Failure modes investigation of pipe structure under excessive seismic loading

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Abstract: Preparation for DEC (design extension condition) is one of the lesson learned from Fukushima nuclear accident. From the structural point of view, it is needed to know the failure modes of the pipe structure to make adequate preparation against excessive seismic loading. But the failure modes under seismic loading are still not clear. Low cycle fatigue is one of the major failure modes observed at seismic experiments. Ratcheting is also observed at some other experiments. And collapse is assumed by design codes. In this article the characteristics of ratcheting and collapse under excessive seismic loading are investigated by simple beam analyses. The results show us some basic understanding on ratcheting propagation and collapse under excessive seismic loading.

Keywords: Failure modes, Pipe structure, Design extension condition, Seismic loading, Ratcheting, Collapse.

1. INTRODUCTION

The concept of nuclear safety has changed a lot after Fukushima. Before Fukushima, severe accident was a part of beyond design basis accident and the designers only considered design basis accidents prior to design. But after Fukushima, beyond design basis accident also included as design basis, so the designer need to consider beyond design basis accident during their design (explain later). The following table 1 and 2 represents the design and beyond design basis cases after and before 2012.

Though the beyond design basis accidents are included in the design basis as design extension condition but the prevention technique for design extension condition and design basis accident are different. For design extension condition the prevention approach is best estimation whereas for design basis accident, the approach is conservative.

From the structural point of view, to prevent design extension conditions or in other words to make the design resistant against design extension condition, designers need to know the failure modes of the specific component under extreme loading. One of the extreme loading is excessive seismic loading.

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There are several studies on failure mode under seismic loading and more or less it is found that low cycle fatigue failure, collapse, ratcheting and the combinations of these are the probable modes of failure. But the occurrence conditions of these failure modes are still not clear.

Table 1 IAEA NS-R-1 (2000)

Operational states		Accident conditions	
Normal operation	Anticipated operational occurrence	Design basis accidents	Beyond Design basis accidents
Plant status			Accident management

Table 2 IAEA SSR-2/1 (2012)

Operational states		Accident conditions	
Normal operation	Anticipated operational occurrence	Design basis accidents (Conservative evaluation)	Beyond Design basis accidents (best estimation)
Plant status (consider in design)			

The objective of this research is to clarify the occurrence condition of failure modes under seismic loading. In this paper the first stage research is presented. In first stage the seismic loading is applied on a beam structure to clarify the occurrence condition of ratcheting and collapse with literature review.

2. Literature Survey

For identification of different types of failure mode caused by seismic loading is done mostly by experimental evaluation. Preliminary vibration test result showed that the probable failure modes are collapse, buckling and low cycle fatigue [1]. On the other hand EPRI test result showed fatigue ratchet and ratchet buckling are the fundamental failure modes for pipe structure [2].

In preliminary vibration test, loading conditions had two different patterns. One was sudden acceleration for investigating effects of the maximum peak acceleration and another was continuous sinusoidal wave around natural vibration frequency. The tests were done on elbow pipe section. The result showed that continuous loading always lead to crack initiation and propagation around few hundred of cycles and on the other hand, plastic deformation was observed under sudden acceleration.

In EPRI test total thirty two specimens (mostly pipe structure of different geometry) were tested under dynamic loading until failure. The input seismic loads were much greater than actual seismic load with different maximum peak acceleration and frequencies. The result was interesting, it has seen that no collapse was occurred and for thirty specimens the failure mode was fatigue ratchet and other two specimens failure occurred because of ratchet buckling.

From the above literature survey it has been clear that due to seismic loading ratchet, collapse and low cycle fatigue are the fundamental cause of failure of pipe structure.

3. NUMERICAL STUDY

To clarify failure modes authors have planned step by step experimental and numerical analysis. First step is to do vibration test on simple beam structure. The experiment has done in Kasahara laboratory, University of Tokyo. The numerical simulation of the beam structure is done by FINAS/FINAS STAR (Finite element nonlinear structural analysis system) software. Here in this paper the numerical analysis of simple beam structure for ratchet and collapse analysis is discussed.

3.1 NUMERICAL ANALYSIS OF RATCHETING

Ratcheting effect, namely the cyclic accumulation of plastic deformation, occurs when the structure is subjected to a primary load with a secondary cyclic load if the applied loads are high enough to make the structure yield. The renowned ratcheting is thermal ratcheting, but the analysis of seismic ratcheting is new. In this work it is tried to find the occurrence condition of seismic ratcheting in a cantilever beam model by putting seismic acceleration at the base of the model. Also it is tried to find whether the seismic load is behave like secondary or primary.

To do that the following beam configuration shown in Table 3 and Fig.1 is used in simulation.

