SIZE EFFECT OF HPFRCC IN UNIAXIAL TENSION

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Abstract

In the framework of safe design of quasi-brittle materials, the importance of size-effect has been widely established and investigated. Even though effective theoretical models and deterministic approaches are available for plain and reinforced concrete, information regarding advanced cement-based composites is still insufficient. A deep comprehension of such scale dependencies is of fundamental concern, since they may dangerously affect the response of structural elements designed accordingly to deflection-hardening constitutive behaviours defined at the material level. In this preliminary research, uniaxial tensile tests on High Performances Fibre Reinforced Cementitious Composite (HPFRCC) dog-bone specimens were carried out, highlighting the influence of specimen size on the load-bearing capacity and the structural ductility. Four different clear lengths, ranging between 20 and 440 mm were considered and results in terms of nominal stress vs. normalized crack opening displacement were derived, leading to relevant conclusions.

Résumé

Dans le cadre d'une conception sûre utilisant les matériaux quasi-fragiles, l'importance de l'effet d'échelle a été largement établie et étudiée. Même si des modèles théoriques efficaces et des approches déterministes sont disponibles pour le béton et le béton armé, les informations concernant les nouveaux composites cimentaires sont encore insuffisantes. Une compréhension profonde de la dépendance des propriétés vis-à-vis de l'échelle est une question fondamentale, car cette dépendance peut affecter dangereusement la réponse des éléments structuraux conçus en fonction de lois de comportement écrouissantes en flexion définies au niveau du matériau. Dans cette recherche préliminaire, des essais de traction uni-axiale sur des éprouvettes en forme de diabolo constituées de composite cimentaire fibrés à hautes performances ont été réalisés, soulignant l'influence de la taille des échantillons sur la capacité portante et la ductilité structurelle. Quatre longueurs utiles différentes, allant de 20 à 440 mm, ont été étudiées et les résultats en termes de contrainte nominale en fonction de l'ouverture de fissure normalisée ont été analysés, ce qui a abouti à des conclusions pertinentes.

1. INTRODUCTION

Scaling problems associated to the tensile behaviour of quasi-brittle materials such as strain-hardening cementitious composites are particularly worthy of attention, since the material performances extracted at the laboratory level might be inadequate to represent the mechanical response of full scale structures [1]. As shown in the literature, the increase of specimen size in steel fibre-reinforced composites affects the tensile behaviour [2] and, consequently, the flexural response [2, 3]. Furthermore, the constitutive laws in uniaxial tension are significantly influenced by the spatial orientation of the embedded fibres [4, 5].

In the case of HPFRCC, the deflection-hardening characteristics of thin unnotched beams are intrinsically related to stress redistributions, energy releases and interplays of brittle micro-scale mechanisms sensitive to the structural size. In the following, the outcomes of a previous research [6] focussing on the flexural behaviour of unnotched beam specimens are compared with the results of four sets of dog-bone specimens. The evidences suggest that mechanical properties such as peak nominal stress, peak equivalent strain and cracking pattern in direct tension are dependent on the testing length and may substantially differ from those indirectly obtained from bending procedures.

2. MATERIAL SPECIFICATION AND SPECIMENS PREPARATION

The considered material consists of a HPC matrix (600 kg/m^3 of cement I 52.5, 977 kg/m^3 of 0÷2 mm siliceous sand, 212.7 l/m^3 of water, 33 kg/m^3 of superplasticizer and 500 kg/m^3 of blast furnace slag), reinforced with 1.2% by volume (100 kg/m^3) of straight high-carbon steel microfibers (length 13 mm, diameter 0.20 mm, aspect ratio 65). The geometrical characteristics of the specimens are displayed in Figure 1. Four different gauge lengths ℓ_0 were taken into consideration (20 mm, 80 mm, 200 mm and 440 mm) and, for each of them, three 20 mm thick nominally identical specimens were produced. The fresh-state matrix, directly poured from one end of the moulds (Figure 3b), could freely flow along the specimens length, ensuring a high orientation factor [4] in the direction of principal tensile stresses. The outer parts were reinforced with two layers of AR-glass textiles aimed at preventing crack localizations out of the observation regions and the samples were finally cured for at least 28 days, in a controlled environment (RH > 90%, T =20±2°C).

