International Conference on Mechanical, Industrial and Energy Engineering 2020
19-21 December, 2020, Khulna, BANGLADESH

ICMIEE20-153

Numerical Investigation of Ratcheting on a Rectangular Beam under Bending-Bending Loading Conditions

Md. Makfidunnabi, Md Abdullah Al Bari, Sajib Kumar Nath, Sk. Tahmid Muhatashin Fuyad*
Department of Mechanical Engineering, Khulna University of Engineering & Technology, Khulna-9203, BANGLADESH

ABSTRACT

This paper deals with the numerical investigation of ratcheting on a rectangular beam and develops a ratchet diagram for bending-bending loading conditions. A dynamic nonlinear elastic-plastic finite element analysis was used to evaluate the occurrence of ratcheting. Two kinds of loads were applied on the beam -primary loading and cyclic secondary loading. Distributed load on the upper part of the cantilever beam acts as a primary load and cyclic displacement load at the free end of the beam act as cyclic secondary loading on the beam. To find the ratcheting effect on the beam, Abaqus FEA software was used. In this paper, the numerical analysis results are verified by the analytical results of Yamashita et al.'s bending-bending ratcheting. The effect of frequency on the occurrence of ratcheting was also investigated. Finally, a ratcheting diagram for bending-bending loading has been proposed.

Key Words: Ratcheting, Bending Load, Dynamic Analysis, FEA

1. Introduction

Ratcheting is a dynamic cyclic inelastic deformation or strain that can occur in a segment that is exposed to varieties of mechanical load, thermal load, or both [1]. It is a failure of material that can also occur by dynamic loading or seismic loading [2]. Ratcheting is a universal failure. It's anything but a failure at a point. A ratcheting issue includes stress limits that endure changeless steady development in measurements per cycle, which is typically brought about by cyclic temperature that developed bending stresses in pressure-containing walls. J. Bree in 1967, [3]described ratcheting as "Unsymmetrical cycles of stress between prescribed limits will cause progressive 'creep' or 'ratcheting' in the direction of the mean stress". Concerning material behavior, ratcheting is a conduct wherein plastic distortion amasses because of cyclic mechanical or thermal stress. Ratcheting is a dynamic, gradual inelastic distortion portrayed by a move of the stress-strain hysteresis circle along the strain axis [4]. At the point when the amplitude of cyclic stresses increased as far as possible, the plastic misshaping that happens continue gathering clearing route for a cataclysmic failure of the structure. Nonlinear kinematic hardening which happens when the stress state arrives at the yield surface is considered as the fundamental component behind ratcheting. A few components impact the degree of ratcheting including stress amplitude, mean pressure, load condition, stress proportion, plastic slip, load history, disengagement development, and cell misshapenness [5].

Applying cyclic loading to pressure vessels may bring about steady development in ratcheting. It is an unsatisfactory physical condition from which a vessel must be secured. Orders for safety against ratcheting failure on the plastic basis are given in the ASME B&PV Code [6]. Two assignments are included: (1) figuring of the most extreme strain extend that is being cycled, and (2) exhibition of plastic shakedown at the area at which the strain is greatest. The shakedown prerequisite doesn't address failure however a condition required for the utilization of strain-based ratcheting configuration curves. Code orders for assurance of vessels against ratcheting failure by plastic examination offer no direction on how they are to be executed. The code gives rules to the assurance of vessels from thermal stress ratchet for loading that comprises of consistent stress on which cyclic thermal bending stresses are superimposed. These guidelines need not be fulfilled if ratcheting is assessed by plastic examination.

The Bree diagram has been attached in the ASME B&PV Code in the raised temperature Code Case N47 [6]. Figure 1 Shows the Bree diagram.

