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Experimental behavior of precast HSFRC columns in steel socket foundation under cyclic loads

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ABSTRACT

The present paper aims to investigate the influence of steel fibers on the behavior of high strength precast concrete columns in steel socket foundation under cyclic loading. The experimental program was mainly defined to study the effects of the volume fraction and the type of fibers on the behavior of full-scale precast columns subjected to reversed cyclic horizontal loading under constant axial load. Experimental parameters under investigation were: the transverse reinforcement ratio, the axial load, the fiber type and content as well as the effect of steel-to-concrete bond of rebars in the critical region. The latter was investigated since it could considerably govern the local ductility in terms of curvature and of global displacement of the precast column, especially in presence of fibrous reinforcement.

Experimental results highlight the importance of the stirrup spacing in the critical region as well as the positive effect of fibers on the crack development, by preventing the concrete cover to spall-out at earlier stages. Steel Fiber Reinforced Concrete (SFRC) tends to enhance the structural stiffness, the strength and the dissipated energy.

1. Introduction

Structures with ductile behavior have the capacity to absorb and dissipate energy under extreme loads, such as earthquakes, by showing a limited loss of strength. This inelastic behavior is due to the development of plastic hinges that, according to capacity-based design used for seismic structures [1], develop at beam ends and at the bottom of first-story columns or bridge columns.

High Strength Concrete (HSC), which is widely available nowadays, generally allows for a reduction of the dimension and for an enhanced durability of structural elements. Nevertheless, it is generally more brittle than conventional Normal Strength Concrete (NSC) and its use in seismic resistant members, such as columns, could reduce their ductility. For these reasons, most building codes [1] requires a transverse reinforcement ratio depending on the concrete strength and the axial load level, among other variables. These requirements typically lead to reinforcement congestion with the consequent difficulties in concrete casting. A possible solution to this problem could be the addition of fibrous reinforcement to the concrete matrix, which enables a considerable enhancement of concrete post-cracking tensile residual strength and ductility [2–5].

Steel Fiber Reinforced Concrete (SFRC), exhibiting substantially larger strain capacity in tension (as compared with traditional concrete), could be usefully employed for members subjected to large inelastic deformation demands, such as beams, beam–column joints and columns-foundation joints under seismic actions. In fact, it is expected that an enhanced material ductility could result in an analogous enhancement of the global structural ductility.

These advantages, even if less pronounced, are also observed in compression for the enhanced post-peak strength and ultimate deformation [6]. Accordingly, several authors [7,8] demonstrated that appropriate fiber contents may delay the concrete spalling and increase the deformation capacity without loss of ductility and strength. Hence, fibrous reinforcement could partially replace the conventional transverse reinforcement of concrete columns.

As far as fatigue loading is concerned, SFRC generally enhances the fatigue life both in compression [9–11] and in tension [12–14]. With reference to the tensile behavior, fibers are able to bridge microcracks and retard their growth, thereby extending the fatigue life of the composite. Cachim et al. [9] stated that, when cyclic