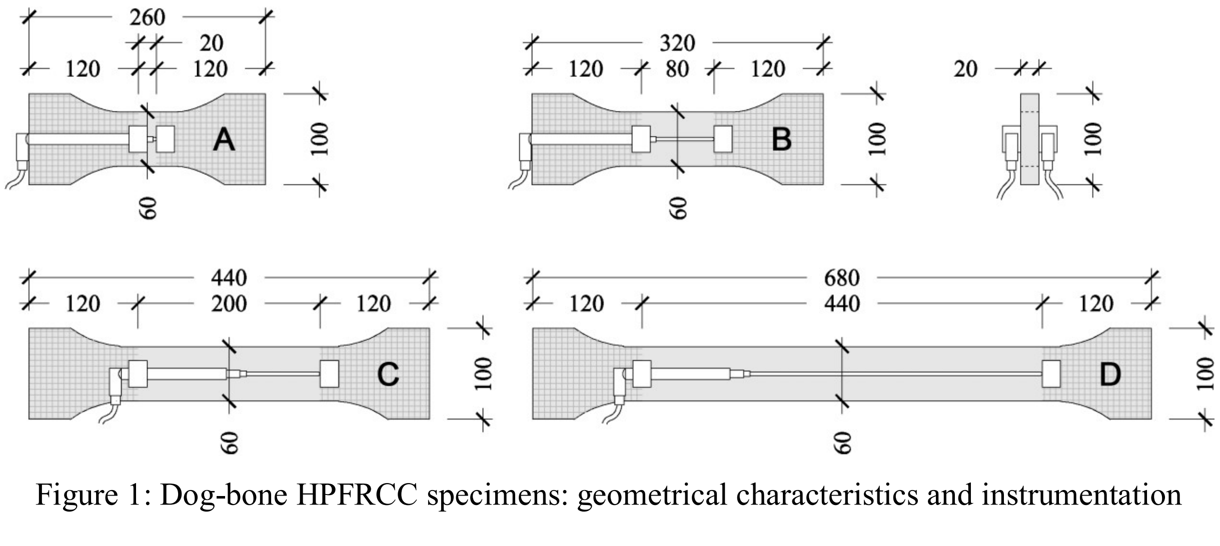


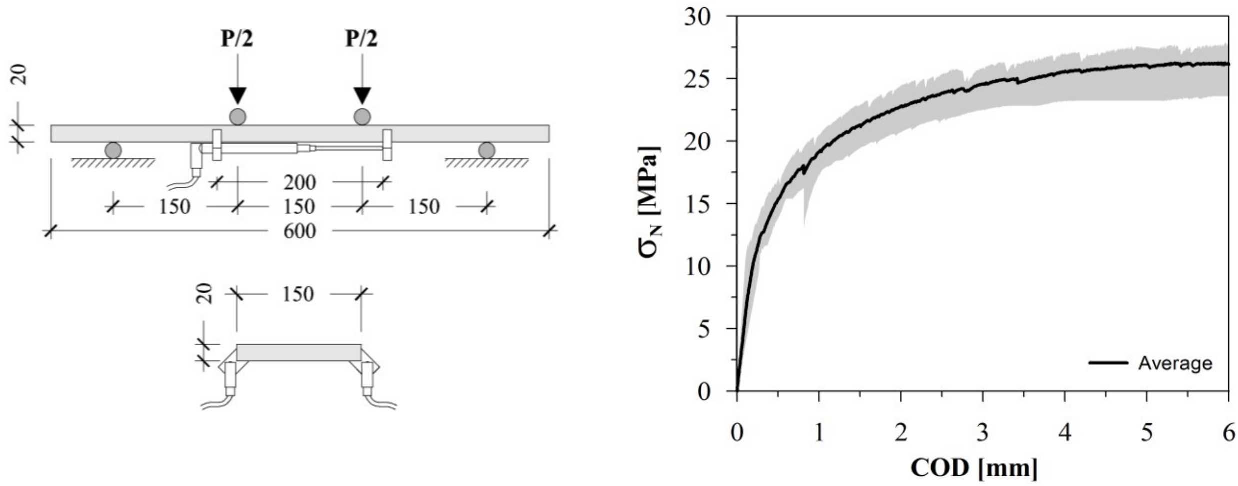
Figure 1: Dog-bone HPFRCC specimens: geometrical characteristics and instrumentation

3. MECHANICAL BEHAVIOR

The mechanical behaviour of the considered HPFRCC was assessed in previous studies [6, 7]. According to Model Code 2010, the material is classified as a 14a class fibre-reinforced composite ($f_{R1,k}$=14.11 MPa; $f_{R3,k}$=8.01 MPa) and a C120 grade concrete.