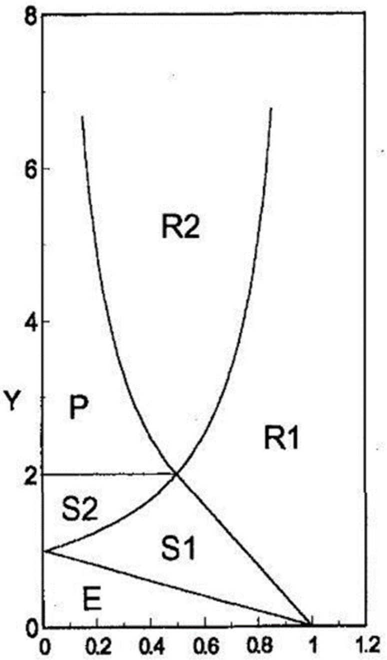

Figure 1: Ratchet diagram by Bree [7]

The ASME Code (1986) rules [8] for controlling essential loads in nuclear power plants perceive the distinction between static and dynamic loads by permitting pressure points of confinement to differ from the yield solidarity to double the yield quality. At present, there are numerous scientific and test investigations being led to assess this criterion [9]. The consequences of this work demonstrated that dynamic strains can essentially surpass the ASME Code when piping is exposed to seismic loads. Under high powerful cyclic loads, failure by ratcheting has been observed [10].

In the structure of high-temperature parts of Fast Breeder Reactors (FBR) which are exposed to the cycling of high thermal load, the anticipation of excessive deformation by thermal ratcheting is a significant subject. With respect to thermal ratcheting, the Bree-type ratcheting which happens under the combination of primary stress, for example, inner weight and cyclic thermal stress is notable and has been examined by Bree [3], O'Donnell and Porowski [11], and Roche *et al.*[12]. The consequences of these investigations are received by configuration codes, for example, ASME Boiler and Pressure Vessel Code and RCC-MR.

Ratcheting due to thermal loading is a common phenomenon in nuclear structure and there are lots of studies have already conducted on this topic and design codes are already taken care of this problem. But it is also seen that ratcheting in the structure can occur due to dynamic loading like seismic loading, but still this type of ratcheting is yet to understand explicitly. This is why the current study focuses on proposing a ratchet diagram due to bending – bending loading condition with the effect of frequency of the loading.

The main objective of this study is to develop a ratchet diagram under primary bending with cyclic secondary bending loading conditions for a rectangular beam. To achieve this goal, the specific objectives are as follows -

- To make a FEM model and validate it by the theoretical result of Yamashita *et al*.'s model
- To develop a ratchet diagram under primary bending with cyclic secondary bending loading condition for a rectangular beam
- To analyze the effect of frequency on ratchet occurrence condition

2. Methodology

A dynamic nonlinear elastic-plastic finite element analysis is carried out in this study. Numerical calculation is done by using Abaqus software. The following are the details of model and analysis conditions.

2.1. Model

A rectangular beam has been used to conduct the current study. The beam dimensions were taken from Md Abdullah Al Bari et al.'s ratchet model [2]. The following dimensions are used in this study. Figure 2 shows the FEM model and Table 1 shows the dimensions of the FEM model.

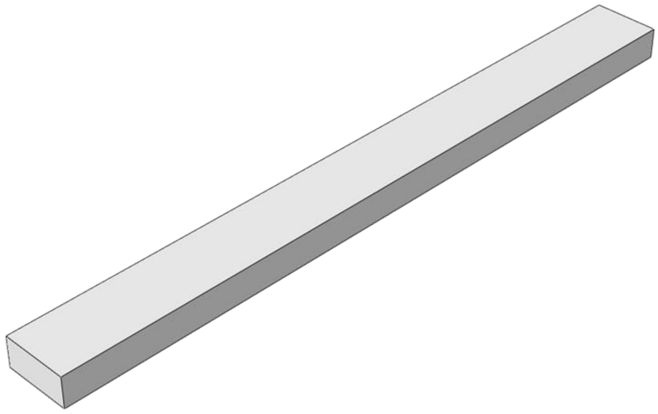

Figure 2: Model of a beam for ratchet analysis

Table 1: Dimension of FEA model

Length (mm)	Hight (mm)	Width (mm)
140	6	13

2.2. Material

Lead (Pb) had been used in this analysis. Lead (Pb) is chosen because several previous studies on ratcheting were also used this material. Furthermore, elastic perfectly plastic material modeling had been used as material modeling in this numerical analysis. The same material modeling was also used by Bree and Yamashita et al. [13]. By using elastic perfectly plastic material modeling, the complicated plasticity modeling could be avoided and the proposed ratchet diagram could be used universally, without considering any specific material property. Table 2 shows the material properties of Lead (Pb).

