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Experimental and numerical studies of inelastic behavior of thin walled elbow and tee joint under seismic load

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ABSTRACT

In the present work, experimental and numerical studies are carried out on inelastic behavior of thin walled elbow and tee joint under incremental seismic load, with an emphasis on fatigue-ratcheting. Initially, a short radius carbon steel (SA106 Gr B) elbow is subjected to internal pressure and incremental seismic excitation till failure. The tested elbow is analyzed using a simplified method to evaluate ratcheting and compared with test results. Simulations are carried out with uniform and actual thickness distribution to study the variation in strain accumulation. Later, a tee joint of same material and size is studied under similar loading conditions till failure. The resulting strain accumulation in elbow and tee joint are compared. The change in natural frequencies of elbow and tee during the test are evaluated using wavelet analysis and the details are provided in the paper.

1. Introduction

Piping networks conveying radioactive fluids play a crucial role in safe operation of nuclear facilities. These networks comprise many piping components such as elbows and tee joints. The elbows and tee joints may deform inelastically under internal pressure and reversing dynamic loads due to earthquakes. The accumulation of the inelastic strain known as ratcheting combined with fatigue is observed to cause failures in piping components, under this kind of sustained pressure and occasional dynamic loads [1–8]. At system level tests also, the observed failure mode of pressurized piping systems under seismic load is fatigue-ratcheting [9–11]. Hence, understanding fatigue-ratcheting is very important to ensure structural integrity and leak tightness of pressurized elbows and tees under seismic load. Even though several studies were conducted on elbows under static cyclic loading [2–7], a very limited experimental data on fatigue-ratcheting in elbows and tee joints under seismic loading is available. Hence, the present work is aimed to study fatigue-ratcheting in pressurized elbow and tee joint under seismic loading. Shake table tests are carried out on a pressurized short radius elbow and tee joint under internal pressure and incremental base excitation till failure. Peak strains obtained from both elbow and tee joint tests are compared. The changes in natural frequencies of the components during the tests are obtained using wavelet analysis.

Ratcheting design provisions of ASME Boiler & Pressure Vessel code [12] post 1995 revision are still under debate by several regulatory agencies. In 1995, the code has incorporated ratcheting by increasing allowable stress limit and providing an alternate strain based approach of limiting ratcheting strain to 5% for Level-D seismic event. The subsequent version of the code has removed the alternate strain based approach. This may be due to lack of sufficient experimental data and inadequate simplified numerical procedures to evaluate ratcheting strains in piping components. Hence there is a need to develop simplified numerical procedures, which can be used by designers to use the strain based criterion and also to evaluate ratcheting strains in piping components. The present work is also aimed to use a simplified numerical procedure, which was validated with system level ratcheting tests [9,10], to evaluate ratcheting strain in elbow. The details of simplified analysis and experimental results are given in this paper.

2. Details of shake table tests on pressurized elbow and tee joint under seismic load

Shake table tests are carried out on pressurized carbon steel elbow and tee using the seismic test facility at Central Power Research Institute (CPRI), Bangalore. The size of the shake table is 3 m x 3 m and has ten ton load capacity.

2.1. Details of the test setup

A 90° short radius elbow and 90° tee joint are used for the test. The schematic of test setup for elbow and tee joint are shown in Fig. 1(a)

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Nomenclature

ξ	Damping of the piping components	h	Elbow parameter
f	Natural frequency of the piping component	I	Moment of Inertia
α_i	Back stress	θ	Angle of cross section
C_i , γ_i	Parameters for Chaboche material model	ϕ	Bend angle
σ_x	Uniaxial stress	δ_L	Limit displacement
ε_x	Uniaxial strain	M	Moment from response spectrum analysis
ε_x^p	Uniaxial plastic strain	M_c	Elbow envelope moment from cyclic analysis
S_m	Permissible stress intensity	j	Iteration number
D	Outside diameter of the elbow	θ_e	Elbow rotation
P	Internal pressure	S_a	Alternating stress
t	Elbow thickness	K_2	Peak stress index
R	Elbow bending radius	U_i	Usage factor
r_m	Mean radius of elbow	ε	Strain
		a_1, a_2 & a_3	Constants
		$A\ (g)$	Zero Period Acceleration (ZPA) of excitation

and (b) respectively. The photographs of elbow and tee joint are shown in Fig. 2(a) and (b) respectively. The material of the elbow and tee is carbon steel of grade SA 106 Gr B. The elbow and tee joints are of same size with an outer diameter of 89 mm and 5.5 mm nominal thickness (3 in. Nominal Bore (NB), schedule 40). Bottom end of the elbow setup is anchored to the shake table and the top end is connected to a rigid attachment carrying 25 kg and 105 kg masses at both ends. Two ends of the tee joint are anchored to shake table and the top end is connected to rigid attachment having 25 kg and 125 kg at both ends. The purpose of rigid attachments and added masses in the test setup is to obtain the frequencies of piping components in the same range of typical frequencies of nuclear power plant piping systems. Four post yield Surface Mounted Electrical Resistance (SMER) strain gauges are installed on two flank (crown) locations of elbow to obtain strain in hoop and axial or meridional directions. The strain gauges in hoop direction are denoted as SG-1H & SG-3H, while in axial direction gauges are denoted by SG-2A & SG-4A at two flank locations. For tee joint, two post yield strain gauges, SG-T1H and SG-T3H are mounted to measure hoop strain at front and rear portions of location-A respectively. Another gauge, SG-T2A is pasted in axial direction at the front portion of location-A. The locations of the strain gauges are shown in Fig. 1.

