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Fatigue failure of 350WT steel under large-strain seismic loading at room and subfreezing temperatures

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HIGHLIGHTS

- CSA 350WT steel tested at room & subfreezing temperatures under different loadings.
- Parameters of low cycle fatigue & cyclic strain hardening models calibrated.
- Ductility & low cycle fatigue of 350WT not affected by subfreezing condition.
- Fatigue models for failure life predicting under variable-amplitude loading evaluated.
- Strain-based fatigue damage model was found more accurate than energy-based ones.
- Miner's rule was accurate for random-loading but may need modification for others.

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ABSTRACT

Due to its high ductility, weldability and toughness at low temperature, CSA G40.21-350WT steel in Canada is primarily used in bridge construction, ship building, and seismic energy dissipation systems. This article presents uniaxial tensile tests and constant- and variable-amplitude cyclic testing performed on 350WT steel at room and subfreezing temperatures. The variable-amplitude tests include common step-loading patterns as well as tests under strain signals obtained from the brace response in building structures subjected to three different types of earthquakes. The ductility of 350WT steel from monotonic tensile tests is essentially same at room and low temperatures (−40 °C). The cyclic test results revealed that cold temperatures as low as −35 °C did not have adverse effects on the low cycle fatigue life of 350WT steel. The benchmark constant-amplitude tests were employed to predict fatigue life under different large-strain variable-amplitude loading patterns both for room and subfreezing temperature conditions. In addition to the common strain-life approach, the adequacy of two well-established energy-life models for predicting fatigue life under variable-amplitude loading was evaluated. The strain-life approach generally performed better than the energy-life methods, particularly for step-loading histories. Comparison between predictions and laboratory observations showed that the fatigue failure life under large strain seismic loading can be accurately estimated, especially at room temperature.

1. Introduction

Earthquake-induced fracture failure of steel structures has been observed and reported in number of post-event reconnaissance reports [49,48,10]. In several cases, failure was attributed to localized fatigue damage caused by large cyclic plastic strains in regions with complex states of stress. Such fractures in critical elements, which occur in a few cycles, can lead to catastrophic failure of engineered structures. In fatigue engineering, materials are studied in two distinctive regimes, namely high cycle and low cycle fatigue (HCF and LCF). In the LCF regime, i.e. less than 10^3–10^4 cycles to failure, plastic strains dominate compared to elastic ones. LCF is more relevant to earthquake engineering applications as the intense seismic vibrations are typically very short and energy-dissipating structural components are subjected to few large plastic deformation cycles, i.e. less than 10–20. Failure under this condition is commonly referred to as extremely- or ultra-low cycle fatigue (ELCF or ULCF) failure and has received more attention in the past decade. Nucleation, initiation and growth of fatigue cracks in this regime is fundamentally different from typical LCF problems where limited plasticity exists. Kamaya [27] showed that cracks under large plastic strains initiate inside the specimen and then propagate to the surface. Kuroda [30] argued that under large

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Nomenclature

C_p	specific heat of material
D	fatigue damage
D_c	diameter of gage area
E	Young's modulus
EL	elongation at fracture
$F_{y,n}$	nominal yield stress
$F_{y,0.2\%}$	lower yield stress measured by 0.2% offset method
$F_{y,Upper}$	upper yield stress
K	coefficient of thermal conductivity
K'	cyclic strength coefficient
N_f	number of cycles to failure
R	ratio of minimum to maximum strain in a half-cycle
R_a	average surface roughness
RA	area reduction at fracture
$P_{\max}$	maximum axial load resisted by specimen
W_a	amplitude of energy density term
W_p	total plastic work in a single loading pass
b	fatigue strength exponent
c	fatigue ductility exponent
e_{pD}	engineering strain at maximum tensile force
h	gage length
h_c	convective heat transfer coefficient
n'	cyclic hardening exponent
n^* and K^*	parameters of master curve (for non-masing materials)
n_i	number of cycles of damaging events for a given intensity
ΔT	total temperature changes during test
$\Delta T_{\max}$	maximum temperature changes in one single pass of seismic-loading
ΔW_0^t	strain energy corresponding to the fatigue limit
ΔW^{e+}	elastic strain energy of tensile stress in one cycle
ΔW^p	plastic strain energy density in one cycle
ΔW^t	total strain energy density in one cycle
$\Delta\epsilon$	strain range
$\Delta\epsilon_e$	elastic strain range
$\Delta\epsilon_p$	plastic strain range
$\Delta\epsilon_{\max}$	largest strain range of the strain signal
$\Delta\sigma$	stress range
$\Sigma(d\epsilon_p)$	sum of plastic strain increments (absolute values)
γ	density
$\epsilon_{\max}$	maximum strain amplitude
ϵ_f	true stress at fracture
ϵ'_f	fatigue ductility exponent
ϵ_m	average of strain signal
ϵ_p	plastic strain
ϵ_{pD}	true strain at maximum tensile force
ϵ_{rms}	root mean-square of the strain signal
κ and α	coefficient and exponent of energy-life fatigue models, respectively
$\sigma_{\max}$	maximum amplitude of tensile stress in one cycle
σ_{FL}	fatigue limit stress (endurance stress)
σ'_f	fatigue strength coefficient
$\sigma_{m,i}$	average of stresses at the beginning and end of the i^{th} counted half-cycle
σ_m	average stress signal
σ_{rms}	root mean-square of the stress signal
σ_u	true ultimate tensile stress

