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Modeling of RC hollow square columns wrapped with CFRP under shear-type load

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ABSTRACT: Concrete bridges including hollow piers have been constructed throughout the world where high seismic actions and natural boundaries required high elevation infrastructures. Bridge piers designed in accordance with old design codes suffered severe damage during recent seismic events, caused by insufficient shear or flexural strength, low ductility and inadequate reinforcement detailing. The FRP strengthening interventions are intended to upgrade seismic capacity in terms of strength and ductility. The proposed confinement model, coupled with the proposed computation algorithm, is able to predict the fundamentals of the behavior of the hollow square members confined with FRP both in terms of strength and ductility, tracing the occurrence of the brittle mechanisms, namely concrete cover spalling and reinforcement buckling (liable of the failure mode of hollow members), the evolution of stresses and strains in the concrete and in the confinement jacket, allowing to evaluate at each load step the multiaxial state of stress and eventually the failure of concrete or the failure of external reinforcement. The main output of the proposed model is also the assessment of the member deformability in terms of both curvature and displacement ductility. Results of theoretical analyses and experimental tests (experimental data available in literature) showed that a good agreement was achieved.

1 INTRODUCTION

Recent earthquakes demonstrated the vulnerability of old reinforced concrete (RC) piers to seismic actions and ductility demands. Hollow concrete cross sections are usually found in tall bridge piers. Many parameters may influence the overall hollow column response such as: the shape of the section, the amount of the longitudinal and transverse reinforcement, the cross section thickness, the axial load ratio and finally the material strength of concrete (core and cover) and steel (reinforcement). The failure of hollow members is strongly affected by the occurrence of premature mechanisms (compressed bars buckling and unrestrained concrete cover spalling), due to inadequate seismic detailing.

FRP materials approached the construction market as a cost viable and time effective solution to retrofit existing concrete bridge piers and structures in general. Different types of advanced composite column jacketing systems have been investigated providing successful solutions for strengthening, repairing, and adding ductility with no traffic disruption, rapid execution, long-term durability, and consequently, lower life-cycle costs (Karbhari & Zhao 2000).

Usually confinement does not change the actual failure mode (steel reinforcement compressive bars buckling and concrete cover spalling), but it is able to delay bars buckling and to let compressive concrete strains reach higher values. As a result higher load carrying capacity and dramatic ductility enhancement can be guaranteed to the retrofitted columns. At lower levels of axial loads, also the brittle effect of reinforcement buckling is less noticeable (Lignola et al. 2007a). The results of the previous works suggest that a reliable numerical procedure to predict hollow cross section behavior under combination of flexure/shear and compression should include appropriate models for compressed bars buckling, concrete cover spalling and, of course, confined concrete behavior in hollow sections.

FRP materials have been widely used and extensively studied in the last two decades in the form of jacketing to enhance shear and flexural strength as well as ductility, and their effectiveness has been extensively proven in many research programs investigating solid columns behavior. At date it is uncertain how these jackets may perform in the retrofit of square hollow columns since very little research has been performed in this area.

The extension of these models to hollow sections is not straightforward due to limited experimental support, but to overcome these limitations, recent studies based on the application of nonlinear finite element analysis demonstrated that confinement effectiveness in hollow sections is inferior to that in their solid counterparts (Papanikolaou & Kappos 2005). Only few studies related to circular and square hollow columns subjected to combined shear and flexural loads with applied low levels of axial load can be found in literature, investigating the performance of the cross sections; a review is given in Lignola et al. (2007b).

2 HOLLOW CROSS SECTION ANALYSIS

Through the use of a fiber model that meshes the concrete cross-sectional geometry into a series of discrete elements/fibers, sections of completely arbitrary cross-sectional shape (including hollow prismatic cross sections) can be modeled. Tension stiffening effect, compressed bars buckling, concrete cover spalling and FRP confinement of concrete are included in the model (Lignola 2006). The spalling of concrete cover and the buckling of the reinforcement are taken into account by considering an unconfined concrete cover behavior more brittle compared to that of concrete core (concrete cover fibers has zero stress at concrete strain equal to buckling strain of steel reinforcement). Mander et al. (1988) model has been considered for unconfined concrete coupled with size effect theory after Hillerborg (1989) for the concrete post peak softening. Stress-strain curve with stress reductions for steel in compression has been adopted according to Cosenza & Prota (2006), depending on reinforcement bar free length over diameter ratio. In unstrengthened columns, when steel reinforcement reaches in compression the buckling stress, as it pushes outward surrounding concrete, the concrete cover spalls out. In the case of members wrapped with FRP, the steel bars, when buckling occurs, push internal unrestrained concrete cover in the inward direction.

