Numerical study on piping failure modes under seismic loading - ratcheting and collapse

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Preparation for DEC (design extension condition) is one of the lessons learned from Fukushima Daiichi nuclear accident. Best estimation is required for DEC. For best estimation of structural strength against seismic load, it is needed to know the failure modes of the piping to make adequate preparation against excessive seismic loading. Ratcheting, collapse and fatigue are the probable failure modes of piping due to seismic loading. But the occurrence conditions of these failure modes under seismic loading are still not clear. Due to seismic loading from the cyclic seismic acceleration, structure undergoes progressive distortion and can cause ratcheting or collapse. Also low cycle fatigue is one of the major failure modes observed at seismic events and experiments. The current study investigates the ratcheting and collapse failure modes at various seismic loading by numeric analyses. The results show us some basic understanding on ratcheting and collapse occurrence condition under excessive seismic loading.

Keywords: Failure modes, Pipe structure, Seismic loading, Ratcheting, Collapse

１. INTRODUCTION

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

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

There are several studies on failure modes under seismic loading and more or less it has 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 not clear yet.

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)	Design extension condition (best estimation)
Plant status (consider in design)			

The objective of this research is to clarify the occurrence condition of failure modes under seismic loading.

2. FAILURE MODES DUE TO SEISMIC LOADING

Identification of different types of failure modes caused by seismic loading is done mostly by experimental evaluation. Preliminary vibration test result showed that the probable failure modes are collapse, brittle fracture and low cycle fatigue [1]. On

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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 study 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. Vibration experiment is being conducted in Kasahara laboratory, University of Tokyo on plate type model in a laboratory scale [1]. The numerical simulation of the similar structure is done by FINAS/FINAS STAR (Finite element nonlinear structural analysis system) software. Here in this paper the numerical analysis of ratchet and collapse analysis is described. .

3.1 NUMERICAL ANALYSIS OF RATCHETING

Ratcheting, namely the cyclic accumulation of plastic deformation, occurs when the structure is subjected to a primary load with a secondary cyclic load that are high enough to make the structure yield. The well understood ratcheting is thermal ratcheting investigated by Bree, Miller and Burgreen. They developed the evaluation method for thermal ratcheting in pressurized cylinder and proposed the 'Bree diagram', which is currently used in ASME code for class-1 components for fast breeder reactor at elevated temperature [3]. Thermal ratcheting occurs due to combination of primary membrane stress and secondary thermal stress (bending). This study investigates the ratcheting due to primary bending stress for gravity and secondary bending stress for base seismic acceleration. Similar theoretical ratcheting model for beam has been proposed by Yamashita *et al.* which is known as 'bending-bending' ratchet diagram (Fig. 2), where the primary bending stress is due to uniformly distributed constant lateral force and secondary bending stress is due to cyclic lateral deflection [4]. There are similarities between Bree diagram and Yamashita's 'bending-bending' ratchet diagram and in some point 'bending-bending' ratchet diagram is an extensions of Bree diagram. Here in our analysis the stress produced by the gravity is considered as primary stress whereas the hypothetical stress which is statically equilibrium to the base acceleration is considered as pseudo secondary stress. Because of the similar loading phenomena, the primary objective of this analysis is to make similar ratchet diagram as in 'bending-bending' ratchet diagram and also to understand the effect of frequency on ratchet occurrence. A numerical analysis along with experiment work has been conducted on beam specimens. The numerical analysis results are shown in Figure 5. The numerical analysis uses a beam shaped model with elastic-perfectly plastic material modeling. The bending moment of piping is analogous to bending moment of rectangular beam. Thus, in order to simplify the ratcheting analysis, in this study rectangular beam is used. The analysis was nonlinear dynamic with large displacement. The numerical model configuration has shown in Table 3 and Figure 1.

