins and actual failure behaviour of piping systems are now the issues of worldwide interest (Labbe et al (2016)).

Meanwhile in JEAC4601-2008, it is determined that the failure mode to be considered in the seismic design of piping systems is fatigue failure, and the fatigue evaluation based on the conventional linear response analysis using a beam element model with stress indices and the penalty factor is provided as simplified elastic-plastic analysis. It means that plastic deformation is allowed in JEAC4601-2008, however, the estimation is based on the elastic response analysis. The elastic-plastic behaviour effect such as the response reduction is not considered. In order to properly estimate the strength of piping systems under a large seismic input, it is necessary to develop an estimation procedure in which the elastic-plastic behaviour of piping systems is considered explicitly in a rational way.

Based on such background, a task group (TG) activity under the Japan Society of Mechanical Engineers (JSME) has been conducted since 2014 (Nakamura et al (2015)) to provide the strain-based criteria and the estimation procedure for inelastic response of piping systems as a Code Case of the JSME Nuclear Codes and Standards. A mandatory appendix for the Code Case that provides the procedure of the inelastic FEM analysis has been also developed (hereinafter, the analytical guideline). In developing the Code Case and the analytical guideline, several benchmark analyses were conducted to confirm the dispersion of the inelastic analysis and the applicability of the Code Case and the analytical guideline. Table 1 shows the overall schedule (as of April 2017) of the TG activity. This paper describes the overview of the TG activity and the deliverables from the activity.

Table 1: Overall schedule of the TG activity (as of April 2017)



★: Launching the TG activity

TASK GROUP ACTIVITY AND THE DELIVERABLES

The TG activity consists mainly two parts; one is the benchmark and the parametric analyses simulating the experimental results, and the other is preparing for the Code Case (Morishita et al (2017)) and the analytical guideline (Otani et al (2017)). As the first step of the TG activity, the benchmark analysis (BA) was conducted on carbon steel pipes (the first stage of BA) (Nakamura et al (2016)). The drafts of the Code Case and the analytical guideline were established based on the result of the first stage of BA. In parallel with making up these drafts, another benchmark analysis on the stainless steel pipes (the second stage of BA) (Watakabe et al (2017)) and the parametric analyses (PA) on the carbon steel pipes (Nakamura et al (2017)) were conducted. As the deliverable of the TG activity, a Code Case titled "An alternative rule on seismic qualification of seismic S class piping systems by detailed inelastic FE response analysis" has been proposed. The Code Case consists of the following contents;

(1) Main body of the Code Case SEGP
Seismic evaluation procedure and the criteria for piping systems in which the elastic-plastic behaviour is taking into account
(2) Mandatory Appendix SEGP-1
The analytical guideline for FEM analysis of seismic elastic-plastic response analysis for piping systems
(3) Non-mandatory Appendix SEGP-A
The method for the verification and validation
(4) Non-mandatory Appendix SEGP-B
The report of the benchmark analyses and the parametric analyses