2.1 *Hollow section confinement model*

A model to assess the behavior of FRP confined hollow members has been proposed; see (Lignola 2006) for a detailed description of this approach). This confinement model for circular hollow sections has been extended to square hollow ones considering an equivalent circular column of diameter D equal to the average side length. The model is able to estimate confinement effectiveness, which is different in the case of solid and hollow sections. Plane strain conditions were adopted to simulate the confinement effect; Braga et al. (2006) proposed a model for solid sections based on the assumption that the increment of stress in the concrete is achieved without any out-of-plane strain. A model based on equilibrium and radial displacement compatibility, has also been presented (Fam & Rizkalla 2001, Eid & Paultre 2007) adopting the equations proposed by Mander et al. (1988) through a step-by-step strain increment technique to trace the lateral dilation of concrete and it was recently simplified in a closed form and into design charts for solid sections through linearization and error minimization of nonlinear expressions, also accounting for buckling of slender confined columns (Albanesi et al. 2007).

The dependence of the lateral strain with the axial strain is explicitly considered through radial equilibrium equations and displacement compatibility. Confining pressure q equation can be explicated in the form $q=q(\varepsilon_c)$, so that at each axial strain ε_c the confining pressure q exerted on concrete by the FRP jacket is associated:

$$q=\frac{\nu_c}{\dfrac{\mathrm{R}_o}{E_f t}\left(1-\nu_f\right)+\dfrac{1+\nu_c}{E_c}\dfrac{\mathrm{R}_o^2}{\mathrm{R}_o^2-\mathrm{R}_i^2}\left[\left(1-2\nu_c\right)+\left(\dfrac{\mathrm{R}_i}{\mathrm{R}_o}\right)^2\right]}\varepsilon_c \tag{1}$$

Previous equation is based on linear elasticity theory for all the involved materials (E_c and ε_c are concrete elastic modulus and Poisson's ratio respectively, while E_f and ε_f are FRP elastic modulus and Poisson's ratio respectively), R_o and R_i are respectively the outer and inner radius of the hollow circular cross section, t is the thickness of the FRP wrap. To account for the nonlinear behavior of concrete, a secant approach can be considered: the elastic modulus and the Poisson's ratio are function of the axial strain and of the confinement pressure q (Jiang & Teng 2007). An iterative procedure is then performed to evaluate, at any given axial strain ε_c, the corresponding stress σ_c.

2.2 *Load-Displacement relationship*

The displacement of column is given by three contributions: the flexural displacement, the shear displacement and the fixed-end rotation. The load versus lateral deflection curve (for the flexural response aspect) is derived from the curvature χ through simple cantilever displacement equation. The shear displacement needs to be considered in the case of short or moderately long members and can be evaluated as:

$$\delta_v = \int_0^L \frac{V}{(GA)_c} \tag{2}$$

where L is the shear span, V the shear force and $(GA)_c$ the cracked shear stiffness. The elastic uncracked shear stiffness is reduced in proportion to $(EI)_c$ the cracked flexural stiffness to account for the influence of cracking according to Priestley et al. (1994). According to this theory, given $(GA)_u$ and $(EI)_u$ the uncracked shear and flexural stiffness, respectively; it is assumed:

$$\frac{(GA)_c}{(EI)_c} = \frac{(GA)_u}{(EI)_u} = constant \tag{3}$$

To account for the fixed-end rotation contribution, the joint model proposed by Cosenza et al. (2006) is assumed to evaluate the slippage between the anchored rebar and concrete. The slip of steel rebars at the column-footing interface is evaluated by an equilibrium equation (4a) for the rebar (with diameter Φ) and a compatibility equation (4b) between steel rebar and concrete in tension:

$$\frac{d\sigma_s}{dx} - \frac{4}{\Phi}\tau = 0 ; \qquad \frac{ds}{dx} = \varepsilon_s(x) - \varepsilon_{ct}(x) \tag{4a;b}$$

Given proper boundary conditions in terms of steel strains $\varepsilon_s(x)$ and stresses $\sigma_s(\varepsilon_s)$ or anchorage displacement (if the anchorage is rigid, the slip s at the lower end of the rebar is equal to zero) and neglecting the concrete in tension $\varepsilon_{ct}(x)$ term, usually smaller if compared to $\varepsilon_s(x)$ particularly when the steel is yielded, it is possible to calculate the end rotation θ related to slip s as:

$$\theta = \frac{s}{h - d_c} \tag{5}$$

where d_c represents the neutral axis depth and h is the effective depth of the cross-section. At date, the steel-concrete interaction in the straight region is described by a bond τ-slip s rigid-plastic law, where $\tau = 1*\sqrt{f_c}$, where f_c is the concrete strength, according to Model Code 90 (1990).