Table 1: Material properties used in the FEA model

Density (kg/m^3)	Young's Modulus (GPa)	Poisson's Ratio	Yield Stress (MPa)
11340	14	0.42	5

Figure 3. Shows the elastic perfectly plastic material modeling of Lead (Pb), which is used in the current analysis.

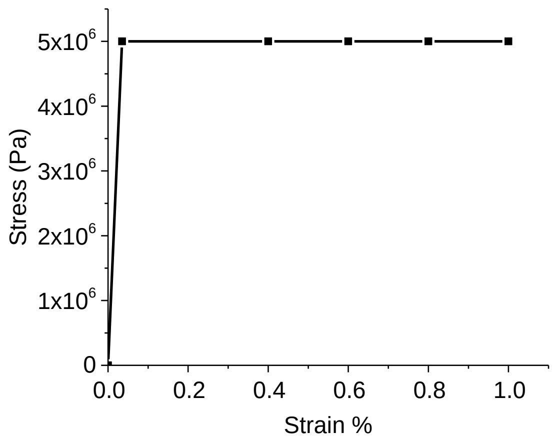

Figure 3: Elastic perfectly plastic material model

2.3. Mesh

Mesh is a system that is framed of cells and points. It can have practically any shape in any size and is utilized to solve Partial Differential Equations. Every cell of the mesh represents an individual solution of the equation which, when consolidated for the entire system, brings about an answer for the whole mesh. In Table 3 mesh properties had been given. C3D4 element type had been used. C3D4 is a universally useful tetrahedral element. Figure 4 shows the C3D4 element which has four nodes and one integration point.

Table 2: Mesh properties for FEM model

Approximate global size	0.001
Element shape	Tetrahedral
Element family	3D stress
Geometric order	Linear
Element type	C3D4
Mesh number	68961

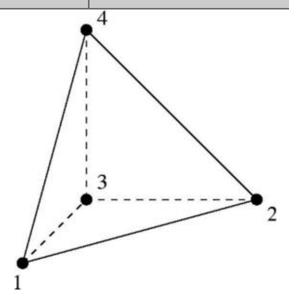

Figure 2: C3D4 mesh element

2.4. Loading and analysis condition

A cantilever beam had been used for this numerical analysis. The distributed load had been used as primary loading and cyclic displacement had been used as secondary loading at the free end.

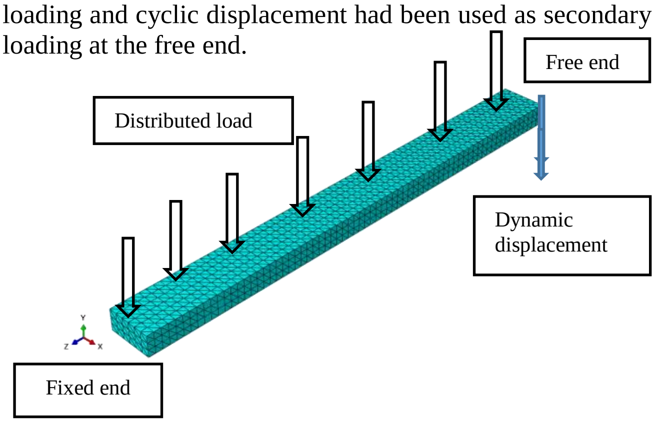

Figure 5: Constrain and loading condition of numerical analysis

Figure 5, shows a cantilever beam, one end is fixed and a cyclic displacement is put on the other end. A total of five different distributed loads was applied on the model which are 1.99 N/m, 9.95 N/m, 19.9 N/m, 29.85 N/m, 39.8 N/m, and 47.76 N/m to get different occurrence conditions of ratcheting. A typical cyclic displacement which had been applied at the free end is shown in Figure 6.

