Numerical and experimental study on failure mode classification of piping components under seismic loading

その他のタイトル	地震荷重を受ける配管構造物の破損モード分類に関する解析および実験による研究
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論 文 の 内 容 の 要 旨

論文題目　Numerical and experimental study on failure mode classification of piping components under seismic loading
（地震荷重を受ける配管構造物の破損モード分類に関する解析および実験による研究）

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Preparation for Beyond Design Basis Events (BDBE) becomes an important issue as the lessons learned from the Fukushima Daiichi nuclear accident. Especially the strength of structure and component against great earthquake is always a matter of anxiety for the designer and public. This research basically focuses on the classification of possible failure modes due to seismic loading. The first chapter contains introduction and background of the research. It also contains the most part of the literature survey.

After Fukushima Daiichi nuclear accident, IAEA changed the defence in depth concept and propose Design Extension Condition (DEC) to consider BDBE in design. New defence in depth concept includes DEC in the plant status which implies that along with design basis cases, DEC cases also need to be considered in the design of a plant. Various extreme loading can cause DEC which includes seismic loading as well. From a view point of structural design, the strength evaluation approach for DEC is somewhat different from conventional one for design basis accident (DBA). For DEC cases, the best estimate approach is essential to take into account. For best estimation of structural strength against seismic load, it is required to know the dominant failure modes of the structure to make adequate preparation against seismic loading.

To know the probable failure mode due to seismic loading, various experiments have been conducted around the world. Out of these experiments, EPRI piping and fitting dynamic reliability test was one of the detailed test which focused on the dynamic behavior and failure mode of typical pressurized piping components including elbows, tees, reducers, nozzles and weld attachments. Shaking table tests were performed with designed input seismic wave. The probable failure modes found for the piping components were fatigue with ratcheting and collapse with ratcheting. Some experiments were also performed in Japan like large scale piping system model test and trial model test. All of these experiments confirmed that the dominant failure modes due to seismic loading are ratcheting, collapse and fatigue. But the occurrence conditions of these failure modes are not enough clear. So, one of the objectives of this study is to clarify the ratcheting, collapse and fatigue failure modes under seismic loading. In the case of seismic loading, the characteristic of seismic loading is still ambiguous. Some authors and codes consider seismic loading as load-controlled loading but some recent studies found that it can act as displacement-controlled loading as well. So, to clarify the characteristics of seismic loading is another objective of this study. Ratcheting, collapse and fatigue are the probable failure modes under seismic loading. Because of several different failure modes candidate due to seismic loading, it is helpful to put the occurrence conditions of all these failure modes in a same plot which can be named as failure mode map. The current studies also want to make a failure mode map due to seismic loading which includes the ratcheting, collapse and fatigue failure modes.

In the second chapter, the methodology of this research is discussed. A combined experimental and numerical approach is adopted to investigate the failure modes. A dynamic nonlinear elastic-plastic finite element analysis has been carried out to evaluate the occurrence condition of failure modes under bending-bending (primary-secondary loading) loading condition at various frequencies of acceleration. Two models are made for finite element analysis. One is simple a beam model and another is an elbow pipe model. To validate the finite element analysis results experiments were also conducted. In experiments, the beam models were tested on a shaking table with similar loading condition as numerical analysis. The methodology also includes theoretical study for existing ratcheting model and compared with the FEA results.

In the third chapter, the theory of ratcheting is explained and then the results of ratcheting are discussed. Mainly two theoretical ratchet models are related to the ratcheting analyses we do in this study. These two models are Bree model and Yamashita's model. The Bree diagram is the mother of all ratchet diagrams and Yamashita's bending-bending ratchet diagram is an extension of Bree diagram with different loading conditions. The results of FEA analyses are put in a non-dimensional stress plot similar to Bree diagram. The loadings of our ratcheting were more close to Yamashita's model for beam. So the results of our ratcheting analyses were compared with Yamashita's bending-bending ratchet diagram and similarity is found between these two results. In this research, three parameters are changing during the evaluation of occurrence conditions. These are - additional mass at top which makes the gravity loading, the input sinusoidal wave for seismic loading which makes the inertia loading and the input frequency of the sinusoidal wave to see the effect of frequency on occurrence of failure. From the results of FEA for beam model, it has found that at higher frequency the results were close to Yamashita's ratchet diagram but at lower frequency case it was following the theoretical collapse line. This indicates that at low frequency the seismic loading is acting more as load-controlled case and at higher frequency it is acting as displacement-controlled case. The experimental results were also compared with FEA results and similar trend has found between these two results, which validates the numerical scheme. After successful completion of beam model analyses, the ratcheting analyses were extended to elbow pipe model. A good resemblance has been found between beam model results and elbow pipe results.

The fourth chapter discussed about the results of other failure modes which include collapse and fatigue. Similar to ratcheting, collapse was also analyzed by FEA and experiment for beam model and only FEA for elbow pipe model. The occurrence of collapse is difficult to understand. So initially experiments have been conducted to understand the collapse and it has found that relatively low strain was sufficient to occur collapse as very high strain was not possible to achieve by the experimental facilities we have in our laboratory. After that, the experimental results were compared with FEA analyses results for low strain increments. Similarity has been found between the two results, which validate the FEA results for collapse. After successful validation of FEA results for low strain, collapse analyses was carried for high strain cases, which is more realistic for the collapse occurrence condition. The strain was considered as 25% for the occurrence of collapse in the case of Lead (Pb). Finally, collapse diagram was constructed similar to ratchet diagram for high strain occurrence condition. Collapse diagram was also extended for elbow pipe model. In the case of pipe, a 5% maximum strain criteria was used for collapse occurrence condition, which is the criteria used by British standard for pressure vessel. The other failure mode is fatigue. In the case of fatigue analyses, only the preliminary experiments have done and the results were put in a non-dimensional stress plot similar to the other two cases.

The fifth chapter is about failure mode map. FEA results of ratcheting, collapse and experimental results of fatigue were put in a same plot for beam model and elbow pipe model which is called as failure mode map. The concept of a failure mode map gives a useful classification tool against seismic loading for the designers of nuclear components.

The final chapter is general conclusion and future scope of this research. In conclusion it is discussed about the outcome of the research and how the objectives were achieved in this study. It also discussed about the explanation of the classical question about the characteristics of seismic loading. This chapter includes the general discussion of the results of ratcheting, collapse and fatigue. Finally it contains the future prospect of this research.

In appendix, the detailed results of ratcheting and collapse experiment are shown.