Ratcheting occurrence conditions of piping under sinusoidal excitations

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Received: 30 March 2020; Revised: 11 May 2020; Accepted: 7 July 2020

Abstract
Ratcheting is one of the dominant failure modes under excessive earthquakes and may cause extreme failures of structures (e.g., collapse). We focused on clarifying the ratcheting mechanism of piping under sinusoidal excitations. Both finite element analyses and experiments were conducted on bent solid bars, which represented piping in this study. Seismic ratcheting occurred due to the combined effect of constant external compressive force and cyclic vibrations. The external compressive force acted as a load-controlled load. Vibrations were applied to provide the source of the dynamic load. Characteristics of vibrations between load-controlled and displacement-controlled properties were studied from the viewpoint of the frequency ratio of the forcing frequency to the natural frequency of the piping model. In addition, the influence of supports on the occurrence of ratcheting was also considered. The results showed that the resonance effect was evident in the piping model compared with the beam model due to the limited plastic area in the piping model. The vibration with a lower frequency had load-controlled characteristics. In contrast, the vibration with a higher frequency presented displacement-controlled properties. In terms of the occurrence of ratcheting, providing more supports sometimes increased the possibility of the occurrence of ratcheting under relatively higher forcing frequencies because more supports increased the natural frequency and decreased the frequency ratio.

Keywords: Ratcheting, Seismic, Piping, Supports, Frequency ratio, Phase delay, Finite element method

1. Introduction

The inelastic progressive accumulation of plastic deformation occurs if the applied cyclic stress is high enough to cause yielding on structures. This phenomenon is called ratcheting or ratcheting effect (Hübel, 1996). The strain accumulates in the direction of the applied stress and may cause more severe failures of structures consequently (e.g., collapse). Therefore, it is essential to identify the occurrence conditions of ratcheting, as considered in many design criteria such as the ASME Boiler and Pressure Vessel Code (ASME, 2017). Those criteria require the structures to remain below the defined ratcheting boundaries (Abdel-Karim, 2005).

So far, many scholars have performed research work on ratcheting. Bree J. investigated the ratcheting mechanism of a pressurized cylinder subjected to cyclic thermal stress, which is known as the Bree diagram (Bree, 1967). Bree diagram identified ratcheting occurrence conditions under the primary membrane load with secondary bending load. Yamashita et al. further developed a theoretical ratchet diagram for rectangular beams subjected to the primary bending load with secondary bending load (Yamashita et al., 1990). However, current methods determining the ratcheting boundary only considers the constant pressure load with varying thermal loads. They are not suitable for the progressive deformation due to the excessive seismic load, especially when considering the mitigation of accident consequences for beyond design basis events (BDBEs). Therefore, investigating the ratcheting behavior under excessive vibrations with reasonable accuracy is necessary for engineering reference.

Excessive vibrations are frequently encountered in piping, which is one of the most basic structures in nuclear power plants. Long-term excessive vibrations can lead to ratcheting until the plastic collapse of the structure occurs. Collapse is usually considered as the failure mode under severe seismic loads in the seismic probabilistic risk
assessment. However, this assumption is not appropriate when considering the best estimation for countermeasures against BDBEs. In addition, many studies have found that ratcheting is one common failure modes of piping under extreme seismic loadings (Ichihashi, 2004) (Tagart et al., 1990) (Nakamura and Kasahara, 2019).

In this research, seismic ratcheting occurred due to the combined effect of constant external force and dynamic cyclic vibrations. Numerical and experimental analyses were performed on bent solid bars, which represented piping in this research. Characteristics of seismic loads between load-controlled and displacement-controlled properties were studied from the viewpoint of the frequency ratio of the harmonic forcing frequency to the natural frequency of the piping model. In addition, the effect of supports on the occurrence of ratcheting was also considered. Differences in flexibility factors of round solid bars from pipes had small influences on conclusions because the current research interest was the relative strength according to external force and supports.

