International Journal of Fatigue 75 (2015) 198–204

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

Fatigue behaviour prediction of steel reinforcement bars using an adapted Navarro and De Los Rios model

Marina Rocha [a,*], Eugen Brühwiler [a], Alain Nussbaumer [b]

[a] Structural Maintenance and Safety Laboratory (MCS), École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
[b] Steel Structures Laboratory (ICOM), École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

ARTICLE INFO

Article history:
Received 3 September 2014
Received in revised form 22 January 2015
Accepted 26 January 2015
Available online 20 February 2015

Keywords:
Steel reinforcement bars
Crack growth model
Surface conditions
Scatter
Fatigue behaviour prediction

ABSTRACT

Fatigue cracks tend to initiate on the rebar surface and therefore, the surface conditions may control their fatigue behaviour. This study investigates the influence of surface microstructure and roughness dispersion on the scatter and fatigue life of hot rolled (HR)–cold worked (CW) and quenched and self-tempered (QST) rebars. The stochastic nature of the fatigue life is mainly affected by the scatter of short cracks in the crack initiation phase. A model adapted from Navarro and De Los Rios (N–R) was developed to predict the crack initiation, including short crack growth, and long crack propagation phases. The crack initiation phase includes the dispersion inherent to the grain size, grain orientation ratio and multiple phases i.e., ferrite–pearlite and martensite as well as the roughness dispersion determined on the rebar surface and the influence of the rib geometry. The stress concentration factor due to the rib geometry was considered as a constant parameter. In the long crack propagation phase, all microstructural features are considered as constants. The model results were compared to experimental data from the literature.

1. Introduction

Fatigue life of structural metallic components until failure can be split into initiation and propagation periods. Initiation is generally defined as the smallest crack that can be detected by non-destructive inspection technique. Propagation follows and in a cracked component, Paris' law [1] is usually applied for fatigue life assessment describing the growth rate from the detected initial-crack. In reinforced concrete elements, where crack detection is impracticable on the embedded steel reinforcement bars (rebars), S–N curve-method is used for fatigue life prediction. However, this method does not provide any information on the presence, or not, of fatigue cracks. Paris' law is only applied when a more detailed investigation is required with a long or conservative initial crack size being assumed in the calculations.

Fatigue strength of metallic materials may be controlled by the short crack growth behaviour as a consequence of the strength offered by the barriers, such as grain-phase boundaries, to the plastic slip. Short cracks can behave significantly different from long cracks predicted by Paris' law [2]. These cracks may propagate during a large fraction of the component life and therefore, Paris' law would fail to predict their fatigue life.

Fatigue cracks tend to initiate at stress raisers on the material surface. As a consequence, the conditions of the surface layer such as roughness and geometrical features is significant for the fatigue behaviour of the material. These stress raisers are introduced in the fabrication process and they can be, in some cases, essential to a component in performing its function.

Surface conditions affect primarily the crack initiation period, especially near the fatigue limit. Initiation, in this case, includes crack nucleation and short crack growth controlled by material barriers. Nucleation can be dependent on local surface irregularities which vary from specimen to specimen and can affect the duration of the crack initiation period. As a consequence, more scatter is found at high number of stress cycles [3].

The stress concentration on a surface irregularity (notch) is usually quantified in terms of stress concentration factor *K*. As *K* increases, the stress required to initiate a crack at the notch decreases. It has been observed that the short crack growth rate at the notch root of steels, for example, can increase with the increase of *K* values although these cracks can arrest or become non-propagating at the notch root after overcoming few barriers [4,5]. This suggests that the initiation of the crack itself is not the key point in the fatigue behaviour of notched steels but rather the capacity of the (short) crack to propagate over successive microstructural barriers.

* Corresponding author.
E-mail address: marina.rocha@alumni.epfl.ch (M. Rocha).

http://dx.doi.org/10.1016/j.ijfatigue.2015.01.015

In this study, the fatigue behaviour of hot rolled (HR), cold worked (CW) and quenched and self-tempered (QST) rebars is investigated using an adapted Navarro and De Los Rios (N-R) model described in [3]. The model includes the influence of surface microstructure i.e., grain size, grain orientation ratio and ferrite–pearlite and martensite as well as the K dispersion obtained from surface roughness analysis in the crack initiation phase. The K value determined for the rib geometry at the critical zone i.e., from where fatigue cracks usually initiate, is considered as a constant. The microstructural features are considered as constants in the long crack propagation phase. The results are compared to experimental data for HR–CW and QST rebars.

2. Crack growth model

The algorithm used in this work is adapted from the N–R model described in [3] for plain specimens and represented in Fig. 1. The present model includes the roughness dispersion determined on the rebar surface as well as the long crack propagation phase to the N–R model [3] to investigate the fatigue behaviour of HR–CW and QST rebars.

