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Combined hardening parameters of high strength steel under low cycle fatigue

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A R T I C L E I N F O

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A B S T R A C T

Ratcheting is a second failure mode in low cycle fatigue loading where plastic strain accumulates in each cycle. It is difficult to precisely estimate component deformation due to the complexities of cyclic hardening. In order to study the deformation, all types of hardening rules must be determined priorly. In this study, the determination procedures of combined hardening parameters are presented using Abaqus software. The experiment data of API-5L X80 from the past research have been utilized. Lastly, the different inputs of non-linear kinematic hardening choices are analyzed and presented.

1. Introduction

Steel tubes are extensively utilized in many industries such as construction, nuclear, oil and gas (Zeinoddini et al., 2016). Typical examples of such components and structures are offshore structures, pressure vessels and piping systems, structures working in earthquake zones, aero-plane landing gears, and nuclear reactors. Because of these conditions, the structural elements are repeatedly subjected to inelastic stresses that gradually accumulate plastic deformation or strain, which may eventually result in low-cycle fatigue failure (Kyriakides & Shaw, 1987; Lu, 2003). Therefore, evaluating such components' fatigue life needs a precise prediction of inelastic strain and its evolution, commonly described as "ratcheting". Ratcheting is a second failure mode in low cycle fatigue loading where plastic strain accumulates in each cycle. Direct collapses lead the material unusable, decreasing the time needed for fatigue failure by initiating internal cracks and excessive deformation are the possible of ratcheting's failure mode (İşler, 2018). Elastic behavior, Elastic shakedown and plastic shakedown are approved under the industrial design code, while ratcheting is not recognized and needs to be studied extensively (Macedo et al., 2020).

Numerous academics have also attempted to model the deformation behavior of a component using numerical analysis. To forecast the behavior of a complex material under cyclic loading conditions, cyclic hardening principles for over five decades are provided. Precise prediction of ratcheting remains a problem until now. Particularly in tubular structures, as it involves applying specialized constitutive models implemented in a finite element framework (Hassan et al., 2015; Islam & Hassan, 2019). To mimic the non-elastic behavior of metals under periodic loads such as cyclic loading, isotropic and kinematic hardening models should be utilized (Rahmatfam et al., 2019). From simple isotropic hardening models to complex combined hardening models established by Chaboche, Ohno, and Wang, numerous models have been developed for use in numerical modeling. Prager's suggested isotropic hardening and linear kinematic hardening are relatively straightforward to apply. Bilinear kinematic hardening (BKH), multilinear kinematic hardness (MKIN), and Chaboche's nonlinear kinematic hardening (NLK) models are frequently utilized in ratcheting behavior research and are now included in commercial finite

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element systems such as ANSYS and ABAQUS. The Chaboche model is the most powerful of the models available in commercial software (Zeinoddini et al., 2017). Previous research has highlighted the need for hardening models(Chaboche, 1986, 1991; Ohno & Wang, 1993). Then the revisions were recommended in other studies (Abdel-Karim & Ohno, 2000; Bari & Hassan, 2002; Jiang & Sehitoglu, 1996a, 1996b; McDowell, 1995). All the stated hardening models are basically derived from studies conducted by Armstrong and Frederick (1966) were to translate the Bauschinger effect shown into mathematical equations. However, there are certain constraints to accurately predicting the hardening curvature and change in the yield surface during cyclic deformations. Chaboche, for example, devised a mixed hardening model that incorporates both isotropic and nonlinear kinematic hardening, as suggested by Amstrong. This model can be used to more precisely forecast deformations. Simulating the response of materials to cyclic loads can also be performed using a combined nonlinear kinematic/isotropic hardening model or a nonlinear kinematic hardening model (Zakavi et al., 2010). Nevertheless, there are several challenges associated with determining these parameters for simulations. This study demonstrates the techniques for determining combined hardening parameters based on minimal material test data. Hysteresis loops and material of API-5L X80 that have been studied by Zeinoddini et al. (2017) were used to determine hardening parameters. A quasistatic axial loading was stimulated using ABAQUS. Then, the available options for the combined hardening rule in ABAQUS were obviously compared.

2. Materials and methods

The material properties have been adopted from the experiment conducted by Zeinoddini et al. (2017). The specimen used in the current study is fabricated from API-5L X80 carbon steel pipes. This type of steel is commonly used as a production riser and line pipe in deep offshore petroleum development operations. The chemical composition of the steel material as stated in Table 1.