Once the M-θ function is known, the footing–column intersection can be considered as a rotational non-linear spring whose behavior is represented by the M–θ relationship.

3 THEORETICAL-EXPERIMENTAL COMPARISON

Experimental tests on FRP confined concrete scaled specimens and prototypes with square hollow cross section, available in scientific literature, have been simulated then according to the proposed model (in following figures experimental peak values of the hysteretic loops are plotted, while continuous lines are used for theoretical monotonic predictions). Only specimens wrapped with CFRP composites in the transverse direction (confinement) are considered herein. These experimental data have been considered to validate the proposed model and good agreement was found between the measured values and the predicted responses. All the specimens developed the estimated flexural strength, while the post peak behavior was different when ultimate performance was dominated by shear (i.e. specimens without FRP). The moment curvature relationship was determined first and then the lateral deflection curve (for the flexural response aspect) is derived from the curvature χ through the procedure described in previous section. Other theoretical curves (Lignola et al. 2007c) where deformability of the element was account for only based on plastic hinge theory (dotted line) are plotted as well in next graphs.

3.1 *Tests by Yeh & Mo (2005)*

Two real scale reinforced concrete square hollow piers (prototypes) were tested under a constant axial force of 3600 kN (ν=0.078) in the case of as built specimen PI2 and 3900 kN (ν=0.15) in the case of FRP strengthened specimen RPI and a cyclic reversed horizontal load. The width of the square column was 1500 mm; the length and wall thickness of the hollow piers were 3.5 m and 300 mm, respectively. The configuration of lateral reinforcement is currently used in bridge design in Taiwan. In these prototypes the spacing of the confining reinforcement does not satisfy usual code design requirements nor do the requirements to prevent buckling of longitudinal rebar. The provided shear reinforcement of the specimens with an expected shear failure is much less than that required by the codes. The average compressive strength of the two mixes of concrete were 18 MPa (RPI) and 32 MPa (PI2) respectively. The strengthening material consisted of unidirectional CFRP sheets.

The seismic performance of the FRP retrofitted specimen was higher if compared with the as built specimen, including ductility and dissipated energy, although the concrete unconfined strength was essentially lower. Good agreement was found between the measured values and the predicted response (figure 2).

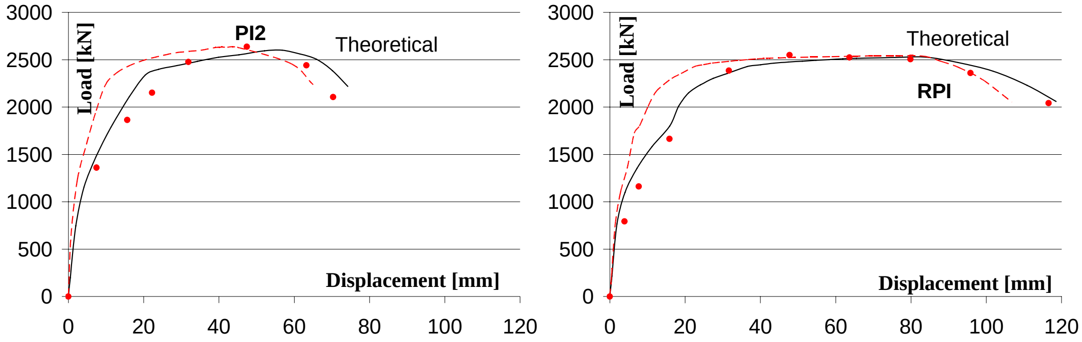

Figure 2 – Predicted response vs. Experimental outcome: Yeh & Mo (2005)

3.2 *Tests by Mo et al. (2004)*

Eight reinforced concrete scaled hollow piers were tested under equivalent axial load ratio ν varying from 0.080 to 0.136 and cyclically reversed horizontal load. Two specimens have been analyzed made by different concretes: the average 28-day compressive strength of the two mixes were 20.2 MPa (NI1-b) and 26.9 MPa (FRP strengthened CR2 specimen) respectively. The strengthening material consisted of unidirectional carbon FRP sheets.

