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Numerical study of confinement effectiveness in solid and hollow reinforced concrete bridge piers: Analysis results and discussion

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ABSTRACT

This paper presents the outcome of a large parametric numerical analysis of solid and hollow reinforced concrete piers taken from actually constructed bridges, based on a consistent three-dimensional nonlinear finite element methodology that was presented in a companion paper. Various transverse reinforcement arrangements and spacings were examined, as well as the effect of high-strength concrete on confinement effectiveness. The interpretation of numerical results mainly focuses on identifying the most convenient confinement configurations in terms of enhanced strength and ductility, as well as ease of construction and cost effectiveness. Furthermore, issues regarding confinement arrangements (often used in practice) that result in reduced section ductility are investigated and possible remedies are suggested. Finally, the broad applicability of the proposed methodology is established by application to a particularly complex (in terms of geometry and reinforcement detailing) hollow pylon section.

1. Introduction

The issue of confinement effectiveness in reinforced concrete (R/C) vertical members has been studied both experimentally and analytically in the past decades. Experimental studies on confined concrete columns of solid section (e.g. [1–3]) showed that the favourable effect of passive confinement depends on various parameters, the key ones being transverse reinforcement strength, amount, spacing and configuration. Calibrated against these experimental results, numerous empirical confinement models have been suggested (e.g. [4–7]), providing 'confinement effectiveness' factors for upscaling the uniaxial monotonic stress–strain relationship of unconfined concrete in terms of strength and deformation capacity, thus implicitly accounting for the triaxial stress state induced by the restrained (due to confinement reinforcement) expansion of concrete. However, the extension of the above models to hollow sections (often adopted in R/C bridge piers) is not straightforward due to their non-standard geometry and the limited experimental support used for their calibration, which mainly focuses on lateral (e.g. [8,9]) rather than axial loading. In order to overcome these limitations, recent studies introduce the application of three-dimensional nonlinear finite element analysis, aiming to explicitly capture the triaxial nature of passive confinement (e.g. [10–12]). Nevertheless, the available literature is still limited to analysis of solid sections and, additionally, there are large discrepancies between suggested constitutive laws and modelling techniques.

In order to extend the applicability of three-dimensional nonlinear finite element analysis to reinforced concrete sections of arbitrary shape and transverse reinforcement configuration, a consistent methodology was presented in a companion paper [13], together with a broad discussion on various modelling and post-processing issues. Moreover, a large parametric model setup, including circular and rectangular piers of solid and hollow section, based on actually constructed bridges across the Egnatia highway in northern Greece was deployed, consisting of 183 different configurations in terms of transverse reinforcement arrangement, spacing, and concrete strength (normal and high). In this paper, the results of this parametric numerical analysis are presented and discussed, mainly with a view to identifying the most convenient confinement configurations in terms of enhanced strength and ductility, as well as ease of construction and cost effectiveness. Furthermore, issues related to confinement arrangements that (although used in several existing bridges) result in reduced section ductility, are investigated and possible remedies are suggested. Finally, in order to verify the applicability of three-dimensional nonlinear finite element analysis to studying confinement, the proposed methodology is applied to a non-standard, complex in terms of geometry and reinforcement detailing, hollow pylon section, taken from the Rion-Antirion cable-stayed bridge in southern Greece.

2. Solid and hollow circular sections

The first part of the parametric analysis included circular piers of solid and hollow section with various transverse reinforcement

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arrangements. A smaller group was also solved for high-strength concrete (C50/60). The finite element modelling procedure was covered in the companion paper [13], however the full model list is provided here in compact form (Table 1), for easy reference. Solid sections are prefixed by 'CSS' and hollow sections by 'CHS1' and 'CHS2', corresponding to 30 cm and 45 cm wall thickness, respectively. Models of plain concrete piers and with longitudinal reinforcement only (unconfined) were also solved for the derivation of confinement effectiveness indices (described in Section 2 of the companion paper [13]).

