LOW CYCLIC FATIGUE OF HG70-STEEL MINING DUMP TRUCK FRAME UNDER LOW-TEMPERATURE: CHABOCHE MODEL AND FINITE ELEMENT ANALYSIS

Z. Y. Qu

School of Mechanical Engineering, Inner Mongolia University of Science and Technology, China

Supervisors: X. F. Guo, B. Yuan

This paper investigates the low cyclic fatigue behavior of a heavy-duty mining dump truck frame manufactured of HG70-steel under low-temperature conditions. The Chaboche cyclic plastic constitutive model is adopted to characterize the viscoplastic properties of the steel. A finite element model of the frame is subsequently implemented to investigate its structural strength and low cycle performance, integrating the intrinsic stress-strain hysteresis loop. The study reveals the softening stages of HG70-steel under low-temperature low cycle fatigue testing conditions, and investigates the stress concentration regions and maximum displacements in the structured frame. The coded in-house program can be used to assess the low cycle fatigue behavior of steels and components, providing valuable insights into the design and safety analysis of heavy-duty mining dump trucks.

Keywords: HG70-steel, Low cycle fatigue, unified viscoplasticity constitutive model.

The mining dump truck frame is a vital load-bearing component that undergoes fatigue damage due to the cyclic loads of its various components and the loads it carries. Exposure to low temperatures, such as –40 °C can accelerate this process [1]. Hence, investigating the low-temperature fatigue behavior of HG70-steel, the primary material used in the frame, under cyclic alternating loads is necessary. In recent years, significant advancements have been made in the development of viscoplasticity modeling frameworks, and the Chaboche Unified Viscoplastic Model has shown the best predictive capability among them [2]. Previous studies have used this model to accurately predict the deformation behavior of different steel alloys, including 9Cr steel and 42CrMo4 tempered low-alloy steel [3, 4]. However, most of these studies focused on material behavior at room temperature and lacked low-temperature fatigue data. Furthermore, while finite element analysis and optimization of dump truck frames are crucial for their design and safety, they rely on the correct material intrinsic structure relationship. Therefore, this study aims to obtain the Chaboche unified viscoplastic material parameters based on low-temperature low-cycle fatigue data of HG70-steel in the frame. It also validates the model's predictive capability for alloy steel under low-temperature and low-cycle fatigue, providing an effective means for finite element analysis of dump truck frames.

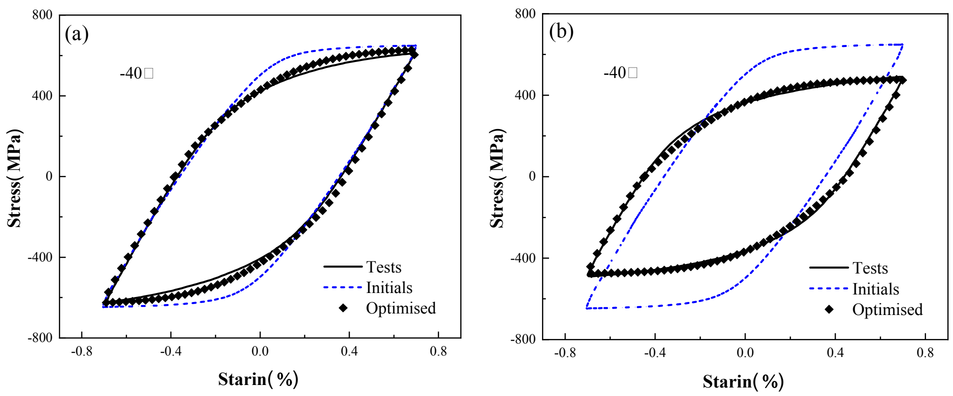
First, the Chaboche unified viscoplastic modelling progress is described. For the flow rate and yield rule of steels, creep (viscous) and plastic strains in terms of inelastic strain rates are expressed as

$$\dot{\varepsilon}_p = \frac{f^n}{Z}\operatorname{sgn}(\sigma-\chi),\ \operatorname{sgn}(x)=\begin{cases}1 & x>0,\\ 0 & x=0,\\ -1 & x<0;\end{cases}\quad \langle x\rangle=\begin{cases}x & x\ge 0,\\ 0 & x<0\end{cases}. \tag{1}$$

