Two parameters analysis of post-peak dynamic behaviour of high performance concrete

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Abstract

As well known the seismic performance of reinforced concrete structures is strongly influenced by structural design and by dynamic behaviour of the adopted construction materials. In particular in reinforced concrete frames the contribution of concrete matrix to dissipative phenomena during oligo-cyclic loading, such as seismic events, may play a very important role in the case of steel fibre reinforcement. On the other hand the dynamic properties of steel fibre reinforced concrete (SFRC) are influenced by concrete matrix and by type, geometry and content of fibres.

In this work by means of direct and cyclic tensile tests on notched cylindrical specimens is shown the essential contribution of high performance cementitious matrix to post-peak behaviour of steel fibre reinforced concrete.

The results have shown that the fatigue life of SFRCs is controlled by two fundamental parameters:
- the crack growth rate under cyclic loading;
- the ductility of SFRC.

The first one is essentially governed by steel fibre adherence to concrete matrix, while the second one to steel fibre reinforcement (type, geometry and content of fibres).

The analysis of these two parameters may allow to design a high performance SFRC with enhanced fatigue life taking into account the role of steel fibre-cementitious matrix interface on crack growth rate of SFRCs.

Very high performance cementitious materials specifically designed in terms of tensile strengths and interfacial properties (fibre matrix) have revealed a very high lifetime at high tensile stresses as compared with that of ordinary cementitious materials, even if they are steel fibre reinforced.
1 Introduction

The widespread utilisation of high strength concrete (HSC) in very important civil engineering works, such as bridges and offshore structures, has allowed the reduction of self weight of the structures, increasing their structural efficiency. As a consequence this has emphasised the structural effects of dynamic loads variability; for this reason the interest in the fatigue behaviour of concrete has been renewed.

Cracks or microcracks are often present in concrete structural elements due to drying shrinkage or thermal gradients, then the correct design of structural elements subjected to variable service loads may needs of a preliminary investigation on the cracking behaviour under variable service loads. In the case of high-cycle fatigue in compression the cracking phenomena mainly concerns the matrix-aggregate interface. Low-cycle fatigue in compression, that involves few load cycles \((=10^3 \div 10^4)\) with high stresses (similar to those induced by earthquakes), causes microcracks in the matrix aggregate interface and additional crack widening in the matrix itself.

In presence of cyclic tensile stresses concrete damage mainly occurs in the microcracked zone around the crack tip (Fracture Process Zone FPZ) (Figure 1).

[Figure 1: Stress distribution along fracture process zone of notched concrete specimens under cyclic loading.]

As a consequence the behaviour of concrete structural elements subjected to low-cycle fatigue in tension or bending can be correctly assessed only if the presence of FPZ is taken into account (Slowik et al. [1]).

At present a considerable extent of experimental data resulting from uncracked (even if notched) specimens are available (Bazant [2], Carpinteri et al. [3], Bazant et al. [4]) but they mostly provide information on the overall behaviour of concrete in tension and does not simulate the damage in a real structure where cracks are already present before the occurrence of loading.

A better evaluation of the maximum number of cycles up to failure was obtained from the slope of the linear branch of the cyclic creep curve (Cornelissen et al. [5]) which takes into account the previous loading history and the actual damage in the FPZ. Since the low-cycle fatigue is mostly governed by
cracking-related phenomena, the fibre reinforcement should have appreciable benefits on fatigue life (Yin et al.[6]).

The aim of the present work is to show the essential contribution of high strength cementitious matrix of Steel Fibre Reinforced Concrete (SFRC) in direct tension.

The role of cementitious matrix is highlighted by two parameter analysis based on:
- the crack growth rate under low-cycle loading;
- the ductility of SFRC.

2 Experimental part

2.1 Materials

Nine different mixes were prepared: four reference mixes (NSC, HSC, HC6 and HHC) respectively characterised by normal, high and very high compressive strength were prepared.

In Table 1a are shown the composition, rheological and strength properties of concrete mixes used for the present research.

