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Optimization procedure for parameter determination of caboche kinematic hardening model

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Abstract. The ratcheting behavior and prediction of 316L stainless steel pipe was developed using numerical finite elementapproach. The Chaboche model parameters to be used in the numerical method were adopted from symmetric post monotonic teston the pipe. The significant property, the elastic limitof the material,was extracted using incremental cyclic uniaxial test. Comparison between two well-known optimization methods, Particle Swarm Optimization and Genetic Algorithm gave the former a slightly better correlation with experimental tests.The Chaboche model in ANSYS was utilized to predict the uniaxial ratcheting behavior of the pipe specimen. Theclose comparison of rate of ratcheting between finite element simulation and experimental test indicates that accurate elastic limit extraction from post monotonic test alone results in improved ratcheting prediction, with PSO method adopted to optimize ratcheting parameters.

Keywords: 316L stainless steel, Ratcheting, Calibration, Chaboche model

1. Introduction

Ratcheting typically appears when a specimen is cyclically loaded beyond of the elastic limit of the material in the presence of significant mean stress [1, 2]. Ratcheting phenomena can occur in pressure vessels, piping systems, structures operating in earthquake zones, offshore structures and nuclear reactors.

The nonlinear kinematic hardening (NLK) theory which was introduced by Chaboche[3, 4]is widely accepted to measure ratcheting. It is formulated into commercial finite element programs such as ANSYS and ABAQUS[5].However there exist deviationsof this model andcomparison with experimental ratcheting test under uniaxial or biaxial loading had been presented[5, 6].To ensure good correlation with tests, accurate models with robust parameters should be presented [7] but parameter identification has become an issue as well[6, 8] Thus, essential techniques are needed to identify ratcheting NLK model parameters[9] A systematic trial-and-error approach is used to determine the Chaboche model parameters[10]but the approach is time consuming because it requires trials. Rahman et al performed

heuristic Genetic Algorithm (GA) approaches to predict the NLK Chaboche model parameters[11]. Another difficulty in analyzing ratcheting is the hardening-ratcheting coupling in which cyclic hardening would influence the rate of ratcheting in unsymmetrical stress cycling[11, 12]. To evaluate the ratcheting parameters the saturated cycle of the hysteresis curve was used. In some cases the ratcheting parameters were evaluated from unidirectional monotonic stress-strain loading curve[9].Ratcheting parameters are closely related to the elastic limitof the material that is to be yielded[9].FromTable Y-2 of SectionII, Part D, in ASME B&PV Code (Code, 2010) and the Nuclear Safety Standards Commission document, KTA 3201.2, Table 7.7-8 13 [9] the elastic limit for stainless steel is assumed to be 0.55 times the yield stress coefficient; this coefficient is either the Yield Strength S_y or the 0.2% strain offset[13].

In this study, a 316L stainless steel pipe which was subjected to uniaxial loading wasinvestigatedfor ratcheting behavior. The elastic limitwas found fromincremental uniaxial cyclic loading test of the pipe. The ratcheting parameters wereevaluated by applying intelligent methods such as Particle Swarm Optimization (PSO) and Genetic Algorithm (GA). The results from these two heuristic approaches were compared in terms of accuracy of parameters identifications from uniaxial tensile test and optimization time.

2. Material Specification

The 316L stainless steel in this study isa commonly used material in the oil and gas field. The mechanical properties are listed in Table 1. The outer diameter and its thickness are 60.3 mm and 3.9 mm respectively. For the post monotonic test the pipe was preparedin a similar way as prepared by Jiao and Paquette et al. [14].

