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Ultra low-cycle fatigue behaviour of a structural steel

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ABSTRACT

Steel structures subjected to extreme loading conditions (e.g. earthquakes, support settlements, industrial plant shutdown) undergo large deformations leading to fracture, either due to monotonic loading or ultra-low-cycle fatigue (ULCF) ($N_f < 100$ cycles). Although developments have been made to understand and to model monotonic ductile damage and low-cycle fatigue (LCF), so far ULCF is neither sufficiently investigated nor understood. This paper presents the results of an investigation concerning the ULCF behaviour of the S185 structural steel. An experimental program was performed to derive ULCF data for notched specimens. LCF and monotonic damage data was also derived for the material under investigation, since ULCF exhibits damage features from both cases. While LCF data was derived for smooth specimens, monotonic tensile tests coupled with image-based methods were carried out on both smooth and notched specimens. Nonlinear finite element models were used to compute the history of relevant parameters of the investigated models for ULCF life prediction. Three existing alternative modelling approaches for ULCF were assessed using available experimental data, and important remarks for further enhancements proposed.

1. Introduction

Extreme loads applied to steel structures can yield either to monotonic ductile failure or to fatigue failure at very small number of cycles (<100 cycles). This fatigue regime is called ultra-low-cycle fatigue (UCLF) or extreme-low-cycle fatigue, in order to distinguish it from low-cycle fatigue (LCF), since ULCF damage mechanisms are distinctive of those typical from LCF. The ULCF fits between the monotonic ductile damage and LCF damage, as shown in Fig. 1, and exhibits damage features from both damaging processes. Concerning the monotonic ductile damage, several models have been proposed in literature, such as the Gurson–Tvergaard–Needleman (GTN) model [2], based on porous plasticity [2], the Johnson–Cook (JC) model [3], the Wilkins model [4], the Cockcroft–Latham model [5] and the Xue–Wierzbicki model [6]. The application of these models requires the definition of adequate experimental procedures in order to calibrate them and allowing the identification of the model constants. In these models, the plastic strain and the stress triaxiality play a central role on damage kinematics, but more recent approaches have also shown a dependency on Lode angle parameter [7].

In contrast with monotonic ductile damage and LCF, ULCF models have been less developed. In addition, concerning ULCF testing, the data available in literature is scarce and there are no specific standards for mechanical testing under high strain level requirements. Typical smooth specimen geometries used in the LCF testing exhibit instability under ULCF loading, requiring special procedures to avoid the specimens buckling.

With respect to ULCF modelling, existing approaches reported in the literature may be classed into coupled and uncoupled models. This classification is usual in monotonic ductile models. Coupled models consider interdependency between plasticity and damage and allows linear or non-linear damage evolution. The coupled plasticity-damage models allow the simulation of the crack initiation (damage onset) and crack propagation (damage spread) [8]. An example of these formulations was proposed by Lemaitre [9]. Also, Leblond et al. [10] proposed an extension of the GTN model for cyclic loading, consisting in the introduction of kinematic hardening in the porous plasticity model, leading to the so called GTN-LPD model [11]. The coupled damage-plasticity models are computationally very expensive and the model parameters identification usually constitutes a complex task due to the interdependency between plasticity and damage. Concerning the uncoupled damage models, damage and plasticity are assumed independent phenomena, which results in simpler approaches requiring less computational costs. The uncoupled approaches

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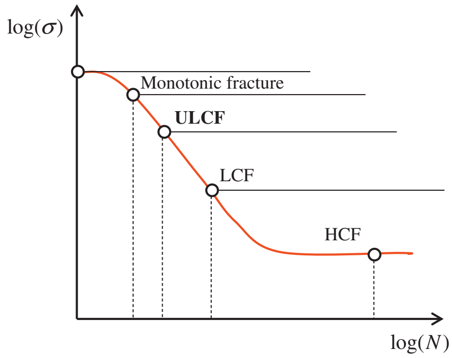

Fig. 1. Relation of ULCF with other damage mechanisms [1].

can be very efficient for crack initiation modelling, and due to the assumed separation between plasticity and damage, they allow simpler parameters identification procedures and the use of more accurate state-of-the art plasticity models.

There are some propositions in literature for uncoupled ULCF models, which are supported by distinct physical assumptions. As mentioned by Komotori and Shimizu [12], the damage accumulation mechanism in fatigue process is different between the large and the small plastic strain amplitude regimes. Therefore, fatigue life in ULCF regime is influenced by ductility, i.e., the large plastic deformations achieve an important fraction of the monotonic fracture strain, which may activate damage mechanisms typical of monotonic damage, such as voids nucleation and growth. Based on these assumptions, a fatigue model has been proposed by Kuroda [13] which divides the ULCF damage into the following three parts: (a) damage due to tensile straining; (b) damage due to ductility exhaustion during cyclic loading; (c) damage due crack propagation. Alternatively, Tateishi and Hanji [14] defined the total damage during ULCF loading as a linear summation between a tensile ductile part and a cyclic damage. Xue proposed an exponential damage rule for fatigue life prediction in the ULCF regime, which overcomes the overestimation limitation of the classical Coffin–Manson approach that has been cited in the literature [15]. The ULCF model based on the cyclic behaviour of micro-voids, proposed by Kanvinde and Deierlein [16] can also be classed as an uncoupled damage model, which postulates the material degradation, by micro-void growth, as a function of the plastic strain weighted with a triaxiality function.