Table 1a. Composition, rheological and strength properties of concrete mixes.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Cement [Kg/m^3]</th>
<th>w/c</th>
<th>Fibres</th>
<th>Slump [mm]</th>
<th>f_{cc} [MPa]</th>
<th>f_{ct} [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC*</td>
<td>370</td>
<td>0.56</td>
<td>-</td>
<td>130</td>
<td>42.0</td>
<td>3.87</td>
</tr>
<tr>
<td>NC-S*</td>
<td>370</td>
<td>0.59</td>
<td>30 A</td>
<td>130</td>
<td>64.8</td>
<td>4.09</td>
</tr>
<tr>
<td>HC*</td>
<td>550</td>
<td>0.29</td>
<td>-</td>
<td>200</td>
<td>106.3</td>
<td>4.96</td>
</tr>
<tr>
<td>HC-S*</td>
<td>550</td>
<td>0.29</td>
<td>30 A</td>
<td>170</td>
<td>116.5</td>
<td>5.45</td>
</tr>
<tr>
<td>HC6**</td>
<td>861</td>
<td>0.25</td>
<td>-</td>
<td>190</td>
<td>134.0</td>
<td>7.2</td>
</tr>
<tr>
<td>HC6-S1**</td>
<td>853</td>
<td>0.25</td>
<td>80 B</td>
<td>180</td>
<td>135.0</td>
<td>19.0</td>
</tr>
<tr>
<td>HC6-S2**</td>
<td>831</td>
<td>0.25</td>
<td>270 C</td>
<td>180</td>
<td></td>
<td>22.0</td>
</tr>
<tr>
<td>HHC***</td>
<td>500</td>
<td>0.29</td>
<td>-</td>
<td>100</td>
<td>123.0</td>
<td></td>
</tr>
<tr>
<td>HHC-HS***</td>
<td>500</td>
<td>0.29</td>
<td>80 D</td>
<td>90</td>
<td>123.0</td>
<td></td>
</tr>
</tbody>
</table>

* - Rounded shaped siliceous aggregate; Φ_{max} = 16 mm
** - Rounded shaped siliceous aggregate; Φ_{max} = 6 mm
*** - Crushed calcareous aggregate; Φ_{max} = 16 mm

Two types of cement were used:
- Class 32.5 R type CEM II/B-L (UNI-ENV-197) for NC mixes;
- Class 52.5 R type CEM I (UNI-ENV-197) for HC, HC6 and HHC mixes.

For HC, HC6 and HHC mixes a silica fume addition of 10% by mass of the cement was used. Melamine plasticisers and acrylic-based superplasticisers were added for normal and high strength concrete mixes respectively. The grading curve of aggregates was very close to the theoretical Bolomey curve. The very
high content of fibre for HC6-S2 mix was chosen in order to obtain the same total lateral surface area of fibres with respect to HC6-S1 mix.

In Table 1b are reported the geometrical and mechanical properties of steel fibres used in the present work.

Table 1b. Geometrical and mechanical properties of steel fibres.

<table>
<thead>
<tr>
<th>Type</th>
<th>L [mm]</th>
<th>L/Φ</th>
<th>Shape</th>
<th>fₕ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>30</td>
<td>60</td>
<td>Hooked</td>
<td>1100</td>
</tr>
<tr>
<td>B</td>
<td>13</td>
<td>65</td>
<td>Straight</td>
<td>1100</td>
</tr>
<tr>
<td>C</td>
<td>20</td>
<td>36</td>
<td>Hooked</td>
<td>900</td>
</tr>
<tr>
<td>D</td>
<td>35</td>
<td>65</td>
<td>Hooked</td>
<td>2300</td>
</tr>
</tbody>
</table>

(1) High carbon content (> 0.79 +0.86%)

2.2 Specimens geometry and instrumentation

The specimens were made by casting mixes into cylindrical moulds (Ø 80 mm x 210 mm). The specimens were demoulded 24 h after casting and then cured under water at 20±2°C for at least 6 months in order to minimize the strength differences among tests carried out at different dates.

In order to obtain the complete stress displacement curve and to force the crack growth in the middle plane of the specimens, a V-shaped notch was carried out in the middle section of the specimens. The depth of the notch was about 10% of specimen diameter. The crack-opening data were acquired by three resistance full-bridge displacement transducers (clip-gauges) type TML-UB5A; these transducers, characterized by a sensitivity of 2.62 mV/μm and a range of 5 mm, were equally spaced (Figure 2). The three clip-gauges were connected in parallel to obtain an averaged signal; it was used as the feed-back signal owing to the high sensitivity of the clip-gauges. The tensile tests can be considered to be carried out in Crack Opening Displacement (C.O.D.) control since the base length of clip-gauges is very small (35 mm) and the contribution of the elastic deformation (to the measured displacement) is negligible.

