Computers and Structures 87 (2009) 1427–1439

Contents lists available at ScienceDirect

Computers and Structures

journal homepage: www.elsevier.com/locate/compstruc

Numerical study of confinement effectiveness in solid and hollow reinforced concrete bridge piers: Methodology

Vassilis K. Papanikolaou *, Andreas J. Kappos

Laboratory of Reinforced Concrete and Masonry Structures, Civil Engineering Department, Aristotle University of Thessaloniki, P.O. Box 482, Thessaloniki 54124, Greece

ARTICLE INFO

Article history:
Received 8 January 2009
Accepted 5 May 2009
Available online 31 May 2009

Keywords:
Confinement
Reinforced concrete
Bridge piers
Hollow sections
Finite elements
Modelling

ABSTRACT

A consistent methodology is suggested for modelling confinement in both solid and hollow reinforced concrete bridge pier sections, within the computational framework of three-dimensional nonlinear finite element analysis. The ultimate goal is to suggest the most convenient transverse reinforcement arrangements in terms of enhanced strength and ductility, as well as ease of construction and cost-effectiveness. The present study is particularly relevant with respect to confinement of hollow sections, for which previous experimental and analytical research is limited. Constitutive laws, modelling techniques, post-processing issues and preliminary applications are first introduced, and a large parametric model setup for circular and rectangular bridge piers of solid and hollow section, is subsequently presented. A detailed discussion follows on various issues concerning confinement modelling, aiming to broaden the scope and applicability of the suggested methodology. The respective numerical results and their interpretation and evaluation will be presented in a companion paper.

1. Introduction

Efficient seismic design and detailing of bridge piers and pylons requires adequate section deformation capacity (ductility) without significant loss of strength inside the critical regions, especially in the case of monolithic construction, where piers should transfer not only gravity, but also lateral (seismic), forces from the superstructure to the foundations. In order to satisfy these demands, various configurations of section shapes, reinforcement arrangements, and material properties can be employed, usually following code prescriptions and design recommendations (e.g. [1–3]). Amongst available solutions, hollow pier sections have become increasingly popular in bridge construction during the last decades, especially in Europe [4], featuring considerably reduced concrete mass and hence inertia (seismic) actions. Fig. 1 shows a typical configuration of section geometry and transverse (hoop) reinforcement arrangement in circular and rectangular hollow bridge piers.

A key feature that positively contributes to the strength and ductility enhancement of a pier section is the resulting confinement effectiveness. It is well known that the passive confinement mechanism is based on the activation of transverse reinforcement (development of tensile stress), which restrains the physical lateral expansion of concrete (Poisson's effect), induced by compressive loading. The ensuing triaxial stress state in the confined material finally leads to a significant increase in the overall strength and deformation capacity of the structural element itself [5].

Previous experimental studies mainly conducted during the 80's (e.g. [6,7] for normal concrete and [8,9] for high-strength concrete) have clarified most of the parameters that favourably or adversely affect the effectiveness of passive confinement. The common ground of these studies was the experimental testing of rectangular and circular solid columns confined with various lateral reinforcement arrangements under concentric compressive loading. As a result, various empirical confinement models were proposed, directly based on the above experimental data (e.g. [10–12]). These models usually provide empirical 'confinement effectiveness' factors, based on the aforementioned experimental parameters (section geometry, transverse reinforcement volumetric ratio, strength and arrangement, to name a few), which upscale the uniaxial response of plain concrete in terms of strength and ductility, accounting for the presence of confinement reinforcement.

However, to the best of the authors' knowledge, the above analytical models are limited to solid reinforced concrete sections (upon which they were originally calibrated) and their extension to the assessment of hollow pier sections is not straightforward. This is due to the non-standard geometric characteristics of hollow sections, and specifically due to the presence of inner void, which drastically reduces the effectively confined region. As a result, 'negative confinement' effects may arise, leading to early cracking of the inner concrete cover (implosion) and hence to a reduction of section ductility [13]. As far as the previous experimental work on hollow sections is concerned (e.g. [14–17]), it is mainly focused on their

* Corresponding author. Tel.: +30 2310995662.
E-mail address: billy@civil.auth.gr (V.K. Papanikolaou).

0045-7949/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compstruc.2009.05.004

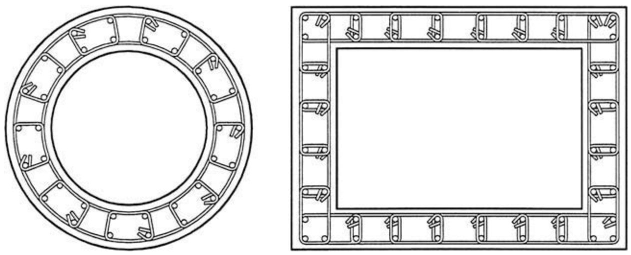

Fig. 1. Typical circular (left) and rectangular (right) hollow bridge pier sections [3].

flexural and shear behaviour under lateral cyclic (seismic) excitation. This is justified by the fact that research on the seismic behaviour of hollow piers is of critical importance to bridge design in earthquake-prone areas (like southern Europe). Nonetheless, studying the issue of confinement requires pure concentric compressive action in order to (a) drive the specimen beyond its ultimate strength, (b) record the complete capacity curve (axial load vs. axial deformation) including softening and (c) derive the strength and ductility enhancement due to confinement. However, this process is prohibited for full-scaled piers due to the huge mechanical means required, and becomes feasible only for small-scaled specimens. In this respect, the available literature is limited to the experimental work by Taylor et al. [18], which included thin-walled hollow sections under low eccentric compression (almost concentric) without, though, any reference to confinement effectiveness, but only to the effect of section thickness on local buckling phenomena. More relevant was the experimental study by Mo et al. [19], including, inter alia, a parametric study on the confinement effectiveness of different lateral reinforcement anchorage types, hoop spacing and material strengths in hollow sections. The specimens were constructed as single vertical panels (one quarter of a hollow section) without concrete cover, and were axially compressed up to failure. The failure patterns showed mainly concrete crushing and a few longitudinal steel buckling cases for large hoop spacings. There was observed negligible difference between different anchorage types, stronger response for smaller spacing and smaller ductility for high-strength concrete, which are deemed reasonable.

A recent analytical alternative to the empirical uniaxial models for studying the confinement effectiveness of reinforced concrete sections is the direct application of three-dimensional nonlinear finite element analysis. Although this numerical method is demanding on computational resources, its application cost is way reduced compared to its experimental counterpart. Another important advantage is that there are almost no modelling restrictions regarding section geometry and complexity of transverse reinforcement arrangements. It should be also pointed out that finite element analysis can describe the confinement effect on its fundamental basis, without empirical modifications to material constitutive laws, for properly capturing the expected strength and ductility enhancement. The latter remains a drawback for empirical models, which are often limited to the specific experimental setups employed for their calibration [20]. In the last two decades, the boost of available computational power led to a significant number of numerical studies on three-dimensional nonlinear finite element modelling of vertical reinforced concrete elements, featuring various constitutive models, modelling techniques, loading types and confinement arrangements (Table 1). However, the available literature is still limited to solid sections, with the exception of the work by Faria et al. [21], where hollow cross-sections are modelled in plane as equivalent I-sections.

In this paper, the main goal is to suggest a consistent methodology for modelling both solid and hollow reinforced concrete bridge pier sections (and generally vertical members) with various transverse reinforcement arrangements, using a general-purpose finite element software, properly enhanced in terms of the concrete constitutive law. The ultimate objective of the present research is to suggest the most convenient confinement arrangements in terms of enhanced strength and ductility, as well as ease of construction and cost effectiveness. Constitutive laws, modelling techniques, post-processing issues and preliminary applications are covered in the subsequent section. The following section presents a large parametric model setup, including circular and rectangular bridge piers of solid and hollow section, which were based on actually constructed bridges. This is followed by a detailed discussion on various issues concerning confinement modelling, aiming to broaden the scope and applicability of the suggested methodology. The respective numerical results and their interpretation and evaluation will be presented in a companion paper.

Table 1
Previous studies on three-dimensional nonlinear finite element analysis of confined reinforced concrete vertical members.

Authors	Structural element type	Concrete constitutive law	Reinforcement modelling	Loading type	Confinement type
Abdel-Halim and Abu-Lebdeh [22]	Solid rectangular columns	Nonlinear elasticity	Discrete	Concentric compressive	Transverse reinforcement
Barzear and Maddipudi [23]	Solid rectangular columns	Nonlinear elasticity	Embedded	Concentric compressive	Transverse reinforcement
Foster et al. [24]	Solid circular columns	Microplane	Discrete axisymmetric	Concentric compressive	Transverse reinforcement
Kang et al. [25]	Solid rectangular columns	Plasticity	Discrete	Monotonic horizontal with axial force	Transverse reinforcement
Liu and Foster [26]	Solid rectangular columns	Microplane	Discrete	Concentric compressive	Transverse reinforcement
Barros [27]	Solid circular columns	Plasticity	Smeared axisymmetric	Concentric compressive	Transverse reinforcement
Imran and Pantazopoulou [28]	Solid circular columns	Plasticity	Smeared axisymmetric	Concentric compressive	Transverse reinforcement
Montoya et al. [29]	Solid rectangular columns	Nonlinear elasticity (MCFT)	Smeared (longitudinal) discrete (transverse)	Concentric compressive	Transverse reinforcement
Attarnejad and Amirebrahimi [30]	Solid rectangular columns	Plasticity	Discrete	Concentric compressive	Transverse reinforcement
Johansson and Åkesson [31]	Solid circular columns	Plasticity	Smeared axisymmetric	Concentric compressive	Steel tube
Kwon and Spacone [32]	Solid rectangular columns	Nonlinear elasticity	Discrete	Monotonic horizontal with axial force	Transverse reinforcement
Hu et al. [33]	Solid circular columns	Plasticity	Smeared axisymmetric	Concentric compressive	Steel tube
Faria et al. [21]	Hollow rectangular piers in plane (2D)	Damage	Discrete	Cyclic horizontal with axial force	Transverse reinforcement
Luccioni and Rougier [34]	Solid circular columns	Damage-plasticity	Smeared axisymmetric	Concentric compressive	Steel tube
Grassl and Jirásek [35]	Solid rectangular columns	Damage-plasticity	Discrete	Eccentric compressive	Transverse reinforcement
Zergua and Naimi [36]	Solid rectangular and circular columns	Fracture-Plasticity	Discrete	Concentric compressive	Transverse reinforcement