2. Methodologies

Detailed numerical analyses were applied to obtain the precise ratcheting boundaries at different loading schemes. Experiments were performed to partially validate numerical results.

2.1 Numerical method

In numerical analyses, FINAS/STAR (ITOCHU Techno-Solutions, 2015) performed the finite element analyses (FEA) with the aid of the mesh generation by FEMAP (Siemens Product Lifecycle Management Software Inc, 2009). The nonlinear stress-strain curve of the Pb99%-Sb1% alloy (Fig. 1), which was from the tensile test at room temperature, was applied in numerical analyses. Both kinematic and isotropic hardening rules were included in FEA. The piping models under consideration were divided into two categories: the one without additional supports and the one with three supports in the medium part (Fig. 2). The naming method was according to the external force and supports (Table 1). For example, if one model had three additional supports with the external force equal to 10 Newton, we named the model as “10-S”. Similarly, the model “10-N” meant that the external force was 10 Newton, and this model did not contain three additional supports. Details on the model geometry and configuration would be explained in Section 2.2 (Experimental method).

Fig. 1 Nonlinear stress-strain curve of the Pb99%-Sb1% alloy in FEA. The stress-strain curve was from room temperature tensile tests at the authors’ laboratory. Both kinematic and isotropic hardening rules were included.
Two types of piping models in FEA. The left piping model does not include three external supports in the medium part. In contrast, the right model has three more supports. The vibration direction of the shaking table is in the horizontal Y direction. The diameter (D) of the circular cross section of the solid bar is 20 millimeters.

![Diagram of piping models](image)

(a) The piping model without three external supports. (b) The piping model with three external supports.

### Table 1: Naming method of models

| Model Name | External force | # of additional supports |
|------------|----------------|--------------------------|
| Unit       | N              |                          |
| 0-N        | 0              | None                     |
| 0-S        | 0              | 3                        |
| 10-N       | 10             | None                     |
| 10-S       | 10             | 3                        |
| 15-N       | 15             | None                     |
| 15-S       | 15             | 3                        |

There were two types of loadings applied to the piping model. The first one was the external compressive force at the ends of the piping model, which acted as the load-controlled force and caused primary bending stress. The second loading was cyclic accelerations from the shaking table, acting as the alternating dynamic loadings. The amplitude and frequency of input vibrations were adjusted to determine the onset of ratcheting at various load conditions.

Figure 3 shows one example of input sinusoidal accelerations. There are 50 sinusoidal waves with five increasing cycles at the beginning and five decreasing cycles in the end. Understanding the response of structures to sinusoidal excitations provides insight into how the system responds to seismic loads. Occurrence conditions of ratcheting were observed for loadings with different frequencies. “fn” used in this study means the natural frequency of the piping model. For example, “2.0 fn” means that the frequency of the input load is twice the natural frequency of the piping model, and the frequency ratio (fr) is “2.0”. To draw the ratcheting diagram, a criterion was needed to judge the occurrence condition of ratcheting. In this research, it was determined to be a 0.5% plastic strain at the extrados of the elbow accumulated during 50 sinusoidal cycles.
Fig. 3  One example of input sinusoidal accelerations. There are 50 normal sinusoidal waves with five increasing cycles at the beginning and five decreasing cycles in the end. The frequency is 8.0 Hz.

2.2 Experimental method

Considering the safety concerns and the limitation of the shaking tables at the authors’ lab, the material of the piping specimens used in the study was lead-antimony alloy (Pb99%-Sb1%) (Table 2). The previous study showed that the stress-strain curve of the lead-antimony alloy has a similar trend to the steel but much smaller yield stress (Nakamura and Kasahara, 2016). Besides, the elastic-plastic behaviors of the lead-antimony alloys are analogous with that of carbon steel. Such similarity of the stress-strain relationship indicated that the macroscopic plastic response behavior of structures made of steel could be simulated by the structures made of Pb99%-Sb1% alloys.

| Pb99%-Sb1% | Symbol | Unit        | Value        |
|------------|--------|-------------|--------------|
| Young’s Modulus | E      | MPa         | 19150 (23℃) |
| Poisson’s ratio | ν      | -           | 0.36         |
| Yield stress | σ_y   | MPa         | 8.5 (23℃)   |
| Mass density | P     | kg/m^3      | 11,340       |

(a) Experiment setting (10-S). (b) Geometrical parameters.