3.1 Flexural behaviour of thin unnotched specimens

The loading scheme of Figure 2a refers to the experimental campaign comprising five nominally identical four-point bending tests on 20 mm thick unnotched beam specimens, performed in [6] accordingly to the Italian Guidelines CNR DT 204. Such specimens, named *structural*, are believed to better represent the mechanical behaviour of thin HPFRCC structures, since the derived tensile laws exhibit remarkable differences in peak strength and toughness, with respect to the ones obtained from traditional EN 14651 notched beams [8]. It is important to highlight that, also in this case, a small slide was employed in the casting phase, so as to orient the fibres along the direction of principal tensile stresses. Since the specimens were unnotched, an integral Crack Opening Displacement (COD) was measured by two displacement transducers (LVDT) operating on a gauge length of 200 mm. The experimental results are displayed in Figure 2b, in terms of nominal stress (σ_N) vs. COD; as one should note, the composites showed a stable behaviour up to remarkable COD values; for this reason, thanks to the beneficial fibre orientation, the material could be classified as hardening in bending, according to the internationally established standards.

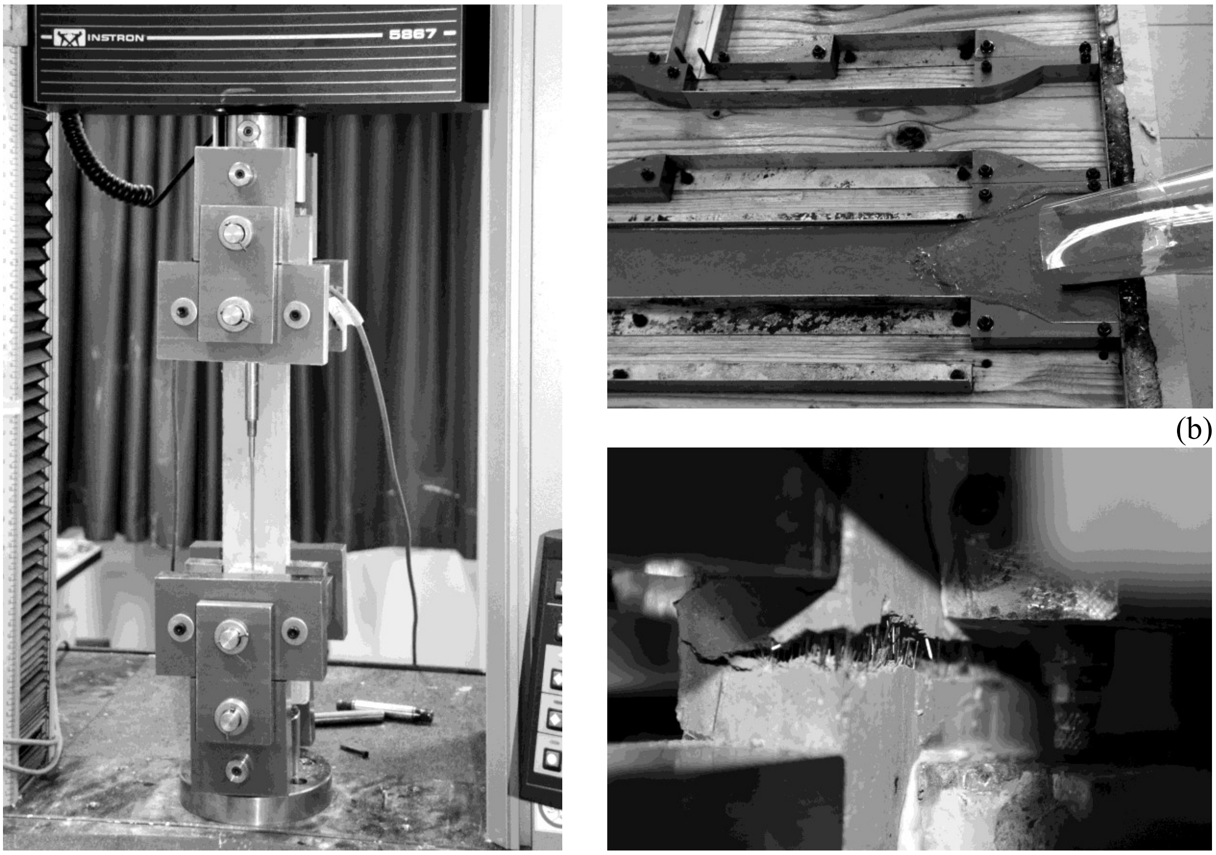


(a) (b)