plastic strains, fatigue damage is dominated by exhaustion of ductility rather than crack propagation; he proposed a new damage accumulation theory. Kanvinde et al. [28,29] developed and implemented an uncoupled continuum-based fatigue damage model to predict initiation of failure in energy-dissipating members of structural systems under large strain seismic demand. This model, which employs accumulated plastic strain and state of stress as damage parameters, needs to be calibrated against results of cyclic tests on notched specimens. Fundamental to any ELCF damage model is the uniaxial behaviour under large cyclic strains. In this context, Dusicka et al. [17] studied uniaxial fatigue life of five types of structural steel plates, ranging from very low yield point to high performance steel, under axial strain amplitudes up to ±7.0% and reported their cyclic hardening and fatigue life parameters. The tests showed that the overall fatigue life of all steel plates was similar and strain rate did not have appreciable effects on their hysteresis behaviour. Nip et al. [39] compared the low and extremely low cycle fatigue behaviour of three types of structural carbon and stainless steels under axial strain amplitude up to ±7% and surface bending strains as large as ±15%. The materials studied showed similar fatigue resistance although their fracture ductility from tensile tests was different.

There has been ever-increasing demand for building sustainable infrastructures in cold regions of the world subjected to subfreezing temperature. These regions are often seismically active and need special considerations for design and construction. Steel, due to its unique features, is a viable construction material in such a complex and harsh climate. ASTM A709 [6] and CSA G40.21-350WT [11] steels are commonly used for bridge structural applications due to their enhanced fracture toughness at low temperature. The 350WT steel is a low carbon, ductile and weldable structural quality steel with a minimum yield strength of 350 MPa. This steel is supplied in 5 categories depending upon the required toughness. According to the standard, Category 4 must have a minimum Charpy V-notch (CVN) toughness of 27 J energy at −45 °C. In Canada, this grade is widely used in ship building industry, bridge construction, and heavy mining equipment operating in cold regions. The superior toughness of this steel allows applications in cold marine environments such as ship hull susceptible to brittle facture due to cold water and impact loadings (e.g. ice collision). The Canadian bridge design code CSA S6-04 [12] specifies high toughness steels with minimum CVN of 40 J at −40 °C in fracture-critical elements of bridges in regions with very low service temperature (−40 °C and below). This steel was also experimentally verified for critical seismic force-resisting elements for building structures that must dissipate earthquake energy by undergoing large cyclic plastic deformations without strength and stiffness degradation [46]. Full-scale tests indicated that 350WT steel can sustain large cyclic plastic strains. High cycle fatigue behaviour of this steel at room and cold temperatures has been the subject of few past studies. Taheri et al. [44] investigated the HCF crack propagation of 350WT steel under constant- and variable-amplitude loadings using standard fracture mechanic procedure at −40 °C. Chen et al. [9] compared the 350WT Category 4 and ASTM A709 HPS grade 485 W steels and concluded that LCF resistance, crack propagation, and low temperature toughness properties of these two steels were similar. Josi et al. [26] reported the crack initiation life of flat specimens made of 350WT steel tested between ±0.1% and ±0.6% axial strain amplitudes. Hamdoon et al. [25] conducted LCF testing of this steel at room and low temperatures (−30 °C). In tests up to strain