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NUMERICAL AND EXPERIMENTAL STUDY ON STRUCTURAL FAILURE MODES UNDER SEISMIC LOADING

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ABSTRACT

Preparation for beyond design basis events (BDBE) becomes important as the lessons learned from the Fukushima Daiichi nuclear accident. Best estimation is required for design extension conditions, which is a part of BDBE. 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. 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 the same diagram which can be named as failure mode map. The current studies describe an attempt to make a failure mode map due to seismic loading which includes the ratcheting and collapse. A combined experimental and numerical approach is adopted to investigate the failure modes in plate type model. In this study the experimental analysis of a beam model for ratcheting and collapse analyses has been discussed under bending-bending (primary-secondary loading) loading condition at various frequencies of acceleration. The beam models were tested on a shaking table with similar loading condition as numerical analysis. For ratcheting the results were compared with Yamashita et al. theoretical bending-bending ratcheting model and as well as results those obtained from experimental analysis. For collapse the finite element analysis results were compared and validate by experimental analysis results. Finally the occurrence conditions are put in the failure mode map by using non dimensional stress parameters as used in the Bree diagram.

INTRODUCTION

On March 11, 2011, a 9.0-magnitude earthquake struck Japan and was followed by about15 m tsunami, resulting in extensive damage to the nuclear power reactors at the Fukushima Dai-ichi facility. After the accident at Fukushima Daiichi Nuclear Power Station several investigation committees issued reports with lessons learned from the accident (International Atomic Energy Agency (IAEA) 2013)(Aa et al. 2011).Among those lessons, some recommendations have been made on beyond design basis accident (BDBA) research. BDBA has a low probability of occurrence but a very high impact on the plant. IAEA proposed design extension condition (DEC) (International Atomic Energy Agency (IAEA) 2000) for considering a part of BDBA that can occur due to extreme loading.

From the structural point of view, the strength evaluation of DEC is different from design basis. Instead of taking the conservative approach as for DBA, DEC adopts best estimation technique. For best estimation approach, it is required to clarify the dominant failure modes under extreme loadings (i.e. high temperature, pressure or excessive seismic loading). Clarification of dominant failure modes includes identification of probable failure modes as well as the occurrence conditions of these failure modes. There are various sources of extreme loading for a plant which can lead the plant to beyond design basis accident; a great earthquake is one of them. Several different failure modes can occur due to dynamic loading like seismic loading. Fatigue is one of the well-known failure modes for such dynamic load

(Kasahara et al. 2014). But other failure modes as ratcheting deformation or collapse can also occur depending on loading conditions (Nakamura and Kasahara 2016).
Ratcheting is generally defined as cyclic accumulation of plastic deformation due to the combined effect of primary load and secondary cyclic load which are high enough to make the structure yield. Ratcheting may lead to other failures like excessive deformation and fatigue. Structures in nuclear power plant need to resist ratcheting due to cyclic thermal stress induced by cyclic temperature or under cyclic bending initiated from seismic or other cyclic loadings (Weiß et al. 2004).
Collapse is another failure mode which can occur due to excessive seismic loading. Collapse refers to the significant plastic deformation occurrence in the structure or a system as a whole (uncontained plastic flow). It occurs when any plastic region of any structure grown to a sufficient extent such that the surrounding elastic regions no longer prevent the overall plastic deformation from occurring. This is considering a real failure and structure will unable to perform its function. Some realistic earthquake evidence of collapse in real structure like, in 1994 Northridge earthquake caused collapse of a large-diameter flexible corrugated metal pipe (Bardet and Davis 1996). One year later Daikai subway station collapsed in Kobe, Japan due to Hyogoken-Nanbu (Kobe) earthquake(Iida et al. 1996) . Research was conducted to understand collapse for nuclear facility too(Ichihashi 2004) .
The one of the characteristic of dynamic load like seismic load is the frequency dependency characteristics. Relatively less work has done on the effect of frequency on the failure occurrence. In this study, the effect of frequency on occurrence of failure is also discussed along with the failure mode diagram for ratcheting and collapse.