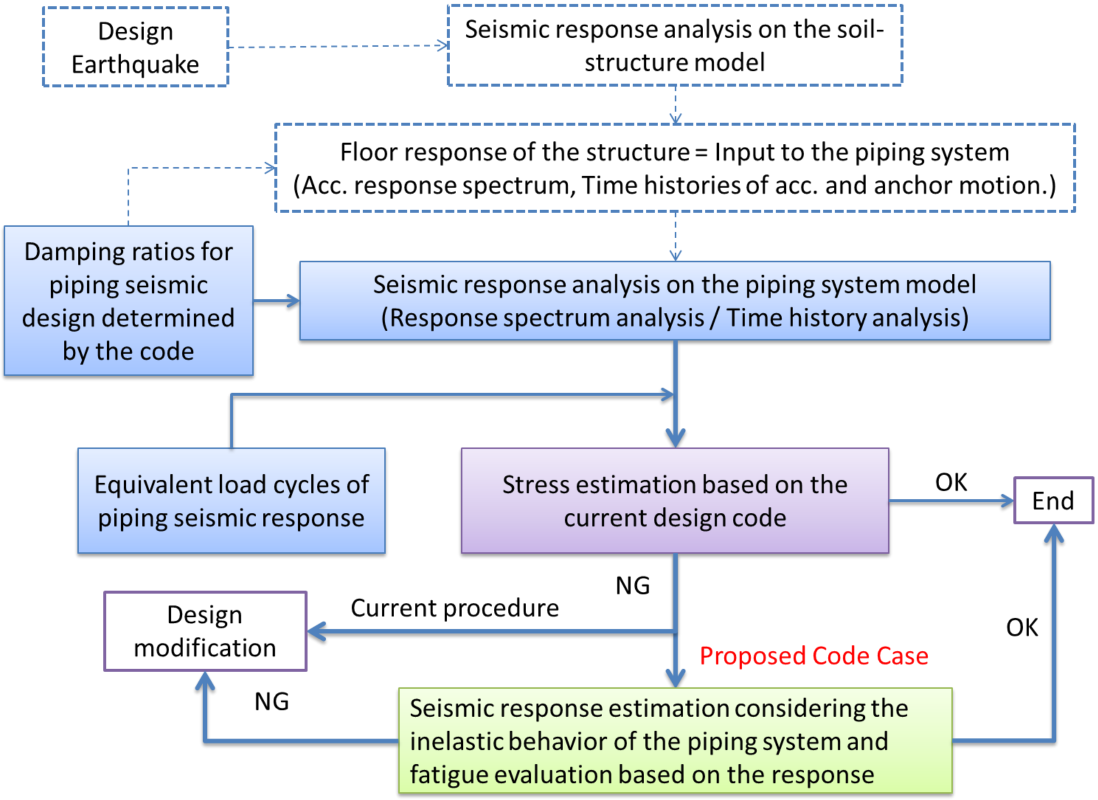


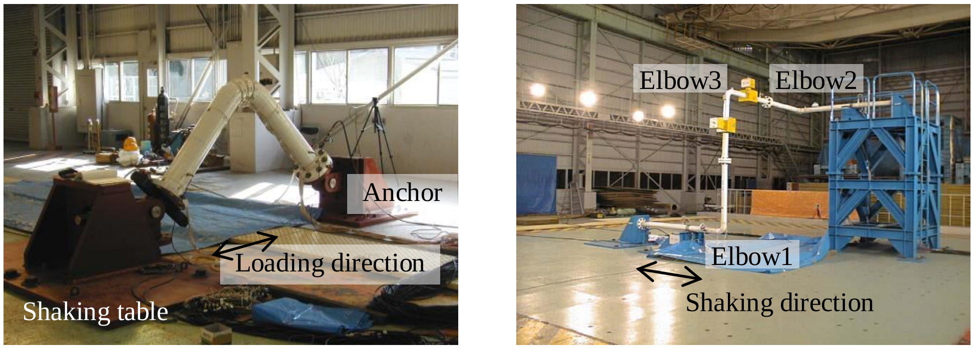
Figure 1. Outline of the seismic design procedure and the application of the Code Case

The developed Code Case is intended to be used as an alternative rule in case the estimated maximum stress on a piping system exceeds the allowable stress determined in JEAC4601-2008. Figure 1 shows the outline of the seismic design procedure and the application of the Code Case.

Benchmark Analyses and Parametric Analysis

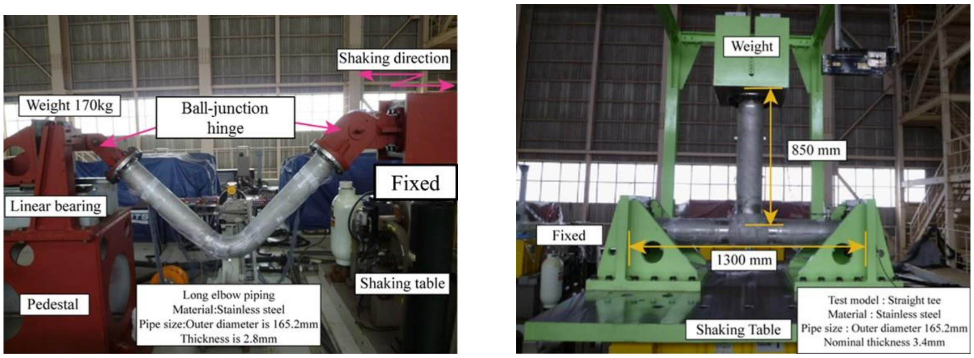
In developing the Code Case and the analytical guideline, the benchmark analyses and the parametric analyses were conducted. The analysis surveys are classified into the following three parts;

