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Simulation of Ratcheting Behaviour in SA 312 Types 304LN Stainless Steel Straight Pipes

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ABSTRACT: Ratcheting is defined as cycle by cycle accumulation of plastic strain on application of cyclic load with constant stress amplitude and nonzero mean stress. Ratcheting occurs when a structure is subjected to cyclic loading, if the mean strain changes during any one loading cycle at one or more points of the structure with respect to the mean strain induced during the preceding cycle due to inelastic material behaviour. Pressurised piping components may encounter ratcheting when they are subjected to cyclic bending leading to a reduction in fatigue life by loss of ductility. In order to simulate ratcheting behaviour in SA 312 Type 304 LN stainless steel straight pipes of 168 mm nominal outer diameter, finite element studies were carried out under combined internal pressure and cyclic bending load. Finite element analysis were carried out using ABAQUS software by direct cyclic method. The length and average thickness of the pipes were 2700 mm and 14.5 mm respectively. The thickness was reduced to 12 mm in the gauge length portion of 200 mm at the centre of the pipe. The ratcheting simulation studies were carried out under three different combinations of internal pressure and cyclic bending load. The internal pressure was varied in the range of 25 MPa to 45 MPa. The bending load was applied in the form of cyclic displacement which was varied in the range of ± 25 mm to ± 45 mm. The elastic-plastic response of the pipes under combined internal pressure and cyclic bending load was simulated by using the Chaboche hardening parameters. Ratcheting strain values were obtained at different locations in the gauge length portion of the pipes and significant ratcheting strain was observed in the circumferential direction when compared to longitudinal direction. Details of the studies carried out and the results of the investigations are discussed in the paper.

KEY WORDS: Ratcheting; SA 312 Type 304LN stainless steel, Straight pipe, Internal pressure, Cyclic bending, Finite element studies, Ratcheting strain

I. INTRODUCTION

Fatigue ratcheting or ratcheting phenomenon is defined as cycle-by-cycle accumulation of plastic strain on application of cyclic load characterized by constant stress amplitude with a nonzero mean stress. Ratcheting occurs when a structure is subjected to cyclic loading, if the mean strain (arithmetic mean of maximum and minimum strains during one loading cycle) changes during any one loading cycle at at least one point of the structure with respect to the mean strain induced during the preceding cycle due to inelastic material behaviour. Ratcheting can reduce the fatigue life or can cause failure of the piping components or systems subjected to seismic or other cyclic loads. Ratcheting phenomenon can be categorized either as material ratcheting or as structural ratcheting. Material ratcheting is a form of ratcheting which can occur in the absence of structural effects, i.e., if the stress is distributed homogeneously in a structure, and is thus a purely material-related effect which can be observed in material tests. Material ratcheting depends on a number of factors such as mean stress, stress amplitude, frequency, loading history and micro-structural characteristics. On the other hand, structural ratcheting can occur owing to inelastic material behaviour under cyclic loading even if there is no material ratcheting. This type of ratcheting is actually produced by the inhomogeneity of the



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state of stress in a structure. Ratcheting was studied by Vishnuvardhan et al. [10] for pressurized SA 312 TP304LN stainless steel straight pipes under cyclic bending. The local bulging, ovalization and consequent thinning of the pipe cross section due to fatigue ratcheting was observed. The uniaxial and biaxial ratcheting characteristics of SA 333 Gr. 6 carbon steel were investigated at room temperature by Kulkarni et al. [6]. It was observed that ratcheting would occur in circumferential direction for a pipe subjected to constant internal pressure and cyclic bending load with no ratcheting in longitudinal direction. The evaluation of cyclic hardening parameters for Type 304LN stainless steel by [13] Jenitha et al. It was observed that in isotropic hardening, the values of Q decreased with increases in strain amplitude. In kinematic hardening, the values of C_1 and γ_1 are constant for all values of strain amplitude.

In the present studies finite element analysis is carried out using FEA based ABAQUS software on 168 mm OD stainless steel straight pipes subjected to combined bending and internal pressure.

II. MATERIAL PROPERTIES

Material used in the present studies was SA 312 Type 304LN stainless steel conforming to ASTM A 312/ 312 M -14 [11]. The chemical composition of the material and the specified values as per ASTM A 312 / A 312 M - 14 standard are given in Table 1. Mechanical properties of the material were determined by carrying out tension tests as per ASTM E 8M - 13a [4]. The average yield strength and ultimate tensile strength of the material were found to be 251 MPa and 611 MPa respectively. The modulus of elasticity and percentage of elongation of the material were found to be 183 GPa and 68 respectively.

