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Buckling of steel and Ni-Ti reinforcements in very high performance concrete (VHPC) elements

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HIGHLIGHTS

- 10 VPHC columns with steel reinforcements were tested to study bar buckling.
- 2 VPHC and 2 HPC columns with Ni-Ti reinforcements were tested to study bar buckling.
- Columns with both Ni-Ti and steel reinforcements were compared.
- VHPC showed adequate to delay local buckling of compressed reinforcements.
- The model to evaluate bar buckling was extended to consider VHPC columns.

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ABSTRACT

Nowadays, the use of new materials is becoming increasingly common in the construction world due to their improved properties. High or Very High Performance Concrete (HPC or VHPC) and Shape Memory Alloys (SMA), specifically those composed of nickel and titanium (Ni-Ti), are some of these new materials. The low austenitic modulus of Ni-Ti as regards the elasticity modulus of steel (40–65 GPa instead of 200 GPa) can cause local buckling. In order to replace steel bars with Ni-Ti bars in reinforced concrete elements, it is convenient to use concrete with a high steel fibre content to delay local bar buckling. Hence employing either High Performance Concrete or VHPC may be appropriate, due to its composition with a high steel fibre content.

For all these reasons, VHPC elements with Ni-Ti reinforcements were studied. The results of an experimental campaign of VHPC columns are shown in this article. The VHPC columns were subjected to monotonic loading where the main goal was to study compressed steel reinforcement buckling. The results of these tests were also used to extend the mixed model proposed by Pereiro-Barceló and Bonet (2017), which determines the buckling critical stress for any transverse reinforcement separation and considers the effect of the concrete cover (with and without steel fibres). This model was recalibrated to consider elements made of VHPC. Besides, specimens made of either High Performance Concrete (HPC) or VHPC, and with Ni-Ti reinforcements, were also tested to study the behaviour of compressed Ni-Ti reinforcements in elements made of high strength fibre-reinforced concrete.

1. Introduction

Compressed reinforcements buckling can reduce the expected ductility, which is why several research works on this matter are currently being conducted [1–4]. Accordingly, design codes limit tie spacing [5–8]. However, these codes do not take into account the positive effect of concrete with a fibres cover to delay buckling. The cover of concrete with fibres can remarkably delay compressed reinforcements buckling depending on fibres content [3,9,10]. These authors proposed different methods to determine the critical buckling load of compressed reinforcements by taking into account the positive effect of the fibre-reinforced concrete cover. In his formulation, Dhakal [9] considered transverse reinforcement and the concrete cover placed discretely at the stirrups position. This method is valid for small tie spacings. Campione [10] considered both transverse reinforcement and concrete cover distributedly along the region involved in instability. This method is valid for both small and very large tie spacings. However, Pereiro-Barceló

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Notation

f_c	nominal concrete compressive strength on cylindrical test piece
f_{cm}	average concrete compressive strength on cylindrical test piece
E_c	concrete elasticity modulus
ε_{c85}	strain that corresponded to a stress of 0.85 f_{cm} denoted after the peak load (measured on the softening branch)
f_{LOP}	limit of proportionality in the flexural tensile strength test
$f_{R,i}$	residual tensile strengths
$f_{R,1}$	residual tensile strengths that correspond to the Crack Mouth Opening of 0.5 mm
f_y	yield stress of steel bar
ε_y	the strain that corresponds to the yield stress of steel bar
f_{sh}	stress at which the hardening branch begins of steel bar
ε_{sh}	strain associated with f_{sh}
f_u	maximum stress of steel bar
ε_u	strain associated with the maximum stress of steel bar
E_s	elasticity modulus of steel bar
s	tie spacing of transversal reinforcement
D	diameter of the longitudinal reinforcement
M_s	temperature at which the transformation from austenite to martensite begins on cooling
$\mathrm{M_f}$	temperature at which the transformation from austenite to martensite finishes on cooling
$\mathrm{A_s}$	temperature at which the transformation from martensite to austenite begins on heating
$\mathrm{A_f}$	temperature at which the transformation from martensite to austenite finishes on heating
ν	normalised vertical load
N	load applied by the hydraulic actuator
A_c	gross area of the section
ε_l	longitudinal reinforcement strain in the zone where compressed bar instability took place
Δ	displacement at the midspan of the specimen
L_{tot}	distance between load hinges of the specimen
N_{max}	maximum applied axial load
N_c	applied axial load in the instability situation of compressed bar
Δ_c	horizontal displacement at midspan of specimen in the instability situation of compressed bar
ε_{crit}	compressed bar strain in the instability situation of compressed bar
$\varepsilon_{crit,\eta\leqslant 1}$	buckling strain of the compressed bar that buckle between the stirrups
σ_{crit}	compressed bar stress in the instability situation of compressed bar
$\varepsilon_{crit,model}$	critical compressed bar strain calculated with the mixed model
σ_{crit}	critical compressed bar stress calculated with the mixed model
E_r	reduced modulus of the longitudinal reinforcement
I	inertia moment of longitudinal reinforcement
A	transverse reinforcement area
c_c	critical adimensional stress
α_s	transverse reinforcement axial stiffness
$\alpha_{s,y}$	transverse reinforcement axial stiffness on the plastic branch
α_c	concrete cover axial stiffness
γ	relation between transverse reinforcement axial stiffness α_s and the bending stiffness of longitudinal bar E_rI
k_{cs}	relation between concrete cover axial stiffness α_c and transverse reinforcement axial stiffness α_s
E_{sw}	tangent modulus of transverse reinforcement
A_{sw}	transverse reinforcement area
L_{ef}	effective transverse reinforcement length
η	relation between length of the longitudinal bar where compressed bar instability takes place and transverse reinforcement separation

and Bonet [3] considered the concrete cover distributedly and transverse reinforcement discretely, which is why this model is valid for any tie spacing. These authors also considered the degradation of the concrete cover. Their proposed model was calibrated for normal strength concrete (NSC), with and without fibres.

Due to the fact that concretes with fibres delay buckling, VHPC can be a suitable concrete for this purpose because it has a high fibre content [11]. In addition, its high strength confers more adherence to fibres with the concrete matrix. Its strength oscillates between 100 and 150 MPa [12], it shows high ductility on the post-peak branch under compression [13], and it develops high flexural tensile strength [12] and high strength and ductility under direct tension [12] compared with either Fibre-Reinforced Normal Strength Concrete (FRNSC) or Fibre-Reinforced High Strength Concrete (FRHSC), which is also called High Performance Concrete (HPC). Several authors have concluded that using concretes with fibres, specially VHPC, could increase the ductility of elements [14–20].

At the same time, several research works [21,22] have studied the possibility of replacing steel longitudinal bars with shape memory alloy (SMA) nickel – titanium based (Ni-Ti) in the critical zones of structures. The aim here is to reduce residual displacements, increase ductility and to gain an energy dissipator element. Ni-Ti alloys are materials characterized by changing into two crystallographic phases, austenite and martensite, by their temperature or stress-strain state being modified. This fact explains the two main properties of Ni-Ti: shape memory effect and superelasticity. Shape memory is the phenomenon by which Ni-Ti changes its crystallographic phase after heating and can recover a predefined shape. Superelasticity is observed when, starting in the austenite phase, martensite is induced by stress increment. When stress disappears, the austenite phase is recovered, as is its original shape [23–26]. These two properties, and their high ductility and damping capacity, make Ni-Ti a suitable material to be applied in structural engineering [27–36]. Nonetheless, the elasticity modulus of this material (between 40 and 60 GPa) is approximately 3 and 4 times lower than conventional steel (200 GPa), which can result in local bar buckling. This phenomenon has not been studied much for Ni-Ti. Only tests on isolated Ni-Ti bars subject to compression are available. Rahman et al. [37] and Rahman and Tani [38] tested Ni-Ti wires (2 mm diameter) under compression and concluded that the bars showed two instability points. After buckling, the Ni-Ti bars were able to elevate the supported load because stiffness increased when the Ni-Ti reached the martensitic region. Finally, the bar reached a second instability point and the supported load decreased due to second-order effects. Pereiro-Barceló and Bonet [4] tested 12 mm-diameter bars and also found two instability points in the least slender specimens. They proposed a method to modify the constitutive equation under compression of SMA bars to consider buckling according to on an analytical procedure and experimental results.

One possible solution for delaying the buckling of compressed reinforcements in concrete elements is to use concrete with steel fibres. In addition, as the strain at which the martensitic transfor-