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

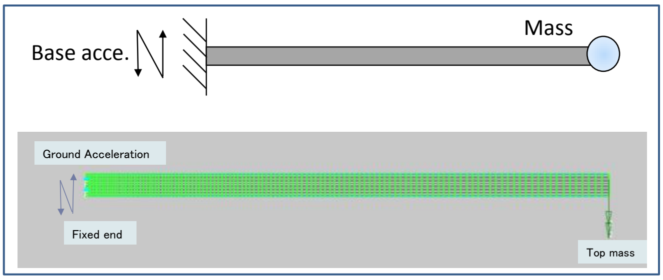

Fig. 1 The beam model for numerical analysis

Plane stress model with fine mesh was made for numerical analysis. At the top of the model various extra masses were loaded to have different values of primary loading. The bottom of the model was fixed and a sinusoidal wave of different accelerations and frequencies was put on base. It was observed that ratchet deformation in vertically downward direction occurred due to the primary stress which is the stress caused by gravity moment and pseudo secondary repetitive seismic stress due to inertia moment. Time history response analysis was carried out to see the accumulation of plastic strain. The ratchet criterion was taken as 1% total strain (surface strain near to the base of the model) at 100 cycles of acceleration.

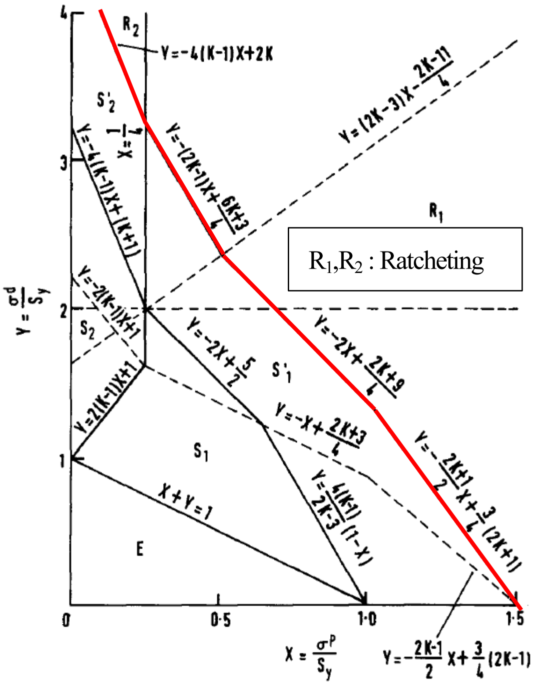

Fig. 2 Yamashita *et al.* 'bending-bending' ratchet diagram

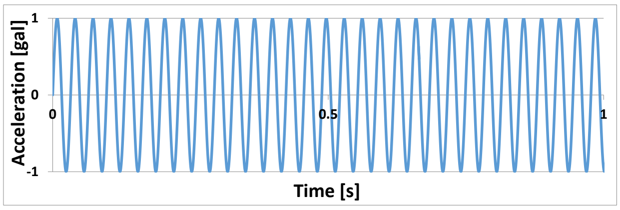

Fig. 3 Input acceleration for ratcheting

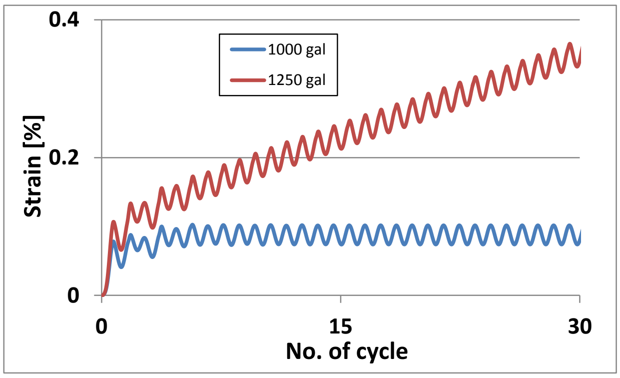

Fig. 4 Analysis of ratcheting

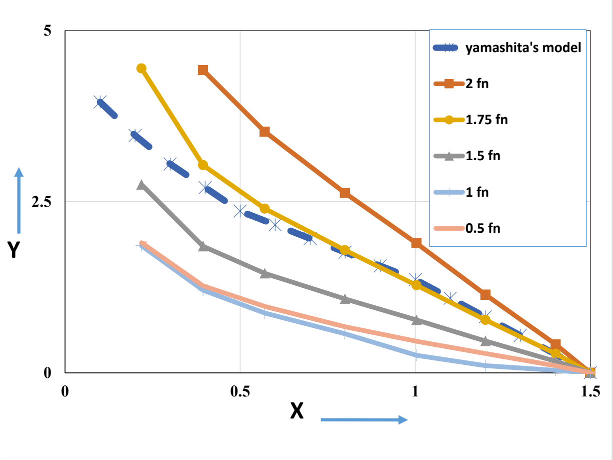

Fig. 5 Ratchet diagram for seismic loading

One of the analysis results showed in Figure 4, here for 1000 gal of acceleration the strain was not accumulated rather keeping the same magnitude whereas for 1250 gal of acceleration it accumulated at each cycle. So by definition 1250 gal causes ratcheting but not 1000 gal. Occurrence condition of ratcheting was evaluated for different frequencies and plot in non-dimensional stress parameter X, Y diagram (Fig. 5). Where, X is the non-dimensional primary stress parameter, which is

$$X = \frac{\sigma^g}{S_y} \qquad (1)$$

Y is the non-dimensional secondary stress parameter and can be expressed as

$$Y = \frac{\sigma^{in}}{S_y}. \qquad (2)$$