As shown in Fig. 1, the crack initiation phase consists of a stochastic process which includes the dispersion inherent to:

- Grain size variation;
- grain orientation ratio (for randomly oriented grains);
- different phases (ferrite–pearlite and martensite);
- stress concentration factors determined from surface roughness analysis.

The microstructural properties i.e., grain size, grain orientation ratio and multiple phases were computed from the same algorithm given in [3].

In the long crack propagation phase, there is no dispersion of the microstructural features and therefore, it is assumed equal grain sizes and consequently equal increments of the plastic zone. The plastic zone size is negligible compared to the crack size.

2.1. Threshold for short crack growth

The short crack growth model for plain specimens [3] defines the condition to activate a plastic slip in terms of applied stress level and crack size; short cracks are unable to overcome microstructural barriers, such as grain-phase boundaries, at stress levels below the fatigue limit $\Delta\tau_{FL}$. This interpretation is in agreement to what has been observed by [4,6].

The applied stress $\Delta\tau_{Li}$ required to propagate a short crack over i grains is given by [3]:

$$\Delta\tau_{Li} = \Delta\tau_{FL}\frac{m_i}{m_1}\sqrt{\frac{d_i}{2c_i}} \tag{1}$$

where $\Delta\tau_{FL}$ is the fatigue limit of the plain specimen, d_i is the mean of the crack length in each grain, c_i is the position of the plastic zone and m_i/m_1 is the grain orientation ratio.

When irregularities (notches) are present on the specimen surface, the crack and its plastic zone growth are controlled by the resistance offered by the grain boundary as it occurs in plain specimens. However, the main difference in the short crack growth behaviour between plain and notched cases is the stress gradient related to the notch: the driving stress can vary significantly as the crack confronts each grain boundary. Depending on the applied stress level and the severity of the stress gradient, a short crack may grow over few grains and then stop as the stress level decreases. The crack propagates to the next grain only if the plastic slip is activated beyond the grain boundary.

The applied stress $\Delta\tau_{Li}^{notch}$ required for the crack to overcome the i-th barrier in a notched specimen is given as [7]:

$$\Delta\tau_{Li}^{notch} = \Delta\tau_{Li}K_f \tag{2}$$

where K_f is the fatigue stress concentration factor. K_f values determined from surface roughness analysis on QST rebar is discussed in Section 3.2.

2.2. f Function

The crack propagation rate da/dN in the N–R model depends on the f function and it is given by:

$$\frac{da}{dN} = f\phi \tag{3}$$

where f represents the fraction of dislocations ahead of the crack tip that contributes to the crack growth process. N is the number of cycles and ϕ is the crack tip plastic displacement. Since f varies as a function of the applied stress (it decreases as the applied stress level decreases) and the fatigue behaviour of rebars in this work is analysed at different stress levels, f functions were then proposed for ferrite, pearlite and martensite depending on the applied stress.

In the N–R model, f is constant at each stress level and is always obtained experimentally. In this work, three equations for the different phases were deduced on the experimental data with low Carbon steel under uniaxial loading as given in [8]. Depending on the fatigue limit of each phase, it was then assumed the same growth rate as found in the literature.

f Functions determined for ferrite, pearlite and martensite are given in Eqs. (4)–(6) respectively:

$$f = 4.89\times10^{-16}\Delta\tau^{5.49} \tag{4}$$

$$f = 1.93\times10^{-20}\Delta\tau^{7.03} \tag{5}$$

$$f = 8.30\times10^{-20}\Delta\tau^{6.81} \tag{6}$$

3. Surface roughness dispersion

Surface roughness is usually associated with the geometric topography of material surface. It depends greatly on the production technique where each fabrication process generates its own characteristic surface. Surface roughness manifests as a sequence of micronotches from where slip bands can emerge. The stress concentration arising from these micronotches may accelerate the fatigue crack nucleation and lead to early short crack growth. The surface roughness of rebars is affected by the introduction of the ribs during the fabrication process; the micronotches are on the free surface and mainly concentrated near the ribs (see Fig. 2).

3.1. 3D surface roughness profile

A photometric stereo technique applied to XL30-FEG Scanning Electron Microscopy (SEM) was used to reconstruct the 3D surface roughness profile of the QST rebar with diameter of 16 mm. An area of 1500×1500 μm, close to a transversal rib, was considered in the analysis. Four images were captured from the same area. The 3D surface reconstruction was then obtained by post-processing of all images based on photometric stereo technique. Fig. 3 shows the 3D surface roughness profile reconstructed by photometric stereo technique using SEM images.

The effect of the surface roughness on the fatigue strength of rebars can be obtained as a function of R_a, R_y and R_z parameters. They were obtained from the roughness profile height distribution (z) recorded over a length (L) and calculated as [9]: