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Original Research Article

Theoretical and experimental in-service long-term deflection response of symmetrically and non-symmetrically reinforced concrete piles

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ABSTRACT

Reinforced concrete piles employed in earth retaining systems are typically designed with symmetric reinforcement. The non-symmetric RC wall piles have recently been introduced by the authors, obtaining savings of up to 50% in weight in longitudinal reinforcing steel compared with the traditional solutions, leading to significant financial savings while also reducing associated environmental impacts.

The structural behavior of this new RC member under long-term loading is studied, comparing it with its symmetrical counterpart. An experimental campaign has been carried out. Full scale specimens with circular cross sections symmetrically and asymmetrically reinforced were tested. Results have shown that asymmetrically RC pile developed a slightly higher deflection than its symmetrical counterpart. A new expression for the effective area of concrete in tension applicable to non-symmetrical piles is introduced. Moreover, a new stress–strain law for cracked concrete that accounts the tension stiffening effect for long-term loading is proposed. Finally, for non-symmetrical RC wall piles, the evolution of the parameter that takes into account the duration of loading in deformations is presented. Although more evidence is needed, it is shown that tension stiffening effect contribution could be overestimated by Eurocode 2 in the case of non-symmetrically or underestimated in case of symmetrically RC piles.

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Nomenclature

A_c	area of concrete
$A_{c,eff.}$	effective area of concrete in tension
A_s	area of steel
$A_{Ø}$	area of steel rebar
E_c, E_{cm}	concrete elastic modulus
$E_{c,eff}$	effective elastic modulus of concrete
E_s	steel elastic modulus
I_{uncr}, I_{cr}	second moments of area of the uncracked and fully cracked transformed cross sections about the horizontal principal axis of inertia
M	bending moment
M_{cr}	cracking bending moment
N	axial load
N_{cr}	cracking axial load
R	cross section radius
$R_{hc,effint}$, $R_{hc,effext}$	radius of the internal and external circles that limit the circular strip of $A_{c,eff.}$
R_{int}	radius of the circle that contains the center of gravity of the rebar
TSz	tension stiffening zone, height of the portion of cross section below the fiber whose deformation is ε_{ctm}
TSz_{top}	portion of TSz located between the mechanical cover and the fiber whose deformation is ε_{ctm}
c	mechanical cover
f_{ck}	characteristic concrete compressive strength
f_{cm}	average concrete compressive strength
f_{ctm}	average concrete tensile strength
f_y	steel yield limit stress
h_1	distance that defines the position of the centroid of the tensioned reinforcement
$h_{c,eff}$	width of the circular strip composing the effective area of concrete in tension
$h_{c,effint}$, $h_{c,effext}$	each of two portions in which $h_{c,eff}$ is divided interior and exterior
n	coefficient of equivalence
t	time
x	position of neutral fiber in the cross section
x_{cr}	neutral fiber depth corresponding to the cracking moment
y	vertical coordinate measured from center of gravity of gross section
$y_{\varepsilon ctm}$	vertical coordinate of the fiber whose strain is ε_{ctm}
α	deformation parameter
α_I,α_{II}	deformation parameter corresponding to uncracked and fully cracked conditions
$\alpha_{hc,effint}$, $\alpha_{hc,effext}$	angular coordinate of the radio vector of the intersection of the interior/exterior circle defining $A_{c,eff}$ and the fiber whose strain is ε_{ctm}
$\alpha_{\varepsilon ctm}$	angular coordinate of the fiber whose strain is ε_{ctm}
β	coefficient taking account of the influence of the duration of the loading
δ	deflection at midspan
δ_{exp}	experimental deflection at midspan
ε	strain
ε_{ap}	apparent yield strain
ε_{cg}	strain at center of gravity of the gross section
ε_{ctm}	concrete limit strain of cracking
ε_{sh}	free shrinkage strain
ε_y	steel yield limit strain
θ	angular coordinate
ξ	distribution coefficient
ρ	reinforcement ratio
σ_c	uncracked concrete stress
σ_{cr}	cracked concrete stress
σ_{cTS}	concrete tension stiffening stress
σ_{crTS}	concrete tension stiffening stress for long-term loading
σ_s	steel stress
σ_{sr}	steel stress calculated on the basis of a cracked section under the loading conditions causing first cracking
ϕ	curvature
ϕ_{cr}	cracked curvature
$\phi_{sh,cr}$	shrinkage-induced curvature on the fully-cracked cross-section (for zero applied load)
$\phi_{sh,uncr}$	shrinkage-induced curvature on the uncracked cross-section (for zero applied load)
ϕ_{uncr}	uncracked curvature
φ	Creep coefficient
Ø	rebar diameter

1. Introduction

Up to date, many research works about optimization in reinforced concrete structures have been published [1–5]. Despite of this fact, in civil engineering, traditional solutions have gained vast experience over the years and, due to this, a new structural element must have an extensive theoretical and experimental background before its widespread use. One of these new structural elements are the wall piles using non-symmetrically longitudinal reinforced cross section (henceforth NSRCS) proposed by Gil-Martín et al. [6] and Hernández-Montes et al. [7] and patented by the University of Granada. In comparison with the symmetrically reinforced concrete pile (henceforth SRCS), whose reinforcement consists of steel bars of the same diameter uniformly spaced around the circumference of the section, in the NSRCS, bar diameters and spacing can vary. Non-symmetrical wall piles can lead to savings of up to 50% in weight in reinforcing of longitudinal steel. As explained in [6], the method of optimization is based on the addition of thick bars at the minimum distance allowed by the design code until the required ultimate bending strength is achieved. Other methods of optimization as in [8–10] could be employed.

After theoretical studies [6,7], tests carried out in the lab and the instrumentalization of several specimens built on trial sites [11] have confirmed that these perform well. This structural element has begun to be used in works such as the retaining walls of the underground floors of Sant Antoni Market in Barcelona in 2014, and in the metro of Riyadh (Fig. 1),