The rigid coupling of the specimen to the loading system was obtained by using two loading plates (Figure 2). The specimens were glued to the plates by an epoxy resin; the plates were fixed to the loading system. The bottom plate was fixed to the bed of the testing machine by four bolts to provide a very rigid constraint. A cylinder of the same diameter of the specimen was made in the bottom plate by mechanical turning (Figure 2). This steel cylinder facilitated the correct placement of the concrete cylinder to limit possible initial eccentricities. The upper plate was screwed to a threaded bolt having the role of transferring the tension to a reversible load cell (HBM-Z12) with a load capacity of ±200 kN and sensitivity of 0.02 kN/mV.
During the tests, the Acoustic Emission (A.E.) was monitored by means of two pre-amplified transducers. These were placed on diametrically opposite points of the cylinders; silicon grease was used as a coupling medium. The range of A.E. transducers was 0-50 MHz, and their signal was amplified to obtain a linear output in the range 0-10V. The A.E. activity was acquired in terms of a cumulative count of acoustic events which could be assumed as a measure of the development of the cracking process during the test (Rossi [7]).

The output signals from all the transducers were amplified and then sent to an A/D converter (16 bit resolution) connected to a personal computer.

2.3 Testing machine

The tests were carried out by means of a very stiff servo-controlled testing machine. The load is applied by a hydraulic double-acting piston without traditional seals to avoid the static friction which takes place during the reversal of the piston stroke direction in the cyclic tests. A Moog servo-valve, with high dynamic response characteristics (400 Hz) was used as the actuator of the hydraulic control loop. The servo-valve was piloted by a current signal (0-10mA) coming from a P.I.D. (Proportional, Integral and Derivative) controller where the feed-back signal was compared with the reference signal generated by the software (Plizzari et al. [8]). On the basis of the configuration parameters, set before starting the test, the reference voltage ramp (in the range of 0-10V) was generated by the software. This signal was sent, through a 16 bit A/D converter, to the PID controller. Furthermore, the software allowed the acquisition of signals from transducers which are suitably amplified and converted from analog to digital by the A/D converter. The noise problems, which unavoidably disturb the signal acquisition, were smoothed by averaging the data acquired every 6 scans.
2.4 Planning and control of cyclic tests

For the low-cycle fatigue tests, four stages of loading were planned with the aim of monitoring the crack growth development in concrete during the test (Figure 3).

- In the first stage (OAB of Figure 3), a constant displacement rate ($\approx 25 \times 10^{-3} \mu m \ s^{-1}$) was imposed up to the peak load. When the load dropped to $\approx 95\%$ of the peak load and then a FPZ is surely present at notch tip, the specimen was unloaded at the same displacement rate up to a preset lower limit $P_{inf}$ (point B of Figure 3).

- In the second stage (BC of Figure 3), the controlled quantity (C.O.D.) was cycled at a chosen frequency (0.5 Hz); the inversion of the reference signal was made by the software whenever the upper and lower load limits ($P_{sup}$ and $P_{inf}$, respectively 75\% and 25\% of $P_{max}$) were reached. The initial quasi-static stage allowed the direct measurement of the actual tensile-strength of the specimens subjected to cyclic loads. Cyclic tests based on tensile strength values not measured directly on the tested specimen, but on similar specimens, even if coming from the same batch, is one of the causes of the large scatter often observed in cyclic tests (Cornelissen [5]). The software was programmed to detect the intersection of the envelope curve (ACDE) which is the locus of broken curves joining the end of a reloading curve to the start of subsequent unloading curve (Figure 3).

- In the third stage (CD), the cyclic loading continued further by imposing the inversion of the feed-back signal (C.O.D.) whenever the load, after reaching the envelope curve, dropped to a preset fraction of $P_{sup}$. This stage ended when the maximum load, detected on the envelope curve, became lower than a preset fraction of $P_{inf}$.

- In the fourth stage (DE), a monotonic increase of the C.O.D. is imposed as long as the load drops to 1\% of $P_{max}$; at this point the test is stopped.
3 Results and discussion

In Figure 4a a typical load-displacement (C.O.D.) curve acquired during a low-cycle fatigue test is shown. It is possible to observe that cumulative A.E. signal sharply increases after the starting of envelope curve cycles. This confirms that material damage related to A.E. (Rossi et al. 1989) takes place (even if not completely) in the CD phase (Figure 3). Experimental results have shown that envelope curve of cyclic tests lies on the curve obtained by static tests (Figure 4b) (Hordjk 1991, ...). In this figure the relationship between residual post-peak stress ($\sigma_r$) and crack opening ($w$) is shown. The crack opening ($w$) was calculated by subtracting to measured displacement (C.O.D.) the contribution of elastic part ($\delta_e$) and irreversible part ($\delta_{irr}$) which is due to FPZ formation.

In the present work the analysis of results is restricted to inner cycles to envelope curve (ABC stage in Figure 3) because they are the most of cycles that the cracked specimens can sustain at preset and relatively high loading range as compared to the few cycles lying on the envelope curve (CD phase in Figure 3).

From the analysis of Figure 3 we can argue that fatigue, total number-{$N_{\text{max}}$} of inner cycles, life of cracked specimens is essentially driven by the “widening” of constitutive law $\sigma$-$w$ and the “speed” at which the envelope curve is reached. In other terms the two parameters, which control the total number ($N_{\text{max}}$) of inner cycles of cracked specimens, are:

- ductility of material expressed as difference between crack opening at envelope curve and initial crack opening ($\Delta w_d = w_u - w_0$; Figure 5a);
- crack growth rate expressed as average crack opening during each cycle ($\Delta w/dn$; Figure 5a).
In Figure 5b is shown a typical cyclic-creep curve which is obtained from Figure 5a by plotting the crack opening (w) versus the cumulative number of cycles. The first ascending branch of cyclic creep curve in this case is absent because the specimens are already cracked at the starting of the cyclic loading. During the cyclic loading inside the envelope curve the crack growth rate (dw/dn) is almost constant and only when the inner cycles reach the envelope curve the crack growth (w) dramatically increases and the failure is reached in a few number of cycles. Also from the analysis of Figure 5b we can observe that the fatigue life (N_max) increases as well as Δw_d increases and/or crack growth rate dw/dn decreases.

On the basis of these considerations may be interesting to plot experimental results in the plane (Δw_d, dw/dn ) where iso-cycle lines are also plotted as straight lines having the following equation:

\[ \Delta W_d = N_{\text{max}} \frac{dw}{dn} \]  

In Figure 6a are reported experimental values of the two parameters detected for reference mixes (NC, HC6).
It is possible to observe that an increase of mechanical strength of reference mixes leads to an appreciable reduction of $dw/dn$; $\Delta w_d$ parameter generally is not significantly influenced instead. The shifting of $dw/dn$, due to strength increase, results in an increase of one order of magnitude of the fatigue life since are matched iso-cycle lines with higher slope (e.g. higher $N_{\text{max}}$).

In Figure 6b it is possible to observe that fibre reinforcement become generally efficient in terms of fatigue life only in presence of high strength matrix. In fact the NC matrix, reinforced with 30 kg/m$^3$ of steel fibre, shows an unappreciable increase in ductility ($\Delta w_d$) at the load level preset as $P_{\text{sup}}$ (Figure 7a). In any case even if a greater content of fibres should have been used, the resulting increase in ductility ($\Delta w_d$) had caused a relatively small increase in fatigue life. In fact if in the plane ($\Delta w_d$, $dw/dn$) we move normally to the abscissa by increasing ductility ($\Delta w_d$) in correspondence of high values of $dw/dn$, typical of NC matrix, we intercept iso-cycle lines differing each other by small difference in fatigue life. On the other hand if the same increase in $\Delta w_d$ take place in correspondence of smaller values of $dw/dn$, typical of high strength matrix, the increase in the fatigue life is remarkably higher. This means that the addition of fibre reinforcement is more efficient for the HPC concrete matrix than for NC matrix, being HPC steel reinforced concrete characterised also by small values of $dw/dn$.

The remarkable increase of ductility, expressed in terms of $\Delta w_d$ is shown in Figure 7b referred to HC6 matrix reinforced 80 kg/m$^3$ of steel fibres. Relatively high content in HC matrix determines an increase in ductility such that the upper limit of the load cycle intercepts the envelope curve for high values of $w$ resulting in large values of $\Delta w_d$.

![Figure 7a: Constitutive laws for NC and NC-S concrete.](image1)

![Figure 7b: Constitutive laws for HC6 and HC6-S1 concrete.](image2)

### 4 Conclusive remarks

In the present work the behaviour of steel fibre reinforced concrete subjected to low-cycle fatigue has been investigated by means of uniaxial tensile cyclic tests on cylindrical notched specimens. The cyclic tests were carried out on cracked specimens were a fracture process zone was already present.
The results are summarised as follows:

- The low-cycle fatigue life is essentially conditioned by two parameters ($\Delta w_d$, $dw/dn$);
- The $dw/dn$ parameter is generally controllable by a suitable increase of mechanical strengths of matrix while it is possible to increase $\Delta w_d$ only by steel fibre addition.

On the basis of obtained results it is possible to conclude that it is possible to obtain high fatigue performances only using high or very high strength cementitious matrix were fibre reinforcement can exhibits efficiently its effects.

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