Figure 2: 4PB *structural* specimens: test setup (a) and nominal stress vs. COD response (b)

3.2 Tensile behaviour and size effect phenomena

Uniaxial tensile tests were carried out on dog-bone specimens in order to check if, although the *structural* samples exhibited a significant multi-cracking hardening phase before the onset of localization, the material might be affected by size effect phenomena. The design of the experimental set-up (Figure 3a) was operated with the aid of simplified calculations and numerical models aimed at verifying whether the ratio between the global stiffness of the set-up and the axial stiffness of the specimens was always greater than 10. This reference value was adopted to guarantee the limitation of the elastic energy associated to the set-up deformations, preventing early localizations due to spurious elastic energy releases. The system was designed as a rotating end apparatus, in order to permit the self-alignment of the specimens along the loading direction, preventing spurious effects. It is important to remember that the main eccentricity of the load with respect to the "effective" cross section depends on fibres distribution and remains relatively small if compared with plain concrete.



(a) (b) (c)

Figure 3: Dog-bone HPFRCC specimens: test setup (a), casting procedure (b) and crack localization on a type-A sample (c)

The tests were executed in displacement control (the load cell stroke was taken as the feedback parameter), on specimens instrumented with two longitudinal LVDTs. Following a pre-loading stage (up to 500 N) at a 2.5 N/s rate, a constant $5 \cdot 10^{-4}$ mm/s stroke rate was imposed to the actuator. One LVDT was applied on the face in direct contact with the mould, while the other was glued on the free upper one; this choice was made to guarantee a refined collection of data, giving the opportunity to detect fibres segregation in the thickness direction. Since the specimens were unnotched, an integral Crack Opening Displacement (COD) was measured by the two transducers. The results of the tensile tests are shown in Figure 4 and Table 1, in terms of nominal stress (σ_N) versus normalized Crack Opening Displacement (COD/ℓ_0). It is worth mentioning that localization generally occurred about the clear length end; this might be related to the combined effect of the non-uniformity of the stress field at the specimen boundaries and the additional irregularity of the interface between the 60 mm wide part and the enlarged region where, as previously explained, two AR-glass fabrics were introduced.