Fig. 4  Experiment setting and related geometrical parameters. There are three external supports with compressive force as 10 Newton. Therefore this model was named “10-S”.
The experiment setting and geometrical parameters are shown in Fig. 4. There was one mass (10 kg) attached to one end of the piping model and moved with the model. This mass did not provide the force of gravity since it was supported by the shaking table (Fig. 4). The diagram of the curved round solid bar was 20 millimeters. Fig. 5 compares four models in experiments. The naming rule was the same as that in FEA.

3. Results and Discussion
3.1 Correctness of the constitutive equation

The finite element analysis was conducted for one element (0.167 mm × 0.167 mm) to check the correctness of the constitutive equation in Fig. 1, which was from the tensile tests at the authors’ laboratory. One cycle loading was applied to the element. The responses of the one-element model under loadings with two different amplitudes were shown in Fig. 6. The results indicated that the stress-strain performance in FEA had a good correlation with the material test results, which meant that the constitutive equation was correctly applied in FEA.
Fig. 6 Comparison between the material test data and the FEA results. The response of the one-element model under loadings with two amplitudes had a good correlation with the material tests.

3.2 Comparison of natural frequency

Piping supports are usually applied to stop vibration at the supports. It is well known that whenever the frequency of excitation coincides with one of the natural frequencies of the system, resonance occurs and can lead to the failure of the system. Thus in any system, resonance conditions must be avoided. Therefore, it is necessary to check the natural frequencies of the piping to prevent resonance. Table 3 shows the first three natural frequencies of the two types of piping models in FEA, and they were similar to the experimental results in sweep excitation tests. It is obvious that the three external supports increased the natural frequencies of piping. In the current research, only the first natural frequency was considered since the participation factor of the rest frequencies was negligible.

| Parameters | Unit | Piping without three external supports | Piping with three external supports |
|------------|------|---------------------------------------|-----------------------------------|
| Natural frequencies (FINAS/STAR) | Hz    | 4.6                                   | 12.8                              |
|                                           |       | 36.2                                  | 78.0                              |
|                                           |       | 55.7                                  | 140.8                             |

3.3 Frequency-dependent characteristic

Figure 7 shows the FEA results in the frequency ratio to check the effect of external force. The frequency ratio (fr) is the ratio of the frequency of input vibration to the natural frequency of the piping model. The lines are the ratcheting boundaries, and ratcheting occurs in the area above the lines. Results show that the existence of the external force made the occurrence of ratcheting more easily. The lowest cases, which mean the highest possibility of the occurrence of ratcheting, were a smaller than 1.0 fn due to the damping effect: 0.99 fn in 10-N (15-N) and 0.95 fn in 10-S (15-S).
Figure 7 shows the evident frequency ratio dependency characteristics in the occurrence of ratcheting. To prevent catastrophic accidents, it is necessary to clarify the characteristics of seismic loads. In the previous study on the ratcheting occurrence conditions of beam models, authors divided the sinusoidal excitations into load-controlled loading and displacement-controlled loadings according to the frequency ratio (Lyu et al., 2019). In this study, the whole region was divided into three parts: pseudo load-controlled region, pseudo resonance region, and pseudo displacement-controlled region (Fig. 8). The resonance effect is not evident in the beam model; however, it is evident in the piping model. The main reason is that plastic deformation occurred in most parts of the beam. However, in the piping model, due to the horizontal arrangement of system structure, plastic deformation concentrated on the regions around the supports. It did not extend in the straight parts (Fig. 9). Therefore, the damping effect was not dominant in the piping model.