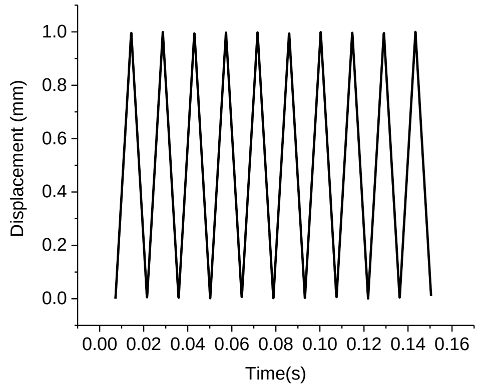

Figure 6: Typical triangular waveform used as displacement in FEA

The input loads and frequencies had been shown in Table 4. Here six different distributed loads were applied as primary load. For every distributed load six different displacements had been applied. Displacement was used as a form of a triangular waveform of 10 cycles shown in Figure 6. The frequency of the displacement wave was also changed to six different frequencies based on the natural frequency of the beam.

The natural frequencies of the beam in different distributed loads had been calculated by the following calculations as well as by the Modal analysis in the Abaqus FEA. Both methods give us almost the same values. Natural frequencies of the beam in different distributed load had been calculated by the following equation

$$f_n = \frac{k_n}{2\pi}\sqrt{\frac{EIg}{wl^4}}$$

Here, f_n = Natural frequency

k_n = 3.52

E = Modulus of Elasticity

I = Area Moment of Inertia

g = Gravitational acceleration

w = Uniform load per unit length

l = Beam length

Table 4: Loads and frequencies used in the analysis

Case No.	Distributed load [N/m]	Natural frequency [Hz]	Input frequency [Hz]	
1	1.99	59.16	0.25fn	14.79
2			0.5fn	29.58
3			1fn	59.16
4			1.5fn	88.74
5			2fn	118.33
6			3fn	177.49
7	9.95	54.92	0.25fn	13.72
8			0.5fn	27.45

9			1fn	54.92
10			1.5fn	82.37
11			2fn	109.83
12			3fn	164.75
13	19.9	38.83	0.25fn	9.7
14			0.5fn	19.41
15			1fn	38.83
16			1.5fn	58.24
17			2fn	77.66
18			3fn	116.49
19	29.85	31.71	0.25fn	7.92
20			0.5fn	15.85
21			1fn	37.71
22			1.5fn	47.56
23			2fn	63.41
24			3fn	95.12
25	39.8	27.46	0.25fn	6.86
26			0.5fn	13.72
27			1fn	27.4
28			1.5fn	41.18
29			2fn	54.91
30			3fn	82.37
31	47.76	25.07	0.25fn	6.26
32			0.5fn	12.53
33			1fn	25.07
34			1.5fn	37.6
35			2fn	50.13
36			3fn	75.2

3. Result and discussion

3.1. Understanding ratcheting

Ratcheting can be understood by strain vs time history graph or integration point vs stress graph. Figure 7 shows strain vs. time graph where the black line represents a ratchet occurrence condition and the blue line represents as not ratchet occurrence condition. The input loading for the ratchet occurrence condition of ratcheting which is shown in Figure 7 was 1.99 N distributed load and a natural frequency of 59.165 Hz. And the secondary lateral deflection was 2.11 mm. In this condition, yielding starts at the first cycle, and after that cycle yielding increased continuously. So, plastic strain increased continuously and reached 0.67% after 10 cycles. The maximum plastic strain had been calculated in X direction near the fixed end of the beam. This is indicating that ratcheting is happening in the structure. In Figure 7 for the blue line, the same conditions had been applied except the secondary loading which was placed only 1.5 mm. The plastic strain is not increasing in every cycle and the maximum axial strain reached only 0.17% after 10 cycles of loading. So, there is no ratcheting in the second case.

