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Low cycle fatigue test and enhanced lifetime estimation of high-strength steel S550 under different strain ratios

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ABSTRACT

This study investigates the low-cycle fatigue (LCF) behavior of the high-strength steel S550 (commonly used in ship and floating structures) under different strain amplitudes with different strain ratios at a room temperature. The test results characterize the cyclic stress-strain relationship, the mean stress relaxation behavior and the cyclic plasticity parameters of S550 steels. The scanning electron microscopy (SEM) examinations on the failure surface reveal the fatigue crack initiation and growth mechanism. Based on the experimental results, this study presents two enhanced approaches to estimate the low-cycle fatigue life of S550 steels. The energy-based approach modifies the original Smith-Watson-Topper model using the applied energy calculated in the first cycle to enhance the accuracy and facilitate engineering implementations. The damage mechanics-based approach calibrates the material parameters from the measured total fatigue life by combining the fatigue crack initiation model and the damage growth model. The computed fatigue life using the calibrated material parameters demonstrates a close agreement with the measured fatigue life in the experiment.

1. Introduction

High-strength steels have become an increasingly popular choice for floating platforms, ships, offshore structures and facilities for storing and transporting liquefied natural gases [1–3]. When these structures experience severe loading-unloadings caused by either the operational conditions or the environmental actions (e.g. wave, current, wind and seismic loadings), the resulting high-strain low-cycle fatigue actions can impose a critical threat to the safety and operation of these structures. Therefore, a detailed understanding on the low-cycle fatigue (LCF) behavior of these high-strength steels induced by the cyclic plasticity and hysteresis remains essential and critical in the structural integrity assessment.

Realistic loadings on structures do not usually correspond to the fully-reversed strain-controlled low-cycle fatigue actions. To describe different loading situations in a laboratory setting, a series of low-cycle fatigue tests with different strain ratios allow direct correlation between the fatigue damage and the strain amplitude. Asymmetric strain-controlled cyclic loadings tend to generate a non-zero mean stress, which can significantly increase or decrease the fatigue life of structures and components [4–7]. A tensile mean stress facilitates the crack opening and thus shortens the fatigue life [6,8]. In addition, the mean stress vanishes gradually with increasing fatigue cycles due to the accumulated irrecoverable plastic strain. Previous researchers [6,9] have named this phenomenon as the Mean Stress Relaxation (MSR). The MSR phenomenon further complicates the effect of the mean stress on the low-cycle fatigue life. Therefore, the study on the stress variation under different strain ratios is necessary to develop a reliable approach to predict the

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Nomenclature

A	constant
A_1	constant
A_w	non-dimensional damage parameter
B	constant
B_1	constant
B_w	non-dimensional damage parameter
C and C_i	initial kinematic hardening modulus (i = 1,2)
C_w	critical energy value
D	damage scalar
E	Young's modulus
E_w	non-dimensional damage parameter
F and F_1	constant
F_w	non-dimensional damage parameter
G and G_1	constant
K	cyclic strain hardening coefficient
K^*	hardening coefficient of the master curve
L	characteristic length in finite element model
L_c	damage related parameters
N_f	fatigue life
N_0	No. of cycles to the damage initiation
P	reaction force
Q_∞	maximum expansion of the yield surface
R_ε	strain ratio
R^2	coefficient of determination
S	cyclic softening ratio
b	fatigue strength exponent
c	fatigue ductility exponent
c_i	damage related parameters (i = 1,2,3,4)
h	the rate of the yield surface change
n	cyclic strain hardening exponent
n^*	hardening coefficient of the master curve
Δw_0	strain energy density in the first cycle
α	backstress tensor
α'	deviatoric backstress tensor
$\Delta\varepsilon^*$	strain range of the master curve
ε^{pl}	effective cumulative plastic strain range
ε_a	strain amplitude
ε_a^e	elastic strain amplitude
ε'_f	fatigue ductility coefficient
ε^{pl}	effective cumulative plastic strain
ε_a^{pl}	plastic strain amplitude
ε_{ij}^{pl}	effective cumulative plastic strain tensor index
γ and γ_i	kinematic hardening parameter (i = 1,2)
σ	stress tensor
σ'	deviator stress tensor
σ_0	stress at first few cycles
$\delta\sigma_0$	proportional limit of non-Masing behavior
$\Delta\sigma^*$	stress range of the master curve
σ_a	stress amplitude at half of fatigue life
$\sigma_a^{N=1}$	stress amplitude at first cycle
$\sigma_a^{N=0.5N_f}$	stress amplitude at half of fatigue life
σ_i^c	first yielding compressive stress at ith cycle
σ'_f	fatigue strength coefficient
σ_{max}	maximum stress
σ_m	mean stress
σ_i^t	peak tensile stress at ith cycle
σ_y	yield strength
σ_y^o	the yield strength at zero plastic strain

low-cycle fatigue life of the high-strength steels.

Different low-cycle fatigue prediction models based on strain [10–12], strain energy density (SED) [13], elastic-plastic fracture mechanics [14,15] and continuum damage mechanics [16,17] have emerged over the last few decades. The prediction indicators based on strain and strain energy density are convenient for engineering implementation. Moreover, the strain energy density based indicators do not rely on the orientation of the reference axis and treat the high- and low-cycle fatigue on a uniform basis [18]. The elastic-plastic fracture mechanics and continuum damage mechanics usually are combined with numerical techniques including the extended finite element method [19], the node release technique [20], the cohesive zone element [21,22] and the virtual crack closure technique [23] to simulate the fatigue initiation and crack propagation of complex structures and components. For numerical simulation of the fatigue life, calibration of the material parameters in the respective model becomes essential for a reasonable assessment of the fatigue performance.

The S550 high-strength steel investigated in this paper has the advantage of high strength to weight ratios, good weldability, improved toughness and good ductility, and has found wide applications in ships, marine and offshore structures and bridges. Most of the previous studies of this steel focus on the fracture properties with existing artificial cracks [24–27] and high-cycle fatigue of welded plate joints [28–30].

This paper reports a series of strain-controlled low-cycle fatigue experiments for high-strength steel S550 under different strain ratios at the room temperature. Based on the experimental results, this paper calibrates the cyclic plasticity parameters and presents the cyclic stress-strain curve, the cyclic softening and the non-Masing behavior. The analysis of the microstructure obtained by the scanning electron microscopy (SEM) reveals the mechanism of the fatigue crack initiation, growth and final failure. Based on the low-cycle fatigue behavior of the high-strength steel under different strain amplitudes with different strain ratios, this study also provides a modified energy-based fatigue life prediction model. In addition, this study extends a direct cyclic analysis based on the accumulated inelastic hysteretic strain energy per cycle proposed by Darveaux [31] and Lau et al. [32]. By combining the damage

Table 1
Weight percentage for chemical compositions of S550 high strength steel.

S550	Fe	C	Si	Mn	P	S	Cu	Cr	Ni	Mo
Weight (%)	96.19	0.106	0.327	1.41	0.010	0.0015	0.121	0.454	0.918	0.462