Engineering Structures 57 (2013) 565–577

Contents lists available at SciVerse ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

An experimental study of steel fiber-reinforced high-strength concrete slender columns under cyclic loading

Karen E. Caballero-Morrison, J.L. Bonet *, Juan Navarro-Gregori, Pedro Serna-Ros

Instituto de Ciencia y Tecnología del Hormigón, Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain

ARTICLE INFO

Article history:
Available online 11 August 2012

Keywords:
Slender column
Confined concrete
High-strength concrete
Steel fiber
Ductility
Cyclic load

ABSTRACT

Structural engineers usually limit the use of HSC columns to seismic active zones because of their brittle behavior in comparison with NSC, even though it presents advantages both in terms of mechanics and durability. A possible solution to improve the ductile behavior of HSC columns is the use of transverse reinforcement and steel fibers simultaneously.

In addition, the use of HSC makes the design of more slender columns possible, with the consequent increase of second-order effects. However, there are few experimental tests on columns of medium slenderness (between 5 and 10) subjected to cyclic loads including or excluding steel fibers.

This article presents experimental research work on the behavior of slender columns subjected to combined constant compression and cyclic lateral loads. Fifteen tests were carried out in order to study the behavior of such elements.

The following variables were studied: concrete strength, slenderness, axial load level, transverse reinforcement ratio, and volumetric steel-fiber ratio. The maximum load and deformation capacity of the columns were analyzed. The fact that the inclusion of steel fibers into the concrete mixture increases the deformation capacity was verified. Moreover, a minimum transverse reinforcement is required in order to improve the effectiveness of the steel fibers with no significant decrease in the carrying capacity under cyclic loading. The inclusion of steel fibers in HSC can ensure similar ductility values to those of NSC. It was shown that slenderness influences the deformation capacity.

1. Introduction

In recent years, the use of high-strength concrete (HSC) in construction has increased and been accepted by designers and builders. The immediate benefits of using this type of concrete in columns focus on increasing the load capacity and material savings, and result in smaller cross-sections, and more slender columns, with the consequent increase of second-order effects.

Currently, the criterion of capacity-based design [13,14] guaranteeing that plastic hinges appear in the beam ends and in the bottom of first-storey columns or bridge columns. Thus, reinforced concrete columns have to provide a significant inelastic response with a minor decrease of load capacity without a significance loss of load capacity.

Since the behavior of high-strength concrete in columns is more brittle than that of normal-strength concrete [21,16], its use is gradually being accepted in seismic zones [20]. In order to guarantee a ductile behavior of the columns, and therefore their safety, design codes [11,13,1] include a minimum transverse reinforcement ratio. In general, this ratio is proportional to the concrete strength and the axial load level among other variables. HSC columns require a greater transverse reinforcement ratio than NSC ones, and this makes concrete casting difficult, especially for high axial load levels. Transverse reinforcement improves the column ductility, and its ability to absorb and dissipate energy without a significant loss of load capacity under accidental actions. Another solution for the improvement of the column ductility is adding steel fibers to the concrete mixture [26]. The combined use of steel fibers and transverse reinforcement can reduce the transverse reinforcement ratio required by codes, especially for the case of seismic design [6]. However, code proposals neglect the favorable effect of steel fibers [13,1].

Several authors, including [17,22,7] have studied the behavior of fiber-reinforced high-strength concrete. These studies show the typical stress–strain constitutive relationships of concrete in compression, in which the inclusion of steel fibers represents a minor increase in the peak stress, a significant increase in strain at peak stress, and a substantial increase in toughness. Recent research [15,2,29,8,27] has shown that the presence of steel fibers delays concrete spalling, and increases the deformation capacity of concrete columns subjected to compressive axial load and constant eccentricity.

* Corresponding author. Tel.: +34 96 387 7007x75615; fax: +34 96 387 7569.
E-mail address: jlbonet@cst.upv.es (J.L. Bonet).

0141-0296/$ - see front matter
http://dx.doi.org/10.1016/j.engstruct.2012.06.052

There are numerous publications concerning the study of the strength and deformation capacity of columns under cyclic loading [5,9]. Experimental tests available focus on reinforced concrete columns (without fibers) with shear slenderness (λ_V) under 6.5 [25]. There are some laboratory tests of steel fiber-reinforced concrete columns subjected to combinations of axial and lateral loads [6].

Second-order effects (P–Δ effect) have a significant influence on the deformation capacity of slender columns [3], and there are a few tests on columns with slenderness over 6.5 only for normal-strength concrete [6]. As a result, it is necessary to study the behavior of HSC columns subjected to constant axial load combined with cyclic lateral loads.

This research work presents an experimental program on the behavior of slender normal-strength and high-strength concrete columns, under constant compression and cyclic loads, with and without steel fibers. The effect of confinement and the presence of steel fibers are studied through the following variables: axial load level, concrete strength, and slenderness of the column. These results can be used to calibrate numerical models, and to validate simplified methods included in codes.

2. Test program

Test specimens were designed to represent two semi-columns of two adjacent storeys connected by a stub. The geometric details of the specimens are shown in Fig. 1, and the cross-section details of the semi-columns are shown in Fig. 2. This type of specimen has been previously employed by Yamashiro and Sies [37], Priestley and Park [28], and Barrera et al. [4] among others.

