Numerical evaluation of core concrete quality on the response of concrete jacketed columns

Evaluación numérica de la calidad del concreto del núcleo en la respuesta de las columnas de concreto con cubierta

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Abstract

Reinforced concrete jacketing is one of the most frequently used methods for strengthening of reinforced concrete (RC) columns. A large number of experimental studies have been carried out to investigate the effectiveness of repair and strengthening techniques and interface treatment on the response of concrete jacketed columns. However, the effects of potential damage in existing column and quality of core concrete on the response of jacketed RC columns have not been investigated. One of the main goals of this study is to examine how the material properties of the existing column affect the overall response of the jacketed RC columns. Two computer models were developed and nonlinear analyses were performed to determine the moment-curvature relationships and axial load-moment interaction diagrams of concrete jacketed RC cross sections. The effects of material strength and magnitude of axial loads were investigated. It is determined that the strength of core concrete has no effect on the response of concrete jacketed RC columns under lower axial loads while it increases the strength and reduces the ductility under higher axial load levels.

Keywords: Strengthened columns, concrete jacketing, core concrete quality, reinforced concrete, moment-curvature.

Resumen

El revestimiento de hormigón armado es uno de los métodos más utilizados para reforzar las columnas de hormigón armado (RC). Se han llevado a cabo una gran cantidad de estudios experimentales para investigar la efectividad de las técnicas de reparación y fortalecimiento, y el tratamiento de la interfaz en la respuesta de columnas encamisadas de concreto. Sin embargo, no se han investigado los efectos del daño potencial en la columna existente y la calidad del concreto del núcleo en la respuesta de las columnas RC encamisadas. Uno de los objetivos principales de este estudio es examinar cómo las propiedades del material de la columna existente afectan la respuesta general de las columnas RC encamisadas. Se desarrollaron dos modelos de computadora y se realizaron análisis no lineales para determinar la relación entre el momento y la curvatura de las secciones transversales de RC encamisadas de concreto. Se investigaron los efectos de la resistencia del material y la magnitud de las cargas axiales. Se determina que la resistencia del núcleo de hormigón no afecta la respuesta de la columna RC con camisa de concreto bajo cargas axiales más bajas, mientras que aumenta la resistencia y reduce la ductilidad en niveles de carga axial más altos.

Palabras clave: Columnas fortalecidas, revestimiento de hormigón, calidad del concreto del núcleo, concreto reforzado, curvatura del momento.

Introduction

Recent major earthquakes caused significant casualties and severe damage to many buildings, which were designed according to older codes, as observed after the April 2009 L'Aquila (Italy), August 1999 Izmit (Turkey) and September 1999 Athens (Greece) earthquakes. These earthquakes have revealed the vulnerability of older reinforced concrete (RC) buildings and their columns. Some of the important structural deficiencies included low-quality concrete, poor confinement of the potential inelastic regions of members, weak column-strong beam behavior, short column behavior, inadequate splice lengths, and improper hooks of transverse reinforcement (Lekkas, 2001; Sezen et al., 2003; Elenas, 2003; Kawashima et al., 2010; Sarnoa et al., 2011; Celebi et al., 2013). Most of the older RC buildings have been designed to resist mainly gravity loads or much lower earthquake loads than the current expected seism design loads. Thus, they

cannot provide the required ductility, lateral stiffness and strength as required by the current seismic design codes. These RC buildings should be strengthened because they are vulnerable to collapse in future earthquakes.

Different jacketing procedures are used as the main solution to strengthen RC columns in existing and older buildings. Various jacketing methods such as steel jacket (Nakahara & Yin, 2018; Chai et al., 1991), concrete jacket (Thermou et al., 2014; Rupp et al., 2014), Fiber Reinforced Polymers (FRP) (Juntanalikit et al., 2016; Hosseini, et al., 2005), and high performance fiber reinforced concrete (HPFRC) jacketing (Di Carlo et al., 2017) have been studied to investigate the strengthening techniques effects on the behavior of RC columns under earthquake loads.

Research Significance

Concrete jacketing is one of the most commonly used methods to strengthen older RC buildings which do not meet the seismic design requirements of current codes. New and higher quality reinforced concrete placed around the existing column, or concrete jacket, provides confinement to the existing weaker concrete. As a result, the strength and ductility of the existing concrete increase, and in turn, stiffness, strength and ductility of the structural member and the structural system improve.

A large number of numerical and experimental studies have been carried out to investigate the effectiveness of repair and strengthening techniques, and interface treatment on the response of concrete jacketed RC columns (Achillopoulou, 2017; Di Carlo et al., 2017; Chaulagain et al., 2015; Thermou et al., 2014; Júlio & Branco, 2008; Vandoros & Dritsos, 2008; Sezen & Miller, 2007; Bousias et al., 2007; Thermou et al., 2007; Rodriguez & Park, 1994; Ersoy et al., 1993). Concrete with a low compressive strength of approximately 10–16 MPa was used in many older RC buildings (Elenas, 2003; Kawashima et al., 2010; Celebi et al., 2013). However, the effect of concrete quality of existing column or core concrete on the response of jacketed column has not been investigated. The main goal of this study is to examine how the core concrete quality and axial load level affect flexural performance of the concrete jacketed RC columns. The lateral and axial loads on the column can be due to man-made or natural hazards such as earthquakes. For this purpose, nonlinear analyses of three types of concrete jacketed RC columns are performed for different core concrete properties and axial load magnitudes. In this study, the axial load was assumed to be applied on the entire cross section of the strengthened reinforced column, including both core and jacket concrete.