RATCHETING

Ratcheting is the progressive deformation due to the combined effect of primary and secondary loads [56]. Ratcheting occurs where there is a combination of two different loading, namely- constant primary loading and cyclic secondary loading. If these two loads are high enough, the structure can exhibit an accumulation of plastic strain in each cycle. The ratcheting mechanism of a pressurized cylinder subjected to cyclic thermal stresses was investigated by Bree(BREE 1967). The classical case of structural ratcheting diagram is known as Bree diagram. Like other failure modes such as fatigue and creep, ratcheting has also been considered in many design criteria in many structural engineering code, including ASME Code Section III(American Society of Mechanical Engineers 2007), EN13445 (BS, 2014 2002). These criteria require the structures to remain below the defined ratcheting boundaries where elastic or plastic shakedown occurs. However, current methods to determine the ratcheting boundaries can be too conservative or sometimes non-conservative (Chen et al. 2013). It is therefore worth to investigate the ratcheting behaviour and predict the ratchet boundary for different loading conditions, which has already been an interest for the researcher for last two decades.
In general, there are three types of modes of ratcheting. First mode (mode I) ratcheting is due to the both membrane primary and secondary stresses without any bending. This type of ratcheting can be modelled by a two-bar structure. The second type (mode II) ratcheting can occur due to the combination of primary membrane stress and secondary bending stress. This type of ratcheting was analysed by Bree and the proposed diagram is Bree diagram [56]. Finally, mode III ratcheting occurs by the combination of primary and secondary bending loading. The third type of ratcheting is more relevant in the case of seismic loading with gravity load. The third type of ratcheting was been theoretically analysed by Yamashita et. al. (Yamashita et al. 1990) for rectangular beam.

Test Specimen for dynamic experiment of ratcheting

In order to clarify the ratcheting occurrence conditions by experiment, following beam model was tested by shaking table in our laboratory. The beam model used in this experiment were made of lead allow (Pb99%-Sb1%). The use of lead is because of limitation of our laboratory facility. Though in actual plant steel is used as material for most of the structural components but it is difficult to accomplish failure of steel specimen in laboratory because of high external force is needed. Figure 1 showed the specimen was used for ratcheting experiment. The beam was 140 mm long and 6 mm thick with 13 mm width. The lower part was to attach the specimen on the shaking table.

Test Condition

Excitation tests were conducted to obtain occurrence conditions of ratcheting. The test setup is shown in Fig 2. The bottom of the beam is fixed to the table, and an additional mass was fixed at the top of the beam. Additional top mass was placed at the top of the specimen by an offset position to get a desired gravity loading. The gravity load by the top weight is acted as a primary load of the setup. The base acceleration coming from the shaking table was the source of pseudo secondary load. The weight of the top additional mass and the own weight of the beam contribute to the inertia load. The ratcheting occurrence conditions were recorded for mainly four different frequencies (0.5, 1.0, 1.5 and 2.0 times of natural frequency) at four different gravity loading conditions. The acceleration was adjusted to obtain ratcheting at different conditions as mentioned above. The shaking table produced the desired waveforms from the input waveforms. The waveforms used in this study were mainly sinusoidal with varying frequency. The waveforms were tapered at the beginning and end of the steady amplitude, shown in Fig. 3.The taped part was about 10 to 15 % of the total length of waveforms. Generally the number of cycles of each of the waveform was 50, among these 50 cycles with 5 to 6 cycles of additional tapered part. This was the first attempt to conduct experiment of ratcheting, so the input parameters were changed by trial and error basis. There were three parameters taking into consideration in the ratcheting analysis, the top additional mass, the input acceleration and the frequency of input acceleration. Due to each top mass, the input acceleration was changed to get desired failure. During this time the frequency was unchanged. After that, the frequency was changed and repeats the whole procedure. All the experiments were done at room temperature. The experimental analysis conditions were given below in Table 1.

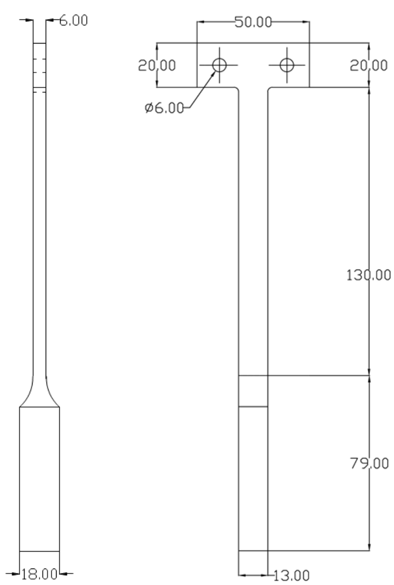

Figure 1 Configuration of beam shaped specimen for experiment

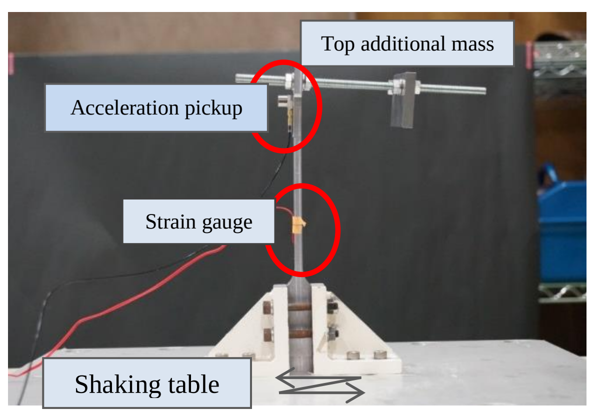

Figure 2 Experimental setup for ratcheting experiment

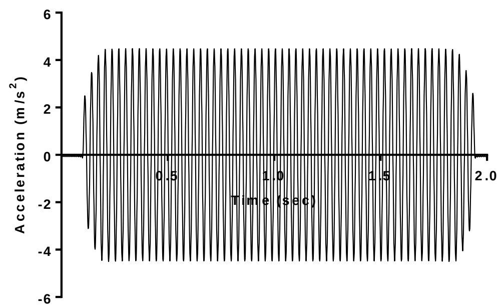

Figure 3 5Typical input acceleration for experiment

Table 1 Experimental analysis conditions for ratcheting for beam model

Case No.	Top additional mass [kg]	Natural Frequency [Hz]	Input frequency [Hz]	
1	0.245	15.625	0.5fn	7.81
2			1.0fn	15.63
3			1.5fn	23.43
4			2.0fn	31.25
5	0.340	11.718	0.5fn	5.85
6			1.0fn	11.72
7			1.5fn	17.58
8			2.0fn	23.44
11	0.530	9.375	0.5fn	4.69
12			1.0fn	9.38
13			1.5fn	14.06
14			1.75fn	18.75
16	0.805	8.79	0.5fn	4.39
17			1.0fn	8.79
18			1.5fn	13.16
20			2.0fn	17.58

Experimental results and its plot on the ratchet diagram similar to Bree diagram

Occurrence condition of ratcheting was evaluated for different frequencies and plotted in a non-dimensional stress parameter X, Y diagram (Fig. 6) similar to Bree diagram. Where, X is the non-dimensional primary stress parameter and Y is the non-dimensional primary stress parameter, which can be written as

$$X = \frac{\sigma_1}{\sigma_y} \qquad (1)$$

$$Y = \frac{\sigma_2}{\sigma_y} \quad (2)$$

Here,
σ_1 = bending stress due to gravity calculated elastically
σ_2 = bending stress due to maximum acceleration calculated elastically
σ_y = yield stress
Bending stresses are calculated by the following equations,

$$\sigma_1 = \frac{M_g}{Z} \quad (3)$$

$$\sigma_2 = \frac{M_{in}}{Z} \quad (4)$$

Whereas, M_g and M_{in} are the moments dues to gravity and inertia force and Z is the section modulus. The moment due to gravity is calculating by considering the weight of the additional mass and self-weight of the beam and the link which hold the additional mass. The moment due to inertia is calculated by considering the maximum input acceleration. To make ratchet diagram, a criteria is needed to judge the occurrence condition of ratcheting. Since the number of repetitions of earthquakes presumed by the design standard is 100, in this research the ratcheting is judged by 1% plastic strain per 100 cycles of wave. That is, 0.1% for 10 cycles and 0.5% for 50 cycles are the criteria for the occurrence of ratcheting. For experiment it is taken 50 cycles of acceleration wave and 0.5% or above is the occurrence condition of ratcheting. A typical strain response in the presence of ratcheting in FE results has shown in Fig. 4.

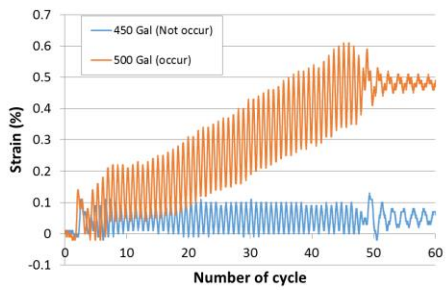

Figure 4 Typical strain response in presence at the occurrence of ratcheting

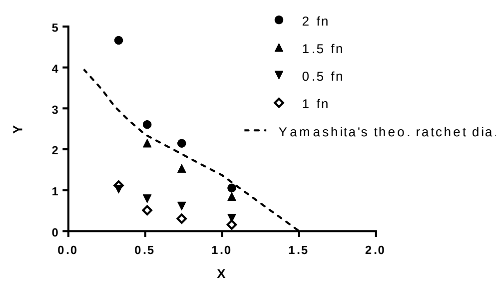

Figure 5 Experimental ratchet diagram

After evaluating the ratcheting criteria for each of the frequencies at each of the top mass condition, the ratchet diagram was made which is shown in Fig. 5. Here, the term fn is the ratio of the natural frequency of the model to the input frequency of the acceleration.
The different line presents in ratchet diagram is for different frequencies. It has been seen that at lower frequency the ratchet diagram stays bottom part of the graph whereas at high frequency the diagram follows the theoretical ratchet diagram proposed by Yamashita *et. al.*. The more explanation of frequency dependency characteristic is presented later part of this paper.

FE analysis results and comparison with experimental results

A finite element analyses was also carried out for evaluating the occurrence condition of ratcheting and making a detailed ratchet diagram. The results of this section were presented in another paper . To make further analyses by finite element method it was needed to validate the finite element results by experiment. A finite element analyses was carried out on beam model by similar loading conditions. The dynamic elastic plastic finite element analysis was done by approximate the elastic-perfectly plastic material modelling and geometrical non-linearity.
First the validation part was carried out by comparing the results between FE analyses and experimental analyses for each of the frequency. The results have been showing below for each of the frequency.

From the above figures, it has seen that, both results follow the similar trends. In most of the cases, the numerical results over predict the non-dimensional secondary stress parameter Y, except for 1.5 fn cases. The results become more similar at high X (non-dimensional primary stress parameter) values. Though both of the results follow the similar trend, but there were deviations too. In some cases deviations of experimental results from finite element prediction become more than 20% whereas in some cases it only 5%. The reasons for these differences are numerous, one of the reasons is the material modelling considered in finite element analyses. Finite element analyses used simple elastic perfectly plastic material modelling, which cannot predict the realistic material behaviour. The realistic material modelling is complicated to predict in numerical analysis. Furthermore, for the experiment it was chosen 0.5% strain per 50 cycle. But it was difficult in the experiment to get exactly 0.5% strains for each case. Sometimes the strain exceeds the desired value, and the opposite also happened. Material homogeneity of the experimental specimen also affects the results. Despite all these reasons, the trend of experimental and finite element results follow the similar trend and results are is good coherence, which validates the FEM scheme used for ratcheting analyses.