Here, σ^{g} is bending stress due to gravity; σ^{in} is hypothetical stress which is statically equilibrium to the base acceleration and S_y is the yield stress of the material. The frequency of seismic wave (assumed to be sinusoidal) plays role on ratchet occurrence; it can be seen in the proposed ratchet diagram (Fig. 5). The various lines in the diagram represent ratchet occurrence condition at different frequencies of input seismic wave; the frequencies were function of the natural frequencies of corresponding model. From the ratchet diagram it has been shown that at frequency 1.75 times of the natural frequency, the numerical result best matches with Yamashita *et al.* 'bending-bending' ratchet diagram and the most damaging frequency occur at natural frequency. Due to this the line represent natural frequency is the bottom most line of the ratchet diagram. The next to the bottom most line is due to frequency 0.5 times of natural frequency, although the frequency is smaller than natural frequency but it is less fatal. The reason behind it can be explained by amplification factor because of frequency which is shown in Figure 6.

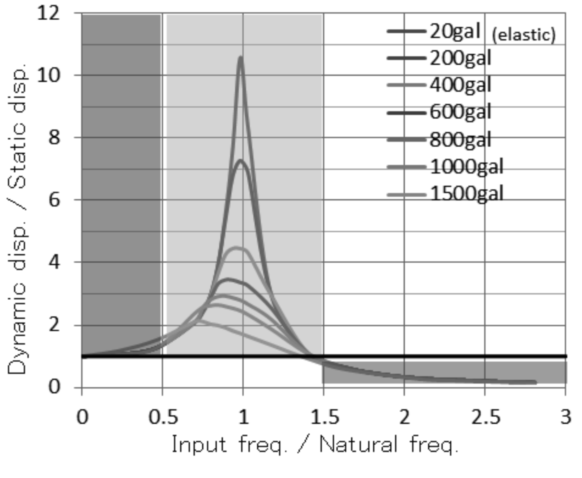

Fig. 6 Amplification factor

Figure 6 shows that the response displacement ratio (non-dimensional) varies with frequency ratio, and most dangerous or unstable region is the green region. It is also observes that the frequency ratio 0.5 has higher amplification than frequency ratio 1.5 and so on. This phenomenon also observed in the ratchet diagram, since the line for higher frequency ratio make the upper part of the ratchet diagram.

One of the ambiguities about seismic loading is whether it is primary (load-controlled) or secondary (displacement-controlled). Since the similarity is found between the stress caused by seismic load and the secondary stress caused by lateral deflection from the Yamashita's model, authors thought that stress due to seismic load can act as secondary stress but it depends on frequency. In our analyses the frequency ratio 1.5 to 2 the behavior of seismic loading has similar to the behavior of secondary load. So from the above discussion it can be said that seismic load is a frequency dependent secondary load.