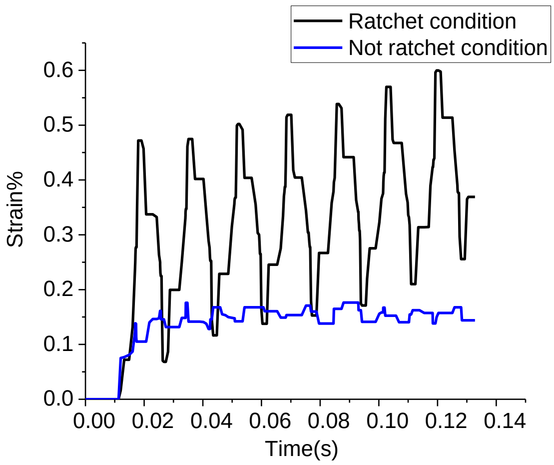

Figure 7: Strain vs. Time graph

Ratcheting can also be understood by observing the stress distribution in the beam. Here, Figure 8 shows the integration point vs stress graph. In Figure 8, the black line represents the ratchet occurrence condition and the red line represent not ratchet condition. 1.99 N distributed load and 1.41 mm of cyclic deflection at a natural frequency of 59.165 Hz had been applied for the black line. For this condition, stress data was taken in six integration points along the thickness direction of the beam. All six elements reached the yield stress, half is in tension and another half is in compression. This condition indicates that ratcheting has occurred in structure. In Figure 8, all applied conditions were the same for the red line, only lateral deflection was put 1 mm and, in this condition, none of the six elements are in yield stress. So, there is no ratcheting in structure.

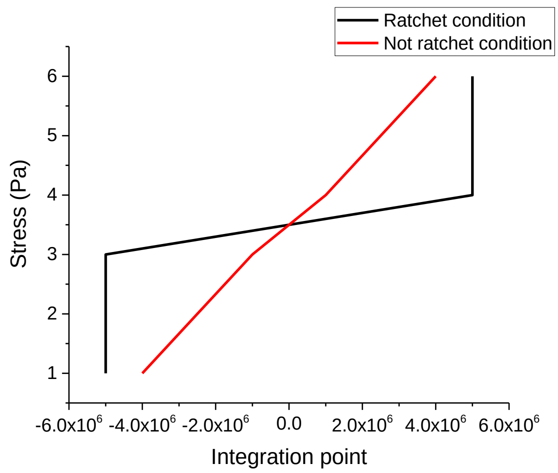

Figure 8: Integration point vs. stress graph

3.2. Validation

This numerical analysis was based on Yamashita et al's theoretical bending–bending ratcheting analysis [13]. In his work, Yamashita and his team proposed a ratchet diagram for a rectangular beam for similar loading conditions as the current study**.** Figure 9 shows Yamashita's ratchet diagram.

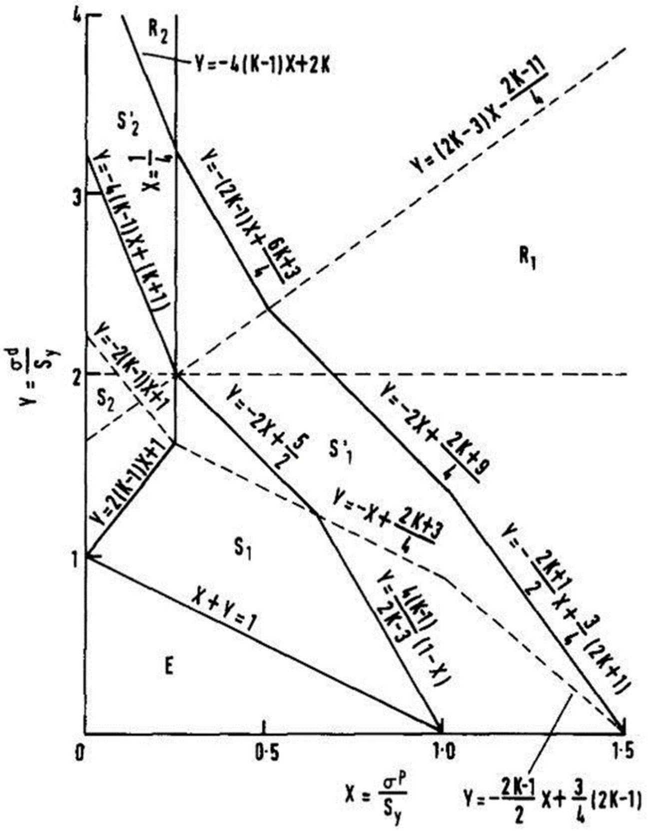

Figure 9: Yamashita's ratchet diagram for bending-bending loading conditions [13]

Yamashita et al. plotted their ratchet diagram in a non-dimensional stress parameter plot similar to the Bree diagram. The following are the definition of non-dimensional stress parameters.

Here X = $\frac{\sigma^P}{S_Y}$

Y = $\frac{\sigma^d}{S_y}$

Here, σ^P= Bending stress due to distributed force calculated elastically

σ^d = Bending stress due to lateral deflection calculated elastically

Bending stresses had been calculated by the following equations

$\sigma^p = \frac{M_p C}{I}$

$\sigma^d = \frac{M_d C}{I}$

Here, M_p = Moment due to distributed force calculated elastically

M_d = Moment due to lateral deflection calculated elastically

C = Distance from the neutral axis.

I = Moment of inertia

Yamashita et al. made their ratchet diagram by analytical method. They did their study on a rectangular cantilever beam model. The distributed load was applied on the top of the beam as the primary load and cyclic lateral deflection load was applied at the free end.

In this numerical analysis, a similar beam model is created to show the validation of Yamashita's ratchet diagram by numerical analysis. From Figure 10, between X = 0 to X = 0.5, values of secondary stress parameter Y for both Yamashita's ratchet line and the analysis result of the FEM model are almost the same. After X = 0.5, the deference between Yamashita's ratchet line and our FEM model's ratchet line is increasing and the deference is maximum at X = 0.75. After X = 0.75, the deference between Yamashita's ratchet line and the FEM model ratchet line is again decreased. The maximum deviation is recorded by 8.84%. The reason behind this deviation between Yamashita's theoretical ratchet line and the FEM model ratchet line is mainly because Yamashita et al. solved the ratchet problem analytically whereas the current study solved it numerically. Another cause of deviation might come from the frequency effect, in Yamashita et al.'s study frequency effect was ignored but in the current study, the frequency effect is taken into consideration. For comparing the analytical result and numerical result, the natural frequency of the beam of 59.16 Hz had been used.

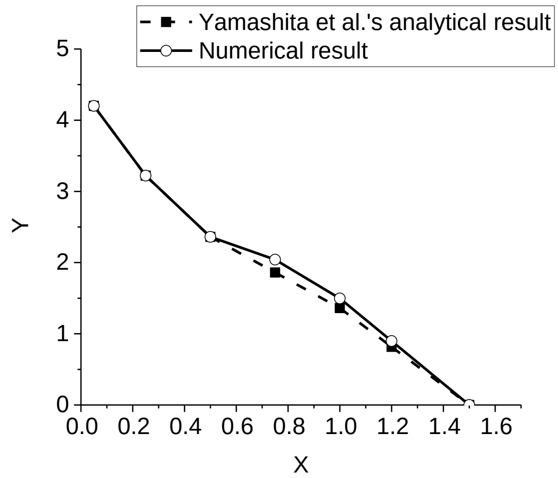

Figure 10: Validation of FEM result by Yamashita et al.'s analytical result

3.3. Proposed ratchet diagram

Yamashita et al. took the stress base approach to identify ratcheting [13]. When every element of a structure at yield stress, Yamashita identifies this phenomenon as ratcheting. This phenomenon is also called the plastic hinge. Numerical ratchet diagram had been proposed by following the stress-based approach so that it had been validated by Yamashita's work.

Figure 11 shows the proposed ratchet diagram developed by using the stress base approach. For the stress-based approach, the occurrence of ratcheting is understood by Figure 7. For input distributed loads and frequencies, **Table** had been followed. Here, ratcheting has occurred when every element (integration point) is at-least touches the yield stress of the material. Six ratchet lines for six different frequencies such as natural frequency, 0.25fn, 0.5fn, 1.5fn, 2fn and 3fn had been developed.

Here, fn = Natural frequency

The natural frequency of the beam had been calculated by modal analysis in Abaqus.

The ratchet line for natural frequency is at the bottom of other frequencies. So, it indicates that the ratcheting effect is higher in natural frequency because every element of the structure is at yield stress at lower cyclic displacement than other frequencies. So, values of Y are less at the natural frequency and higher at other frequencies.

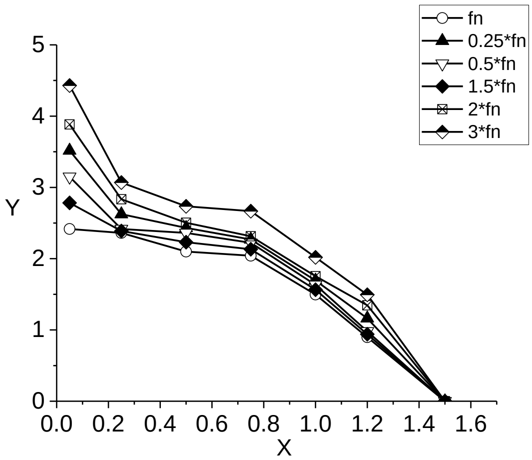

Figure 11: Proposed ratchet diagram

3.4. Effect of frequency on ratchet occurrence

The frequency effect on ratchet occurrence condition can be described by using the amplification factor graph by Md Abdullah Al Bari et al. [2] Amplification factor graph has been shown in Figure 12. Different dynamic displacement had been added to the numerical model at the free end and dynamic displacement was calculated. Static displacement had been calculated from the distributed load at the free end of the beam. The ratio of dynamic displacement and static displacement had been put at the ordinate and the ratio of input frequency to the natural frequency at abscissa.

The amplification factor graph can be divided into three areas for three different ranges of frequencies. The first area consists of a frequency range of 0 to 0.5. In this area value of dynamic displacement was lower than static displacement. That's mean frequency effect is low for 0fn to 0.5fn. In the second area, dynamic displacement was higher than static displacement. So, in the second area frequency effect was higher. This second area was for a frequency range of higher than 0.5 to 1.5. Area three was for frequency higher than 1.5 to 3. In this area, dynamic displacement was very low than static displacement. So, the frequency effect was very low for very high frequency.

In natural frequency, dynamic displacement was very high than static displacement. So that, a bump was created at the natural frequency. It indicates that the ratcheting effect on a structure was higher at the natural frequency than any other frequencies.

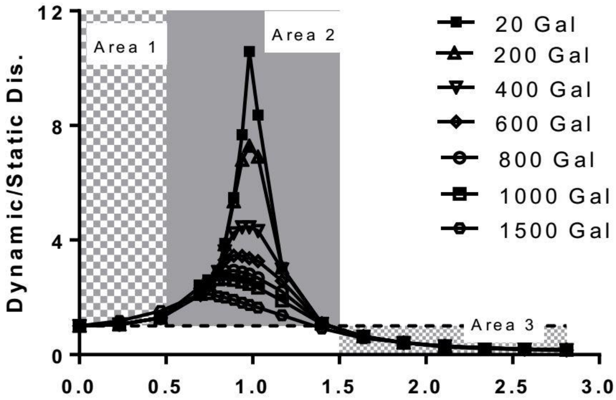

Figure 12: Amplification factor graph

4. Conclusions

In this research, a non-linear dynamic elastic-plastic analysis was carried out by Abaqus numerical software. An FEA model of a rectangular beam was prepared to develop a ratchet diagram and the beam model had been validated by Yamashita et al.'s analytical beam model. It is seen that the current FEA model predicts the result of Yamashita et al.'s analytical model. Stress base approach had been applied to develop and propose ratchet diagrams. A strong frequency effect of input secondary load is observed in the ratcheting diagram. The effect of frequency is also analyzed by the amplification graph. It is seen that at the natural frequency the effect of dynamic loading is highest.