	Chemical composition (% weight)			
Elements	Tested values	ASTM A312 / A312 M - 14 (%) [12]		
Carbon	0.025	0.035		
Manganese	1.790	2.000		
Phosphorus	0.022	0.045		
Sulphur	<0.001	0.030		
Silicon	0.357	1.000		
Chromium	18.980	18.000 - 20.000		
Nickel	9.350	8.000 - 12.000		
Molybdenum	0.173	-		
Titanium	0.005	-		
Nitrogen	0.092	0.100 - 0.160		
Vanadium	0.065	-		
Copper	0.190	-		
Cobalt	0.068	-		

TABLE 1 CHEMICAL PROPERTIES OF THE STAINLESS STEEL

Details of specimen

Ratcheting studies were carried out on 168 mm nominal outer diameter straight pipe made of SA 312 Type 304 LN stainless steel. Average length of the pipes was 2700 mm. Figure 1 gives the details of a typical pipe specimen. Two threadolets were provided in the pipe specimens at a distance of 150 mm from the centre of the weld, as shown in the figure. The thickness of the specimens was gradually reduced from the normal section to the gauge section by machining over a distance of 200 mm on both sides. The gauge length was 200 mm. Thickness in the gauge length



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portion was maintained uniform. The circumferential and axial lengths of the test or gauge area were divided into twelve (pitch = 30°) and eight (pitch = 25 mm) equal segments along the circumferential and longitudinal directions respectively and grid lines were marked. The circumferential grid lines were numbered in sequence from 1 to 12. Similarly the axial grid lines were marked in sequence from 'A' to 'I'; grid line 'E' being at the centre of the pipe. Circumferential lines were also marked at the inner and outer span locations of the pipe and named as IS1, IS2, OS1 and OS2. Two more circumferential lines, NS1 and NS2, were marked at locations 80 mm away from IS1 and IS2 and towards the centre of the pipe.

III. FINITE ELEMENT ANALYSIS

Finite element analysis (FEA) is a numerical method which provides solutions to problems that would otherwise be difficult to obtain. In the present studies, analysis was carried out by using FE software ABAQUS 6.13 to predict the ratcheting behavior.

Every complete FEA consists of 3 separate stages:

- Pre-processing or modeling: This stage involves creating an input file which contains an engineer's design for a finite-element analyzer (also called "solver").
- Processing or finite element analysis: This stage produces an output visual file.
- Post-processing or generating report, image, animation, etc. from the output file: This stage is a visual rendering stage.

Specimen Modelling

Finite element analysis was conducted on SA 312 Type 304LN stainless steel pipe. Figure 1 shows the configuration and dimensions of the pipe specimen. The length of the pipe was 2700 mm, thickness of the pipe was 14.5mm and the thickness is reduced to 12 mm.at the gauge section. The length of the gauge section was 200 mm. The specimen was subjected to internal pressure and cyclic bending. Table 2 shows the internal pressure and displacement details.



All dimensions are in mm.

Fig. 1 Dimensions of the pipe specimen

TABLE 2 Internal pressure and displacement details

Case	Internal pressure	Displacement	Number of
No.	(MPa)	(mm)	cycles
1	25	±45	50
2	45	±25	50

Procedure for Finite Element Analysis

The pipe specimen was first created as a part using 3D deformable solid element using revolution. The pipe section is revolved to 360°. Figure 2 shows the geometry model of the pipe specimen. Figure 3 shows the solid model of the pipe specimen.



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Fig. 2 Geometry model of the pipe specimen



Elastic and cyclic hardening properties of material

The elastic property of the material is assigned as $\mu = 0.3$ and $E = 198 \times 10^3$ MPa, where μ defines poisson's ratio and E defines young's modulus. The plastic property of the material is assigned as combined hardening parameters, i.e (combination of kinematic hardening and isotropic hardening parameters). The hardening parameters used in this model was chaboche hardening values. The value of kinematic hardening are defined by means of three back stresses, $\sigma_0 = 137.45$, $C_1 = 106137$ MPa, $\gamma_1 = 4407$, $C_2 = 71250$ MPa, $\gamma_2 = 366$, $C_3 = 4264$ MPa, $\gamma_3 = 9$, Where σ_0 defines the yield stress at zero plastic strain, C is the hardening modulus and γ is the rate at which the kinematic hardening modulus decreases with increase in plastic deformation. The value of isotropic hardening parameters are defined by using cyclic hardening option by specifying the parameters Q = 99.24 MPa and b = 0.0135, where Q is the maximum change in the size of the yield surface and b is the rate at which the size of the yield surface changes at plastic straining develops. The entire specimen was defined as a solid homogeneous section. Figure 4 shows the assigning of the property modules.

Loading and Boundary conditions

The load was applied as pressure on the inner section of the pipe along X direction. The applied pressure was 25 MPa for one case and 45 MPa for the other case. The boundary condition of the specimens are symmetric pinned on the outer span of the pipe and the displacement is provided by adding another boundary condition by releasing U2 (45 mm and 25 mm) boundary condition. The cyclic action is described by applying amplitude corresponding to the sinusoidal wave form. Figure 5 shows the loading conditions. Figure 6 shows the support boundary conditions. Figure 7 shows the displacement boundary conditions.





