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Energy-based low cycle fatigue analysis of low yield point steels

Gang Shi [a,*], Yang Gao [a], Xun Wang [b], Yao Cui [c]

[a] Key Laboratory of Civil Engineering Safety and Durability of China Education Ministry, Department of Civil Engineering, Tsinghua University, Beijing 100084, PR China
[b] East China Architectural Design & Research Institute Co., Ltd., Shanghai 200002, PR China
[c] State Key Laboratory of Costal and Offshore Engineering, School of Civil Engineering, Dalian University of Technology, Dalian 116024, PR China

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ABSTRACT

As examples of the new advanced high-performance structural steels, low yield point steels have attracted increasing interest owing to their excellent properties in the technology of energy dissipation and seismic design. Because dynamic cyclic loading is inevitable during service life in engineering applications, it is critical to develop in-depth understanding of the fatigue behavior of this material. Here, the low cycle fatigue behavior of low yield point steels produced in China, namely LY100, LY160, and LY225, is investigated using an energy-based approach. Axial steel coupons are tested by fully reversed and push-pull cyclic loading with a nominal strain ratio $R = -1$ at a constant strain rate of 0.1% S^{-1}. The strain amplitudes range from 0.5% to 6.0% in 0.5% increments. First, experimental details and results of fatigue life are introduced. Subsequently, using an energy-based approach, the cyclic plastic strain energy, cyclic hysteresis loop properties, and fatigue life prediction are thoroughly analyzed. Finally, a simplified method for fatigue life prediction is proposed. The results show that plastic strain energy density is an important parameter for predicting the low cycle fatigue life of low yield point steels with an acceptable degree of accuracy. The proposed simplified method can provide an effective and reliable alternative for low cycle fatigue life prediction of low yield point steels.

1. Introduction

Low yield point steels are widely used in structural energy-dissipating components [1]. Such components inevitably experience dynamic cyclic loading from earthquake and/or gusty wind during their service life, which may eventually lead to low cycle fatigue (LCF) of material [2]. For safe and efficient design and evaluation of engineering materials that experience dynamic cyclic loading in service, it is essential to investigate their LCF properties.

Currently, LCF analysis approaches are based mainly on the criteria of stress [3], strain [4,5], and plastic energy [6], etc. [7]. When a material is assumed to be tested elastically under high cycle fatigue conditions with relatively small strain amplitudes, the Basquin's law of stress-based method can be used [3]. When the material's fatigue damage is assumed to be caused mainly by plastic strain, the well-known classical strain-based method developed by Manson and Coffin [4,5] is usually applied for fatigue analysis. Furthermore, considering that fatigue damage in most engineering materials is a phenomenon of both high-cycle and low-cycle fatigue, a combination of Basquin's law and the Manson-Coffin model has also been adopted by many researchers [8–10]. Meanwhile, from a macroscopic viewpoint, it has been suggested that the fatigue process is a procedure of energy defusing and accumulation [11]. Thus, an energy-based method can serve as a reasonable alternative for fatigue life analysis. In fact, attempts to apply the energy parameter in fatigue analysis can be traced back about 100 years [6]. In recent years, this topic has aroused the interest of many researchers, such as Luo et al. for high strength structural steel [12], Sarkar et al. for C-Mn rail steel [13], Abdalla et al. for BS 460B and BS B500B steel bars [14], Fekete for reactor steels [15], Song et al. for non-load-carrying cruciform welded joints [16], Callaghan et al. for 2.25Cr–1Mo steel [17], Dutta et al. for 316 stainless steel [18], Lv et al. for extruded magnesium alloy [19], and Gloanec et al. for TiAl alloys [20]. Besides, there are also some new energy-based fatigue analysis models have been proposed [21,22]. All those literatures reveal the applicability of energy-based approach in fatigue analysis. However, few studies have been reported with respect to low yield point steels.

In an energy-dissipating material with significant cyclic hardening when subjected to cyclic loading [23], the LCF behavior of low yield point steel may be properly described by an energy-based method. The present investigation uses an energy-based method to study the mechanical and fatigue characteristics of low yield point steels. First, based on the results obtained from strain-controlled LCF tests, the cyclic plastic strain energy properties and cyclic hysteretic loop properties are characterized and evaluated. Subsequently, the LCF damage mechanism and fatigue life prediction are analyzed using the plastic strain energy. At the end, a simplified method for LCF life prediction that considering the material's cyclic stress-strain response, plastic strain energy

* Corresponding author.
E-mail address: shigang@tsinghua.edu.cn (G. Shi).

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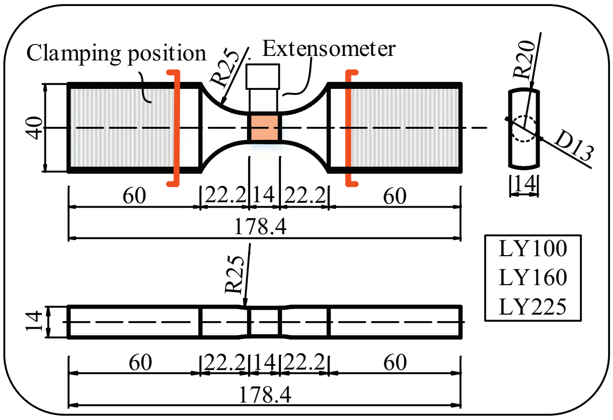

Fig. 1. Details of the specimens (mm).

calculation, and plastic strain energy-life relationship is proposed and proved to be a suitable and reliable alternative to energy-based LCF life prediction with relatively high degree of accuracy. The results obtained and the discussion presented will be helpful for better understanding of the relationship between the LCF properties and the plastic strain energy of low yield point steels and also for further investigation.