After successful validation of finite element analyses, ratchet diagram was also proposed and it was more detailed. The ratchet diagram is shown in Fig. 11.

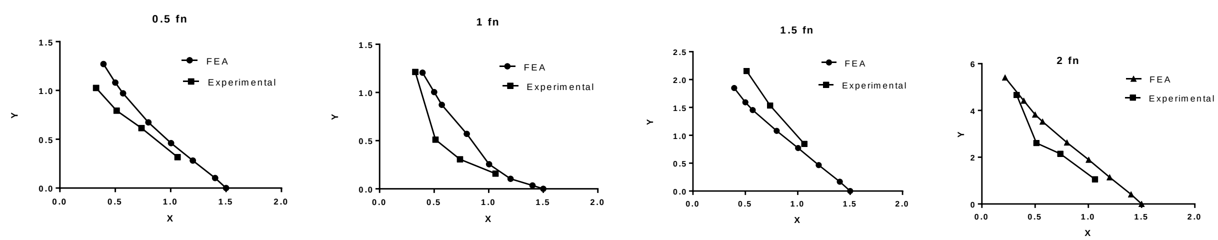

Figure 6 Comparison between FEA results and Experimental results at 0.50 fn

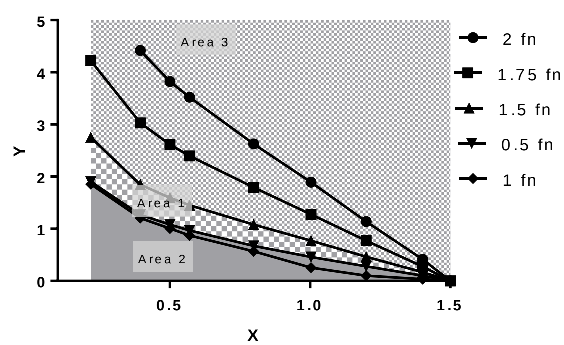

Figure 7 Proposed ratchet diagram by FE analysis

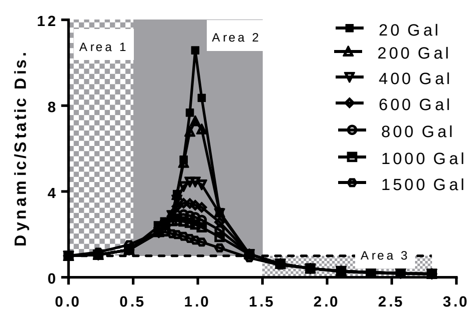

Figure 8 Displacement amplification factor graph

The various lines in the proposed ratchet diagram represent the ratchet occurrence conditions at different frequencies of input wave. It can be seen that at natural frequency (1fn) the lies on the bottom, which indicates that at 1fn it needs less acceleration than other cases. Here, Y value is directly proportional to input acceleration. For the same occurrence condition, at 2 fn the input acceleration needs very high value as compared to 1 fn, which makes the Y value for 2 fn is higher. The strong frequency dependency characteristics can be partially explained by the displacement amplification factor graph shown in Fig. 12. The amplification factor graph is made by putting different level of acceleration from 20Gal to 1500Gal on a 0.2 kg top mass beam model by putting different accelerations at different frequencies, the dynamic displacement is recorded. At the same time the static displacement is also calculated by putting equivalent force of base acceleration at top. Finally, the amplification graph is made by putting the non-dimensional frequency which is the input frequency over natural frequency of the structure in abscissa and ratio of dynamic displacement to static one over static displacement at ordinate. Three distinct areas were identified in the amplification factor graph for three ranges of non-dimensional frequencies. The first area (area 1) is for low input frequencies where the non-dimensional frequency rages from 0 to 0.5. In this area, the dynamic displacement and the static displacement are almost the same. In the middle part of the diagram (area 2), where the non-dimensional frequency range start from more than 0.5 and ends at less than 1.5, here very high dynamic response can be seen as compared to static response. This area is usually called resonance zone. The last area (area 3) where the input frequencies are very high and completely different phenomena has been reported as compared to the other two. In this area, the dynamic displacement has lower magnitude than static displacement. Similar response of dynamic loading can be identified in the ratchet diagram. As resonance frequency makes very high dynamic response, it needs low dynamic load to occur ratcheting. That is why; the lower most line of the ratchet diagram was due to natural frequency (frequency from resonance region). On the contrary, the area 1 of amplification factor graph (Fig 3-4) represents the lower frequency area which has low dynamic response over static response has placed in area1 region of Fig. 11of ratchet diagram, which needs slightly higher Y value (acceleration too) than area2. And the last area 3 makes the upper part of the ratchet diagram as expected. Because of very low dynamic response compared to static response, it needs very high acceleration to occur ratcheting.