The following parameters were analyzed: (a) the shear slenderness ($\lambda_V = L_s/h = M/(V \cdot h)$, where h was the total depth of the cross-section, M and V were the bending moment and the shear load applied); (b) the relative normal force ($\nu = N/[b \cdot h \cdot f_c]$, where N was the axial load applied, b was the width of the cross-section, and f_c was the concrete compressive strength); (c) the confinement effectiveness of the transverse reinforcement ($\alpha \cdot \omega_\omega$, where α was the confinement effectiveness factor, this factor takes into account the spacing and the arrangement of the stirrups in the section, and ω_ω was the volumetric transverse reinforcement ratio [13] Section 5.4.3.2.2 (8)); and (d) the steel fiber content.

In the experimental program each parameter studied ranges as follows:

- Concrete strength (f_c). Nominal strengths of 30 and 75 MPa were chosen.
- Relative normal force (ν). The following three levels were considered: 0.10 and 0.35.
- Shear slenderness ratio (λ_V). Values of 5.77 and 10.71 were taken into account. Second-order effects cannot be neglected in either case, and the values chosen are greater than those included in the literature.
- Longitudinal reinforcement ratio (ρ_l). Two similar values were considered: 1.44% if $\lambda_V = 10.71$ and 1.74% if $\lambda_V = 5.77$.

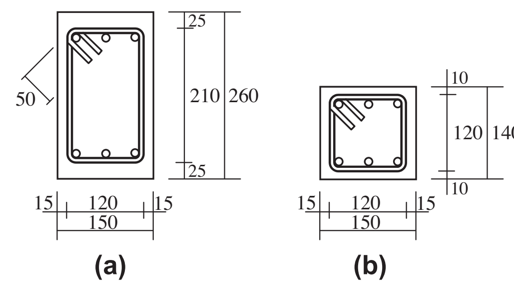

Fig. 2. Cross-section details (unit: mm).

- Effective volumetric mechanical ratio of confinement ($\alpha \cdot \omega_\omega$). Three levels were taken into account: high (0.05), medium (0.02), and low (0.01). Given a transverse reinforcement diameter $\phi_t = 8$ mm: (a) $\alpha \cdot \omega_\omega = 0.05$ was obtained for HSC assuming a transverse reinforcement spacing (s_t) of 50 mm if $\lambda_V = 5.77$, and $s_t = 70$ mm if $\lambda_V = 10.71$, and for NSC with $s_t = 100$ mm if $\lambda_V = 5.77$; (b) $\alpha \cdot \omega_\omega = 0.02$ was obtained for HSC with $s_t = 100$ mm if $\lambda_V = 5.77$; and (c) $\alpha \cdot \omega_\omega = 0.01$ taking $s_t = 600$ mm if $\lambda_V = 5.77$ for both HSC and NSC. The latter level is considered for analysis if it is possible to replace the transverse reinforcement with steel fibers, for cases with larger volume of steel fibers.
- Steel fiber content: 30 and 60 kg/m^3, corresponding to volumetric steel-fiber ratios of 0.38% and 0.76% respectively.

Table 1 shows the details of the 15 specimens included in the experimental program.

All specimens were tested at 28 days. To determine the average concrete compressive strength three cylinders (150 × 300 mm) [31] were tested for each specimen (see Table 1).

2.1. Material properties

Cement Portland CEM I 52,5R [33], and crushed limestone gravel with sizes ranging from 4 to 7 mm were used. The dosages considered are listed in Table 2.

The steel used was B 500 SD [11], and C class [12]. The results of the characterization tests following UNE EN-10002-1 [30] are shown in Fig. 3. To determinate the average values of the steel mechanical properties two pieces of reinforcing steel were tested for each nominal diameter.

The steel fibers used were DRAMIX RC-65/35-BN, with aspect ratio $l/d = 35/0.55 = 63.63$, and 1100 MPa tensile strength for NSC, and DRAMIX RC-80/40-BP, with aspect ratio $l/d = 40/0.50 = 80$, and 2600 MPa tensile strength for HSC. A greater tensile strength for HSC has been chosen to ensure that the failure is due to a loss of bond-slip in the steel fibers, because the bond strength between steel fibers and concrete increases with the concrete strength. A 550 × 150 × 150 mm prismatic specimen was made for each mixture, and a 3-point bending test was performed complying with

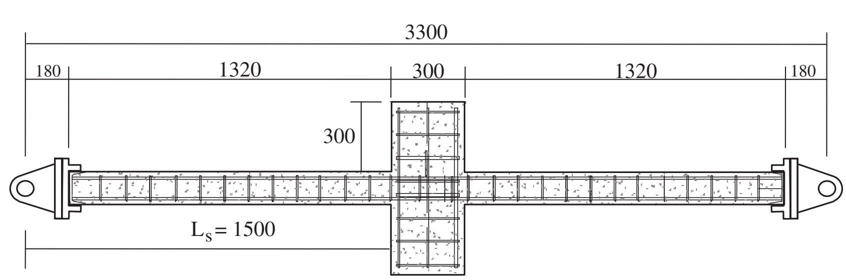

Fig. 1. Dimensions of test specimens (unit: mm).