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Microstructural length scale parameters to model the high-cycle fatigue behaviour of notched plain concrete

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ABSTRACT

The present paper investigates the importance and relevance of using microstructural length scale parameters in estimating the high-cycle fatigue strength of notched plain concrete. In particular, the accuracy and reliability of the Theory of Critical Distances and Gradient Elasticity are checked against a number of experimental results generated by testing, under cyclic bending, square section beams of plain concrete containing stress concentrators of different sharpness. The common feature of these two modelling approaches is that the required effective stress is calculated by using a length scale which depends on the microstructural material morphology. The performed validation exercise demonstrates that microstructural length scale parameters are successful in modelling the behaviour of notched plain concrete in the high-cycle fatigue regime.

1. Introduction

As reported by the World Business Council for Sustainable Development (http://www.wbcsd.org), concrete is the most widely used structural material. Consequently, the continuous development of the civil infrastructure sector requires the production of about 2.35 billion tons of concrete per year. From a green-design point of view, one of the most urgent issues to be addressed is the improvement of the in-service performance of concrete structures by simultaneously reducing the production, maintenance and energy costs, as well as a reduction of carbon emissions. In this setting, performing the static assessment of concrete structures has been investigated for decades by the international scientific community, and concrete structures nowadays can efficiently be designed against static loading by adopting relatively low safety factors. This results in slender structures, allowing a markedly reduced usage of natural resources with positive effects on sustainability and carbon emissions.

However, a decrease in the size of concrete structural components leads to an inevitable increase of the magnitude of in-service local stresses, making concrete structures more susceptible to fatigue. As far as both plain and short-fibre/particle reinforced concretes are concerned, in a recent investigation [1] it has been proven that, when the design is performed by using safety factors lower than 2.5, the presence of time-variable loading can no longer be ignored. This aspect is important because several key concrete structures undergo in-service time-variable loading, such as, for instance, runways subjected to repeated loads due to passing aircrafts, asphalt concretes subjected to cyclic local pressures due to the action of tyres, bridges fatigued by travelling vehicles, and concrete foundations of wind turbines. Further, in 2012 a British working group [2] operating under the auspices of both the Department of Energy and Climate Change and the Office for Nuclear Development has explicitly indicated fatigue as one of the key structural issues to be addressed when designing concrete structures for the nuclear sector. In this scenario, properly performing the fatigue assessment of concrete infrastructures is complicated by the fact that their structural parts experience stress/strain concentration phenomena due to local geometrical features (here termed "notches").

To rationalise the usage of natural resources and minimise carbon emissions, structural engineers will increasingly be requested to design structural components by using the least amount of material needed to reach an adequate level of safety. This would result in the design of concrete structural parts/details having complex shape, with such geometrical features inevitably causing localised stress/strain concentration phenomena. These considerations clearly indicate that fatigue of notched concrete is a research area which is expected to become more and more important in the near future. However, examination of the state-of-the-art suggests that, apart from three isolated investigations [3–5], the problem of

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Nomenclature

d	specimen depth
f_T, f_C, f_B	static strength determined under tension, compression and bending
k	S–N curve's negative inverse slope
ℓ	intrinsic material length scale determined according to GM
r_n	notch root radius
t	time
w	specimen width
K_t	net stress concentration factor
K, δ	constants in Dixon's equation
L	intrinsic material length scale determined according to TCD
$M(t)$	cyclic bending moment
N_f	number of cycles to failure
N_0	reference number of cycles to failure
Oxyz	system of coordinates
$P(t)$	cyclic axial force
P_S	probability of survival
R	load ratio ($R = \sigma_{min}/\sigma_{max}$)
T_σ	scatter ratio of the endurance limit for 90% and 10% probabilities of survival.
θ, r	polar coordinates
$\sigma_{0,MAX}$	maximum value of the un-notched endurance limit
σ_1	local maximum principal stress
$\sigma_{1,max}$	maximum value of local stress component σ_1
σ_a	stress amplitude
σ_{Design}	design stress
$\sigma_{eff,max}$	maximum value of the effective stress
$\sigma_{GE0,max}$	maximum value of the endurance limit determined via GE
σ_{LT}	stress level characterising the last test run according to Dixon's method
σ_m	mean stress
σ_{max}	maximum stress
σ_{MAX}	maximum value of the endurance limit for $\sigma_{max} > 0$
$\lvert\sigma_{MIN}\rvert$	absolute minimum value of the endurance limit for $\sigma_{max} \leqslant 0$
σ_{min}	minimum stress
σ_S	reference static strength
σ_y	local stress parallel to axis y
$\sigma_{y,max}$	maximum value of stress component σ_y
ΔK_{th}	threshold value of the stress intensity factor range
$\Delta\sigma_1$	range of the maximum principal stress
$\Delta\sigma_{eff}$	range of the effective stress
$\Delta\sigma_y$	range of stress component σ_y
$\Delta\sigma_0$	range of the un-notched endurance limit