Table 1. Chemical composition of steel materials for the test

Grade	C%	S%	Mn%	P%	S%
X80	0.21	0.54	1.55	0.024	0.025

From the monotonic uniaxial tensile coupon test, the average data for the Young's modulus, yield stress (σ, y) , ultimate stress (σ, u) and elongation at room temperature are 206 GPa, 645 MPa, 780 MPa and 20%, respectively (Fig. 1). The findings of hysteresis loop tests are used to calculate the cyclical plasticity characteristics of material properties in order to characterise the inelastic behaviour of tubes. Fig. 2 depicts a typical hysteresis loop for a sample tested at a strain amplitude of 7%, as conducted by Zeinoddini et al. (2017). As can be observed, the stress-strain pathway saturates and stabilises after a number of cycles. In addition, the API-X80 steel reveals a visible cyclic softening trait. The cyclic softening/hardening characteristics of the material have a great influence on the number of cycles to the failure and the ratcheting rate (Zeinoddini et al., 2014).

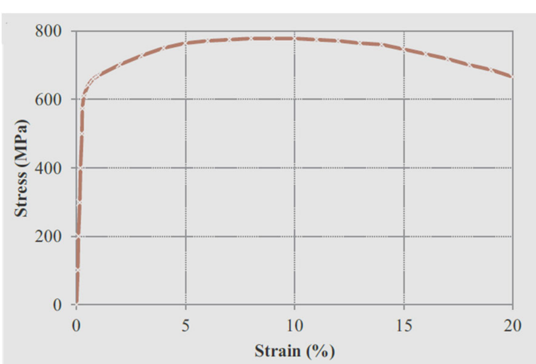

Fig. 1. Stress-strain reaction after monotonic uniaxial tensile coupon experiments

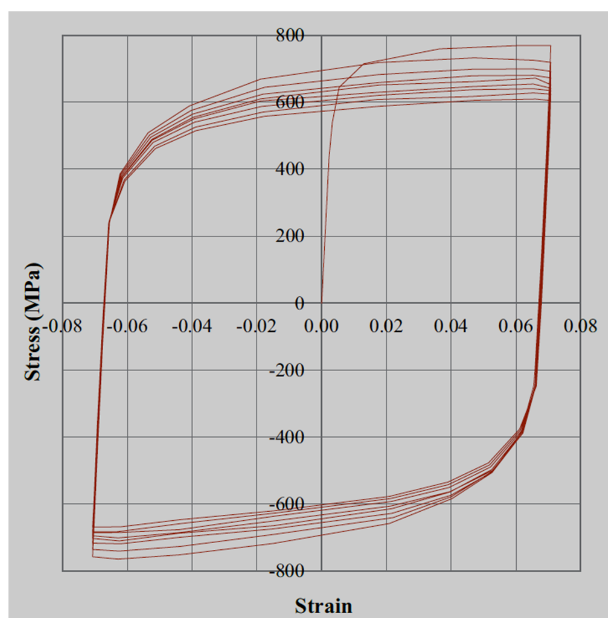

Fig. 2. Stress reaction under cyclic straining at a strain amplitude of 7%

3. Combined hardening model

Before the curve fitting, the preparation of the data needs to be done. The data have been extracted from Fig. 2. There are three existing ways in the ABAQUS, in applying kinematic hardening which are half-cycle, stabilized cycle and parameter (ABAQUS (2014) Analysis User's Manual, 2014). Many researchers recommended using parameter options (Azadeh & Taheri, 2016). In this research, all three options have been employed. Half cycle utilizes only the first cycle curve. Stabilized cycles utilize the last cycles that formed throughout the cyclic loading. Lastly, the parameters option can be used after material parameter identification by various methods such as trial & error, curve fitting using ABAQUS (2014) Analysis User's Manual 2014) and algorithm method used by Moslemi et al. (2019).

3.1 Isotropic hardening

$$\sigma^0 = \sigma|_0 + Q_\infty\left(1 - e^{-b\bar{\varepsilon}^{pl}}\right). \tag{1}$$

According to Eq. (1), whereby b and Q_∞ are material properties and $\sigma|_0$ is the yield stress at zero plastic strain. Q_∞ represents the largest change in the size of the yield surface, while b describes the rate that the yield surface size changed as plastic straining developed. The model is reduced to a nonlinear kinematic hardening model when the equivalent stress defining the size of the yield surface remains constant $(\sigma^0 = \sigma|_0)$. In order to obtain the isotropic hardening parameters, MATLAB's Curve Fitter application by The MathWorks (2020) have been used. With utilizing the application, the parameter Q_∞ and b have been identified by the curve fit shown in Fig. 3 where the stress is in: MPa. The value of Q_∞ and b are -37 and 1 respectively.

