論 文 の 内 容 の 要 旨

論文題目　Study on Ratcheting Occurrence Conditions of Piping under Seismic Loads

（地震荷重下の配管ラチェット発生条件に関する研究）

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The accident that occurred at the Fukushima Daiichi nuclear power plant in March 2011 due to a massive earthquake and tsunami was one of the most severe accidents ever experienced in the nuclear energy industry. This accident has influenced the use of nuclear energy profoundly all over the world. One of the essential lessons learned from the Fukushima Daiichi nuclear accident is that the mitigation of accident consequences for beyond design basis events (BDBEs), which may occur due to excessive seismic loading, becomes essential.

Operation experiences indicate that the events which are outside of the design basis would lead to terrible consequences, though they have a low likelihood of occurrence and are characterized by large uncertainties. Those events are called BDBEs. Considering BDBEs is an essential component of the defense approach in ensuring nuclear safety. Requirements and required functions are different between design basis events (DBEs) and BDBEs. Requirements for DBEs are safety, availability, and serviceability; therefore, any failure should be prevented. However, requirements for BDBEs are safety and resilience; therefore, limited failure locations are allowable, and failure consequences should be mitigated. For BDBEs, the prediction of actual failure phenomena is necessary to find weak points and determine effective countermeasures. The design produced by the conventional approach may be feasible and reasonable; however, it tends to be conservative and, by no means, optimal in terms of cost and performance. Therefore, conservative methods are not suitable to predict actual failure locations and their order.

Countermeasures for BDBEs require the best strength evaluation methods of nuclear power plant components. For this purpose, it is necessary to clarify the dominant failure modes due to

extreme loading, which includes the identification of probable failure modes as well as the occurrence conditions of these failure modes. The current study focuses on ratcheting, which is one dominant failure mode of piping under seismic loading. The strain accumulating in the direction of the applied stress causes the occurrence of ratcheting and may cause failures of structures consequently (e.g., collapse). Therefore, it is essential to identify the occurrence conditions of ratcheting, as considered in many design criteria. Those criteria require the structures to remain below the defined ratcheting boundaries. 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 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. There are several studies on failure modes under seismic loading, and those studies have found that ratcheting is one probable failure mode under extreme seismic loadings. For example, the National Research Institute for Earth Science and Disaster Resilience conducted experimental investigations on failure behaviors of piping systems to clarify the possible failure modes under the beyond design level seismic loads. That research found that the most typical failure mode from the shaking table test was the ratchet and subsequent collapse. However, the occurrence conditions of ratcheting are not clear yet.

There are two types of models in this study: beam and piping models. The beam model was under consideration to identify the basic mechanisms of the occurrence conditions of ratcheting due to strong vibrations and compare thermal ratcheting (the Bree diagram and the Yamashita diagram) with vibration ratcheting. The analyses of the piping model were to extend the basic mechanisms to realistic structures. These two models are closely connected. For example, for a hollow cylinder, if the wall thickness is very much less than the mean radius, the effects of curvature may be neglected. Therefore the thin cylinder may be regarded as a two-dimensional beam model. The characteristic of the seismic load is ambiguous so that the classification of seismic loading characteristic with frequency effect is also under consideration. In addition, this study also tries to propose countermeasures against ratcheting for engineering reference.

Chapter 2 focuses on clarifying the ratcheting mechanism of beams subjected to the combination of gravity and seismic loads. The analogy between thermal ratcheting and vibration ratcheting was taken into consideration to investigate the characteristics of seismic loads.

Seismic ratcheting occurred due to the combined effect of load-controlled loading (e.g., gravity) and alternative cyclic accelerations. The criterion to judge the occurrence condition of ratcheting was decided to be 1% plastic strain accumulation during100 cycles of waves at the root part of the specimen. Dynamic inelastic finite element analyses were performed on a beam-shaped model under different loading conditions. FINAS/STAR did the finite element analyses (FEA) with the aid of the mesh generation by FEMAP. There were three types of vibrations in this chapter: sinusoidal excitations (it is called "SIN" excitations later), superposition of two sinusoidal acceleration excitations (it is called "SIN+SIN" excitations later), and seismic excitations. Experiments were carried out to validate the analytical analyses of the seismic excitations partially. Extreme loading conditions such as larger input accelerations are necessary to conduct an in-depth investigation of failure behaviors under BDBEs. However, it is difficult to realize those conditions for steel models due to the limitation of the performance of testing facilities and safety concerns during experiments. Thus, this study proposed an experimental method using specimens made of simulation materials instead of steel pipes to investigate failure modes under seismic loading with several reasonable assumptions. Characteristics of seismic loads between load-controlled and displacement-controlled properties were studied from the viewpoint of the frequency ratio of input loads to the natural frequencies. All the results were placed in a diagram similar to the Bree diagram to clarify the occurrence conditions of ratcheting. Results showed that the lower frequency loading had a relatively lower Y value, which means ratcheting is highly possible to occur. With lower frequency input, the load acts like load-controlled stress. With higher frequency input, the load acts like displacement-controlled stress. In addition, it is meaningful to use simple SIN waves instead of the complicated seismic wave to judge the occurrence of ratcheting if the major frequency of the seismic wave is the same as the SIN wave.

In Chapter 3, experimental and numerical analyses were performed on bent solid bars, which represented piping. Similar to the beam model, considering the limitation of the shaking tables at the authors' lab and the safety concerns, the material of the piping specimens used was also lead alloy. 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 source of alternating dynamic loadings. The nonlinear stress-strain curve of the Pb99%-Sb1% alloy, which was from the tensile test at room temperature at the authors' laboratory, was applied in numerical analyses. Both kinematic and isotropic hardening rules were included in this study. The piping models in FEM were divided into two categories: the piping model without additional supports and the piping model with three supports in the medium part. For the piping model, the criterion of ratcheting it was determined to be a 0.5% plastic strain at the extrados of the elbow accumulated during 50 sinusoidal cycles. Characteristics of seismic loads between load-controlled and displacement-controlled properties were studied from the viewpoint of the frequency ratio of the harmonic force frequency over the natural frequency of the piping model. In addition, the effect of supports on the occurrence of ratcheting was also considered. Results show 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. At higher frequency, ratcheting was easier to occur in the piping with supports because additional supports increased natural frequencies and decreased frequency ratio. Providing more supports the possibility of the occurrence of ratcheting. The vibration with a lower frequency ratio showed load-controlled characteristics. In contrast, the vibration with a higher frequency ratio has displacement-controlled characteristics.

Chapter 4 focused on the comparison of the ratcheting occurrence conditions between the beam model and the piping model, together with the Bree diagram and the Yamashita diagram. This chapter proposed one normalized vibration ratcheting diagram to show and compare ratcheting occurrence conditions with different materials and shapes.

The final chapter presented the general conclusions on the occurrence of ratcheting. In addition, countermeasures against ratcheting were also proposed in this chapter.