![Fig. 8 Three parts according to the frequency ratio.](image)

![Fig. 9 Deformation of Model 15-S by the end of vibration (1.0 fn, A = 3 m/s²). The purple line is the model before vibrations. Deformation concentrated on the support regions and the plastic region does not extend in the straight parts.](image)
3.4 Influence of supports

In order to check the influence of supports, numerical analysis results are shown in forcing frequency (Fig. 10). The lines also mean ratcheting boundaries. At the lower frequency (smaller than 7.8 Hz), ratcheting was easier to occur in the piping without three more supports. In contrast, at the higher frequency (larger than 7.8 Hz), ratcheting occurred easily in the piping with three more supports. This phenomenon was due to the frequency ratio. Supports increased the natural frequency of piping and therefore decreased the frequency ratio. Therefore in terms of the occurrence of ratcheting, providing more supports does not increase the safety of piping. We have to point out that the results can not be used to determine that the application of supports increases the possibility of failure of the piping. Supports may help to avoid other failure modes except for ratcheting. But those failure modes are beyond the scope of this paper.

![Figure 10](image1.png)

(a) The external force is 10 N. (b) The external force is 15 N.

3.5 Energy consumption and phase delay

The energy dissipated by damping is defined as the area enclosed by the inelastic stress-strain curve. Figure 11 shows the stress-strain curves of Model 15-S with different loading frequencies. By calculating the area enclosed by the curves, the energy lost in the elbow part of the curved rods is shown in Fig. 12. It is obvious that more energy was consumed with lower forcing frequency. This phenomenon was due to the phase delay, which is the time by which the response lags behind the force. The loading force and related response of the extrados of the elbow in Model 15-S with different loading frequencies are shown in Fig. 13. If the forcing frequency is 0.5 fn, the excitation slowly varied, and the displacement was generally in phase with the applied excitation. At 1.5 fn, the excitation quickly varied, and the displacement was almost of opposite phase relative to the applied excitation. The phase delay caused the difference in energy transferred to the piping, therefore with 0.5 fn, more energy was dissipated.

![Figure 11](image2.png)

(a) 15-S, 0.5 fn. (b) 15-S, 1.5 fn.
Fig. 12  Accumulated energy in all 60 cycles of Model 15-S with 0.5 fn and 1.5 fn.

Fig. 13  Force and the related response of the extrados of the elbow in Model 15-S with different loading frequencies.

3.6 Experimental results
The frequency of input sinusoidal wave was 8.0 Hz, which intermediated between the natural frequency of 0-N (4.9 Hz) and 0-S (12.0 Hz) in experiments. The same phenomenon in Fig.7 was also observed in experiments: the external force increased the accumulated strain in the extrados (Fig. 14). Besides, adding three supports increased the strain (Fig. 15). Therefore, when the forcing frequency was 8.0 Hz, ratcheting occurred more easily in the piping with three more supports. This conclusion is the same in Fig. 10, in which the ratcheting boundary of 10-S (15-S) is lower than that of 10-N (15-N) at 8 Hz.
4. Conclusions

Finite element analyses and experiments were conducted to obtain the ratcheting occurrence conditions of the solid bent bars, which represented piping in this research. The resonance effect was evident in the piping model compared with the beam model due to the limited plastic area in the piping model. At higher input frequency, ratcheting was easier to occur in the piping with three more supports because the supports increased the natural frequency and decreased the frequency ratio. Therefore, in terms of the occurrence of ratcheting, providing more supports does not mean increasing the safety of piping. The vibration with a lower frequency ratio showed load-controlled characteristics. In contrast, the vibration with a higher frequency ratio had displacement-controlled characteristics.

Nomenclature

fn: natural frequency
fr: frequency ratio
BDBEs: beyond design basis accidents
A: the amplitude of input acceleration
FEA: finite element analyses
E: Young’s modulus
ν : Poisson's ratio
σy: yield stress
ρ: mass density

Acknowledgment

This work has been sponsored by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT), and Tokyo Electric Power Company Holdings (TEPCO).

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