Flexural cracks perpendicular to the column's axis developed first in the region close to the base of the column. For the specimen without FRP the flexural cracks became inclined and extended into the web zone of the columns due to the influence of shear. At ultimate, this specimen failed due to a very clear shear crack through the plastic hinge region. The failure mode changed from shear for specimen NI1-b to flexure for specimen CR2. FRP eliminated the shear cracks and changed the failure mode from shear to flexure. Satisfactory agreement was found between the measured values and the predicted response (figure 1) while the slope was sometimes overestimated probably due to the reference unconfined concrete mechanical properties (i.e. Young Modulus) which are overestimated in the input of the theoretical model.

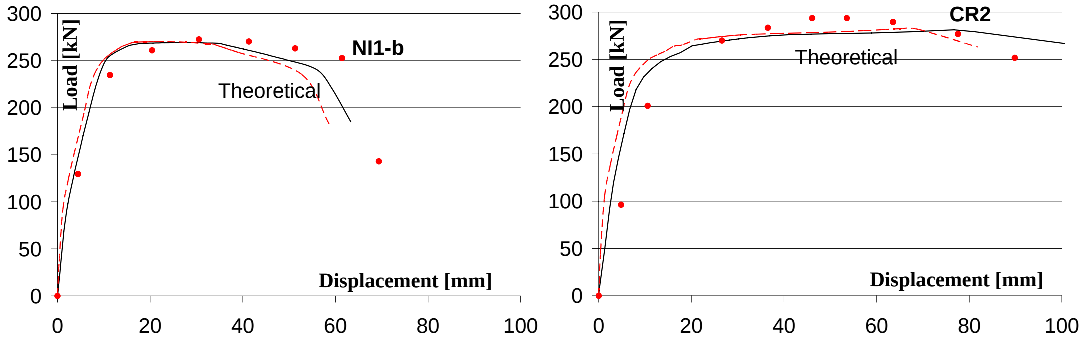

Figure 1. Predicted response vs. Experimental outcome: Mo et al. (2004)

In this kind of sections (common in high-speed rail projects in Taiwan), with one layer only of steel reinforcement close to the outer side of the wall, the major improvement is for the outer side of the compressed walls where FRP wrapping avoids steel reinforcement buckling and concrete cover spalling, while in the inner side steel reinforcement reaches in compression the buckling stress pushing inward the unrestrained concrete cover which spalls out.

4 CONCLUSIONS

The present work is included into a wider activity that aims to improve the knowledge and develop a cost and time effective design method for fast FRP strengthening of hollow bridge columns so that bridge function can be quickly restored. The strengthening intends to upgrade seismic capacity in terms of strength and ductility.

Results of experimental tests available in literature on hollow concrete columns subjected to compression and shear loads, and theoretical analyses show that a good agreement was achieved and that FRP jacketing can enhance the ultimate load and significantly the ductility also in the case of hollow concrete cross sections. To fully simulate the behavior of hollow members it is crucial to model the occurrence of premature mechanisms (compressed bars buckling and unrestrained concrete cover spalling). Usually confinement does not change these brittle failure modes (steel reinforcement compressive bars buckling and concrete cover spalling), but it is able to delay bars buckling and to let compressive concrete strains attain higher values, thus resulting in higher load carrying capacity of the column and significantly in ductility enhancement.

The assessment of such type of RC structures especially requires advanced tools. A refined model and numerical procedure for the non-linear analysis of reinforced concrete hollow members is presented including shear and flexural deformability and Fixed-end rotation contribution to member deformability. The proposed confinement model coupled with the proposed computation algorithm is able to predict the fundamentals of the behavior of the hollow square members confined with FRP both in terms of strength and ductility giving a clear picture of the mechanisms affecting the response of this kind of elements. The model is able to trace the occurrence of the brittle mechanisms, namely concrete cover spalling and reinforcement buckling (generally these two mechanisms are liable of the failure mode of hollow members), the evolution of stresses and strains in the concrete and in the confinement jacket. The main output of the proposed model is also the assessment of the member deformability in terms of displacement ductility. It is very important to include the three contributions of flexural and shear displacement and the fixed-end rotation, because the plastic hinge model only, gives limited predictions in terms of deformability.

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