Table 3 Geometry and material properties of beam

Geometry			Material		
Length	Thickness	Width	Elastic Modulus	Density	Yield stress
140 mm	6 mm	13 mm	15250 MPa	11.34 gm/cm^3	5 MPa

Fig. 1 The model beam for numerical analysis

At the top node of the beam extra 4 different masses (0.1kg, 0.2 kg, 0.3 kg and 0.4 kg) was loaded to check the effect of maximum mass on the occurrence condition of ratcheting. The bottom node was fixed and a sinusoidal wave of different acceleration was put on this node. It was observed that ratchet deformation in vertically downward direction occurred due to the primary stress which is the stress caused by weight moment and secondary repetitive seismic stress due to inertia moment of the top mass. Time history response analysis was carried out whereas the elastic perfectly plastic stress strain constitutive equation was used. The frequency used in the analysis is twice the natural frequency of the model. One of the analysis results for 0.2kg showed that 5000gal acceleration has not occurred ratcheting deformation but 6000gal has occurred ratcheting deformation (Fig. 2). Occurrence condition of ratcheting, red dots indicated ratcheting whereas blue dots are not (Fig. 3).

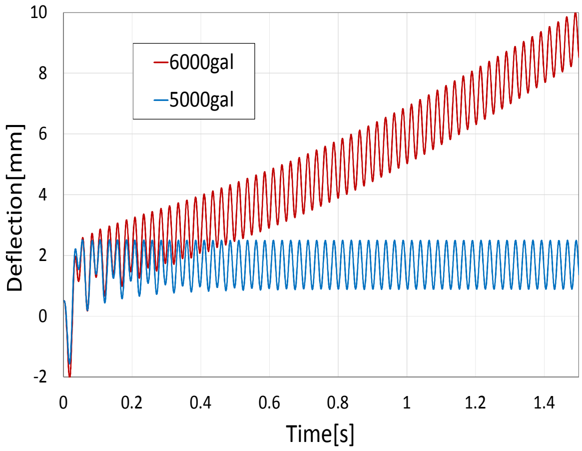

Fig. 2 Analysis results of deformation of ratcheting

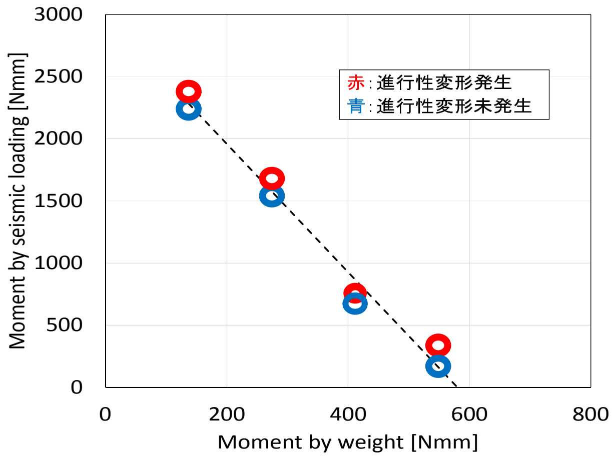

Fig. 3 Occurrence condition of ratcheting caused by seismic load

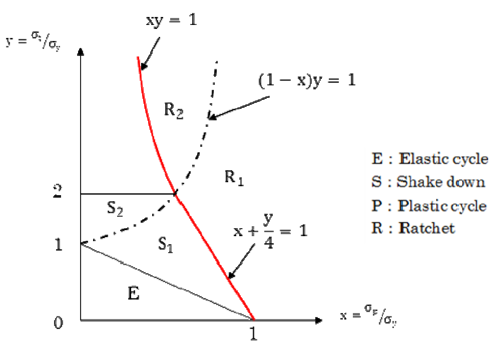

Fig. 4 Thermal ratcheting occurrence condition (Bree diagram [3])

The renowned Bree diagram (Fig. 4) is the occurrence condition for thermal ratchetting [3]. Horizontal axis expressed the primary pressure stress and vertical axis represents secondary thermal stress. Compared the Bree diagram with seismic ratchetting diagram it has seen that for the both the occurrence condition line has similar shape and also it has seen that ratcheting deformation is less likely to occur at high thermal loads which is similar in the case of seismic load. Since the similarity is found between the stress caused by seismic load and thermal load, authors thought that stress caused by the seismic load is also characterized as secondary stress manner.

3.2 NUMERICAL ANALYSIS OF COLLAPSE

Collapse is the excessive deformation of the structure, it occurs when the load doesn't satisfy the equilibrium condition. In other words due to stress the stiffness of structure reduces gradually with the deformation and resulting in complete loss of stiffness. For collapse analysis similar beam model was also used like ratcheting. The same material and geometrical properties were used along with the same 4 masses at the top node. The only difference was the input wave. The shape of acceleration wave was half sinusoidal (Fig. 5) but for ratcheting it was full sinusoidal wave. Also the frequency used in the case is natural frequency which is different from ratcheting analysis. The reason of using half sinusoidal wave was that half sinusoidal wave is similar to sudden pulse type wave and collapse is prone to occur for pulse type wave than continuous full sinusoidal wave.