Fig. 1 shows a typical capacity curve (axial load vs. axial strain) for a hollow section model (CHS2-06), accompanied with all post-derivations according to the suggested methodology. Fig. 2 shows two typical histograms of confinement indices K_R (strength) and K_{W85} (ductility based on energy, see Fig. 4 in [13]) for the complete range of confined CHS2 models. A thorough presentation of all analysis results cannot be accommodated here and can be found in [14]. Nevertheless, from the interpretation of all available numerical data for circular models, the main conclusions are discussed in the following:

– The difference in confinement effectiveness between spirals and circular hoops is marginal. A minor advantage of hoops is recorded due to their perfectly horizontal arrangement that coincides with the concrete expansion plane, as opposed to the slightly inclined spirals (by angle $\tan^{-1}[s/(d-2c)]$). This is depicted in the stress contours of Fig. 3, where the effectively confined region in the case of spirals appears asymmetric, especially for larger spacings (20 cm). Nevertheless, the use of spirals is preferred in practice, due to ease and speed of construction.
– In circular hollow sections, it was observed that the presence of an inner spiral (or hoop) does not significantly contribute to the strength and ductility of the confined section. Particularly in the thicker hollow section (CHS2), the addition of an inner spiral led to reduced ductility, compared to the sole presence of an outer spiral. A snapshot of the axial stress state (at ultimate strength) for this section (Fig. 4) shows that the inner spiral unfavourably confines only the inner concrete cover, leaving an unconfined ring-shaped region around the inner spiral. As a result, the inner concrete cover tends to crack and spall off at high levels of axial strain (implosion), leading to the observed reduced ductility. This adverse effect can be referred as 'negative confinement'. Since there is generally no contribution in terms of strength and ductility from the use of inner transverse reinforcement, the respective economic indices suggest an uneconomical solution due to the larger steel volume required. Nevertheless, it is common practice, especially in Europe, to apply a sparsely spaced inner spiral in circular hollow sections, in order to control cracking due to environmental effects (serviceability limit state).

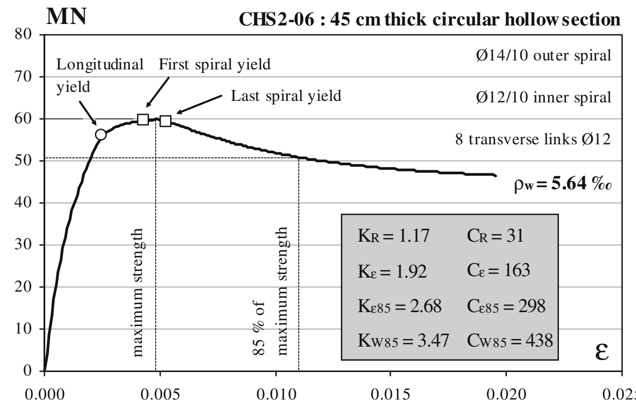

Fig. 1. Typical capacity curve of a circular hollow section model (CHS-06).

Table 1
Solid and hollow circular section models (shaded cells indicate 'yes').

CSS Features	01	02	03	04	05	06	07	08	09	10	11	12	13	14
Longitudinal 32Ø25		■	■	■	■	■	■	■	■	■	■	■	■	■
Transverse Ø14			■	■	■	■	■	■	■	■	■	■	■	■
Spirals			■	■	■	■	■	■						
Hoops									■	■	■	■	■	■
2 transverse links Ø12				■			■			■			■	
4 transverse links Ø12					■			■			■			■
s = 10 cm			■	■	■				■	■	■			
s = 20 cm						■	■	■				■	■	■
Models 15-27 are identical to 02-14 but with a double layer of transverse reinforcement Concrete C20/25 | Steel S500s | Models 01, 15, 22 and 24 were also solved for C50/60														

CHS1 & CHS2 Features	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
Longitudinal outer 32Ø25		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Longitudinal inner 16Ø14			■		■	■	■		■	■	■		■	■	■		■	■	■
Transverse outer Ø14				■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Transverse inner Ø12					■	■	■		■	■	■		■	■	■		■	■	■
Spirals				■	■	■	■	■	■	■	■								
Hoops												■	■	■	■	■	■	■	■
8 transverse links Ø12						■				■				■				■	
16 transverse links Ø12							■				■				■				■
s = 10 cm				■	■	■	■					■	■	■	■				
s = 20 cm								■	■	■	■					■	■	■	■
Concrete C20/25 | Steel S500s | Models 01, 03, 13 and 15 were also solved for C50/60																			