(1) The first stage of BA
  - Blind analysis on displacement controlled in-plane bending test on a carbon steel elbow (Pipe element test) and on one-directional shaking table test for the carbon steel piping system (Piping system test). The analysis objects are shown in Figure 2.
  - The analyses were conducted at three level of input intensity for each test; 1) ±15 mm and 80 gal - almost elastic level (within the current seismic design level), 2) ±30 mm and 700 gal - the level at approximately 1% strain range, and 3) ±70 mm and 1850 gal - the level that caused low cycle fatigue failure in the experiments.
  - The analytical conditions, such as the choice of the analysis codes, the way to approximate the material property, the detail of element mesh breakdowns in the analysis, were left for each participant's decision.
  - The aim of the first stage of BA is to investigate the dispersion of the elastic-plastic analysis procedures and the results among with the analysts under the blind condition, and to clarify the factors which affect the analytical results.



(a) Pipe element test (b) Piping system test

Figure 2. Analysis objects in the first stage of BA and PA (Carbon steel pipes)



(a) Test on an elbow (b) Test on a tee

Figure 3. Analysis objects in the second stage of BA (Stainless steel pipes)

(2) The second stage of BA
  - Blind analysis on one-directional shaking table test on a stainless steel elbow and a stainless steel tee. Figure 3 shows the analysis objects.
  - The second stage of BA was conducted at the time when the outline of the Code Case and the analytical guideline were almost drafted. Most of the participants conducted their analysis based on the proposed analytical guideline.
  - The analysis was conducted at the input acceleration level by which the maximum strain amplitude was approximately 1%.
  - The aim of the second stage of BA is to confirm the applicability of the analytical estimation procedure for stainless steel piping. The applicability of the proposed procedure by the analytical guideline for tee piping, that has more complicated shape than elbow piping, is also investigated.

(3) The PA
  - Parametric analyses on the same analysis objects for the first stage of BA (carbon steel pipes).
  - The PA was conducted at the time when the outline of the Code Case and the analytical guideline were almost drafted. Basic analysis conditions were specified.
  - The analyses were conducted mainly at the level of input intensity ±30 mm and 700 gal.
  - The aim of the PA is to investigate whether the proposed analytical procedure would mitigate the dispersion of analytical results among the different analysts. The sensitivity of the parameters is also estimated, especially for the yield stress and the work hardening modulus in modelling the stress-strain curve by bi-linear approximation.

Here, The strain amplitude (half of the strain range) 0.5-1% in the second stage of BA and the PA is the level where the Code Case is assumed to be applied, as described in the following section. The details of these analytical investigations are described in other papers (Nakamura et al (2016), Nakamura et al (2017), Watakabe et al (2017)). The summary of the findings are as follows;

(1) The determination of the yield stress in the material property approximation has a large effect on the estimation of the load–deflection curve and strain behaviour. Conversely, the determination of the work hardening modulus or the difference of the approximation method of the stress–strain relationship in the plastic range only slightly affected the analytical results.
(2) The strain range could be estimated reasonably by the elastic–plastic static analyses if the yield stress is determined at the actual strength of the pipe. On the other hand, the residual strain caused by the ratchet phenomena is difficult to predict.
(3) The strain distribution is fairly well predicted by the inelastic FEM analysis for both of the carbon steel elbow and the stainless steel elbow, while some analytical cases on the tee resulted in predicting the different strain distributions from the experimental result. The cause of such discrepancy is supposed to be due to the geometric difference between the actual tee and the analytical model.
(4) The strain range by the PA, which complied with the analytical guideline, was estimated to be larger than the actual experimental results. This means that the conservative estimation can be conducted by the inelastic FEM analysis according to the analytical guideline.
(5) The dispersions in the PA were reduced compared to those in the first stage of BA, both in the pipe element analyses and the piping system analyses. This result indicates that using the recommended analytical procedure when conducting the inelastic FEM analysis would be effective for reducing the dispersion among the different analysts.

