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Fatigue-Ratcheting Study of Pressurized Piping System under Seismic Load

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ABSTRACT

It has been observed that nuclear power plant piping systems may be loaded into the plastic range due to large amplitude reversible cyclic loading like seismic excitation. During such events, fatigue-ratcheting causes failure of pressurized piping systems. To understand the phenomenon, analytical and experimental studies are carried out on a typical pressurized piping system. The piping system is pressurized with water and subjected to continuous base excitation through shake table. Free vibration characteristics of the piping system are evaluated by sine sweep test. Analysis is performed using equivalent inertial forces. Chaboche nonlinear kinematic hardening model is used for ratcheting simulation. Fatigue life evaluation also carried out for the tested piping system as per ASME Boiler and Pressure Vessel Code, Section-III, Div-I, NB-3000. Experimental and analytical results are presented in the paper.

KEY WORDS: Ratcheting, Sine Sweep Test, Seismic Response, Test response spectrum (TRS), Chaboche model

1. INTRODUCTION

Piping networks employed in nuclear power plants play a vital role in safe operation of the plant. The piping systems are subjected to static sustained loads such as pressure and dynamic loads such as earthquake. Typically, a piping system consists of straight pipes, elbows and tee joints. These piping components and portions of piping at anchor locations deform inelastically under the influence of large forces, which could arise due to the earthquake. Seismic design of pressurized pipelines based on an equivalent static approach, leads to over-conservative designs which in consequence requires large number of supports which is in conflict with the requirement of flexibility for reducing thermal stresses. In recent years, research is aimed at improving the seismic design of the piping system in nuclear industry. This has lead to experimental programmes being initiated to assess the behaviour of the piping system under severe dynamic loadings that simulates the earthquake loading conditions [1-3].

An experimental finding from the tests on shake table is that very often the observed failure mode is fatigue ratcheting [4]; which is a cumulative effect of fatigue (cyclic content of the seismic response of the component) and accumulated plastic strains (combination of the pressure and the cyclic content of the response). This failure mode is not the one assumed by the design criteria (where plastic instability is assumed). In BARC several experimental and analytical studies are being carried out to understand ratcheting phenomenon in piping systems & components under various loading conditions [5-8]. These studies are being carried out at material, component and system levels. The uniaxial experiments [5] showed that specimens exhibited shakedown at low stress amplitude after some strain accumulation. However, specimens experienced continuous ratcheting at higher stress amplitudes with no shakedown before failure. Ratcheting behaviour under stress-controlled conditions has been studied [7] at different stress ratios and stress rate combinations. The ratcheting experiments have shown that strain accumulation depends on both stress rate and stress ratio.

In the biaxial test on straight pipe [5], ballooning of pipe cross section was observed when the pipe was subjected to constant internal pressure and cyclic bending load. The pipe did not show any shakedown behaviour for the given cycles of loading and exhibited continuous ratcheting under the varying amplitude loading. Similar observations were made during shake table test on pressurized elbow [8]. In the present paper, the results of shake table test for a three dimensional piping system are presented.

2. DESCRIPTION OF PIPING SYSTEM TEST

Shake table test on a three-dimensional piping system was carried out to understand dynamic behaviour and failure modes of piping systems. The configuration of the piping system used for the test is shown in Fig. 1. The piping system is made of carbon steel grade SA 106 Gr B, Schedule 40. It has 89 mm outer diameter and thickness of 5.5 mm. The piping system contains nine 90^0 short radius elbows. Two 36 kg masses and one 52 kg mass are clamped to the piping to have typical frequencies of piping systems in the nuclear power plants. Both ends of the piping system are anchored to the shake table. The piping system was pressurized up to a pressure of 23 MPa. Free vibration characteristics of the piping system have been evaluated by sine sweep test. Further seismic tests have been carried out in which the pressurized piping system is subjected to seismic loading applied in all the three directions.

3. FE MODEL DETAILS

Fig. 2 shows the Finite Element model of the piping system. The piping system is modelled using four noded shell elements. The piping model consists of 3960 shell elements. Fine mesh is chosen for meshing of elbows and coarse mesh for the straight pipe portions. At the nodes corresponding to the anchor location, all the degrees of freedom are constrained. Internal pressurization is modelled by applying pressure normal to each shell element.