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Nomenclature

A_{c}	cross-sectional area of concrete
d	top horizontal displacement of the column
d_{u}	ultimate displacement
d'_{y}	first yield displacement
d_{y}	conventional yield displacement
D_0	FRC ductility index at SLS, according to EN 11039
D_1	FRC ductility index at ULS, according to EN 11039
E_{c}	concrete elastic modulus
E_{cum}	total energy dissipated, cumulative energy
$E_{\mathrm{diss,i}}$	energy dissipated at each cycle
EJ	flexural secant stiffness at first yield
E_{m}	mortar elastic modulus
E_{s}	reinforcing steel elastic modulus
f_{cd}	design cylindrical compressive concrete strength
f_{cm}	mean cylindrical compressive concrete strength
$f_{\mathrm{cm,cube}}$	mean cubic compressive concrete strength
f_{ctm}	mean cylindrical tensile concrete strength
$f_{\mathrm{eq(0.6-3)}}$	equivalent residual flexural strength of fiber reinforced concrete corresponding to CTOD range of 0.6–3 mm, according to EN 11039
$f_{\mathrm{eq(0-0.6)}}$	equivalent residual flexural strength of fiber reinforced concrete corresponding to CTOD range of 0–0.6 mm, according to EN 11039
f_{If}	conventional flexural tensile strength at first cracking, according to EN 11039
f_{mm}	mean cylindrical compressive mortar strength
$f_{\mathrm{mtm,fl}}$	mean flexural tensile mortar strength
$f_{\mathrm{PVC,tu}}$	ultimate tensile strength of PVC flexible tube
f_{R1}	residual flexural tensile strength of fiber reinforced concrete corresponding to CMOD = 0.5 mm, according to EN 14651
f_{R3}	residual flexural tensile strength of fiber reinforced concrete corresponding to CMOD = 2.5 mm, according to EN 14651
f_{sym}	mean yield strength of reinforcing steel in tension
f_{syd}	design yield strength of reinforcing steel in tension
f_{sum}	mean ultimate strength of reinforcing steel in tension
f_{uf}	ultimate tensile strength of fiber's wire
h	effective length of the column
H	horizontal load applied to the column
H_{max}	maximum horizontal load applied to the column
L_{f}	fiber length
$L_{\mathrm{f}}/\phi_{\mathrm{f}}$	fiber aspect ratio
M'_{y}	first yield moment
M_{max}	maximum moment
M_{rd}	design flexural resistance
N	axial force applied to the column
V_{f}	volume fraction of fibers
$\varepsilon_{\mathrm{PVC,tu}}$	ultimate tensile strain of PVC flexible tube
$\mu_{\Delta\mathrm{u}}$	ultimate displacement ductility factor
$\mu_{\chi\mathrm{u}}$	ultimate curvature ductility factor
ν	actual normalized axial force
ν_{d}	normalized design axial force
ϕ	reinforcing steel bar diameter
ϕ_{cyl}	diameter of cylindrical concrete/mortar sample
ϕ_{f}	fiber diameter
ρ	total longitudinal reinforcing bar ratio
ρ_{PVC}	PVC mean density of flexible tube
χ_{u}	ultimate curvature
χ'_{y}	first yield curvature
χ_{y}	conventional yield curvature
ω_{wd}	mechanical volumetric ratio of confining reinforcement

compression loads were applied, the addition of fibers to concrete provided an increase in the deformation at failure; moreover, Barros et al. [11] demonstrated that the transverse reinforcement can be partially replaced by a given content of steel fibers. It is worthwhile noticing that, both in compression [10] and in tension [14], the benefits of the fibers addition are more pronounced in the low-cycle region typical of earthquakes, resulting a possible suitable material for seismic resistant elements such as columns.

In structural members under seismic actions, it is also desirable to minimize seismic damage for reducing post-earthquake repairing costs. Consequently, the use of SFRC can be promising in order to limit the damage that mainly occurs in critical regions such as plastic hinges. To this aim, a further benefit is the better crack control achievable by combining fibers with conventional rebars [15]. Hence, SFRC is expected to guarantee high performance levels in terms of economical assessment of residual structural damage.

Concerning the study of the strength and deformation capacity of Reinforced Concrete (RC) columns under cyclic loading, several publications are available in literature [16,17] but there are few experimental campaigns concerning SFRC columns subjected to axial and lateral loads [18–21] and, in addition, the experimental results seem to be controversial. Generally, it was found that the inclusion of steel fibers reduced the damage by delaying the concrete spalling and the buckling of longitudinal bars in compression and by reducing the critical region length [18–21]. Germano et al. [21] stated that, by adding steel fibers, the column displacement ductility improved moderately in case of mono-axial loading and remained constant when a bi-axial load was applied, whereas Palmieri et al. [20] observed significant improvement in both the previously mentioned loading conditions. The addition of fibers did not seem to significantly increase the maximum load capacity in case of mono-axial and bi-axial load [19,21]. Nevertheless, the opposite trend was observed by Palmieri et al. [20] with bi-axial loading conditions. Referring to the stirrups congestion at the column base, the role of fibrous reinforcement is still a matter of debate. Palmieri et al. [20] proved that SFRCs reduced the stirrup strains by providing extra confinement and, hence, SFRC seemed to be promising for limiting the amount of stirrups adopted in the column critical regions; similar trends were found by Caballero-Morison et al. [19]. However, Germano et al. [21] stated that, when higher stirrup spacing was employed, the ductility tended to decrease.

Eventually, none of the experimental studies available clearly identifies the influence of the SFRC on structural behavior of HSC columns, which are generally used in precast concrete structural systems in combination with a concrete socket foundation. The latter influences the behavior of precast columns under cyclic loading according to the connections employed (smooth or rough socket [22,23] and mechanical or grouted sleeve connections [24]).

Within this framework, the column embedded region as well as the stiffness of a suitable steel socket foundation were designed in order to guarantee a fixed-end at the column base and to ensure a column failure outside of the embedded region.

The present paper describes the main results obtained from eleven full-scale cantilever precast columns placed in a steel socket foundation and made of High Strength Fiber Reinforced Concrete (HSFRC). Columns were tested under reversed cyclic horizontal load and constant axial load, focusing on the following structural