The Main Body of the Code Case

The essential part of the Code Case is the fatigue failure evaluation procedure. Current seismic design code, JEAC4601-2008, also determines the procedure of the fatigue failure evaluation, but it is based on elastic response analysis and stress based fatigue criteria. Conversely, the proposed Code Case provides the fatigue evaluation procedures mainly based on detailed elastic-plastic seismic response analysis of piping systems and strain based fatigue criteria. The Code Case provides following two procedures;

(1) Evaluation based on the response spectrum analysis with additional damping
  - Response spectrum based evaluation procedure that is the same as the current design except that the additional damping is adapted in order to take into account the response reduction effect by energy absorption due to plasticity.

(2) Evaluation based on detailed FEM seismic response analysis
  - Evaluation procedure using the strain time history obtained by the elastic-plastic FEM seismic response analysis.
    For this procedure, the Code Case provides following two routes;
    (2-a) Limit to the maximum value of equivalent strain amplitude
    (2-b) Limit to the fatigue usage factor calculated from the series of the equivalent strain amplitude
  - Standard procedure of detailed inelastic analysis is provided in the analytical guideline (the mandatory appendix).

To calculate the usage factor, the design fatigue curve (The JSME (2012)) is used in any of the above procedures. Equivalent strain that is independent of spatial directions is used for fatigue evaluation, because there may be the cases where the orientation of the fatigue cracks would be unknown.

In the procedure (1), the proposed additional damping in the Code Case is 2%. One reason to propose 2% additional damping lies in the relatively conservative damping ratio in the current seismic design in Japan. The designated damping value in JEAC4601-2008 is 0.5-3.0% depending on piping support and insulation conditions, while most of the typical international standards allow 4-5% damping (International Atomic Energy Agency (2007), U.S. Nuclear Regulatory Commission (2007), The American Society of Mechanical Engineers (2015), American Society of Civil Engineers (2005)). Moreover, the adequacy of the additional 2% damping was confirmed by trial analyses on a simple piping

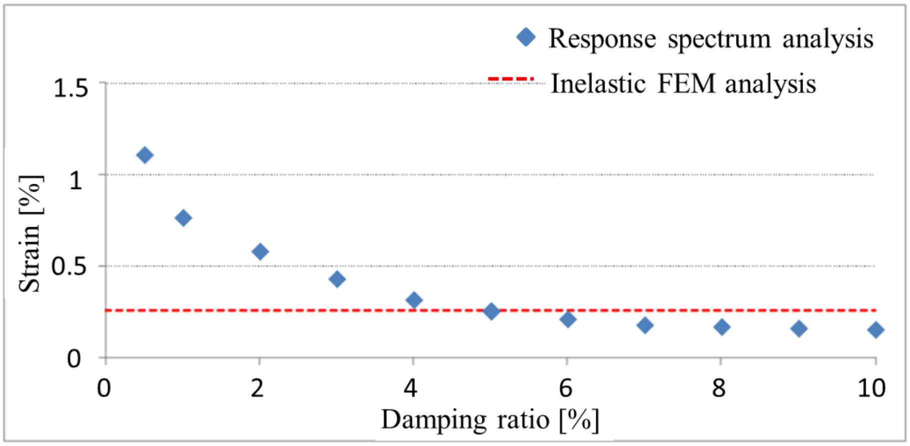


Figure 4. Comparison between the strain by the inelastic time history response analysis and the strain calculated based on the response spectrum analyses with various damping ratios

model (Morishita et al (2017)). Figure 4 shows the comparison between the strain obtained by the inelastic time history response analysis and the calculated strain based on the response spectrum analyses with various damping ratios. The damping ratio in the response spectrum analysis that caused the comparable amount of the strain to the inelastic analysis was approximately 5%, while the designated damping ratio was 0.5% according to JEAC4601-2008.