2. Experimental details

2.1. Materials and coupons

All grades of low yield point steel that have currently been developed in China, namely LY100, LY160, and LY225, were taken into consideration in the present investigation. Axisymmetric cylindrical smooth bar specimens 14 mm in thickness, 13 mm in diameter, and 14 mm in effective length machined from steel plates were used to evaluate the LCF properties. Typical configuration and dimensions of the specimens are shown in Fig. 1. The chemical compositions (in wt%) and mechanical properties of the steels are given in Table 1.

2.2. Testing procedure

Low cycle fatigue (LCF) tests were conducted in air at room temperature on a ± 10kN capacity universal testing machine (UTM), INSTRON Model 8801, as shown in Fig. 2. The specimen was positioned between the two grips of the test machine that could be actuated independently. The tests were strain-controlled and began with tensile excursion. Fully reversed and push-pull cyclic loading with a nominal strain ratio $R = -1$ at a constant strain rate of 0.1% S^{-1} was designed, using fully reversed triangular waveforms. The applied strain amplitudes ranged from 0.5% to 6.0% in 0.5% increments. The longitudinal strain was measured continuously using a dynamic extensometer with a 12.5 mm gauge length attached to the specimen. The applied load and the fatigue life were recorded by the test machine. Each specimen was tested until fracture (i.e. complete separation of the specimen).

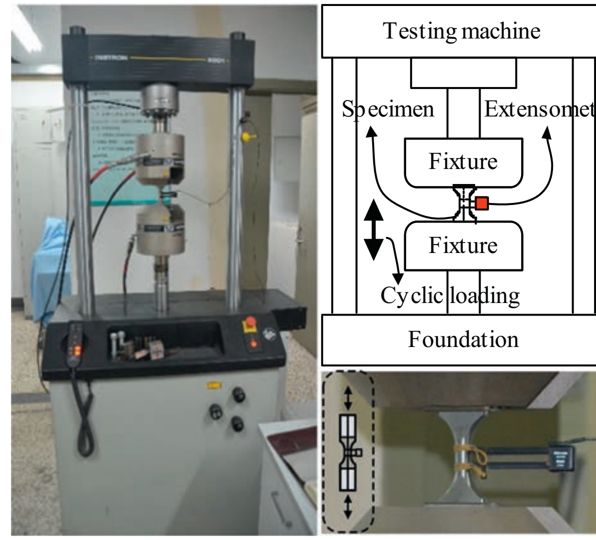

Fig. 2. Test setup.

3. Results and discussion

3.1. Fatigue life

The LCF life N_f given by the number of cycles to fracture of specimens under different strain amplitudes is summarized in Table 2. Note that not all the experimental results were effective for further analysis. Some specimens under low strain amplitude fractured outside the effective length, due to crack initiation at the contact interfaces between the specimen and the knife edges of the extensometer, whereas buckling often occurred in specimens subjected to large strain amplitudes. Experimental data corresponding to those specimens was deemed invalid and was abandoned in the subsequent analysis.

3.2. Cyclic plastic strain energy

Previous studies [8,23] have indicated the significant cyclic hardening of low yield point steels when subjected to cyclic loading and the cyclic stress hardening did not reach the state of stabilization. This an important factor that should be carefully considered in engineering analysis and design. Researchers [12–14,24–29] have clearly demonstrated that a strain energy-based approach can be adopted effectively in the LCF analysis of cyclically nonstabilized (cyclic hardening or softening) materials.

The curves of plastic strain energy density ΔW_P in terms of hysteresis loop area as a function of number of cycles at different strain amplitudes for different grades of steel are presented in Fig. 3. Note that in the cases where more than one effective test result was available (e.g. 1% strain amplitude for LY100, 2% strain amplitude for LY160, etc.), the first set of valid experimental data for each grade of steel under different strain amplitudes (i.e. corresponding to the data in the first row for each grade of steel in Table 2) was adopted in the analysis. Clearly, as a result of the direct relationship between the size of the hysteresis loop area and the applied strain amplitudes, the plastic strain energy density

Table 1

Chemical composition (wt%)							Grade	Mechanical properties					
C	Si	Mn	P	S	Ti	Al		E/MPa	f_y /MPa	f_u/MPa	A/%	f_y / f_u	ε_u/%
≤0.005	≤0.04	≤0.08	≤0.012	≤0.006	0.02–0.05	0.015–0.045	LY100	199,000	128	252	47.3	0.51	27.02
≤0.008	≤0.06	0.08–0.3	≤0.012	≤0.006	0.02–0.05	0.015–0.045	LY160	194,000	186	294	44.5	0.63	24.16
0.02–0.08	≤0.10	0.3–0.8	≤0.012	≤0.006	0.03–0.08	0.015–0.045	LY225	202,500	191	295	44.0	0.65	23.32