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Low-cycle compression fatigue of reinforced concrete structures

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Abstract

Paper reports on experiments performed in the low-cycle compression fatigue domain, considering two relatively high upper load levels and several lower ones. Two frequency levels were emphasized, i.e. 17.5 Hz and 0.175 Hz. An overview is given of characteristics of mechanical behaviour and of the state of damage close to fracture. Particular attention is given to the larger amplitude case of 17.5 Hz because of an order of magnitude drop in the number of cycles to fracture. The normal process of damage evolution is sketched as well as the process for this specific case, where damage evolution due to stress release is initiating premature fracture. Underlying mechanisms are outlined.

Keywords: Concrete, crack mechanisms, damage evolution, amplitude, frequency, low-cycle fatigue.

1. Introduction

Design of reinforced concrete (RC) structures is governed by load-bearing capacity. Moreover, RC structures subjected to high frequency repeated loadings are designed for fatigue. However, a wide range of structures is subjected to repeated loadings of lower frequencies. High rise buildings are subjected to wind loading, and bridges to repeated traffic loading. Coastal and off-shore structures have to withstand loads by waves and streaming water. These loading situations can be derived from relevant observations on real structures or experiments in laboratory. More complicated situations arise due to variations in temperature and humidity. The resulting fluctuating stresses can reach ultimate values.

Hence, this paper focuses on a certain range of frequencies in the low-cycle compression fatigue domain. Initially, this was considered relevant for application of RC structures in the off shore field. However, indirect stress states due to fluctuations in temperature and humidity are basically also covered. As to the off-shore structures, projected life span was relative short, so usage of higher stress levels was considered for design. Experiments above the endurance limit should provide evidence whether normal fatigue concepts for the high frequency domain were...
also applicable in the low frequency domain. Only scare evidence is available up till now such as in [1].

Load amplitude and frequency were the major parameters in the experimental program. Additionally, the state of internal damage shortly before final fracture was assessed by quantitative image analysis. It is already recognized for long times that below the endurance limit no differences in micro-cracking occurs as compared to the traditional short term monotonically increasing compressive strength test [2-5]. In other approaches [6,7], an observation sensitivity was used significantly lower than in the present case. So, their observations can hardly be used as a reference, seeing fractal nature of cracking.

Damage evolution in the aforementioned traditional compressive strength test has been thoroughly investigated. Most interesting in the present context is the formation of “fracture elements” consisting of aggregate particles provided with conical mortar deposits on top and bottom parts (so, in the loading direction). They have been independently found by various authors [8-10]. These elements are the result of the formation of “en echelon” tensile crack arrays at the surface of the tri-axially compressed matrix material in these conical regions. These pre-weakened zones thereupon undergo slip. These elements will be shown forming the key to explaining differences in mechanical behaviour under low-cycle fatigue loading above the endurance limit. So, fracture behaviour can be correlated qualitatively to damage evolution characteristics. On the basis of such observations, fracture mechanisms are proposed that underlie low cycle fatigue behaviour in different low-cycle frequency-amplitude domains. On some aspects of the experiments we have been reporting earlier. The interested reader is referred to these publications for further details [11-13].

2. Experimental

Two levels of upper loading were selected, i.e. 85% and 87.5% of 28-day’s short term prismatic compressive strength. Lower strength levels were emphasized in the range between 85% and 40% of the same compressive strength. Sinusoidal loads with constant amplitude, but with frequencies of 17.5 Hz and 0.175 Hz were applied. In what follows, we will successively refer to these “high” and “low” frequency cases. Constant loading situations were additionally investigated for comparison reasons at both upper loading levels.

A servo-hydraulic testing machine was employed for subjecting prismatic concrete specimens of 100x100x345 mm³ to the required low-cycle compression fatigue loading. Tests were automatically terminated when transverse strain rate, \( \dot{\varepsilon}_t \) (increase in transverse strain, \( \varepsilon_t \), as a function of the number of load cycles, \( N \)) exceeded a limiting value [13]. From these tests, specimens were selected that revealed mechanical characteristics as close as possible to average behaviour. These were the ones subjected to quantitative image analysis operations. To do so, the specimens were serially sectioned in longitudinal direction after termination of the mechanical tests. A single internal surface of all 4 slices was sprayed with fluorescent oil [10,14,15], so that cracks became observable under illumination by UV light. 2D and 3D damage characteristics were thereupon determined from these images by directed secants approach, and results were averaged over the 4 images of the same specimen.

Deformations were measured in longitudinal and transverse direction by strain gauges mounted at mid-sections on two opposite surfaces of the prisms. Length of strain gauges was 80 mm in longitudinal direction and 75 mm in transverse one, i.e., about 10 times maximum grain size. Strains were continuously recorded during testing, which rendered possible plotting maximum and average values, reflecting complete deformation history of all specimens.

3. Materials

Concrete was designed with 8 mm maximum grain size and 360 kg/m³ Portland cement to yield for a water to cement ratio of 0.46 a standard compressive strength value of 53 N/mm². Overall compressive strength level for 12 production days of 6 specimens per day amounted to 56.2 N/mm² (coefficient of variation being 3%). Sieve curve was in between A₈ and B₈ of former DIN 1045.