The Mises yield criterion is used in this model and the specific yield function is $f=(\sigma-\chi)-R-k$. Furthermore, for the isotropic hardening model controlling the expansion or contraction of the yield surface, the evolution of the associated resistance stress is $\dot{R} = b(Q - R)\dot{p}$. Next, to describe the translation of the yield surface in the stress space, a nonlinear motion hardening rule is used, that is, $\chi = \sum_{i=1}^{2} \chi_i$ and $\dot{\chi}_i = C_i(a_i\dot{\varepsilon} - \chi_i\dot{p})$. In addition, the model predicting the strain hardening and cyclic hardening/softening of engineering materials can be generated by using the viscous stress $\sigma_v = Zp^{1/n}$. Finally, the total stress can be expressed as

$$\sigma = \chi + (R + k + \sigma_v)\,\mathrm{sgn}(\sigma - \chi) = E(\varepsilon - \varepsilon_p). \qquad (2)$$

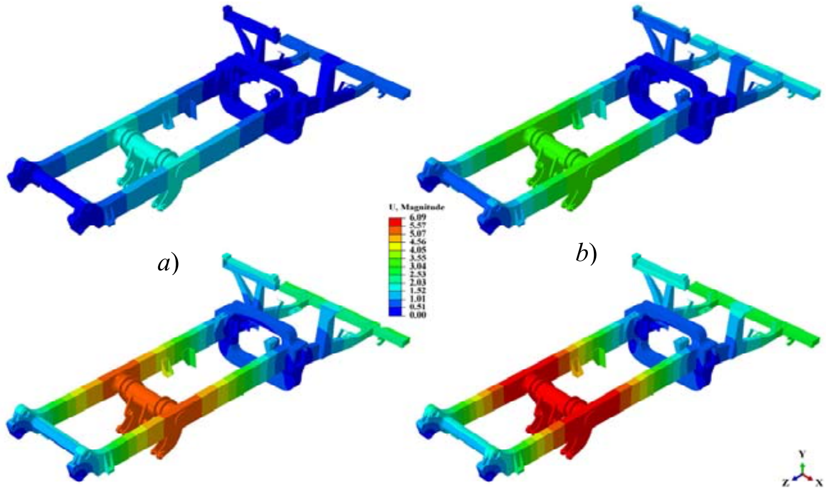
Second, fatigue tests were conducted on the MTS810 machine under the stain variation of ±0.7 %, and the stress-strain hysteresis loop data were recorded by Instron TMF software. By using the above-mentioned theoretical formulae and the low-temperature low cycle fatigue data of HG70-steel, the material constants can be identified, and the predictions of stress-strain hysteresis loops are presented in fig. 1. It is seen that the developed mechanical model is of high accuracy and validity.



a) *b*)

Fig. 1. Cyclic stress-strain curves obtained from experimental assessment and numerical simulation:
a – Initial stage; *b* – Steady state stage

Third, the Chaboche Unified Viscoplastic Model is implemented in the Fortran language using the user subroutine interface provided by the ABAQUS finite element software. The material constants obtained through optimization are incorporated into the model to define the material properties of the frame. A finite element analysis of the frame is then conducted using time series load spectra under cyclic loading conditions, and color legends with the same scale are used to facilitate comparisons of frame changes with the number of loading cycles. fig. 2, *a–d* illustrate the displacements of the frame as the dynamic load factor increases. The results indicate that frame displacements occur primarily around the torsion barrel and its surrounding rear longitudinal beam and bumper, with the majority of deformation concentrated in the former. This corresponds to the actual damage location of the frame as reported by the company and confirms that the simulation using the model can accurately predict the fracture location, thus providing convincing results.



a) *b*)

c) *d*)

Fig. 2. Effective displacement contour maps of the frame
at different time points in the third cycles

R e f e r e n c e s

1. Mechanical properties of normal strength mild steel and high strength steel S690 in low temperature relevant to Arctic environment / J.-B. Yan [et al.] // Materials & Design. – 2014. – Vol. 61. – P. 150–159.
2. Chaboche, J. L. Cyclic inelastic constitutive equations and their impact on the fatigue life predictions / J. L. Chaboche, P. Kanouté, F. Azzouz // International Journal of Plasticity. – 2012. – Vol. 35. – P. 44–66.
3. Study on Ramberg-Osgood and Chaboche models for 42CrMo4 steel and some approximations / R. Basan [et al.] // Journal of Constructional Steel Research. – 2017. – Vol. 136. – P. 65–74.
4. Predicting damage and failure under low cycle fatigue in a 9Cr steel / F. Biglari [et al.] // Fatigue & Fracture of Engineering Materials & Structures. – 2012. – N 12, Vol. 35. – P. 1079–1087.