2.2. *Details of sine sweep tests*

Initially the elbow and tee are filled with water and sine sweep test with amplitude of 0.05 g is carried out in the frequency range of 1–50 Hz to evaluate free vibration characteristics. One fourth octave per minute is the sweep rate of the test. Both ends of the 3 in. NB, schedule 40 elbow are attached with straight pipes of same size as shown in Fig. 1(a). An inverted ‘L’- shape straight pipe attachment of size 1.05 m x 0.3 m is connected to the top end of the elbow setup as shown. Pipes of 3 in. NB, Schedule 160 sizes are used for the attachment. A straight pipe of 2 in. NB, schedule 40 is diagonally connected to the attachment for improving rigidity. In the tee joint test setup, all three ends of 3 in. NB, schedule 40 tee joint are connected to straight pipes of same size as shown in Fig. 1(b). An ‘I’ – shape straight pipe attachment of 1.4 m length is connected to the top end of the tee joint setup. Pipe of 3 in. NB, Schedule 160 size is used for the attachment.

The natural frequencies and damping for the elbow and tee joint from sine sweep tests are given in Table 1. The first natural frequency of the elbow is 4.4 Hz and corresponding damping using half-power method is 2.2%. The second and third frequencies are 4.6 Hz and 27.2 Hz respectively. Corresponding damping values are 2.3% and 1.1% respectively. From the sine sweep test on tee joint, the first and second natural frequencies are 4.2 Hz and 5.3 Hz respectively. The corresponding damping values by half-power method are 2.7% and 2.2% respectively.

2.3. *Details of fatigue-ratcheting tests*

Fatigue-ratcheting tests are carried out by subjecting the elbow and tee joint to internal pressure and incremental tri-axial earthquake load. The elbow and tee joint are pressurized up to 21.3 MPa to generate hoop stress equals to design limit based on yield stress. Test Response spectra (TRS) in X, Y & Z directions for 2% damping with 0.25 g Zero Period Acceleration (ZPA) are shown in Fig. 3. As it is a common seismic design practice to have a lower vertical component than horizontal component of seismic ground motion, the TRS in vertical (Y) direction is considered lower than that of horizontal direction. It is observed that the piping components will be subjected to maximum dynamic amplification as their fundamental frequencies correspond to the peak response zone of the TRS. Acceleration time histories corresponding to TRS in X, Y and Z directions are shown in Fig. 4(a), (b) and (c) respectively.

The test is started by applying this base excitation for five times and the response of the elbow is recorded. Later the ZPA of excitation is increased to 0.5 g and subsequently increased till 2.25 g with an increment of 0.25 g. Due to the recommended practice of five Operating Basis Earthquakes (OBE) and one Safe Shutdown Earthquake (SSE) for seismic qualification [13], the ratcheting tests of both piping components are started by applying five OBEs with ZPA of 0.25 g and one SSE with ZPA of 0.5 g. For further excitation, a minimum five passes are applied corresponding to each excitation with ZPA of 0.5 g onwards. During ratcheting tests, strains at various locations are monitored and strain accumulation is used as the criterion for repeating each excitation level. If very little strain accumulation takes place during a particular excitation level after five passes, the amplitude is increased to next level. The loading details are provided in Table 2. Hoop and axial strain time histories of first flank location of elbow (SG-1H, SG-2A) are shown in Fig. 5(a) and (b) respectively. The maximum strains for SG-1H are 1735 με, 2455 με and 2800 με for excitations with ZPA of 0.25 g, 0.5 g and 0.75 g respectively. No strain accumulation is observed in hoop direction till excitation of 1 g ZPA. During excitation of 1 g ZPA, strain accumulation has started and reached a maximum value of 4170 με. Peak strains for 1.25 g ZPA and 1.5 g ZPA are 10450 με and 16330 με respectively and the strain gauge, SG-1H has de-bonded during excitation with 1.5 g ZPA. A very little strain accumulation with a peak value of 6100 με has been observed in axial direction for gauge SG-2A. Hoop and axial strain time histories of second flank location of elbow (SG-3H, SG-4A) are shown in Fig. 6(a) and (b) respectively. De-bonding of SG-3H is occurred after observing a peak strain of 10140 με during 1.25 g excitation. It is observed that negligible strain accumulation has occurred in axial direction for other gauge, SG-4A.

Hoop and axial strain time histories at front portion of location-A at tee junction (SG-T1H, SG-T2A) are shown in Fig. 7(a) and (b) respectively. A maximum strain of 7160 με with little accumulation is noticed