Optimization procedure for parameter determination of cabouche kinematic hardening model

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Abstract. The ratcheting behavior and prediction of 316L stainless steel pipe was developed using numerical finite element approach. The Chaboche model parameters to be used in the numerical method were adopted from symmetric post monotonic test on the pipe. The significant property, the elastic limit of 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. The close 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 its 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 deviations of this model and comparison 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
The heuristic Genetic Algorithm (GA) approaches to predict the NLK Chaboche model parameters\cite{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\cite{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\cite{9}. Ratcheting parameters are closely related to the elastic limit of the material that is to be yielded\cite{9}. From Table Y-2 of Section II, Part D, in ASME B&PV Code (Code, 2010) and the Nuclear Safety Standards Commission document, KTA 3201.2, Table 7.7-8 \cite{13}, 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\cite{13}. In this study, a 316L stainless steel pipe which was subjected to uniaxial loading was investigated for ratcheting behavior. The elastic limit was found from incremental uniaxial cyclic loading test of the pipe. The ratcheting parameters were evaluated 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 is a 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 prepared in a similar way as prepared by Jiao and Paquette et al. \cite{14}.

| $\sigma_y$ (Offset 0.2%) (MPa) | $\sigma_U$ (MPa) | $E$ (GPa) |
|-----------------------------|------------------|-----------|
| 275                         | 601              | 172       |

The pipe specimen Fig.1 was used 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 welding was 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.

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 unloading until a permanent elongation was observed. For example, when the specimen was stressed to 244 MPa and then unloaded, the strain started
at 0\(\mu\varepsilon\) then reached 1500 \(\mu\varepsilon\) and recovered the 0 \(\mu\varepsilon\) value when no load was acting. But when stressed to 248MPa and then unloaded, the strain remained at 7.5 \(\mu\varepsilon\) when no load was acting. Hence 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 \(\mu\varepsilon\) per cycle (ratcheting rate) and after 25 cycles the strain is constant and does not increase beyond 5500\(\mu\varepsilon\). The accumulated axial strain at each cycle is recorded in Fig.5b.

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 parameters can 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 at\(E_{off}\) of 0.2% is used. [9] recommended the elastic limit to be 0.55 times the yield stress. This results in a yield stress of 305 MPa and elastic limit of 167.2 MPa for monotonic curve, see Fig.6(a).
However, an alternative approach, the incremental uniaxial method that was 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 stress is calculated and plotted in Fig. 6.

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 |
| \gamma_{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 \( \alpha_{NLK} \) is described as:

\[
\alpha_{NLK} = \sum_{i=1}^{M} \alpha_i , \quad (1)
\]

Where \( \alpha_i \) is extracted from the monotonic test by the Equation below:

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

To evaluate the \( \alpha_{NLK} \) back stress curve the estimation of the number of component is needed. In the first step, the initial estimates of \( C \) and \( \gamma \) are generated based on Eqn. 3 which is adopted for whole plastic strain data proportional to back stress \( \alpha_{NLK} \), but \( \gamma_3 \) is set to zero.

\[
\alpha_{NLK} = \alpha_1 + \alpha_2 + \alpha_4 + \left( C_3 * \varepsilon_p \right), \quad (3)
\]

To optimize the parameters, two intelligent methods are used namely, 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 \( \alpha \). In this optimization the

Figure 6. Stress-plastic strain and back stress obtained from monotonic curve for (a) elastic limit=167.2 MPa (b) elastic limit=244 MPa
MSE is considered cost function which requires minimization. Finally, the value of $\gamma_3$ 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 parameters in PSO and GA are estimated based on 224 MPa as the elastic limit. The values of $\alpha$ and $a_{NLK}$ 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 parameters driven 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 |
| $\gamma_{1-4}$ | 27439, 291, 0, 21179, 335, 0 | 2296870, 17958, 2118, 20508 |

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 for 316L 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 subsequently in 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.

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References

[1] A. Ravikiran, P. Dubey, M. Agrawal, G. Reddy, R. Singh, K. Vaze, Experimental and Numerical Studies of Ratcheting in a Pressurized Piping System Under Seismic Load, Journal of Pressure Vessel Technology 137(3) (2015) 031011.

[2] J. Shen, H. Chen, Y. Liu, A new four-dimensional ratcheting boundary: Derivation and numerical validation, European Journal of Mechanics-A/Solids 71 (2018) 101-112.

[3] J.-L. Chaboche, Time-independent constitutive theories for cyclic plasticity, International Journal of plasticity 2(2) (1986) 149-188.

[4] J.-L. Chaboche, On some modifications of kinematic hardening to improve the description of ratchetting effects, International journal of plasticity 7(7) (1991) 661-678.

[5] X. Chen, X. Chen, D. Yu, B. Gao, Recent progresses in experimental investigation and finite element analysis of ratcheting in pressurized piping, International Journal of Pressure Vessels and Piping 101 (2013) 113-142.

[6] J. Rojiček, R. Halama, Numerical simulations of pipeline bending tests, Applied and Computational Mechanics 2 (2008) 347-356.

[7] J. Rojicek, Identification of material parameters by FEM, Modern Machinery Science Journal (2010).

[8] R. Halama, Z. Poruba, Tangent modulus in numerical integration of constitutive relations and its influence on convergence of NR method, Applied and Computational Mechanics 3 (2009) 27-38.

[9] A. Kalnins, J. Rudolph, A. Willuweit, Using the nonlinear kinematic hardening material model of Chaboche for elastic–plastic ratcheting analysis, Journal of Pressure Vessel Technology 137(3) (2015) 031006.

[10] S. Bari, T. Hassan, Kinematic hardening rules in uncoupled modeling for multiaxial ratcheting simulation, International Journal of Plasticity 17(7) (2001) 885-905.

[11] S.M. Rahman, Finite element analysis and related numerical schemes for ratcheting simulation, (2006).
[12] S.M. Rahman, T. Hassan, E. Corona, Evaluation of cyclic plasticity models in ratcheting simulation of straight pipes under cyclic bending and steady internal pressure, International Journal of Plasticity 24(10) (2008) 1756-1791.

[13] J. Zhou, Z. Sun, P. Kanouté, D. Retraint, Experimental analysis and constitutive modelling of cyclic behaviour of 316L steels including hardening/softening and strain range memory effect in LCF regime, International Journal of Plasticity (2018).

[14] R. Jiao, S. Kyriakides, Ratcheting and wrinkling of tubes due to axial cycling under internal pressure: Part I experiments, International Journal of Solids and Structures 48(20) (2011) 2814-2826.

[15] J. Kennedy, Particle swarm optimization, Encyclopedia of machine learning, Springer2011, pp. 760-766.

[16] D. Agius, M. Kajtaz, K.I. Kourousis, C. Wallbrink, C.H. Wang, W. Hu, J. Silva, Sensitivity and optimisation of the Chaboche plasticity model parameters in strain-life fatigue predictions, Materials & Design 118 (2017) 107-121.