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Size effect and life estimation for welded plate joints under low cycle actions at room and low ambient temperatures

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ABSTRACT

To understand the size effect and the low temperature effect on the low-cycle fatigue behaviour of welded plate joints, this study reports a series of low-cycle fatigue tests of welded cruciform joints with different geometries under the room temperature (28°C) and the low temperature (– 60°C). The experimental results reveal the opposing size effect during the fatigue crack initiation and propagation stages. The comparison of the fatigue life under different temperatures implies a negligible influence caused by the low temperature on the total low-cycle fatigue life of welded plate connections. In addition, this study predicts numerically the low-cycle fatigue life for the welded specimens based on the continuum damage mechanics and achieves a reasonable agreement with experimental results. To simplify the numerical estimation of the local energy-based fatigue driving force at the weld toe, this paper proposes an improved modified Neuber's rule (IMNR), which quantifies the effect of the yield strength for connections under intermediate fatigue driving force. The improved modified Neuber's rule enhances the accuracy of evaluating the local inelastic stress and strain state at the weld toe.

1. Introduction

The rich petroleum reserve in the Arctic stimulates the demand for ice-classed offshore structures and facilities for storing and transporting liquefied natural gases. The temperature in most Arctic areas varies between – 30°C and – 40°C in winter seasons [1]. The lowest temperature can decrease to – 60°C over a large part of the Arctic. The harsh and cold environments impose additional challenges on the failure assessment of these structures and components. The high-strength steel, as an increasingly popular material choice for infrastructures, offshore structures and facilities for storing and transporting liquefied natural gases [2–4], anticipates further research efforts to quantify its mechanical performance at low temperatures [3,4]. As the welded plate connections made of high-strength steels in these structures experience severe cyclic loadings caused by either the operational conditions or the environmental actions, the resulting high-strain low-cycle fatigue actions create a critical threat to the safety and operation of these structures [5,6]. Existing works [7–9] on this topic have shown controversial conclusions that the effect caused by the low temperature can be negligible, beneficial or detrimental on the low-cycle fatigue life of metals. Therefore, a detailed investigation on the low-cycle fatigue behaviour of welded plate connections made of high-strength steels becomes critical and essential in the structural integrity assessment.

The geometric parameters, loading conditions and material properties impose strong influences on the fatigue life of structural components [10]. In contrast to the extensive research works [10–17] on the high-cycle fatigue assessment of welded plate connections, the thickness effect coupled with the elastic-plastic material property in the low-cycle fatigue requires additional experimental and numerical efforts. Raujol-veillé et al. [18] have investigated the thickness effect on the low-cycle fatigue crack initiation life of welded plate joints. Saiprasertkit et al. [5] have assessed the high- and low-cycle fatigue initiation locations in the welded plate joints. To quantify the effect of local plastic deformation near the weld toe of a welded connection, different local fatigue driving forces [16,19–22] based on the stress, strain or strain energy density at the location of the geometric discontinuity have emerged in the evolution of various approaches to assess low-cycle fatigue. In contrast to joints subjected to the high-cycle actions, the welded plate connections experience multiaxial stress and strain conditions with varying principal axes at the weld toe under low-cycle loadings. Superior to the stress or strain-based indicators, the energy-based indicators do not rely on the orientation of the reference axis and treat the high- and low-cycle fatigue on a uniform basis [23].

The low-cycle fatigue actions require time-consuming elastic-plastic numerical analyses to compute the local stress-strain field near the weld toe. In lieu of the time-consuming finite element analysis, a simplified