Table 1. Basic mechanical properties

σ_y(Offset 0.2 %)(MPa)	σ_U(MPa)	E (GPa)
275	601	172

The pipe specimen Fig.1 wasused for uniaxial tests. The pipes have 40 mm of parallel lengths at both ends, 55 mm of tapered lengths and 32 mm of test section in the middle length of the pipe. The test section was machined down from 3.9 to 1.44 mm of wall thickness.The linear taper was introduced to reduce sudden change in geometry and to induce ratcheting in the test section.The high quality of weldingwas assured by performing non-destructive test. To eliminate the thermal effect from machining process and welding, the specimen was heat treated.
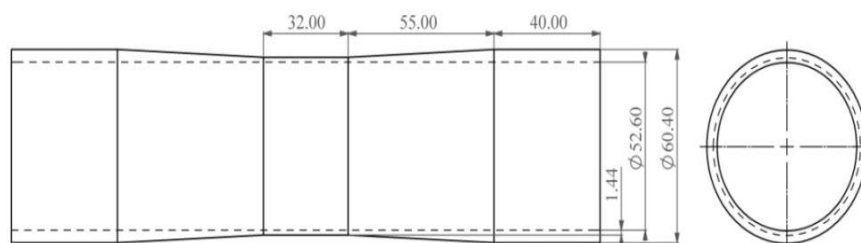

Figure 1. Pipe specimen dimension (mm)

3. Experimental Setup

The Instron universal testing machine was used to apply uniaxial loading and a digital high speed data acquisition system for logging strain and force data from strain gages and force transducers. High elongation strain gages were bonded on diametrically opposite sides of the pipes in order to cancel the bending effect. The load and strain were recorded for a loading speed of 0.75 mm/min and logging time interval of 0.5 seconds. The experiment test setup is illustrated in Fig. 2.

To eliminate the effect of coupling between hardening and ratcheting rate the specimen was first stabilized under uniaxial symmetric strain cycling [11]. The samples were subjected to cyclic strain controlled strain hardening followed by post monotonic incremental test to find the elastic limit and to carry out uniaxial ratcheting test. There are two purposes in conducting uniaxial testing; the first is to implement cyclic loading and complete unloading to get the elastic limit of 316L stainless steel. After every cycle of loading and unloading, the load is incremented by 4MPa. The elastic limit is the highest stress which will not result in permanent elongation. The second purpose is performing cyclic uniaxial with 65 MPa mean stress to study ratcheting.
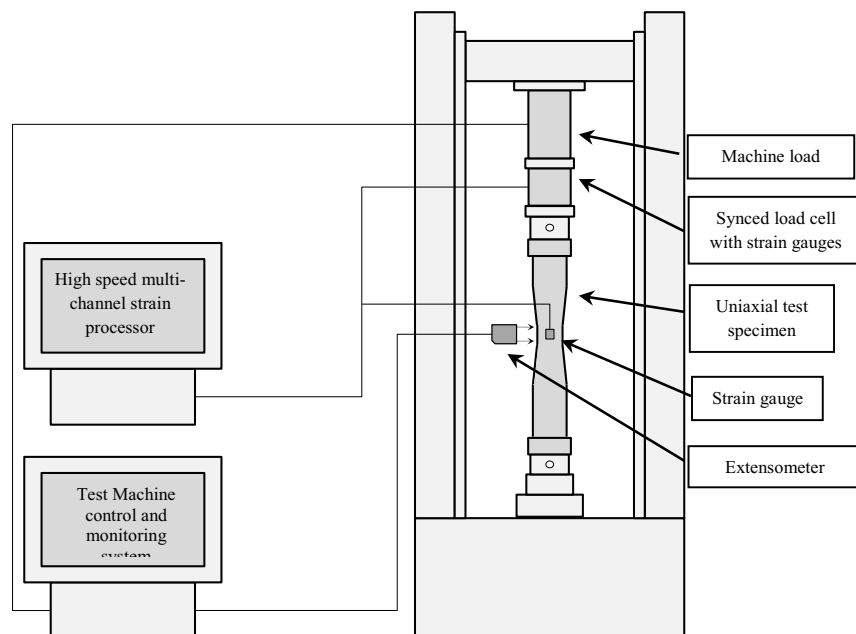