COLLAPSE

Collapse is another failure mode which can occur due to excessive seismic loading. Collapse can be defined as 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 [67]. Collapse experiment was done by similar way to ratchet experiment by using the same geometry and material. Similar excitation tests were conducted to obtain occurrence condition of ratcheting. Only the input wave was different. The objective of collapse analysis was to investigate the dynamic effect of sudden failure of structure with unusual large deformation rather than the accumulated damage (like ratcheting) from cyclic deformation. Due to this, the half cycle of acceleration was taken into account. By putting half sinusoidal wave as acceleration, the effect of peak ground acceleration can also be evaluated. Generally, practical seismic acceleration has one or two big peak accelerations along with several small acceleration cycles. But, due to vibration machine safety, a single half sinusoidal wave could not be set as an input wave, it was needed two more small wave at beginning and end of the wave. These two small waves have similar frequency but 20% of the input acceleration. Typical input acceleration for collapse is show in Fig. 9. By observing the physical shape after the tests and strain at the bottom, collapse occurrence condition has been decided. It has observed that in the experiment the collapse was occurred when the strain at the bottom of the beam reaches 3%. After that the collapse occurrence conditions have put in X,Y graph shown in Fig. 11.

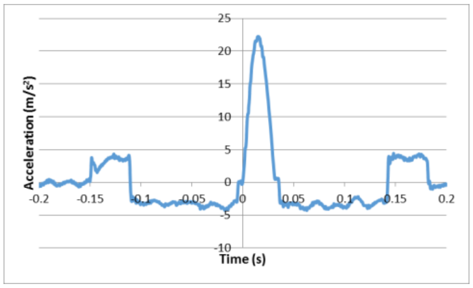

Figure 9 Typical input acceleration of collapse experiment

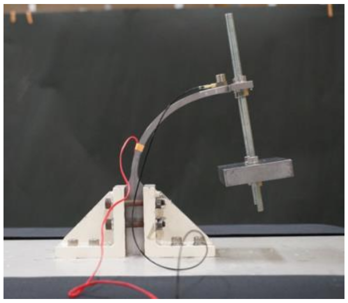

Figure 10 Collapse specimen after the experiment

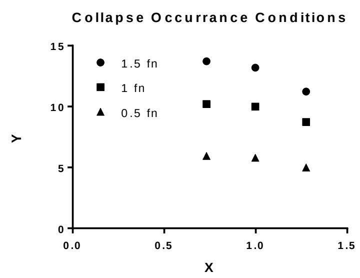

Figure 11 Collapse boundary by experiment

FE analysis results and comparison with experimental results

Similar comparison has been done for collapse results as ratcheting results between experiments and FEA. And similar results have been found which make the validation of FE analysis for collapse results. In the experiment only 3% strain was used as criteria, but various codes recommended higher strain criteria than this one. So, a more realistic collapse criterion was put which is taken from Colombo and Negro's model where it needs around 25% of strain for the collapse failure of a beam model. After implementing this criterion a collapse diagram has been made similar to ratchet diagram. The collapse diagram is shown in Fig. 12. A similar frequency response is also observed in collapse diagram which can be seen from the various areas.