3.2 NUMERICAL ANALYSIS OF COLLAPSE

Collapse refers to the inability of a structural system to sustain gravity loads in the presence of seismic effect which can be characterized by widespread propagation of failure [5]. In other words collapse is the excessive deformation of the structure, it occurs when the load doesn't satisfy the equilibrium condition.

In order to define collapse failure occurrence there are various damage indices have been proposed for various structural material. Out of these Colombo and Negro [6] proposed a generalized index that can be used independently of the structural material. In this analysis the generalized damage index shown below was employed to indicate damage level -

$$D = 1 - \frac{M_{ac}}{M_y} \qquad (3)$$

$$M_{ac} = M_y . f(\mu . \int dE) \qquad (4)$$

Here, M_{ac} is the deteriorated value of the yield moment and M_y is the theoretical yield moment of the structural member. From Eq. (4), the deteriorated value of the yield moment is calculated by the evaluation equation $f(\mu . \int dE)$, and is a function of the maximum attained deformation μ and dissipated energy $\int dE$. The energy-based function has two different terms affecting ductile and brittle behavior of structural member. Since the damage index is employed for damage assessment of beam like structure in collapse analysis, the ductility-based function was adopted in this case.

$$\mathrm{f}(\mu . \int dE) = \mathrm{f}(\beta_1, \mu) = \left(1 - \frac{\mu_{max}}{\mu_u}\right)^{\frac{1}{\beta_1}} \qquad (5)$$

Where μ_u and μ_{max} represent the ultimate and the maximum attained ductility, respectively, and β_1 is the accelerator factor modifies the slope of the hardening/softening branch of the stress-strain curve. The damage index D has a range of value from 0 (no damage) to 1 (total damage). In this analysis when the damage index reaches 1, it is indicated as collapse failure. So it implies, when the strain reaches to the ultimate strain (for material lead (Pb), $\mu_u \cong 30\%$), it considered collapse.

For collapse analysis similar plain-stress model was used as ratcheting. The same material and geometrical properties were used along with the top node mass. The only difference was the input wave. The shape of acceleration wave was half sinusoidal (Fig. 7) wave with varying frequency. The objective of collapse analysis is to investigate the dynamic effect due to sudden failure of structure with unusual large deformation rather than the accumulated damage from cyclic deformation. Due to this the half cycle of acceleration was taken into account. Also it has been seen that many of real world earthquakes have only one large pick compared to other very small peaks, which can be simulated by half cycle of acceleration.