In the procedure (1) and (2-a), the equivalent number of earthquake load cycles is used to estimate the fatigue failure. The commonly used load cycles in Japanese NPPs range around 50 to 300 cycles depending on plant site conditions. Because the Code Case uses the design fatigue curve to calculate the usage factor, the allowable strain amplitude becomes approximately 0.5-1%.

The Analytical Guideline

The analytical guideline provides the methodology to obtain the elastic and plastic strains in seismic response. It contains the descriptions for analysis code, FE modelling including material property definition, time history analysis method, damping, seismic input condition and verification & validation method. Findings from the BA and the PA are reflected to write up the analytical guideline. In this paper, a provision for material property setting is introduced as an example of the rules determined in the analytical guideline.

The analytical guideline recommends using the kinematic hardening rule with a bi-linear stress-strain curve when the users model the material property, though more sophisticated constitutive law is accepted if it is confirmed as a reliable model. Yield stress (σ_y) and work hardening modulus (E_2) for the bi-linear approximation are determined as following equations;

$$\sigma_y = C_y \cdot S_y \tag{1}$$

$$E_2 = \frac{E}{C_E} \tag{2}$$

Where, σ_y: Yield stress of bi-linear stress-strain curve [MPa], C_y: coefficient of yield stress, S_y: the yield stress specified in design code [MPa], E_2: work hardening modulus (the secondary slope of bi-linear stress-strain curve), C_E: coefficient of the secondary slope, E: Young's modules. S_y and E in these equations are specified in the JSME material code (The JSME (2013)).

Specific determination for C_y and C_E are as follows;

As for carbon steel pipe: C_y=1.2, C_E=100

As for stainless steel pipe:

As for SUS304 (JIS):

$$C_y = 2.29 \times 10^{-4} \cdot T + 1.24 \tag{3}$$

C_E=69

As for SUS316 (JIS)

$$C_y = 2.16 \times 10^{-4} \cdot T + 1.28 \tag{4}$$

C_E=75

Where, T: temperature (degrees Celsius, RT≤T≤425).

C_y and C_E for carbon steel pipe was decided by reference to the previous research (Nara et al (2004)) and the results of the BA and the PA. As for stainless steel pipe, it is not so easy to determine a bi-linear approximation. In the analytical guideline, the equations for stress-strain curve of stainless steel

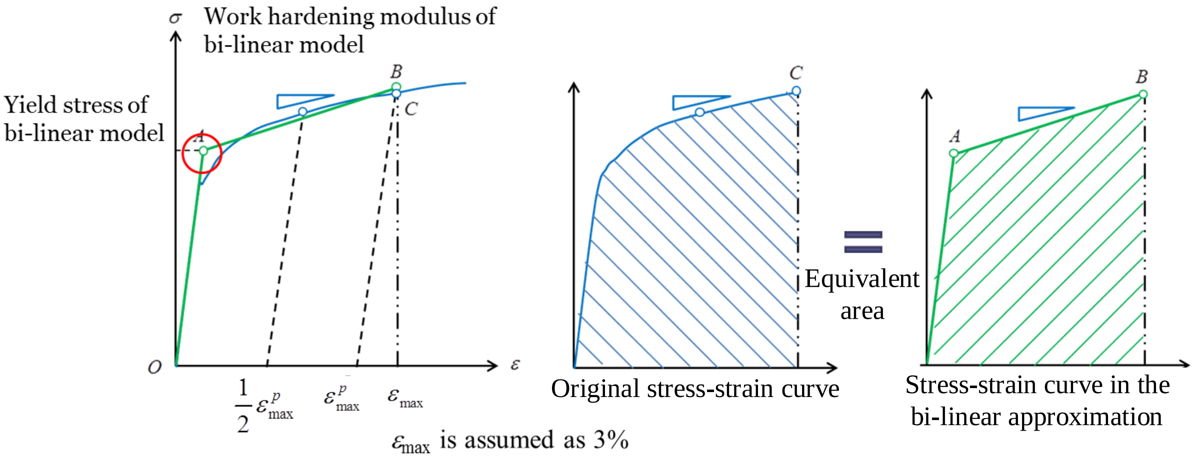


Figure 5. The bi-linear approximation procedure for stainless steel pipe's stress-strain curve