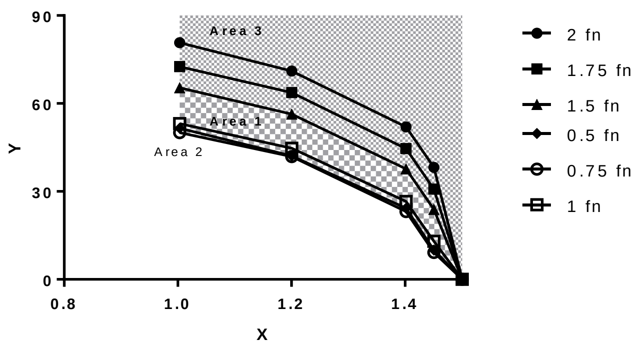

Figure 12 Proposed collapse diagram for beam model

FAILURE MODE MAP

The failure mode map is defined as a map which visualizes the different failure modes due to combination of two or more loading in one plot. The concept of a failure mode map gives a useful classification tool (Triantafillou and Gibson 1987) against seismic loading for the designers of nuclear components. In this case, the failure mode map gives the relative idea of dynamic loads which can occur ratcheting and collapse for certain gravity load. As it has seen that ratcheting, collapse and fatigue are the probable failure modes due to dynamic loading, so the target of this study is to make a failure mode map which includes all the three basic failure modes. In this phase of research only the ratcheting and collapse failure modes were analyzed. The failure mode map is shown in Fig. 13. The left vertical axis of failure mode map has been shown the scale of ratcheting and right vertical axis shown the scale of collapse for same X values. It can be seen from the failure mode map that ratcheting lies the bottom of the graph whereas collapse at top, which means that collapse need very high dynamic loading as compared to ratcheting. Also the frequency effect can be observed from the graph.

The failure mode map for ratcheting and collapse for beam model by finite element is shown in Fig13. Here, the vertical axis at right indicated the Y value for collapse and vertical axis at left side showed the ratcheting scale. It is clear from this diagram that, ratcheting occurs at lower base acceleration than collapse. Other than that the frequency effect on failure was also visible.

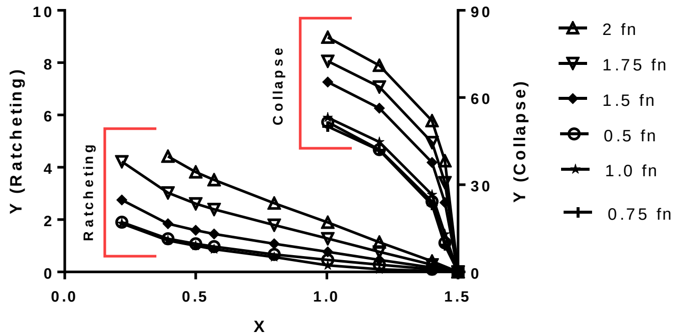

Figure 13 Failure mode map of ratcheting and collapse for beam model

CONCLUSION

The one of the aims of this study is to characterisation of seismic loading with frequency effects on failure modes. And another objective is to make a failure mode map for dominant failure modes due to seismic loading. The frequency characteristic was explained by amplification factor graph and it has seen that at higher frequency the results follows the Yamashita's bending-bending ratchet diagram, which indicates that at higher frequency the seismic loading act as displacement-controlled loading and at lower frequency it more act like load-controlled loading. Finally the failure mode map has constructed for ratcheting and collapse failure mode.

ACKNOWLEDGMENTS

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