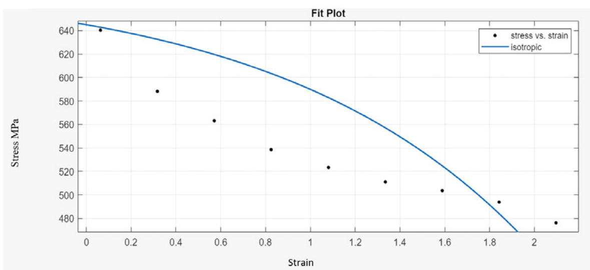

Fig. 3. Curve Fit for Isotropic Hardening from Stress-Strain Curve

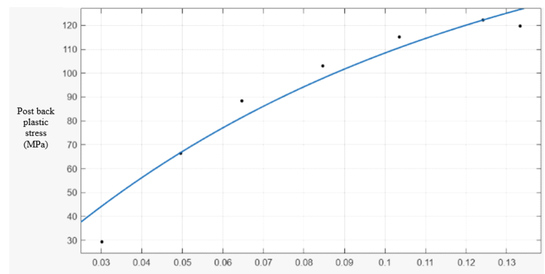

Fig. 4. Curve Fit for Kinematic Hardening

3.2 Kinematic hardening

$$\alpha_k = \frac{C_k}{\gamma_k}\left(1 - e^{-\gamma_k g^{pl}}\right). \tag{2}$$

From the Eq. (2), the material parameters C_k and γ_k are the kinematic hardening component of the model. For all three options, the data that have been extracted from the hysteresis loop and it have been converted to plastic strain by removing the elastic strain. Half and stabilized cycles selections can be directly input into the ABAQUS after the data preparation. While for parameters options, further data processing is required. In this study, the curve fitting method has been chosen. MATLAB software has been utilized for the curve fitting of kinematic hardening. The dedicated curve fitting app in MATLAB has been used to find the initial material parameters for kinematic hardening. According to the curve fitting, the values of and are 1696 and 9.731 respectively with an RMSE of 8.67.

4. Finite element analysis

The result from MATLAB was then applied to the finite element modelling software, ABAQUS. A simple model has been created in ABAQUS for this research. To ease the computation, the model shown in Fig. 5 was a shell element model with the dimension of 35 mm (*L*), 5 mm (*W*) and thickness of 5 mm. A single reference point was created at the end of each side, RP-1 and RP-2. RP-2 was applied displacement-controlled loading in axial loading according to Fig. 6 while RP-1 as fixed connection. The meshing of the model in Fig. 6 was equally divided into 10 elements with 3.5mm length. The axial test would be ensured in a quasi-static displacement-controlled loading regime with 0.2 mm/s of displacement rate. This type of loading as shown in Fig. 6 applied to remove the influence of dynamic loading and isolate the effect of cyclic loads on fracture resistance (Rudland et al., 1996).

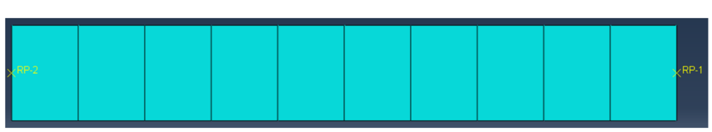

Fig.5. Mesh Model

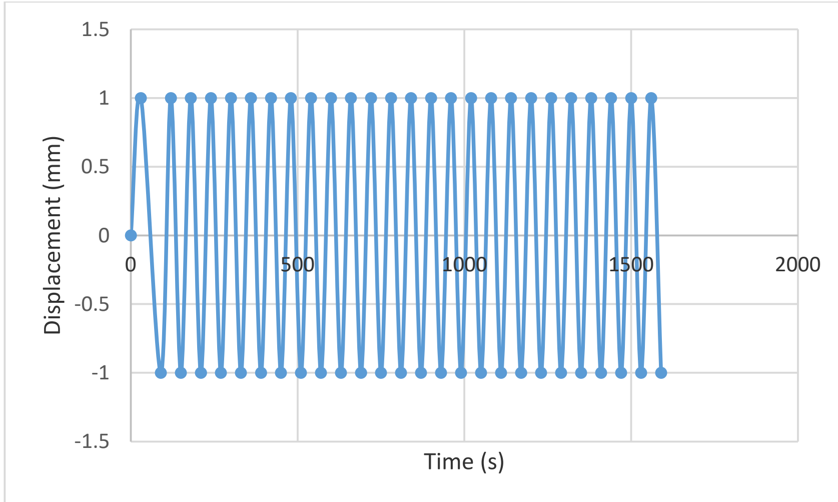

Fig. 6. Quasi-static loading rate

5. Results and discussion

According to the results obtained, it can be concluded that the half-cycle and stabilized cycles options do not suffice for cyclic loading that consists of a high number of cycles. Figs. 7 and 8 indicate that those two options would not be able to complete one whole cycle mainly to the loading displacement 1mm which is considerably high. Both of these results also show that these two options are not suitable for low-cycle fatigue and ratcheting analysis. Half and stabilized cycle indicate that these two options in ABAQUS could not stimulate softening behavior. This can be seen right after the first cycle, the curve could not behave in softening and failed. The failed stress of the half and stabilized cycle is 682 MPa & 691 MPa respectively after completing one cycle of loading while the parameter option is 634 MPa. Hence, the half and stabilized cycles overpredict the stress compared to parameter methods. The parameter methods are able to stimulate softening where after completing the first cycle where the stress is lowered that the yield stress. This proves the occurrence of softening behavior. Fig. 9 depicts a similar shape as Fig. 2. The percentage error of stress between these two figures is 5.98% error. Although the error percentage is low, the strain range of the simulated need to be improved as can be observed where the strain grows steadily bigger compared to Fig. 2. To enhance the strain range, parameters of kinematic need to be further iterated and improved. As with low percentage error, it indicates the appropriate level of acceptance on this study especially on the kinematic parameters. According to the observation in Fig. 9, stress value decreases gradually in small change value at discrete scale. Additionally, the ABAQUS software still could be able to fully simulate softening characteristics. This softening characteristic is mainly governed by isotropic hardening. It can also be noticed that the applied loading shall be adequately enough in order to extract the hysteresis curve. Thus, the parameter of isotropic is still sufficient for this comparison experiment.

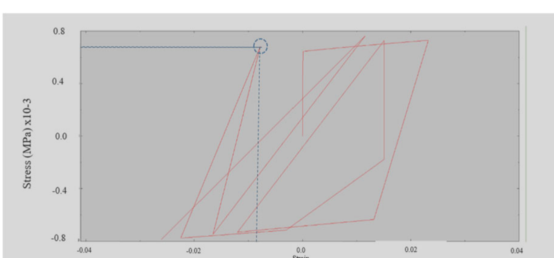

Fig. 7. Half cycle's response

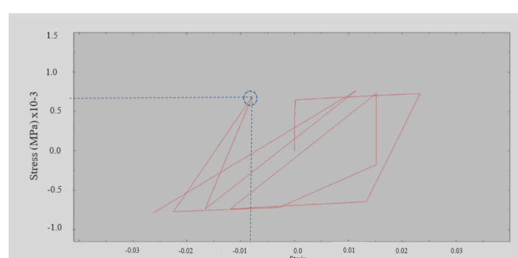

Fig. 8. Stabilized cycle's response

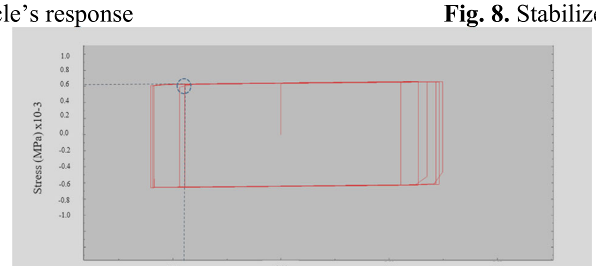

Fig. 9. Response parameters

6. Conclusion

This study explores the technique for determining the parameters of a combined hardening model using minimal material test results. The influence of nonlinear kinematic methods was investigated, and appropriate simulation parameters were identified in order to effectively mimic the deformation behavior of cyclic loading. The parameters of the isotropic hardening model were determined by the difference between cyclic and monotonic stress - strain curve, while the parameters of nonlinear kinematic hardening models have been obtained from hysteresis loop results from the literature-based strain-controlled test. As a result, simulation using the derived parameters is much more accurate. Hence, all three nonlinear kinematic choices have been presented. Moreover, the simulation can be enhanced further with the improved derived parameters by using different methods aside from curve-fitting like the algorithm method by Moslemi et. al (2019). By having a different strain of amplitude for experiment, these can be helped to produce better parameters. Loading rate and isotropic hardening need to be developed further for better precision of the simulation result.

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