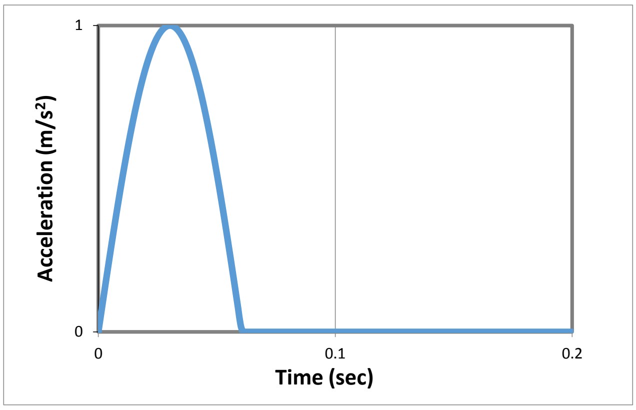

Fig. 7 Pulse type input acceleration for collapse

The analysis result of strain for 0.35 kg of top weight showed that for 5000 gal of acceleration the collapse didn't occur but it occurs at 11000 gal of acceleration because at 11000 gal the maximum strain reaches to 30% (Fig. 8). Since the occurrence condition of collapse is related to the ultimate strain of the material, which is 30% for lead (Pb) (material used in our numerical analysis). The occurrence condition of collapse has been shown in Figure 9. Similar effect of frequency has been observed in the collapse analyses as like ratcheting analyses. The least value of seismic acceleration which makes the structure collapse is due to the natural frequency. Form the collapse diagram it is observed that the collapse occurrence is largely depends on non-dimensional primary stress parameter X than non-dimensional secondary stress parameter Y, that is why X closes to 1.5 takes lower value of Y and vice versa. The X equal to 1.5 is the theoretical static collapse point for beam. Our numerical results also show the similar phenomenon. Furthermore, in our numerical analysis the minimum value of X that can occur collapse is 1, below that our numerical model didn't converge. So from our numerical analyses results it can be said that, collapse occur only at certain range of X values and below that collapse don't occur. In this case X less than 1 is safe zone.

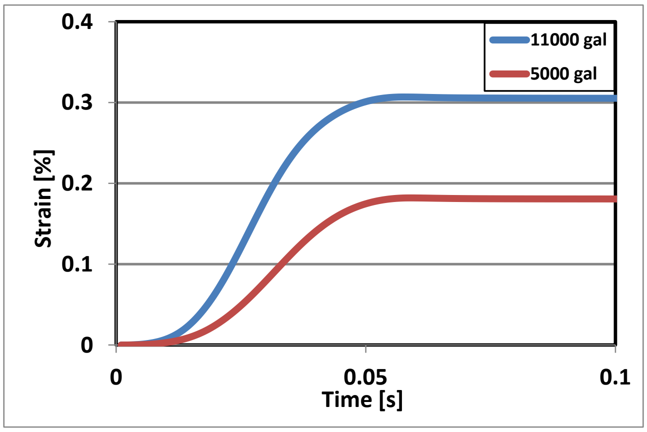

Fig. 8 Estimated strain of collapse analysis

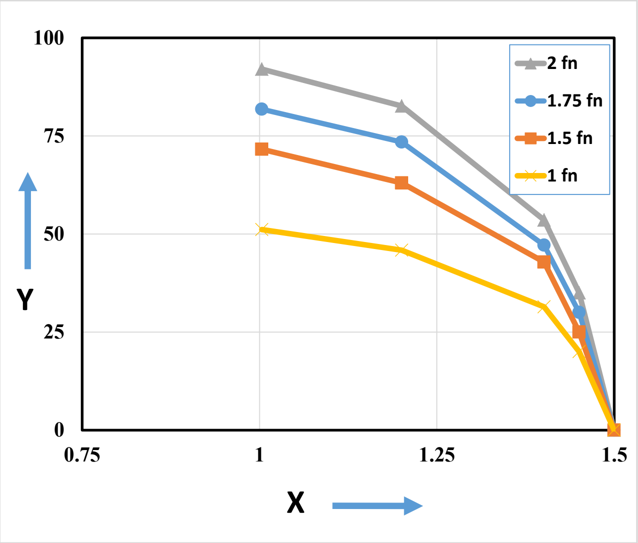

Fig. 9 Collapse diagram for seismic loading

4. CONCLUSION

After Fukushima Daiichi nuclear accident, it is important to strengthen the nuclear facility in such a way that core melt can be prevented in any circumstances. To make structure tough enough against excessive earthquake, it is prerequisite to know the exact failure modes of the structure due to earthquake. In this study the occurrence condition of two major failure modes ratcheting and collapse has been investigated by numerical analyses for seismic loading. The large deformation dynamic elastic-plastic numerical analyses were done on the beam shaped structure by the fine meshed plane-stress element model. From the analysis, the similarity has been found between Yamashita *et al.* theoretical 'bending-bending' ratchet diagram and numerical results of seismic ratchet diagram. The characteristics of seismic load depend on its frequency, and for certain frequencies the seismic load act as secondary load. The experimental analysis for similar model has done for ratcheting but not included in this paper, also supports the numerical analyses results. For the collapse analysis, it can conclude that load-controlled constant stress by gravity has more impact on collapse than stress by seismic load. However this is the preliminary stage of this research. Future objective is to present the occurrence condition of all possible failure modes due to seismic load in the same diagram.

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