Deformation capacity of column-beam union with SMA reinforcements

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Abstract: The use of new materials in construction world is being more and more widespread currently. This research tries to study the deformation capacity of the column-beam union in structural frames experimentally. The results of two specimens are shown, one made with steel reinforcements and another with SMA-NiTi reinforcements. The deformation capacity of NiTi reinforced specimen is higher than the steel reinforced one, unlike load capacity.

Keywords: SMA, deformation capacity, union.

1 Introduction

The design codes \cite{1,2} aim to improve the deformation capacity of structures, to overcome the effects of earthquakes on the structures, by forming plastic hinges in the critical regions. These hinges must be formed in the beams (strong column and weak beam). However, according to ACI 441R-96 (1996) \cite{3}, the hinges end up appearing at the ends of the columns during the earthquake. As a consequence, reinforced concrete columns have to offer an important deformation capacity (ductility) maintaining the strength capacity.

An option to improve ductility is the addition of steel fibers in concrete \cite{4-7}. These authors verified that the addition of steel fibers causes an increase of the total dissipated energy before the failure, smaller damage and a greater deformation capacity under compressive axial loads, or even under axial loads with eccentricity. In this context, Very-High-Performance Concrete (VHPC) is suitable concrete to use because of its high fiber content and ductility. In addition, Shape Memory Alloys (SMA) - Nickel and Titanium alloy (NiTi) \cite{8-10} can improve the ductility of the structure if the longitudinal steel passive reinforcements are replaced by SMA bars in the critical areas (Saïdi et al. (2015) \cite{11}, Bonet et al. (2016) \cite{12}).

Therefore, the objective of this article is to study the influence of replacing steel reinforcements by NiTi bars in the critical region of a VHPC column.

2 Experimental program

2.1 Specimens

Test specimen was designed to represent two semi-columns of two adjacent stories connected by a central element (stub) subjected to a constant axial load and a cyclic lateral load. The stub can simulate the effect of an intermediate slab, beam or column-foundation joint.
Figure 1 shows the geometrical details. Shear slenderness ratio ($\lambda_V = L_s/h$, where $h$ is the total depth of cross section) is equal to 5.77. The relative normal force applied ($\nu = N/[b \cdot h \cdot f_{cm}]$, where $N$ is the axial load applied, $b$ is the width of the cross-section, and $f_{cm}$ is the mean concrete compressive strength) is 0.2. Transverse reinforcement spacing is 10. The support was subjected to combined efforts of constant axial load and cyclic lateral load. In the connection zone, the B-500SD bars are replaced by NiTi bars, being joined by shear screw coupler connectors. The length of the NiTi bar is 750 mm. 150 mm are within the stub zone. The zone of the support where there were not NiTi bars, was reinforced with additional steel bars of 16 mm diameter to guarantee that the failure occurs in the area with NiTi bars.

Figure 1: Specimen details (a) Dimensions; (b) Longitudinal reinforcement; (c) Cross-section details. Unit: m.

2.2 Material characterization
The VHPC has an average compressive strength in the cylindrical specimen of 300x150 mm of 118.78 MPa (UNE-EN 12390-3 [13]). The elasticity modulus of concrete is 47905 MPa, the limit of proportionality in the flexural tensile strength test is 11.84 MPa, $f_{R1}$ is 19.83 MPa and $f_{R3}$ is 14.01 MPa (measured on 550 x 150 x 500 mm prisms according to UNE EN 14651: 2007 [14]). Steel rebars used in the critical zone are 12 mm diameter and they have an elasticity modulus of 193818 MPa and a yield stress of 562.58 MPa (UNE EN-10002-1 (2002) [15]).

As for the NiTi bars, they are 12 mm with the polished surface. The four transformation temperatures are determined in accordance with the ASTM F2004-05 (2010) [16] standard: $M_f$ = -49.15°C, $M_s$ = -31.23°C, $A_s$ = -20.75°C and $A_f$ = -7.70°C. The austenitic modulus at the temperature of the test room (27-30 °C) is 64647 MPa, the martensitic modulus is 2104 MPa, the stress at the start of the martensitic transformation is 450.21 MPa, and the stress of the end of martensitic transformation is 609.83 MPa for a strain of 65.6%.

2.3 Test procedure
First, the horizontal load corresponding to the relative normal force is applied and kept constant during the test. The lateral load is then applied with displacement control and a constant speed of 0.2 ± 0.05 mm/min. The test sequence of displacement controlled cycles is expressed in terms of drift ratio ($\Delta/L_s$). For each drift ratio ($0.5 - 0.75 - 1 - 1.5 - 2 - 2.5 - 3 \ldots$) three complete cycles are performed. The drift ratio $\Delta/L_s$ is obtained as a quotient between the displacement at the end of the column $\Delta$ and the length of the half-column $L_s$ [6].
3 Test results and observations

Figure 2 shows the experimental lateral load - drift ratio results. In these curves, the cycles until the specimen undergoes 20% loss of strength capacity (0.8 · $V_{max}$ or 0.8 · $V_{min}$) are represented with a continuous black line. For the rest of the cycles a continuous gray line is used.

Figure 2: Experimental lateral load – drift ratio curve.

3.1 Deformation capacity.

The envelopes of each loading direction were obtained from the lateral load - drift ratio responses. The average envelope was also obtained. To determine the deformation capacity of the specimens, an idealized bilinear diagram of the experimental envelopes used by Caballero Morrison (2013) [6], Pam and Ho (2009) [17] and Paultre et al. (2001) [18] is employed. This diagram is formed by a growing elastic branch and a decreasing inelastic branch (Figure 3). The elastic branch passes through the origin and the point corresponding to 75% of the load and ends at the maximum lateral load value. The decreasing inelastic branch begins at the point at which the elastic branch ends and ends at the point defined by a displacement for a loss of strength of 20% and by the theoretical load obtained after performing the equality of areas of the idealized and experimental curves.

The ultimate displacement ductility is defined as $\mu_{\Delta u} = \Delta_u / \Delta_{y1}$ where $\Delta_u$ is the ultimate displacement of the column corresponding to 0.80 of the maximum load in the descending branch and $\Delta_{y1}$ is the effective elastic displacement. The result of the ultimate ductility was $\mu_{\Delta u} = 5.52$.

3.2 Effect of SMA bars inclusion.

The effect of replacing steel bars with SMA NiTi bars in the critical region of the specimen is analyzed. The VHPC-V02S100 specimen is compared with the specimen AS11-3 analyzed by Castro (2016) [7]. This specimen had the same mechanical and geometric characteristics than the VHPC-V02S100 specimen. The dosage used for the manufacture of the VHPC is the same in both specimens. The mean compressive strength in a cylindrical specimen is $f_{cm}$ is 119.35 MPa in the specimen AS11-3 and 118.78 MPa in the specimen VHPC-V02S100.

Table 1 shows the differences between both specimens from the point of view of strength capacity (maximum lateral load ($V_{max}$)), as well as deformation capacity (displacement ductility ($\mu_{\Delta u}$)).
4. Conclusions.

The conclusions drawn from this research are described in this section:

A column-beam union made of Very-High-Performance Concrete (VHPC) and both NiTi bars in the critical zone and steel bars in the rest has been compared with the analogous column made of VHPC and only steel reinforcements. The substitution of the steel bars, which had a yield stress of 528.03 MPa, by SMA NiTi bars whose forward martensitic transformation begins at the stress $f_A = 450.2$ MPa, implied a loss of strength capacity of less than 10%, while the displacement ductility increased by more than 65%. Specimen displayed low damage after performing the load cycles.

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