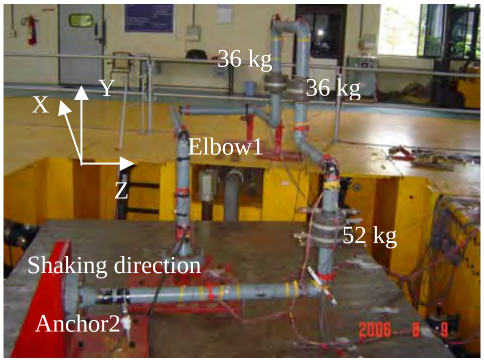

Fig. 1 Test setup of the piping system

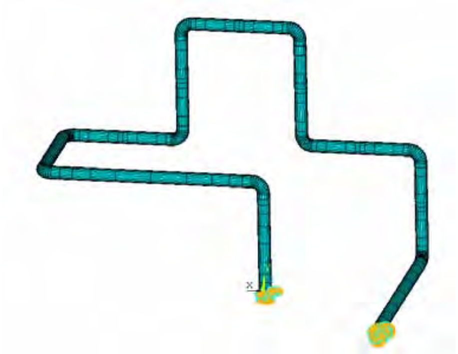

Fig. 2 FE model of the piping system

4. FREE VIBRATION CHARACTERISTICS OF PIPING

Sine sweep test has been carried out at a sweep rate of one quarter octave per minute in the frequency range of 1-50 Hz. The natural frequencies of the piping system obtained from experiment and analysis are given in Table 1. First and second vibration modes of the piping system are shown in Fig. 3 and Fig. 4 respectively.

Table 1 Comparison of natural frequencies of piping system

Mode no	Natural frequency by Sine sweep test (Hz)	Natural Frequency by Analysis (Hz)
1	4.5	4.579
2	9.25	10.351
3	13.75	14.84

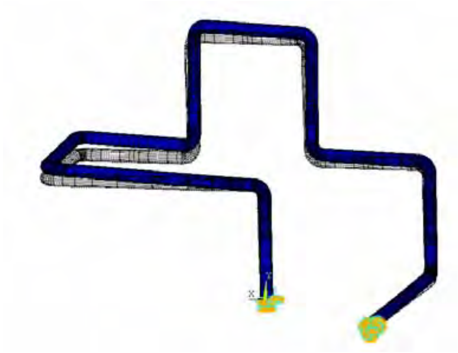

Fig. 3 First vibration mode of the piping system

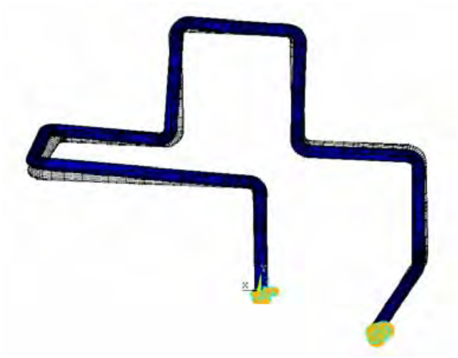

Fig. 4 Second vibration mode of the piping system

5. INPUT SEISMIC WAVE

A triaxial shake table system with six degrees of freedom and ten ton payload capacity has been used for the test. The piping system is subjected to a three dimensional excitation as indicated in Fig. 1. Test response spectra (100% TRS) in three directions for 2% damping are shown in Fig. 5 to 7. The shape of the test input spectra has been broadened such that it has all the dominant modes of the piping system on the peak of the spectrum. Acceleration time histories of the shake table input are shown in Fig. 8 to 10. Seismic ratcheting tests were conducted on the pressurized piping system with a series of table time histories. Table 2 gives the details of loading applied to the piping system.

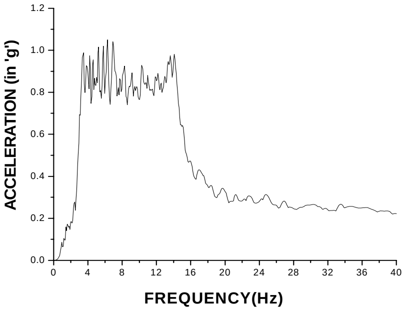

Fig. 5 Test response spectrum (100% TRS) in X-direction (horizontal)