Figure 2. Sketch of biaxial testing setup

3.1. Experimental results

The saturated uniaxial strain control test is presented in Fig.3 where the cyclic curves are seen to have stabilized after 11 cycles in which the specimen attains the stiffest property.After pre hardening, the specimen was subjected to post stabilized monotonic uniaxial loading as shown in Fig 3. The post-stabilized monotonic uniaxial curve is superimposed on the cyclic strain control stress-strain curves. The figure shows that the stabilized material hardening curve is closely correlated to the post-stabilized monotonic curve.The cyclic incremental loading and complete unloading behavior of the specimen is shown in Fig.4. The load was incremented by 4MPa after each unloadinguntil a permanent elongation was observed. For example, when the specimen was stressed to 244 MPa and then unloaded, the strain started

at $0\mu\epsilon$ then reached 1500 $\mu\epsilon$ and recovered the 0 $\mu\epsilon$ value when no load was acting. But when stressed to 248MPa and then unloaded, the strain remained at 7.5 $\mu\epsilon$ when no load was actingHence the elastic limit is 244MPa whereas the yield stress is 305MPa at 0.2% of strain offset.

The ratcheting behavior of the specimen is determined from uniaxial stress control test. The axial stress-strain result is shown in Fig. 5a where the stress ranges from 320 MPa to -190 MPa with mean stress of 65 MPa. From the graph it is calculated that the strain increases by 100 $\mu\epsilon$ per cycle (ratcheting rate) and after 25 cycles the strain is constant and does not increase beyond $5500\mu\epsilon$. The accumulated axial strain at each cycle is recorded in Fig.5b.
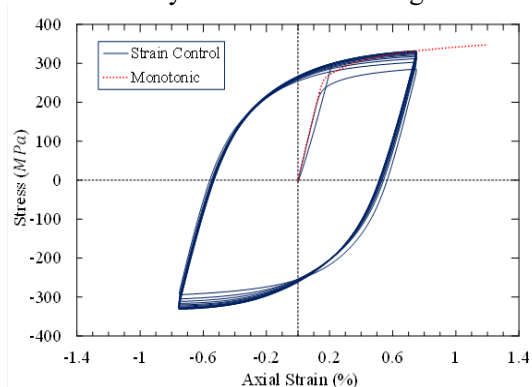

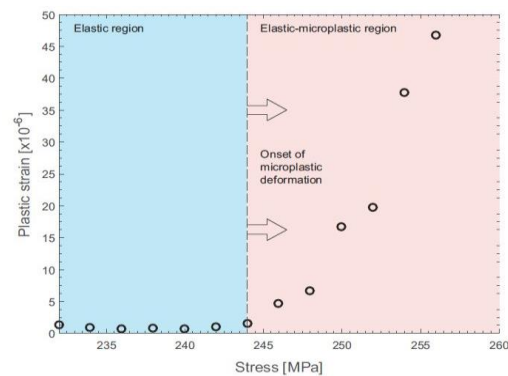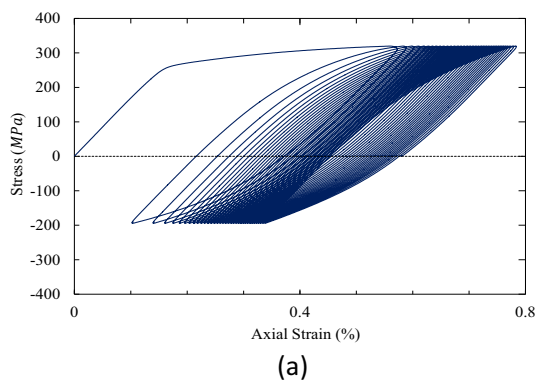**Figure 3**. Comparison of cyclic strain control and post monotonic tests
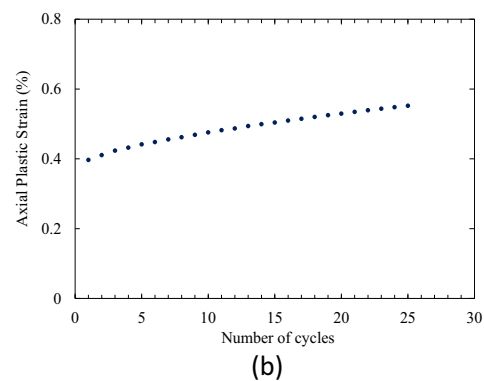

