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Behaviour of steel-fibre-reinforced normal-strength concrete slender columns under cyclic loading

K.E. Caballero-Morrison, J.L. Bonet *, Juan Navarro-Gregori, J.R. Martí-Vargas

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

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ABSTRACT

The inclusion of ductility requirements is necessary to guarantee the safety design of any concrete structure subjected to unexpected and/or reversal loads. It is important to outline that plastic hinges may be developed in columns of reinforced concrete buildings, especially in column-foundation joints. The deformation capacity of the column depends on its slenderness. However, few experimental tests of normal and fibre-reinforced concrete columns in the range of medium slenderness (between 5 and 10) have been performed for the case of cyclic loading. This paper presents an experimental research study on the behaviour of slender columns subjected to combinations of constant axial and lateral cyclic loads. In order to study the behaviour of this type of element fourteen experimental tests were performed. The experimental results make it possible to calibrate numerical models, and to validate simplified methods. The following variables are studied: slenderness, axial load level, transverse reinforcement ratio, and volumetric steel-fibre ratio. The maximum load and deformation capacity of the columns are analyzed. It is interesting to note that the deformation capacity depends on the four test variables analyzed. Moreover, the inclusion of steel fibres into the concrete mixture increases the deformation capacity. The inclusion of a minimum transverse reinforcement is required in order to improve the effectiveness of the steel fibres. Thus, the column behaviour suffers moderate strength losses due to cyclic loads. Finally, slenderness influences the deformation capacity if second-order effects are important, the cross-section displays ductile behaviour, and the capacity of the materials is reached.

1. Introduction

Structures with ductile behaviour have the capacity to absorb and dissipate energy under accidental loads, without a significant loss of strength. This inelastic behaviour is due to the development of plastic hinges. The capacity of ductile structures to dissipate energy is taken into account in the seismic design of concrete structures. Nowadays, the criterion of capacity-based design (EC-8 [14], FEMA P-750 [17]) is used in the seismic design of structures. This criterion is based on the protection of the fragile elements and regions of the structure, which are strengthened in comparison to the ductile ones. As a result, ductile failure mechanisms can be reached more easily. For this reason, it is necessary to guarantee that plastic hinges are developed earlier in the beams than in the columns ('strong column – weak beam'). However, according to ACI 441R-97 [3], it has been stated that hinges should appear at the ends of the columns after an earthquake [20]. Consequently, reinforced concrete columns have to provide an important inelastic response without a significant decrease of strength capacity, particularly in bridge columns or in column-foundation joints.

In order to guarantee the ductile behaviour of the columns, EC-8 [14], and ACI-318(08) [1] codes specify the transverse reinforcement ratio to be included in critical zones where a plastic hinge could be developed. For high levels of axial force it is necessary to include a significant amount of transverse reinforcement. This may cause difficulties while concrete is being cast. A possible solution to this problem [29] is adding steel fibres to the concrete mixture. The combined use of steel fibres and transverse reinforcement can reduce the transverse reinforcement ratios required by design codes, particularly in the case of seismic design. However, the expressions proposed in the codes disregard the favourable effect of steel fibres (EC-8 [14], ACI-318(08) [1]).

Several authors have studied the behaviour of fibre-reinforced normal-strength concrete (e.g. [16,15,25]). These studies show the typical stress-strain constitutive equations of the concrete in compression, in which the inclusion of steel fibres represents a minor increase in peak stress, a significant increase in the strain corresponding to peak stress, and a substantial toughness increase. This is reflected in an increase of the total energy the material absorbs prior to failure. Recent research (e.g. [18,4,9,28]) has shown that the presence of steel fibres delays concrete spalling, and increases the deformation capacity of concrete columns subjected to compressive axial load, or combinations of axial load and

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

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constant eccentricity. Lately, several design codes (NZS 3101: Part: 2006 [31], CNR-DT 204/2006 [12], ACI-318(08) [1], EHE-08 [11], ACI 544.4R-88 (Reapproved 2009) [2], MC-2010 [21] among others) have included prescriptions concerning the use of fibre-reinforced concrete such as description of materials properties, design procedures or detailing provisions.

There are numerous publications concerning the study of the strength and deformation capacity of columns under cyclic loading [8,10]. Experimental tests available are focused on reinforced concrete columns (without fibres) with shear slenderness (λ_V) below 6.5 [27]. Laboratory tests of steel-fibre concrete columns subjected to combination of axial and lateral loads have not been reported so far.

Second-order effects (P–Δ effects) have an influence on the deformation capacity of slender columns [5], and there is also a lack of experimental work on columns with slenderness over 6.5. As a result, it is necessary to study the load and deformation capacities of reinforced concrete slender columns subjected to constant axial load combined with monotonic or cyclic lateral loads.

In this research work an experimental program is presented to fill the gap existing in the literature on slender normal-strength concrete column tests, including or excluding steel fibres, under constant axial and cyclic loads.