Fig. 4 Property model of the pipe specimen

Fig. 5 Internal pressure applied on pipe specimen



Fig. 6 Support condition on outer span of pipe specimen



Fig. 7 Displacement condition on inner span of pipe specimen

Mesh Description

The specimen was first seeded using the seed by edge option. The cross section edges were seeded to a size of 1 and the partitioned portions were seeded to a size of 25. The mesh was generated with hexahedron elements using



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structured meshing technique. The element type was given as linear for pipe specimen. Thus C3D8R (Continuum three dimensional 8 nodded linear brick reduced integration) were used. Figure 8 shows the mesh modelling of the specimen



Fig. 8 Mesh modelling on specimen

IV. RESULTS AND DISCUSSION

Tables 3 and 4 gives the maximum strain values obtained in hoop and longitudinal directions at different locations for both the cases under combined internal pressure and cyclic bending. Strain values were observed to be maximum in the hoop direction when compared to longitudinal direction at all the locations. The pipe experienced significant ovalization and ballooning during ratcheting. Figure 9 shows the deformed shape of specimen 1. Figure 10 shows the deformed shape of the specimen 2. Figures 11 and 12 show the displacement vs. number of cycles curves. Figures 13 and 14 show the load vs. load line displacement curves. Figures 15and 16 show the strain variation at different locations with increase in number of cycles. Figures 17 and 18 show the stress-strain curves.



Fig. 9 Deformed shape of pipe subjected to internal pressure of 25 MPa and cyclic displacement of ±45 mm.



Fig. 10 Deformed shape of pipe subjected to internal pressure of 45 MPa and cyclic displacement of ± 25 mm.





Fig. 12 Displacement vs. number of cycles curve for pipe subjected to internal pressure of 45 MPa and cyclic displacement of ±25 mm

Number of cycles

30

20

0

10

-20

-30

(mm)

Displacement



20

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Load (kN)

-20





Load-line displacement (mm) Load-line displacement (mm)

Fig. 13 Load vs. load line displacement curve for pipe subjected to internal pressure of 25 MPa and cyclic displacement of ±45 mm

Fig. 14 Load vs. load line displacement curve for pipe subjected to internal pressure of 45 MPa and cyclic displacement of ± 25 mm

300

200

-100

-300

TABLE 3 STRAIN VALUES AT DIFFERENT LOCATIONS IN THE GAUGE SECTION

Specimen No	Internal pressure (MPa)	Applied load-line displacement (mm)	Strain location	Longitudinal strain (με)		Circumferential strain (με)	
				Minimum	Maximum	Minimum	Maximum
1 25 N		±45 mm	B1	-322.194	182.753	-5540.950	0.000
			E1	-322.441	184.046	-5539.540	0.000
			H1	-322.194	182.753	-5540.950	0.000
			B4	-238.849	4.197	0.000	4225.500
			E4	-226.211	4.027	0.000	4247.490
	25 MDa		H4	-238.849	4.197	0.000	4225.500
	23 WIF a		B7	-190.117	209.490	-5634.520	0.000
			E7	-190.183	213.330	-5629.920	0.000
			H7	-190.117	209.490	-5634.520	0.000
			B10	-238.849	4.197	0.000	4225.500
			E10	-226.211	4.027	0.000	4247.490
			H10	-238.849	4.198	0.000	4225.500

TABLE 4 STRAIN VALUES AT DIFFERENT LOCATIONS IN THE GAUGE SECTION

Specimen No	Internal pressure (MPa)	Applied load-line displacement (mm)	Strain location	Longitudinal strain (με)		Circumferential strain (με)	
				Minimum	Maximum	Minimum	Maximum
		a ±25 mm	B1	-260.719	71.621	-9989.440	0.000
			E1	-272.363	70.878	-10012.200	0.000
2 45 MPa			H1	-260.719	71.621	-9989.440	0.000
			B4	-334.982	0.000	0.000	3618.900
			E4	-340.008	0.000	0.000	3718.930
	45 MDa		H4	-334.982	0.000	0.000	3618.900
	45 MPa		B7	-150.129	77.403	-10043.500	0.000
			E7	-155.122	76.697	-10065.300	0.000
			H7	-150.129	77.403	-10043.500	0.000
			B10	-334.982	0.000	0.000	3618.900
			E10	-340.008	0.000	0.000	3718.930
			H10	-334.982	0.000	0.000	3618.900



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V. CONCLUSIONS

Finite element studies were carried out on a SA 312 Type 304 LN stainless steel straight pipes under combined internal pressure and cyclic bending load. The elastic-plastic response of the pipe was simulated by using the Chaboche hardening parameters. Significant ratcheting was observed in the circumferential and longitudinal direction at twelve locations of the pipes. It is observed that the accumulation of ratcheting strain is higher in circumferential direction when compared with longitudinal strain.

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