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Nomenclature

A^e, A^F	constants
a	crack length
B	width of the welded joints
b, h	weld leg sizes
C	kinematic hardening parameter
C^e, C^F	constants
c_i	damage related parameters ($i = 1, 2, 3, 4$)
D	damage state scalar
D^e, D^F	constants
E	Young's modulus
E^e, E^F	constants
e_{depth}	element size in the thickness direction
e_{length}	element size along the surface
F	elastic-plastic notch reduction factor in the MNR
F^e, F^F	constants
H	height of the attachment plate
g	isotropic hardening parameter
K_N	stress and strain concentration factor
K_N^e	elastic stress and strain concentration factor
K_t	concentration factor in Neuber's rule
K_ε	strain concentration factor
K_σ	stress concentration factor
L	characteristic length in finite element model
L_c	damage related parameter
L_w	length of the welded plate joints
N_0	cycles to initiate the damage
N_f	total fatigue life
$N_f^{\exp}$	experimental total fatigue life
N_f^{FEM}	numerically calculated total fatigue life
N_i	fatigue initiation life
n	hardening exponent
P	external load
Q_∞	limit surface of the isotropic hardening
r	weld notch radius
r_{ref}	reference weld notch radius
S_c	distance between two probes crossing the crack
S_r	distance between two reference probes
t	main plate thickness
t'	attachment plate thickness
t_{ref}	reference main plate thickness
V_c	current between two probes crossing the crack
V_r	current between two reference probes
W_c	critical strain energy density value
ΔW^e	elastic strain energy density
ΔW^p	plastic strain energy density
Δw	accumulated hysteresis energy per cycle
Δw_0	accumulated hysteresis energy per cycle in the first cycle
α	backstress tensor
α'	deviatoric backstress tensor
γ	kinematic hardening parameter
$\Delta\varepsilon_{ij}$	strain range tensor
$\Delta\varepsilon_{ij}^e$	elastic strain range tensor
$\Delta\varepsilon_{ij}^p$	plastic strain range tensor
$\Delta\varepsilon_{nom}$	nominal strain range
$\Delta\sigma_{ij}$	stress range tensor
$\Delta\sigma_{ij}^e$	elastic stress range tensor
$\Delta\sigma_{nom}$	nominal stress range
ε^a	strain amplitude
ε^{pl}	effective accumulative plastic strain
σ	stress tensor
σ'	deviatoric stress tensor
σ_y	yield strength
σ_y^o	yield strength at zero plastic strain
Δ	displacement

method to estimate the local stress and strain near the weld notch thus becomes essential in deriving the energy-based fatigue driving force. Over the past few decades, different methods [23–28] have evolved to capture the local inelastic stress and strain at the weld toe. Neuber's rule [27] represents one of the most widely acknowledged approaches, which articulates that the geometrical mean of the effective stress and strain concentration factors is equal to the elastic theoretical stress concentration factor. However, Neuber's rule has an underlying ambit which confines its application to the small-scale yielding condition. As the applied nominal stress approaches the yield strength, Nebuer' rule overestimates the local stress and strain due to the increasingly severe redistribution of stresses and strains near the weld toe. Feng and Qian [23] have, therefore, proposed and validated a modified Neuber's rule (MNR) based on the observed evolution in the notch stresses and strains at the weld toe of welded plate connections to consider the redistribution of stresses and strains at the weld toe. However, the modified Neuber' rule does not consider the effect of material yield strength on the transition phase, where the joints experience intermediate magnitude of applied stresses and strains. This may lead to the overestimation or underestimation of the concentration factor during the transition phase for different yield strengths.

The numerical analysis provides an inexpensive approach to predict the fatigue life of complex structures and components, as an alternative to the costly full-scale experimental tests. Different numerical techniques including the extended finite element method [29], the node release technique [30], the cohesive zone element [31] and the virtual crack closure technique [32] have emerged to predict the low-cycle fatigue life based on fracture mechanics and continuum damage mechanics. In these numerical methods, calibration of the material parameters becomes critical to ensure a reasonable assessment of the fatigue performance. Feng and Qian [33] have proposed an approach to calibrate the damage material parameters by combing the continuum damage models [34,35] in fatigue initiation and propagation phases in coupon specimens, and have validated the accuracy of the calibrated parameters in evaluating the low-cycle fatigue life of standard coupon specimens. However, the proposed calibration approach for more complex structural components requires further validations.

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, which has a wide application in offshore structures and bridges. Previous studies on this steel have investigated the monotonic properties and fracture properties with existing artificial cracks at low temperatures [36–39], high-cycle fatigue of welded plate joints at the room temperature [16,40,41] and low-cycle fatigue properties of coupon specimens at the room temperature [33]. There is limited data on the low-cycle fatigue tests of welded plate connections of S550 under the room and low temperatures.

This study first reports a series of low-cycle fatigue test of coupon specimens and welded plate joints under the room (28°C) and a low temperature (– 60°C). Based on the experimental tests, this paper investigates the cyclic material plasticity, the fatigue crack initiation and propagation behaviour, the size effect and the effect caused by the low temperature on the fatigue life. In addition, this paper develops an Improved Modified Neuber's Rule (IMNR) to quantify the effect of the yield strength on the transition phase in MNR, and illustrates an enhanced estimation of the local energy indicator at the weld toe. Finally, this paper presents a numerical estimation of the fatigue life of the welded cruciform joints based on continuum damage mechanics, with reasonable accuracy compared to the experimental data.

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