Figure 4. Incremental cyclic uniaxial test to distinguish elastic limit of 316L stainless steel

(a)

(b)

Figure 5. (a) Uniaxial ratcheting response (b) uniaxial ratcheting rate (axial plastic strain per cycle)

4. Automated Parameter Calibration of Chaboche Model

The Chaboche parameters can be identified and calibrated based on stress-plastic strain adopted from monotonic loading curve, as shown in Fig. 6. For ratcheting analysis, the parameterscan be used for any geometry and cyclic loading, provided the same stress range is selected such as that shown in Fig. 3.

4.1. Stress-Plastic Strain Extraction from Stress-Strain Curve Data

For the determination of elastic limit,the yield stress atϵ_{off} of 0.2% is used. [9]recommended the elastic limit to be 0.55 times the yield stress. This resultsina yield stress of 305 MPa andelastic limit of 167.2 MPa for monotonic curve, see Fig.6(a).

However, an alternative approach, the incremental uniaxial method thatwas used to determine the elastic limit of 316L had resulted in a value of 244MPa (Fig.4) and plotted in Fig 6(b). The back stressis calculated and plottedin Fig. 6.
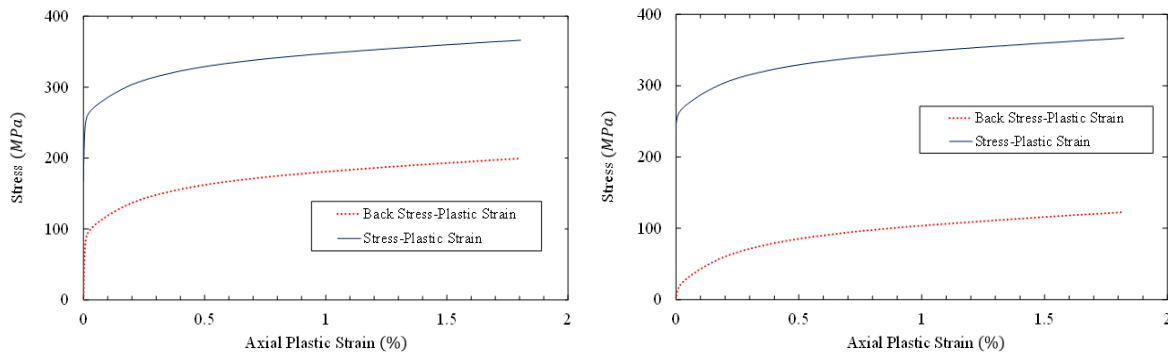

Figure 6. Stress-plastic strain and back stress obtained from monotonic curve for (a) elastic limit=167.2 MPa (b) elastic limit=244 MPa

Table 2. PSO and GA calibration of ratcheting parameters for monotonic curve with elastic limit 244 MPa

Type	PSO Calibration method	GA Calibration method
C_{1-4}	296870,17958,2118,20508	300871,25155,2118,14182
γ_{1-4}	21179,335,0,1196	21803,402,0,1903
Optimization time (s)	617	721
MSE	0.325	0.691

4.2.Parameter identification based on the physical meaning of parameters
By considering the Chaboche model with M components, the back stress α_{NLK} is described as:

$$\alpha_{NLK} = \sum_{i=1}^{M} \alpha_i \, , \tag{1}$$

Where α_i is extracted from the monotonic test bythe Equation below:

$$\alpha_i = \left(\frac{C_i}{\gamma_i}\right)[1 - \exp(-\gamma_i \, \varepsilon_p)], \tag{2}$$

To evaluate the α_{NLK} back stress curve the estimation of the number of component is needed. In the first step, the initial estimates of C and$\gamma$are generatedbased on Eqn. 3which is adopted for whole plastic strain data proportional to back stressα_{NLK}, but γ_3 is set zero.