In order to analyze the effect of confinement and the inclusion of steel fibres, the variables considered in the test program are the axial load level and the slenderness of the column. The experimental tests provide results on the general behaviour, deformation, energy dissipation, and strength capacity of the column. In addition, the results make it possible to calibrate numerical models, and to validate simplified methods proposed in the codes.

2. Test program

Test specimens were designed to represent two semi-columns of two adjacent storeys connected by a central element (stub). This can simulate the stiffening effect of an intermediate slab, or a column-foundation joint represented by the central element of the specimen. Fig. 1 shows the geometric details of the specimens. The length of each semi-column (L_s) is greater than the potential length of a plastic hinge (ACI-318(08) [1], EC-8 [14]). Fig. 2 shows cross-section details of the semi-columns. This type of specimen has already been employed by Yamashiro and Sies [37], Priestley and Park [30] and Barrera et al. [7] among others.

The distribution of the longitudinal reinforcement remains constant along the specimen. The ratio between the mechanical concrete cover (distance from the centroid of the tensile bar to the outer surface of the concrete) and the total depth of the section is 0.15. All the stirrups were anchored with 135° bends extending 50 mm (6.25ϕ_t, where ϕ_t is the nominal diameter of the stirrup) into the concrete core. This length satisfies the requirements of EC-2 [13] (5ϕ_t > 50 mm) and ACI-318(08) [1] (6ϕ_t), even though it is less than the minimum length reported in ACI-318(08) [1]

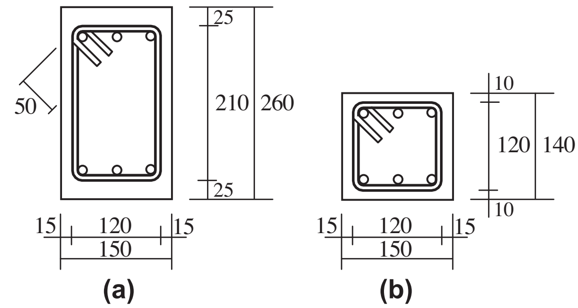

Fig. 2. Cross-section details (unit: mm).

for the case of seismic actions (76 mm). Spanish code EHE-08 [11] does not take this design detail into account.

The parameters analyzed are: (a) shear slenderness ($\lambda_V = L_s/h = M/(V \cdot h)$, where h is the total depth of the cross-section, M and V are the bending moment, and the shear load applied); (b) the relative normal force ($\nu = N/[b \cdot h \cdot f_c]$, where N is the axial load applied, b is the width of the cross-section, and f_c is the concrete compressive strength); (c) the confinement effectiveness of the transverse reinforcement ($\alpha \cdot \omega_\omega$, where α is the confinement effectiveness factor, this factor takes into account the spacing and the arrangement of the stirrups in the section, and ω_ω is the volumetric transverse reinforcement ratio (EC-8 [14] Section 5.4.3.2.2)); and (d) the steel-fibre content.

In the experimental program each parameter studied ranges as follows:

- Concrete strength (f_c). A nominal strength of 30 MPa has been chosen.
- Shear slenderness ratio (λ_V). Values of 5.77 and 10.71 have been taken into account. Second-order effects cannot be neglected in either case, and the values chosen are greater than those reported in the literature. EC-8 [14] code can be applied to columns with shear slenderness below 10. Columns with slightly higher ratios than those reported in this code are analyzed.
- Relative normal force (ν). The following three levels have been considered: 0.10, 0.35 and 0.55. The minimum and maximum values correspond to the limits in accordance with EHE-08 [11], EC-8 [14], and ACI-318 (08) [1]. In EC-8 [14] code it is stated that the relative normal force cannot exceed 0.65 when designing columns with medium-ductility (DCM), and 0.55 for the case of high-ductility (DCH). Moreover, according to EHE-08 (Annex 10) [11], and ACI-318(08) (21.6.1) [1], the minimum relative normal force to be considered in columns under seismic actions is 0.10.
- Longitudinal reinforcement ratio (ρ_l). Two similar values have been considered: 1.44% if $\lambda_V = 10.71$ and 1.74% if $\lambda_V = 5.77$. The objective is to compare the deformation capacity in all tests while the other parameters remain constant.

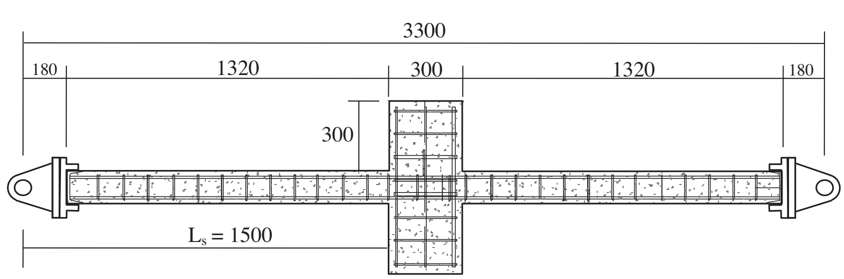

Fig. 1. Dimensions of test specimens (unit: mm).