Specimens were in vertical position casted and compacted by vibration in the traditional way on the laboratory vibration table. They were de-moulded after 1 day, and stored for 10 days submerged in water, thereupon for 7 days under controlled conditions of temperature (22°C) and humidity (50% RH), and finally during the last period under laboratory conditions. Specimens subjected to a particular combination of amplitude and frequency values all came from the same batch. The top and bottom surfaces were made plan parallel before testing.
4. Damage analysis

Photographs under UV light were made of the 51x102 mm$^2$ central area of the sprayed surfaces, which revealed the damage pattern shortly before ultimate fracture. Slides of the damage pattern were projected on a screen at about 5x magnification. All cracks exceeding 1mm in length were copied on transparent paper. This governs the microscopic level taken into consideration, seeing the fractal nature of cracking. A step-wise rotating lineal grid was superimposed on the images and the number of intersections was determined as a function of the orientation angle of the lineal grid, $\theta$. Total line length of the grid was 1734 mm. Data obtained by an automatic image analyser on a centrally located area of 40x40 mm$^2$ were compared with manually obtained data on the larger area. Although this is not the very topic of this paper, it is worth mentioning that orientation distribution of cracks and data on crack extent in 2D and 3D derived from such data are biased when based on digitized images [16,17]. This does not affect the conclusions on crack mechanisms drawn from the experimental program.

From the image analysis approach we have obtained information on $L_A$ and $S_V$ (crack length per unit of area, and crack surface area per unit of volume, respectively), $\omega_2$ and $\omega_3$ (degree of crack orientation in 2D and 3D, respectively), and $N_d$ (number of cracks per unit of area). For the stereological relationships, see the relevant literature [14-16]. The ratio of $L_A$ over $N_d$ provided average crack length ($\bar{x}$), assuming an exponential distribution of crack length. The automatic image analyser also the probability density function of crack length, supporting this assumption.

5. Results on fracture behaviour

5.1. General performance

Transverse strains properly reflect general behaviour, since axial cracking is the dominant feature at increasing $N$. Alternatively, Poisson’s ratio $\nu$ and volumetric strain $e$ can be used for that purpose. They all reveal an initial stage governed by lateral strains that increase disproportionally but to a diminishing degree. Thereupon, lateral strains increase proportionally with $N$, up to the fracture stage when lateral strains start increasing faster and faster until strain rate exceeds the aforementioned value and the test is terminated. Roughly, initial and fracture stages are similar in the constant frequency cases. So, the extent of the linear portion depends on the number of cycles to fracture, $N_f$. Curves of $\nu$-$N$ and $e$-$N$ reveal similar features. Longitudinal strains at fracture were proportional to $S$, in conformity with earlier results of Awad & Hilsdorf [18], whereby $S$ stands for twice the amplitude normalized by the short term compressive strength value.

5.2. Influence of upper load level and amplitude.

For both upper loading cases, an S-shaped curve was obtained in the high frequency case for amplitude versus number of cycles to fracture, as earlier reported in the literature. The highest amplitude case resulted in an optimum number of cycles to fracture at a lower loading of about 80% of ultimate short term compressive strength. This optimum value declined for the lower upper loading case to about 70%. For load levels below about 50% of ultimate short term compressive strength, the cycles to fracture did not decline further.

5.3. Influence of frequency

For the lower frequency case, the number of cycles to fracture was significantly lower; distance between both curves at minimum amplitude is about 100 cycles, whereas this is at maximum amplitude about 10 cycles. Thus, time to fracture is similar for the two frequency cases at minimum amplitude; however, the life span difference between the two frequency cases amounts to a factor of 10 at highest amplitude. So, larger amplitudes in the high frequency case lead to a dramatic reduction in the number of cycles to fracture. Amplitude influence on $N_f$ was found considerable smaller in the low frequency case.
6. Results on damage near fracture

This report on damage characteristics focuses on the high frequency case because of the dramatic influence of amplitude on time (and cycles) to fracture.

6.1. Crack orientation distribution.

Fig. 1 presents the roses of the number of intersections for minimum and maximum amplitude cases. Because of the high-sensitivity approach, the contribution of the random crack portion exceeds that of the linear one considerably [13,19]. Nevertheless, the rose for $S=0$ reveals more cracks in the loading direction, whereas the rose for $S=0.35$ is showing apart from more intensive cracking also a prevailing direction perpendicular to the loading direction! Specifically, for $S=0$ the partially linear system is characterized by portions in intersection counts: $P(\alpha), = 456$ and $P(\alpha), = 48$, so that $P(\alpha) = P(\alpha), + P(\alpha), = 456 + 48 \sin \alpha$ defines the rose of intersections. For the high amplitude case $S=0.35$: $P(\alpha), = 572$ and $P(\alpha), = 26$, so that orientation distribution is governed by $P(\alpha) = 572 + 26 \cos \alpha$. The orientation angle $\theta$ of the lineal grid and $\alpha$ of the rose are complementary, so that $\alpha + \theta = \pi / 2$. But what is of crucial importance is that prevailing direction of cracking in the high amplitude case is perpendicular to that in the low amplitude case, where this is in the compressive loading direction. Cracking perpendicular to low-cycle compressive loading regime has been recorded already long ago [20].

![Fig. 1. Orientation distribution of the number of intersections $P(\theta)$ between lineal grid and cracks for cases $S=0$ and $S=0.35$.](image)

6.2. Crack extension

By stereological expressions, the orthogonal values of intersection counts were transformed into $L_A$ and $S_Y$ values, of which major results are collected in Table 1. Further, probability density functions revealed an exponential shape of the curves. Initially, upon increase of $S$, the number of small cracks was found reduced at $S=0.075$ (case of $N_{\text{max}}$), however at further increase of $S$ finally strongly increased at $S=0.35$. So, the high amplitude loading in the 17.5 Hz frequency case showed significantly deviating behaviour with all other loading situations, also involving the low frequency case. Specifically, compared to the low amplitude results ($S=0.075$), the number of cycles to fracture declined by one order of magnitude. Despite shorter life time, the material was more intensively

| $S$ | $L_A$ (m/m²) | $\omega_2$ (%) | $S_Y$ (m²/m³) | $\omega_3$ (%) | $N_{\text{max}}$ | $\overline{x}$ (mm) | $\hat{x}$ (mm) | $N_{f} 10^3$ | $\varepsilon_{\text{ul}}$ (%) | $\varepsilon_{\text{ut}}$ (%) |
|-----|--------------|----------------|---------------|----------------|------------------|-------------------|---------------|----------------|-----------------|----------------|
| 0   | 440          | 6              | 561           | 8              | 0.21             | 2.6               | 19.5          | 42.8           | 3.9             | 3.0             |
| 0.075 | 472          | 9              | 601           | 11             | 0.17             | 3.0               | 22.3          | 136.3          | 3.5             | 3.6             |
| 0.35 | 532          | -3             | 678           | -3             | 0.26             | 2.7               | 20.4          | 4.6            | 2.4             | 1.7             |
damaged at $S=0.35$, disproportionately by a large number of small cracks that revealed a preferred orientation perpendicular to the loading direction. Fracture occurred under smaller deformations in longitudinal ($\varepsilon_{ul}$) as well as in transverse direction ($\varepsilon_{ut}$).

### 7. Fracture mechanisms

Damage evolution under monotonically increasing compressive stresses in short-term tests has been extensively described in the literature. The discontinuity point (or elastic limit) can be associated with the slip along the “en échelon” crack arrays because this causes a disproportional increase in transverse deformations. Crack coalescence, predominantly in the loading direction bridges through the matrix these “fracture elements” in statu nascendi. Larger cracks are formed that upon further coalescence will finally de-compartmentalise the specimen in a column-like structure, whereby the columns on average have linear dimensions of about maximum grain size [21]. This only occurs when shear stresses at the stress initiation sites will be eliminated. Otherwise, the well-known hourglass type of fracture will develop.

This established damage evolution process is stimulated by low-cycle fatigue stress fluctuations. However, stress amplitudes whereby upper loading level significantly exceeds the discontinuity stage and the lower level is below discontinuity may lead to additional damage evolution due to stress release. This was obviously the case under stress fluctuations of 17.5 Hz and maximum stress amplitude ($S=0.35$). Under stress release the material tries to recover the situation before slip. However, reversed slip along the rough slip path is impossible in the given short period of time. Instead, axially oriented tensile stresses are introduced in the “fracture elements”, which will lead at the weakest location, i.e. the interface between aggregate grain and matrix, to de-bonding. The small cracks perpendicular to the loading are created in this way. They cause a premature collapse of the column-like structure. The local stress path pertaining to the point A at the interface is sketched in Fig. 2. Intersection with the limit state for cracking is likely to occur under stress release.

### 8. Conclusions

Amplitude was found having only minor influence on life span of concrete at lower frequencies (here: 0.175 Hz) in the low-cycle fatigue domain. At higher frequencies, small amplitude loading leads to an increase in life span as compared to permanent loading under the upper load level. This can be attributed to a reduction in average loading. Using the upper load level in design would be a safe approach. Life span of the concrete drops by an order of magnitude, however, at higher frequencies (here: 17.5 Hz) and larger amplitudes. In that situation, damage evolution during stress release triggers the collapse of the column-like load-bearing structure, which normally develops under higher compressive monotonically increasing loadings.

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Fig. 2. (left) En échelon crack array at top of aggregate grain; (center) “fracture element”; (right) stress path in point A at particle-matrix interface of bonded conical hats in 3D limit state for cracking; I: monotonically increasing tri-axial compressive state; II: slip along en échelon crack arrays during increasing loading leads to partial stress release in $A$; III: unloading leads to monotonically declining tri-axial stresses until intersection with the limit state causes de-bonding at the interface due to state of tension and biaxial compression.
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