$$\alpha_{NLK} = \alpha_1 + \alpha_2 + \alpha_4 + (C_3 * \varepsilon_p) \, , \tag{3}$$

To optimize the parameters, two intelligent methodsare usednamely, PSO [15]and GA[11, 16]to ensure the minimum deviation between numerical simulation and ratcheting experiment. The accuracy of the parameters is measured by the Mean Square Error (MSE)between $\alpha_{NLK}$and α.In this optimization the

MSE is considered cost function which requiresminimization.Finally the value of γ_3 is calibrated when other parameters are kept constant. Calibration is carried out within the range of $0-10$for uniaxial simulation, as described in Section 5.

4.3. Discussion on the best parameters identification
The ratcheting parametersin PSO and GA are estimatedbased on 224 MPa as the elastic limit. The values of α and $\alpha_{NLK}$are obtained by Equation 2 and 5.$\gamma_3$is considered to be zero.From Table 2 the PSO gives less *MSE* compared to GA and PSO contains less mathematical operations. After each iteration the cost function of each member in PSO approaches calculated to be compared with past, local and global in order to detect the more eligible member. The ratcheting parameters with two different elastic limits, namely, 167.2 MPa and 244 MPa, using PSO,are presented in Table 3.The parametersdriven from monotonic test are assigned as set A and B respectively.

5. Finite Element Model
A ¼-pipe is modeled using a finite element commercial software ANSYS. The simulated uniaxial cyclic loading condition is the same as in the experimental test. The Chaboche plasticity model is chosen from the ANSYS library. The FE model uses estimated parameters from experiment and PSO approaches. The Chaboche model simulation for uniaxial test which employs Chaboche parameters is presented in Table 3.

Table 3. PSO method - Calibration for Set A, and Set B.

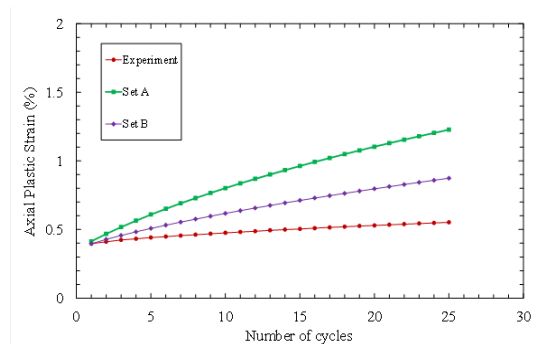| Type	Set A	Set B
C_{1-4}	2446600, 12207, 2118, 24246	296870, 17958, 2118, 20508
γ_{1-4}	27439, 291, 0,	21179, 335, 0,

Figure. 7. Chaboche model of ratcheting simulation results using ratcheting parameters presented in Table 3 for uniaxial ratcheting test

6. Finite Element Results and Discussions
Fig. 7 shows the Chaboche model simulation results for the uniaxial loading. The value of$\gamma_3 = 3$ had been calibrated using uniaxial loading simulation. Adopting an accurate elastic limit in Set B gives a more precise yield stress surface, compared to Set A. The ratcheting rate predicted in uniaxial loading with parameters obtained from Set B is quite close to experimental results, with slight overestimation but with similar trend of the curve.

7. Conclusion

The prediction of ratchetting using Chaboche model in ANSYS depends much on extraction and calibration of parameters from uniaxial tensile tests.

The Chaboche ratcheting parameters were obtained for316L stainless steel pipe from post monotonic test. For parameters identification and calibration the PSO and GA approaches were compared. The PSO gave lower *MSE* and faster optimization time and was utilized subsequentlyin this study.

The most accurate Chaboche ratcheting parameters came from stabilized hardening strain control test followed by post monotonic test, and from the elastic limit that was obtained from incremental uniaxial test. The theoretical stress-plastic strain curve was then employed to find the C and γ ratcheting parameters using PSO and GA methods. Uniaxial ratcheting tests were conducted to verify uniaxial ratcheting rate simulation.

Acknowledgments

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