References

[1] R. Directives and T. Execution, "Shakedown and Ratcheting Directives of ASME B&PV Code and Their Execution," in *Proceedings of PVP2002 2002 ASME Pressure Vessels and Piping Conference August 5-9, 2002, Vancouver, BC, Canada*, 2016, pp. 1–9.

[2] M. A. Al Bari, R. Sakemi, Y. Katsura, and N. Kasahara, "Proposal of Failure Mode Map Under Dynamic Loading—Ratcheting and Collapse," *J. Press. Vessel Technol.*, vol. 140, no. 5, p. 051202, 2018, doi: 10.1115/1.4040892.

[3] J. Bree, "Elastic-plastic behaviour of thin tubes subjected to internal pressure and intermittent high-heat fluxes with application to fast-nuclear-reactor fuel elements," *J. Strain Anal.*, vol. 2, no. 3, pp. 226–238, 2007, doi: 10.1243/03093247v023226.

[4] R. J. D. Tilley and J. Wiley, "PART 2 Classes of materials," *Composites*, vol. 5, 2004.

[5] E. Abdollahi and T. N. Chakherlou, "Numerical and experimental study of ratcheting in cold expanded plate of Al-alloy 2024-T3 in double shear lap joints," *Fatigue Fract. Eng. Mater. Struct.*, vol. 41, no. 1, pp. 41–56, 2018, doi: 10.1111/ffe.12643.

[6] D. J. Boussaa, K. D. Van, R. Aroné, and H. T. Tang, "Fatigue-seismic ratcheting interactions in pressurized elbows," *J. Press. Vessel Technol. Trans. ASME*, vol. 116, no. 4, pp. 396–402, 1994, doi: 10.1115/1.2929607.

[7] H. W. Ng and C. Nadarajah, "Biaxial ratcheting and cyclic plasticity for bree-type loading-part I: Finite element analysis," *J. Press. Vessel Technol. Trans. ASME*, vol. 118, no. 2, pp. 154–160, 1996, doi: 10.1115/1.2842174.

[8] R. J. Scavuzzo, P. C. Lam, and J. S. Gail, "Experimental studies of ratcheting of pressurized pipe," *J. Press. Vessel Technol. Trans. ASME*, vol. 113, no. 2, pp. 210–218, 1991, doi: 10.1115/1.2928748.

[9] D. Guzy, "Nuclear Engineering and Design 107 (1988) 161-167 PIPING D E S I G N C R I T E R I A A N D R E S E A R C H CURRENT NRC ACTIVITIES IN DYNAMIC DESIGN Received 1 June 1987 The current design process for nuclear power plant piping relies heavily on detailed," vol. 107, pp. 161–167, 1988.

[10] S. W. Tagart, Y. K. Tang, D. J. Guzy, and S. Ranganath, "Piping dynamic reliability and code rule change recommendations," *Nucl. Eng. Des.*, vol. 123, no. 2–3, pp. 373–385, 1990, doi: 10.1016/0029-5493(90)90258-Y.

[11] W. J. O' Donnell and J. Porowski, "Upper bounds for accumulated strains due to creep ratcheting," *J. Press. Vessel Technol. Trans. ASME*, vol. 96, no. 3, pp. 150–154, 1974, doi: 10.1115/1.3454160.

[12] R. L. Roche, D. Moulin, and J. Lebey, "Practical Analysis of Ratchetting," vol. 55, no. May 2008, p. 2008, 1982.

[13] T. Yamashita, K. Tsukimori, M. Nakamura, K. Iwata, and A. Imazu, "A simplified method of evaluating ratcheting in bellows and a test of its validation," *Int. J. Press. Vessel. Pip.*, vol. 42, no. 3, pp. 263–285, 1990, doi: 10.1016/0308-0161(90)90027-F.