provided by the JSME design code for fast reactor power plant facilities (The JSME (2015)) is applied to model the true stress-true strain curve, and then the bi-linear approximation is conducted. C_y and C_E for stainless steel pipe is decided so that the energy of original stress strain curve and the energy of bi-linear approximation are equivalent under the condition that the maximum strain is 3%. Figure 5 shows the schematic illustration of this procedure. Using a result from an actual material test instead of the true stress-true strain curve determined by the code is also allowed. The adequacy of the determined C_y and C_E for carbon steel pipe was confirmed by the PA, and that for stainless steel pipe was confirmed by the second stage of BA.

DISCUSSION AND FUTURE ISSUES

Since the proposed Code Case is expected to be used in the actual seismic design practice, the basic concept to write up the Code Case is that it should be a simple and convenient procedure applicable in the practical use. This is one reason for the adoption of the conventional linear kinematic hardening model as the approximation of the stress-strain curve.

It is well known that the ratchet strain would occur on pressurized piping systems subjected to the high-level seismic load. The nonlinear kinematic models such as the Chaboche model should be used to predict the ratchet strain, but these models require complex calibration to predict ratcheting. Then, the Code Case does not require consideration of ratchet strain in fatigue evaluation. One reason is that the ratchet strain on the actual piping systems would not be negligibly small under the applicable range supposed in the Code Case (up to approximately 2% in strain range). Furthermore, it was confirmed that the experimental fatigue lives accompanied with large ratchet strain still included the design margin compared to the design fatigue curve (Arai et al (2016)). So the ratchet strain could be ignored in the fatigue estimation under the applicable range of the Code Case.

Through the second stage of BA, it was confirmed that reproducing the accurate geometry of tee in the analysis model was preferable to obtain the reasonable analytical result. It remains as the future issue to investigate the dispersion of the configuration and the wall thickness of actual tee products and to examine the influence of the modelling error on the analytical results. Such investigation would be effective to confirm the validation of the Code Case and the analytical guideline.

The applicability of the additional 2% damping in the evaluation based on the response spectrum analysis with additional damping may be still remained as a controversial issue. The main question for the additional damping is the adequacy to reduce the whole piping response by applying the additional damping, though the plastic deformation would occur on the local areas in the piping system. More analytical examples based on this Code Case would be necessary for this issue.

CONCLUSION

In order to properly estimate the strength of piping systems under a large seismic input by considering the elastic-plastic behaviour of piping systems in a rational way, a task group activity has been conducted since 2014. As the deliverables of the task group activity, a Code Case that provides the fatigue evaluation procedures and an analytical guideline for inelastic FEM time history analysis on piping systems have been proposed. The developed Code Case is intended to use as an alternative rule in case the maximum estimated stress on a piping system exceeds the allowable stress determined in the current seismic design. In order to establish the Code Case and the analytical guideline and confirm the applicability of them, a series of benchmark analyses and parametric analysis on existing experimental results were conducted.

The Code Case provides two types of strain-based criteria. In these criteria, the fatigue evaluation is conducted based on the equivalent strain amplitude obtained from a detailed inelastic analysis and the design fatigue curve. More simplified estimation procedure using the additional damping on the response spectrum analysis is also proposed in the Code Case. The analytical guideline provides the methodology to obtain the appropriate elastic and plastic strains in seismic response. These are available in the fatigue evaluation provided in the Code Case. The analytical survey results suggest that the inelastic analysis procedure based on the analytical guideline is adequate both for carbon steel pipes and for stainless steel pipes.

ACKNOWLEDGMENT

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