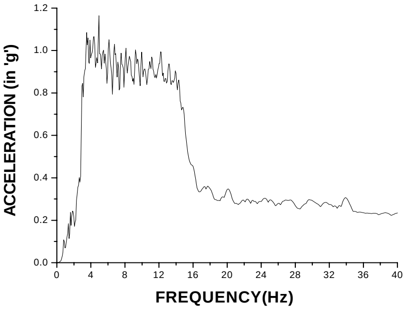

Fig. 6 Test response spectrum (100% TRS) in Z-direction (horizontal)

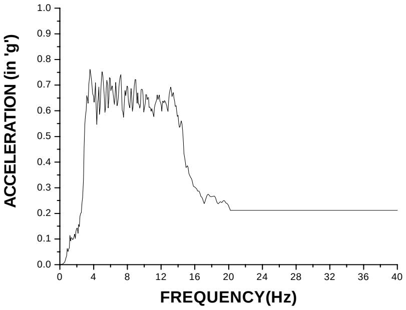

Fig. 7 Test response spectrum (100% TRS) in Y-direction (vertical)

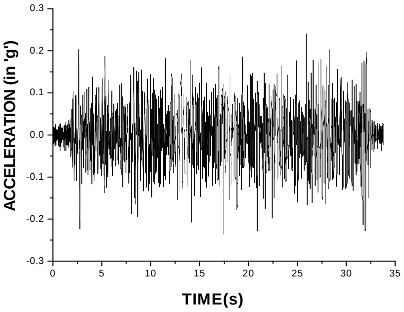

Fig. 8 Acceleration time history in X-direction (horizontal)

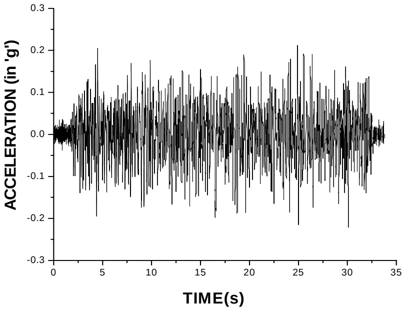

Fig. 9 Acceleration time history in Z-direction (horizontal)

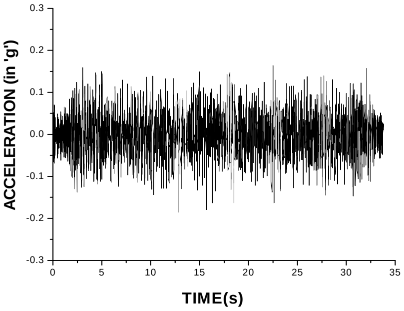

Fig. 10 Acceleration time history in Y-direction (vertical)

6. RATCHETING TEST AND ANALYSIS

Seismic ratcheting test was conducted on the pressurized piping system. Acceleration time history compatible with test response spectrum was applied to the shake table and the response of the piping was recorded. The test started with six input acceleration time histories which are compatible with 100% TRS. Then the base excitation was increased to the extent which is compatible with 200% TRS, and applied for three times. Further the base excitation was increased as given in Table 2. The strain history at an anchor location of the piping system is shown in Fig. 11. It can be observed that significant strain accumulation has taken place when the base excitation was 600% TRS. During the third input time history which is compatible with 800% TRS, a crack has been formed at a weld location of elbow-1 and water jet has come out. Photograph of the crack is shown in Fig. 12.

Table 2 Details of various levels of base excitation

Base excitation (%TRS)	100	200	300	400	500	600	700	800
No. of base excitation time histories	6	3	12	9	9	9	9	3