Several uncoupled models were assessed and reviewed in this paper, using ULCF data generated for the S185 structural steel. In particular, the classical Coffin–Manson relation [17,18], the Kanvinde–Deierlein model and the Xue model are considered in this study. Besides the ULCF models, the empirical model proposed by Johnson and Cook, for monotonic ductile damage is considered, since it will be used to compute the equivalent plastic strain at fracture, as a function of the stress triaxiality, for the investigated geometries. It is demonstrated that the monotonic equivalent plastic strain at fracture of a particular detail has a significant influence on the ULCF behaviour of that detail. Experimental image-based techniques, such as digital image correlation and features tracking methods, were coupled with monotonic tensile tests yielding full-field measurements which allowed the inspection of the mechanical tests and provided a diversity of experimental data for plasticity model validation. The load–displacement experimental curves were used to calibrate elastoplastic finite element models.

In the next subsections a brief review of the damage models that will be assessed in this paper is presented. In particular, the Johnson–Cook model for monotonic ductile damage is described. The classical Coffin–Manson relation for LCF is presented and the Kanvinde–Deierlein and Xue models for ULCF are described.

1.1. Johnson–Cook model

The JC model for monotonic ductile damage provides the relation between the equivalent plastic strain at fracture and a monotonic function of the stress triaxiality [3], expressed as:

$$\bar{\varepsilon}_f = C_1 + C_2 \exp(C_3\eta) \tag{1}$$

where the stress triaxiality, η, is defined as the ratio between the hydrostatic pressure and the von Mises equivalent stress:

$$\eta = \frac{p}{\sigma_{VM}} \tag{2}$$

and C_1, C_2 and C_3 are material constants to be determined using data from tensile tests, covering distinct stress triaxialities. In this work, the JC model was calibrated by means of an experimental program of tensile tests on smooth and notched specimens. This model was later used to assess the monotonic fracture strain for the geometries used in ULCF tests. Since the triaxiality in the critical region during the tensile loading is not constant, an average value of this parameter is used [7]:

$$\eta_{av} = \frac{1}{\bar{\varepsilon}_f}\int_0^{\bar{\varepsilon}_f} \eta(\bar{\varepsilon})d\bar{\varepsilon} \tag{3}$$

1.2. Coffin–Manson relation

Coffin and Manson [17,18] proposed an empiric relation, which has been widely used for LCF, as follows:

$$\frac{\Delta\varepsilon^P}{2} = \varepsilon'_f(2N_f)^c \tag{4}$$

Eq. (4) is represented by a linear relation in a bi-logarithm diagram, where $\Delta\varepsilon^P/2$ and N_f are a uniaxial plastic strain amplitude and the number of cycles to failure, respectively; ε'_f is the fatigue ductility coefficient and c is the fatigue ductility exponent. Some authors [13,14,19] have shown that the Coffin–Manson relation does not give a satisfactory description of the ULCF regime, for many metals. They report a fatigue life over prediction when the Coffin–Manson relation is used in ULCF domain. The original Coffin–Manson relation was proposed for uniaxial stress–strain conditions, but its generalisation for multiaxial stress–strain conditions may be performed using an equivalent multiaxial strain definition. The Coffin–Manson model is assessed in the present research in order to verify its performance. Therefore, the experimental program includes two series of smooth specimens of S185 structural steel to be used in the identification of the Coffin–Manson constants, in the LCF region. Then, the model is used to predict ULCF results also generated in this paper.

1.3. Kanvinde–Deierlein model

Kanvinde and Deierlein proposed a model for ULCF based on micromechanical behaviour of voids in a plastic medium, which was a generalisation of a model for monotonic ductile damage [16]. Metallic materials contain voids in its microstructure, which may grow under the action of the plastic deformation. Race and Tracey [20] reported that, for a single spherical void in an infinite continuum, the void growth rate can be described as:

$$dR/R = C\exp(1.5\eta)d\varepsilon_P \tag{5}$$

where R is the average void radius, C is a material constant, η is the stress triaxiality (Eq. (2)) and $d\varepsilon_p = \sqrt{(2/3)d\varepsilon^p_{ij}d\varepsilon^p_{ij}}$ is the incremental equivalent plastic strain. Integrating Eq. (5) and normalising the void radius R with respect to the initial void radius R_0, the following expression is obtained: