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Validation on large scale tests of a new hardening–softening law for the Barcelona plastic damage model

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ABSTRACT

This paper presents the results of finite element simulations made on a bent pipe subjected to an in-plane variable cyclic displacement combined with internal pressure. Special emphasis is put on the capacity of the model to illustrate different failure modes depending on the internal pressure applied on the pipe. The results of the numerical analyses will be compared to experimental ones. The constitutive model used for the simulation of Ultra Low Cycle Fatigue (ULCF) loading and the hardening–softening law used are only briefly touched upon. The monotonic behavior of a large diameter pipe, as obtained from the constitutive model proposed, is also shown and compared to experimental results under two different loading conditions. The total axial load at failure for this case resulted in less than 10% error as compared to the experiments. Regarding the ULCF in-plane bending simulations conducted on a 16-in. 90° elbow, the results were in good agreement with the experimental test in terms of force–displacement hysteresis loops and total fatigue life of the specimen. An analysis of the dependence of the failure mode to the internal pressure applied has been conducted, showing that the formulation is capable of obtaining both habitual failure types.

1. Introduction

ULCF can occur in the metallic materials of modern steel devices that are designed to absorb seismic energy by sustaining large inelastic deformations under cyclic loads. Pipelines installed in seismic or permafrost regions must have sufficient strength against buckling or fracture caused by large ground deformation of buried pipeline.

ULCF can be defined as a failure that occurs at a relatively small number on the repeated stress or strain cycles. The upper limit in low-cycle life has generally been selected arbitrarily by different researchers to lie in the range of 10^4–10^5 cycles. On the other hand, the lower limit of life is the static test which has been represented by various investigators as 1/4, 1/2, 3/4 or even one cycle [1,2]. For ductile metals under periodic plastic loading, materials often fail within a reduced number of life cycles. Within this regime, the failure mechanism is governed by the plastic and damage (or sometimes called ductile damage), which is characterized by micro structure deterioration such as micro void nucleation, growth and coalescence and micro crack initiation and propagation [3]. So, this process is governed by void growth and coalescence-type mechanisms, which are associated, typically, with ductile fracture phenomenon driven by Bauschinger plasticity non-linear mechanical processes, depending of the plastic strain [4].

While previous studies (e.g., Kuwamura and Yamamoto [5]) have identified this issue, models and mechanisms to characterize ULCF are not well established. Prediction models for the cyclic life of materials are thus often based on the alternating plastic and damage strain amplitude. The most commonly used relationship between the alternating damage and plastic strain and the life cycles is the so-called uniaxial Manson–Coffin law [2,6], based on small uniaxial strains formulation. This law is essentially a two parameter power law curve and can be plotted in a log–log scale as a straight line where the slope of the curve depicts the exponent of the power law relationship.

The ULCF mechanical processes cannot be modelled using traditional fracture mechanics and fatigue models. Primarily, ULCF is often accompanied by large inelastic strain (damage and/or plasticity), which may invalidate stress intensity-based ΔK or ΔJ approaches [7]. Second, the induced loading histories are extremely random with very few cycles, making them difficult to adapt

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to conventional cycle counting techniques such as rain flow analysis [8,9] or strain life approaches. Finally, ΔK or ΔJ methods, require an initial sharp crack or flaw, which is absent in many structural details. These limitations, coupled with the large strain advanced finite-element formulation methods, create the need for an improved understanding of the underlying ULCF process and the development of models to predict it.

Since 1950s, numerous experimental programs have been carried out to calibrate the material constants for different steels and a large amount of information is available. The experimental data is usually plotted on a log–log scale with the abscissa the number of life cycles and the coordinate the plastic strain amplitude, which is known as the $\Delta\varepsilon^p - N$ curve. From the experimental results, it is observed that the Manson–Coffin law does not fit well in the range of very low life cycles, i.e. about less than 100 cycles [3].

In this context, a new model for fatigue damage and plasticity assessment under ULCF is presented. ULCF damage is bounded by monotonic ductile failure and low-cycle fatigue (LCF). Typically, models for ULCF are extensions of LCF models. However, it is recognized in the literature that LCF models are not fully adequate without any kind of correction.

Therefore, the proposal presented in Martinez et al. [10] and in the current paper presents a new focus for the ULCF modelling. The complete nonlinear constitutive model is an extension of a given plasticity model to incorporate the damage effects due to cyclic action. It is an energetic based approach that accounts for the energy dissipated during the plastic action and compares it with a fracture energy that has to be calibrated by experiments. This is a coupled approach where damage due to cyclic action impacts directly on the stress–strain response.

The present work is centered on the large scale validation of the nonlinear constitutive model for cyclic and monotonic loading conditions. The model is the well-known Barcelona plastic damage model, proposed by Lubliner et al. [11]. An innovative application is given to this formulation by considering it for the cyclic loading case and incorporating a Friederick-Armstrong kinematic hardening law that allows the description of phenomena like cyclic ratcheting (under stress control conditions) or cyclic stress relaxation (under strain control or elastically constrained conditions). A new isotropic hardening law is also developed especially for steel materials, designed to reproduce their hardening and softening performance under monotonic and cyclic loading conditions. The exact expression of the constitutive law and the thermodynamic formulation of the model are presented in Martinez et al. [10,12] and Barbu et al. [13].

In Sections 2 and 3 a summary of the new isotropic hardening law is presented with emphasis on small improvements made with respect to the expressions presented in Martinez et al. [10]. In Section 4 the complete calibration procedure on small scale samples is presented step by step. In Section 5 results are shown for straight pipes under monotonic combined loading: uniaxial displacement and internal pressure. Two different loading histories are taken into account that exhibit different failure modes. Section 6 illustrates the results made on a 16-in. 90° elbow subjected to a variable in-plane displacement and internal pressure. Finally, in Section 7 conclusions are drawn as to the large scale behavior obtained with the proposed nonlinear constitutive model.

2. ULCF constitutive model

This work will not describe the complete plastic damage model, as it can be obtained from [10,11].

The inelastic theory of plasticity can simulate the material behavior beyond the elastic range, taking into account the change in the strength of the material through the movement of the yield surface, isotropic and kinematic. It is assumed that each point of the solid follows a thermo-elasto-plastic constitutive law (stiffness hardening/softening) [11,14–16].

The yield surface is defined by a function F that accounts for the residual strength of the material, which depends on the current stress state, the temperature and the plastic internal variables. This F function has the following form, taking into account isotropic and kinematic plastic hardening (Bauschinger effect – Lemaitre and Chaboche [17]),

$$F(S_{ij}, \gamma^p, \theta) = f(S_{ij} - \alpha_{ij}) - K(S_{ij}, \kappa^p, \theta) \leqslant 0 \quad (1)$$

where $f(S_{ij} - \alpha_{ij})$ is the uniaxial equivalent stress functions depending of the current value of the stress tensor S_{ij}, α_{ij} is the kinematic hardening internal variable, $K(S_{ij}, \kappa^p, \theta)$ is the plastic strength threshold, κ^p is the plastic isotropic hardening internal variable, and θ is the temperature at current time t [10,11,14–16].

2.1. Kinematic hardening

Kinematic hardening accounts for a translation of the yield function and allows the representation of the Bauschinger effect in the case of cyclic loading.

This translation is driven by the kinematic hardening internal variable α_{ij} which, in a general case, varies proportionally to the plastic strain of the material point [17]. There are several laws that define the evolution of this parameter. Current work uses a non-linear kinematic hardening law, which can be written as:

$$\dot{\alpha}_{ij} = c_k \dot{E}^p_{ij} - d_k \alpha_{ij} \dot{p} \quad (2)$$

where c_k and d_k are material constants, $\dot{E}^p_{ij}$ is the plastic strain increment, and $\dot{p}$ is the increment of accumulative plastic strain, which can be computed as: $\dot{p} = \sqrt{2/3 \cdot \dot{E}^p_{ij} : \dot{E}^p_{kl}}$.

2.2. Isotropic hardening

Isotropic hardening provides an expansion or a contraction of the yield surface. The expansion corresponds to hardening and the contraction to a softening behavior.

The evolution of isotropic hardening is controlled by the evolution of the plastic hardening function K, which is often defined by an internal variable κ^p. The rate equation for these two functions may be defined, respectively:

$$\begin{aligned} \dot{K} &= \dot{\lambda} \cdot H_k = h_k \cdot \dot{\kappa}^p \\ \dot{\kappa}^p &= \dot{\lambda} \cdot H_{\mathbf{k}} = \dot{\lambda} \cdot \left[h_{\mathbf{k}} : \frac{\partial G}{\partial S} \right] = h_{\mathbf{k}} \cdot \dot{E}^p \end{aligned} \quad (3)$$

where k denotes scalar and $\mathbf{k}$ states for a tensor function. Depending on the functions defined to characterize these two parameters different solid performances can be obtained.

3. New isotropic hardening law

In the Barcelona model defined in Lubliner et al. [11], the laws defined are driven by the fracture energy of the material. This work presents a new law, especially developed for steel materials, that has been designed to reproduce their hardening and softening performance under monotonic and cyclic loading conditions. This law also depends on the fracture energy of the material and is derived from the hardening softening law presented in [11,12].