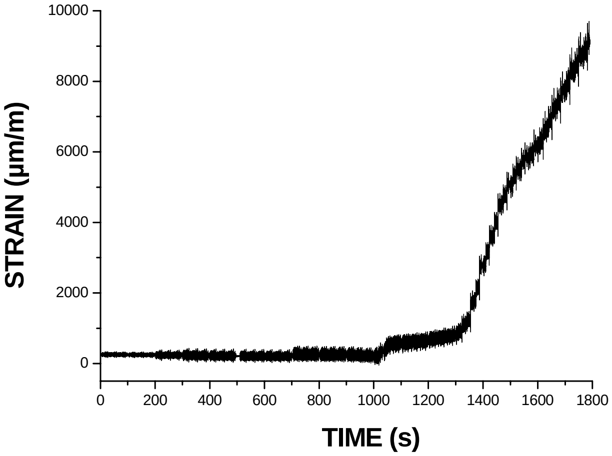

Fig. 11 Experimental strain history at anchor-2 location

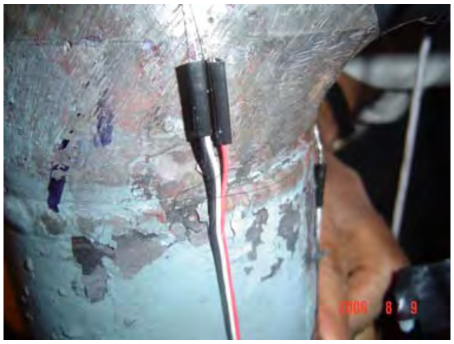

Fig. 12 Photograph of crack at weld location of elbow-1

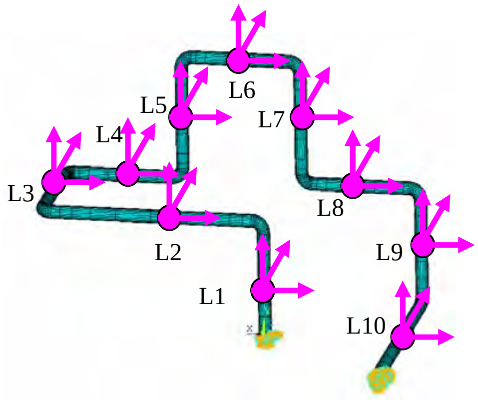

Fig. 13 Location and directions of equivalent inertial forces

Since significant ratcheting was observed with an excitation of 600% TRS, FE simulation has been carried out with that base excitation. Seismic load is simulated by applying equivalent inertial forces at different locations of piping system. Mass of the piping system is lumped at mid location of each straight pipe portion. The comparison of frequencies and mass participation of different modes for distributed and lumped mass models are given in Tables 3 & 4 respectively. It is observed that free vibration characteristics of the piping system are not changed significantly due to the lumping method.

Table 3 Comparison of frequencies for distributed and lumped mass models

Mode no	Natural frequency for distributed mass model (Hz)	Natural Frequency for lumped mass model (Hz)
1	4.579	4.571
2	10.351	10.354
3	14.84	15.31

Table 4 Comparison of mass participation of different modes using distributed and lumped mass models

Mode no	Distributed mass model			Lumped mass model		
	X- mass participation (% mass)	Y- mass participation (% mass)	Z- mass participation (% mass)	X- mass participation (% mass)	Y- mass participation (% mass)	Z- mass participation (% mass)
1	3.26	48.0	23.3	3.21	47.8	23.9
2	40.8	2.26	23.5	41.2	2.52	23.9
3	0.42	1.82	0.13	0.21	2.3	0.29

The equations of motion for the system are given by,

$$M\ddot{U} + C\dot{U} + KU = P(t) \tag{1}$$

Where, M is mass matrix, C is damping matrix, K is stiffness matrix,
U is displacement vector and $P(t)$ is Seismic load vector.

The acceleration histories obtained by accelerometers represent the solution of the equations of motion for the piping system at various locations. The dynamic characteristics and nonlinear behaviour of the piping system are included in the response. These response acceleration time histories are multiplied with lumped masses to obtain the equivalent inertial force time histories at different locations. Fig. 13 shows the directions and location of equivalent inertial forces. In order to overcome the limitations of the analysis code, these forces are applied on the piping model in a quasi-static manner and the strain histories are obtained. Chaboche model is used for simulating ratcheting response. During the base excitation with 600% TRS, a strain increment of 913 με is obtained by the analysis, against 304 με by experiment at anchor-2 location. The results showed that this approach has over predicted the ratcheting strain.

7. EVALUATION OF LINEAR STRESSES AND FATIGUE LIFE FOR THE PIPING SYSTEM

Evaluation of linear stresses and fatigue life has been carried out for the pressurized piping system under various levels of base excitation. The evaluation has been carried out to show the exceedance with respect to the allowable limits given by ASME Boiler and Pressure Vessel Code, Section-III, Div-I, NB-3000 [9]. Maximum primary stress intensity is calculated from the left hand side of Eq. 9 of NB-3600 (for level D service condition), which is given as

$$B_1 \frac{PD_0}{2t} + B_2' \frac{M_i D_0}{2I} \le 3S_m \tag{2}$$

For straight pipe, $B_1 = 0.5$ and $B_2 = 1.0$

For elbows, $B_1 = -0.1 + 0.4h$ and $B_2' = 0.87/h^{2/3}$

Where, $h = \frac{tR}{r_m^2}$

The allowable primary stress for level D service condition is $3S_m$, where S_m is allowable stress-intensity (For SA 106 Gr B, S_m=138.33 MPa). The procedure used for the fatigue life evaluation is described below. Peak stress intensity (S_p) is calculated from Eq. 11 of NB 3600 which is given below.

$$S_p = K_1 C_1 \frac{P_0 D_0}{2t} + K_2 C_2 \frac{D_0}{2I} M_i \tag{3}$$

Using the Simplified Elastic-Plastic Discontinuity Analysis, the alternating stress intensity S_{alt} is calculated as

$$S_{alt}=K_e\, S_p\, /2 \tag{4}$$

Where,

K_e = 1.0 for $S_n \leq 3S_m$

= $1.0 + [(1 - n) / n(m - 1)](S_n/3S_m - 1)$, for $3\, S_m < S_n < 3mS_m$

= $1/n$, for $S_n \geq 3mS_m$

m, n=material parameters given in Table NB-3228.5(b)-1

S_n = Primary plus secondary stress intensity value calculated from Eq. 10 of NB 3600 which is given below.

$$S_n = C_1 \frac{P_0 D_0}{2t} + C_2 \frac{D_0}{2I} M_i \tag{5}$$

Allowable number of cycles (N_i) corresponds to S_{alt} are obtained from the applicable design fatigue curve.

Usage factor is calculated from $U_i = \frac{n_i}{N_i}$ (6)

The cumulative damage is evaluated from cumulative usage factor $U = \sum \frac{n_i}{N_i}$ (7)

Table 5 summarizes the evaluation of maximum primary stress intensity and Cumulative Usage Factor (CUF) for the pressurized piping system under various levels of base excitation. Each time history corresponds to 10 cycles of peak to peak stress range. Internal pressure, dead weight and base excitation are considered for the evaluation of maximum primary stress intensity. The maximum stress in the piping system (at Elbow-1) has exceeded the allowable primary stress when the base excitation is 300% TRS. The piping system has failed during excitation of 800% TRS. The CUF has exceeded unity for the excitation of 600% TRS, which is before the actual failure took place. At the end of three time histories with 800%TRS (when the failure has occurred) the CUF is 7.29. Considering that the design fatigue curve has a built in factor of safety of 20, this indicates a premature failure, which may be attributed to ratcheting.

Table 5 Evaluation of maximum primary stress intensity and Cumulative Usage Factor (CUF) for the piping system under various levels of excitation

Base excitation (%TRS)	No. of base excitation time histories	Maximum primary stress intensity (S_m)	Peak Stress intensity S_p (MPa)	Primary plus secondary stress intensity S_n (MPa)	Factor K_e	Alt. Stress intensity S_{alt} = $K_e\, S_p/2$ (MPa)	Allowable No. of cycles (N_i)	Usage factor (n_i/N_i)	Cumulative Usage factor (CUF)
100	6	1.96	219.11	121.73	1.00	109.55	246280	2.44E-04	2.44E-04
200	3	2.87	438.22	243.46	1.00	219.11	20000	1.50E-03	1.74E-03
300	12	3.84	657.33	365.18	1.00	328.66	5020	2.39E-02	2.56E-02
400	9	4.82	876.44	486.91	1.35	590.09	950	9.47E-02	1.20E-01
500	9	5.81	1095.55	608.64	1.93	1058.95	200	4.50E-01	5.70E-01
600	9	6.81	1314.66	730.37	2.52	1656.36	65	1.38E+00	1.96E+00
700	9	7.80	1533.77	852.09	3.11	2382.30	27	3.33E+00	5.29E+00
800	3	8.80	1752.88	973.82	3.69	3236.78	15	2.00E+00	7.29E+00

8. CONCLUSIONS

Behaviour of a pressurized piping system under large amplitude seismic load was investigated experimentally. The free vibration characteristics of the piping system were obtained by sine sweep test. Ratcheting was observed at anchor location of the piping system. The piping system did not show any shakedown behaviour for the given seismic loading. It is observed that mode of failure of pressurized piping system under large amplitude seismic load is fatigue-ratcheting. FE simulation has been carried out using Chaboche model and the analytical results are higher than the experimental results. Fatigue life evaluation for the tested piping system also has been carried out and it was concluded that the fatigue life was less than that predicted as per ASME Section III Division I, NB 3000, which may be attributed to ratcheting.

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