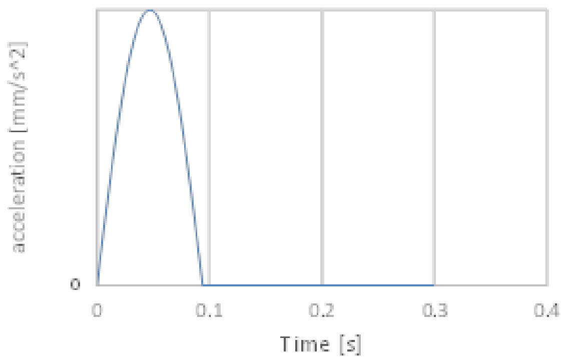

Fig. 5 Input pulse type acceleration for collapse

The analysis result of deformation for 0.2kg weight showed that for 10000 gal the collapse didn't occur because the deformation was not stable but for 15000 gal it occurred because the deformation saturate at the point which is almost the maximum possible deformation of this beam and also the deformation didn't increase by increasing the value of acceleration (Fig. 6). The mass-maximum acceleration curve

(Fig. 7) showed that more the top mass the less the seismic load is needed to occur collapses. The occurrence condition of collapse has also found similar behaviour like ratchetting (Fig. 8). Alike ratchetting the stress by weight which is primary stress has more impact on occurrence of collapse than stress by seismic load, though the occurrence condition line for collapse is not as straight as for ratchetting.

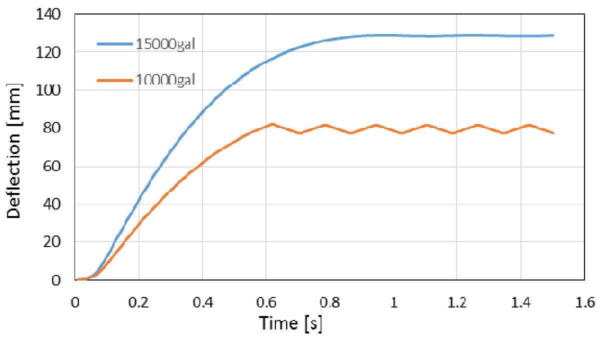

Fig. 6 Analysis results of deformation of collapse

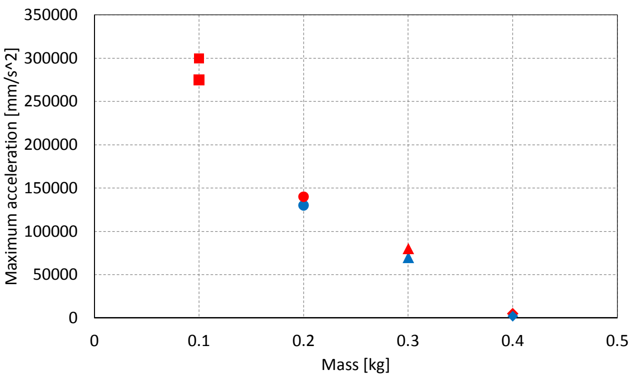

Fig. 7 Effect of maximum acceleration and mass on collapse

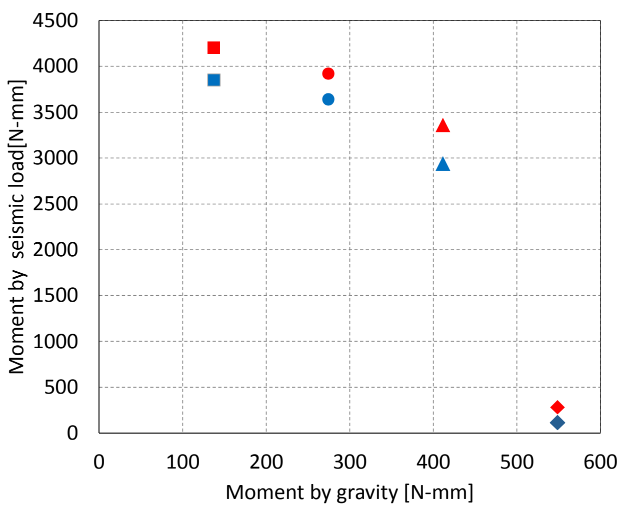

Fig. 8 Occurrence condition of collapse caused by seismic load

4. CONCLUSION

After the Fukushima nuclear accident, it is high time to robust the nuclear facility in such a way that core melting can be prevented in any circumstances. Earthquake is one of the major threats for any type of structure at any time. To make the heavy earthquake resistant design is not so easy; however it is prerequisite to know the exact failure modes of the structure due to earthquake to make the structure earthquake resistant. In this paper it is tried to establish the relation between seismic load and occurrence condition of 2 dominant failure modes for simple beam structure namely ratcheting and collapse. Thermal ratcheting is a well-known phenomenon and it has seen that similar diagram has also found for seismic ratcheting. From the comparison it can also say that seismic loading has similar characteristic like thermal loading which implies that seismic loading is a secondary loading. Also from the collapse analysis it can conclude that weight moment has relatively more impact on collapse than seismic moment. Weight moment is considered as a primary loading. However this is the first step of this research. The next step is to put the occurrence condition of ratcheting, collapse and fatigue in the same graph for beam model and for more realistic model. One of the crucial question about seismic loading is its characteristics. Sometimes it behaves like primary (load-controlled) loading and sometimes like secondary loading (displacement-loading). So the authors also want to clarify the seismic loading characteristic in this case. In future the more detail analysis will present.

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