assessing notched concretes against fatigue has not been studied systematically before.

As far as un-cracked/un-notched concrete structures are concerned, since the early 1900s [6,7] the international scientific community has investigated the fatigue behaviour of plain concrete mainly from an experimental point of view (see Ref. [1] for an up-to-date summary of the data available in the technical literature). Unfortunately, in spite of such a large body of experimental work, no universally accepted design technique yet exists. Perhaps, slightly crudely, it can be said that the experimental work carried out so far has resulted in S–N curves which can be used to design against fatigue solely for those specific concretes that were tested.

In plain concrete cracks can typically initiate in the cement paste, inside the aggregates, or at the interface between matrix and aggregates [8,9]. The last cracking mechanism is seen to be the prevailing one in case of fatigue; consequently, fatigue cracks originate as a result of a progressive deterioration of the bonds under local tensile/shear cyclic stresses and strains [10]. According to this fatigue damage model, aggregates play the role of hard inclusions causing localised stress/strain concentration phenomena. These considerations suggest that the material microstructural features play a primary role in defining the overall fatigue strength of plain concrete. When using continuum mechanics theories to predict the fatigue behaviour of concrete structures or components, it is therefore important that such micro-structural features are taken into account properly. In this complex scenario, the aim of the present paper is to investigate the applicability and accuracy of two continuum mechanics theories that make use of a microstructural length scale parameter – i.e., the Theory of Critical Distances (TCD) and Gradient Elasticity (GE) – in modelling the high-cycle fatigue behaviour of notched plain concrete.

2. Preliminary definitions and assumptions

The fatigue strength of plain concrete is seen to depend on several variables which include: surface roughness, extreme environmental conditions, temperature, type of loading, load history's degree of multiaxiality, water-to-cement ratio, ageing, and presence of shrinkage stresses.

Given the material and the environmental conditions, from a design point of view, the overall fatigue strength of a concrete structure is strongly affected also by the presence of non-zero mean stresses [1]. This implies that the stress quantities to be used to apply both the TCD and GE must be defined so that the mean stress effect in concrete fatigue is taken into account effectively.

To determine the stress quantities of interest, it is important to point out from the start that, in the present study, tensile stresses are taken as positive and compressive stresses as negative.

Consider the beam sketched in Fig. 1 which is hypothesised to be damaged either by a cyclic bending moment $M(t)$ (Fig. 1a) or by a cyclic axial force $P(t)$ (Fig. 1b), t being time. Point O is the location where a fatigue crack is expected to initiate, so that this material point is used also to define a convenient system of coordinates (see Fig. 1a and b). Time-variable force $P(t)$ and bending moment $M(t)$ result in a local stress at point O that varies cyclically as shown in the σ_y vs. t charts reported in Fig. 1c and d, respectively. As soon as the amplitude, σ_a, the mean value, σ_m, the maximum stress, σ_{max}, and the minimum stress, σ_{min}, characterising the loading cycle are known (see Fig. 1c and d), the corresponding load ratio, R, can directly be defined as follows [11]:

$$R = \frac{\sigma_m - \sigma_a}{\sigma_m + \sigma_a} = \frac{\sigma_{min}}{\sigma_{max}} \quad (1)$$

Definition (1) suggests that, as long as the maximum stress is positive (Fig. 1c), the load ratio takes on a value which is always lower than unity, a negative minimum stress resulting in a negative value for R. On the contrary, when the concrete component being assessed is subjected to cyclic compression (Fig. 1d), R takes on a value which is always larger than unity, R diverging to infinity as σ_{max} approaches zero.

By reanalysing about 1500 experimental results taken from the literature and generated by testing both plain and short-fibre/particle reinforced concretes [1], it has been proven that the mean