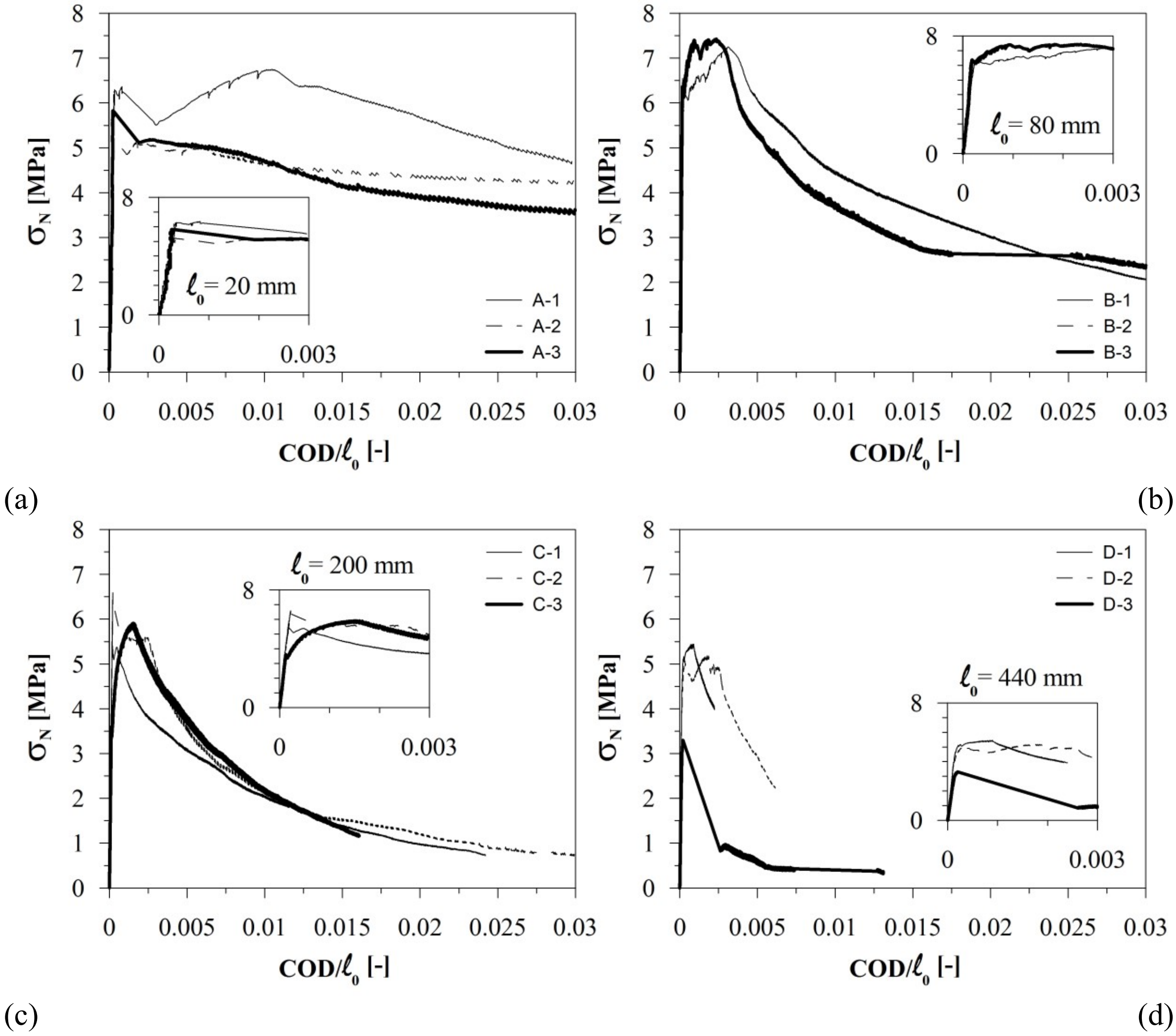


Figure 4: Uniaxial tensile tests results: global responses and zooms in the 0÷0.3% range of normalized Crack Opening Displacement. Please note that specimen B-2 exhibited an early localization outside the gage length

With reference to the post-cracking behaviour, the curves reveal that both peak stresses and peak normalized CODs are controlled by the testing length. In general terms, it might be stated that the longer the specimen, the smaller the strength and the ductility. A finer cracking pattern was found in shorter samples (Figure 5); in particular, only type-B specimens were characterized by a significant multi-cracking branch (Figure 4b). In the shortest specimens (type-A) only a major crack was developed; in this regard it can be observed that since the clear space (20 mm) was too short to guarantee a significant orientation factor and was of the same order of magnitude of the fibres length (13 mm), stress redistributions within the observation area were prevented. In fact, it is interesting to notice that the average peak strength ($\sigma_{N,peak}$) of specimens A is lower than the one associated to specimens B. Although van Vliet and van Mier [9] showed that a decrease in strength in the smallest specimens might be associated to the eigen-stresses caused by differential shrinkage and differential temperatures during the concrete hardening phase, this doesn't seem to apply in this situation, since only the specimen length was varied, keeping constant the 60 mm width.

Table 1: Peak nominal stresses and peak normalized CODs

Specimen	$\sigma_{N,peak}$	$\sigma_{N,peak,av}$ [MPa] (std)	$(COD/\ell_0)_{peak}$ [-]	$(COD/\ell_0)_{peak,av}$ [-] (std)
A-1	6.75	6.30 (0.47)	$1.05\cdot10^{-2}$	$3.70\cdot10^{-3}$ ($5.89\cdot10^{-3}$)
A-2	6.34		$3.50\cdot10^{-4}$	
A-3	5.82		$2.50\cdot10^{-4}$	
B-1	7.25	7.08 (0.46)	$3.12\cdot10^{-3}$	$1.89\cdot10^{-3}$ ($1.52\cdot10^{-3}$)
B-2	6.55		$1.94\cdot10^{-4}$	
B-3	7.43		$2.36\cdot10^{-3}$	
C-1	5.95	6.15 (0.39)	$1.90\cdot10^{-4}$	$6.55\cdot10^{-4}$ ($7.75\cdot10^{-4}$)
C-2	6.60		$2.25\cdot10^{-4}$	
C-3	5.91		$1.55\cdot10^{-3}$	
D-1	5.44	4.65 (1.17)	$9.01\cdot10^{-4}$	$9.50\cdot10^{-4}$ ($7.56\cdot10^{-4}$)
D-2	5.20		$1.73\cdot10^{-3}$	
D-3	3.30		$2.20\cdot10^{-4}$	

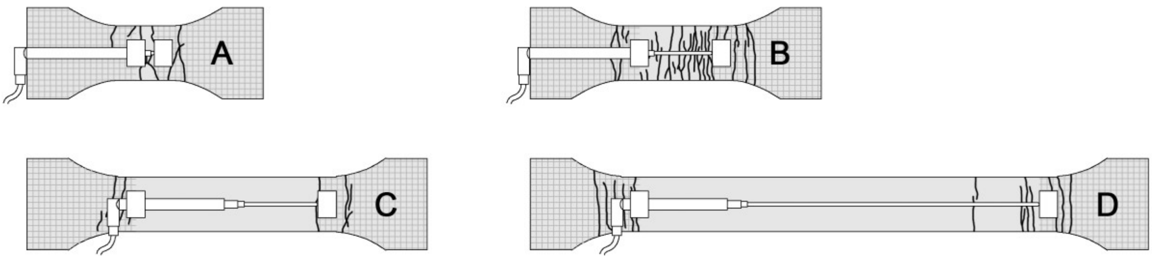
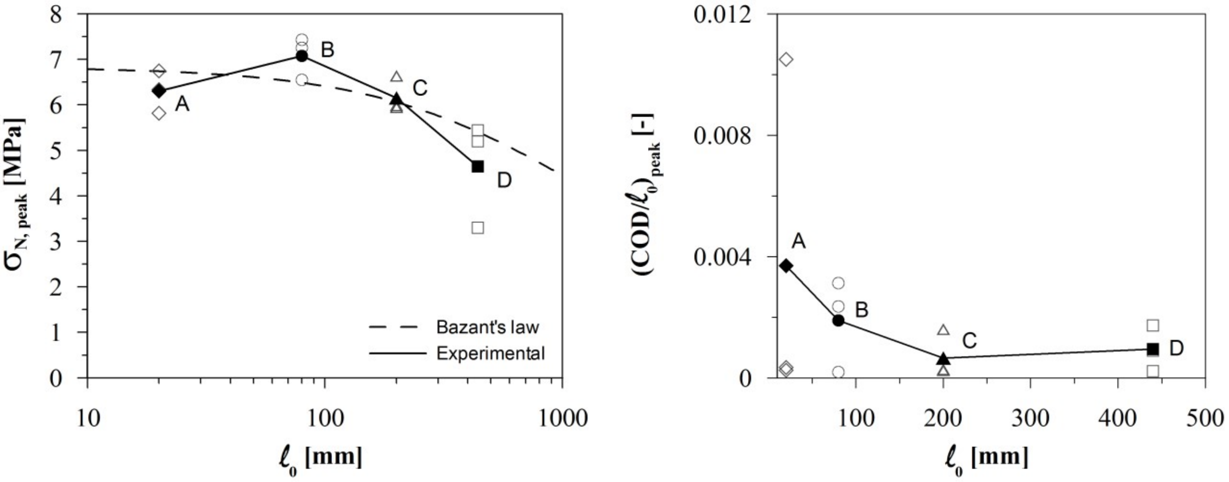


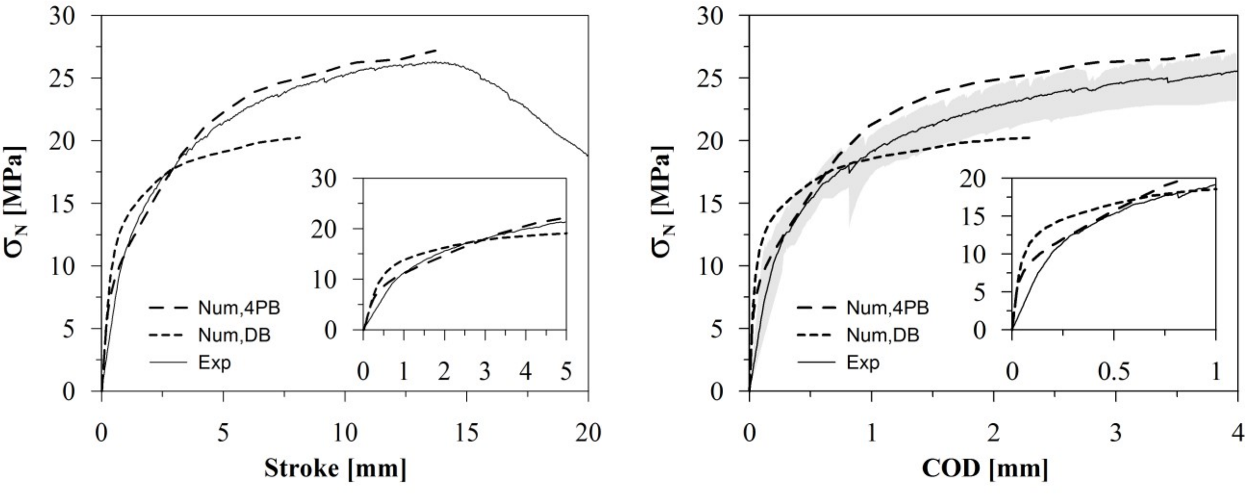
Figure 5: Typical cracking patterns at failure. Please note that cracks were also developed outside the clear length, partially affecting the COD measures

It is worth observing that the $(COD/\ell_0)_{peak}$ values of Table 1 are generally lower than the peak strains evaluated in bending [6] according to the procedures shown in [4]; this might be due to 1) the greater stability of the bending test, which ensures a dense multi-cracking over the gauge length and 2) beneficial second-order effects linked to the small specimen thickness. Furthermore, a slight fibre segregation in *structural* specimens entails on the tensile side – which was in direct contact with the mould – a local increase of the fibre volume fraction, leading to a prominent hardening phase. On the contrary, in direct tension tests segregation phenomena may cause a combined tension and bending loading, with an early localization connected to the weakness of the free-surface layer. This latter hypothesis was proved by the analysis of the two LVDTs outputs, in which unsymmetrical behaviours were randomly observed. Figures 6a and 6b respectively display the dependencies of peak nominal stresses and peak normalized CODs on the gage length. Peak stresses (Figure 6a) are plotted on a logarithmic length scale and compared with Bažant's size effect law [10] based on nonlinear fracture mechanics; despite the limited repeatability and the significant results scatters, the tendency appears to be confirmed. As regards normalized CODs (Figure 6b), an analogous trend was found, proving the presence of scaling dependencies also on peak equivalent strains. By contrast, in previous results [11] interested to assess size effect in the pull-out phase, a reduced effect was observed.



(a) (b)

Figure 6: Peak nominal stresses vs. gage length (logarithmic scale) (a) peak normalized CODs vs. gage length (b) diagrams. Please note that the black-hatched symbols represent the average values of the three nominally identical tests



(a) (b)

Figure 7: Comparison between experimental and numerical results: nominal stress vs. stroke (a) and nominal stress vs. COD (b) diagrams

In Figure 7, the average curves exhibited by *structural* specimens under a four-point bending test are compared with preliminary numerical analyses. Two tensile laws were implemented in the Concrete Damaged Plasticity model available in Abaqus 6.14-5: a first multilinear behaviour, as derived in [6] from flexural tests (4PB) and a second piecewise linear curve fitting the experimental results of specimen B-1 (Figure 4b), which was taken as a reference uniaxial response. As one should note, the adoption of a tensile constitutive relation based on dog-bone (DB) test results leads to a conservative estimation of the mechanical capacity, both in terms of strength and ductility. This might be due to the greater brittleness of uniaxial tensile tests and a non-homogeneous distribution of fibres within samples prepared according to different casting procedures.

4. CONCLUSIONS

Based on the presented results, the following conclusions can be drawn: 1) deflection-hardening materials as the considered HPFRCC are sensitive to size effect; 2) scaling phenomena appear to be related to the statistical distribution of local defects such as segregation, bad orientation and non-uniform distribution of fibres; 3) gage length dependencies affect the material strength and, as a consequence, peak equivalent strains and cracking patterns; 4) tensile constitutive laws obtained from thin dog-bone specimens could reveal conservative results in the simulation of the flexural response of unnotched thin specimens; 5) alternative test configurations based on fixed boundary conditions might be considered in the future.

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