<div align="right">

State of the Art

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Fully confined concrete behavior

The cross section of concrete jacketed RC columns can have three distinct confinement regions depending on the provided degree of confinement. New or jacketing concrete includes concrete cover, which is completely unconfined and called "Unconfined" concrete (Figure 1). Then concrete inside the jacket between the existing column and ties inside the jacket is called "Partially confined" concrete. The entire cross section of the existing column has now better confinement provided by the concrete jacket and transverse steel with 135-degree hooks inside the jacket. In this research, the entire existing column cross section is assumed confined by the new jacket and is called "Fully confined" concrete (Figure 1).

Figure 1. (a) Cross section and (b) Concrete material models for concrete jacketed RC columns. (Self-Elaboration).

(a)   (b)
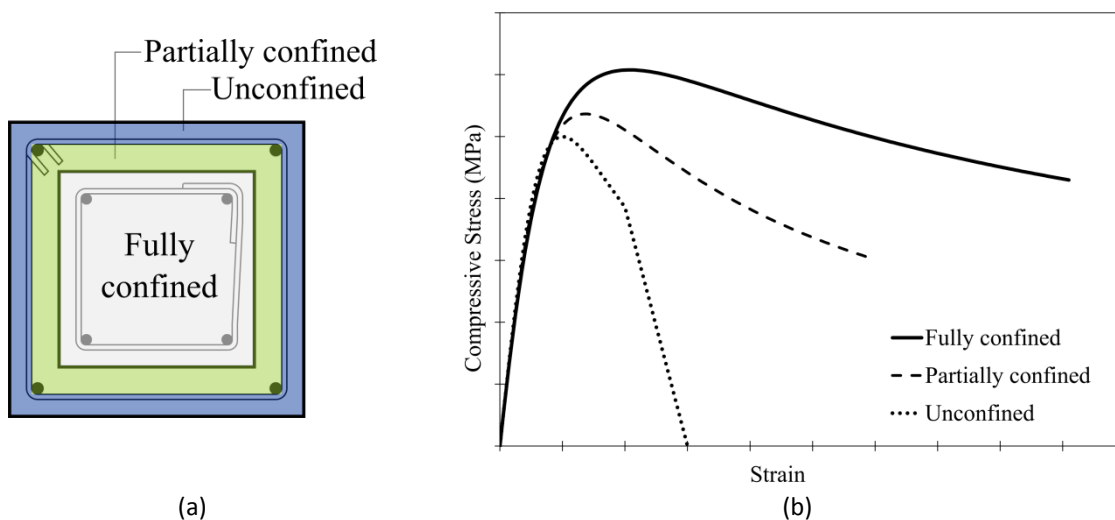
In this study, "Unconfined" and "Partially confined" concretes were modeled with the material model developed by Mander et al. (1988). "Fully confined" concrete was modeled by using the material model developed by Campione et al. (2014). The model proposed by Campione et al. takes into account the effect of the poorly detailed transverse reinforcement in the core or existing column as well as transverse steel inside the jacket of the retrofitted RC column. However, the effects of slip at the interface of old and new concrete, shrinkage, and slipping of bars are not considered in this model for simplification.

The material model by Mander et al. (1988) relates the stress (f_c) and strains (ε_c) of the confined and unconfined concrete with Equation (1).

$$f_c = \frac{f_{cc}' \frac{\varepsilon_c}{\varepsilon_{cc}} r}{r - 1 + (\frac{\varepsilon_c}{\varepsilon_{cc}})^r} \tag{1}$$

where $r = E_c/(E_c - E_{sec})$, with $E_c = 4700\sqrt{f_{co}'}$ (in MPa) and $E_{sec} = f_{cc}'/\varepsilon_{cc}$. f_{cc}' and ε_{cc} are maximum strength and corresponding strain of confined concrete calculated from Equations (2) and (3).

$$f_{cc}' = f_{co}' \left[2.254 \sqrt{1 + \frac{7.94 f_l}{f_{co}'}} - 2\frac{f_l}{f_{co}'} - 1.254 \right] \tag{2}$$

$$\varepsilon_{cc} = \varepsilon_{co} \left[1 + 5\left(\frac{f_{cc}'}{f_{co}'} - 1 \right) \right] \tag{3}$$

where f_{co}' and ε_{co} are maximum strength of unconfined concrete and corresponding strain, respectively. The lateral confinement pressure (f_l) in the section is calculated from equilibrium of forces as shown in Figure 2 (Campione et al., 2014). In this paper, the lateral confinement is calculated by considering the contributions of poorly detailed column ties (with 90-degree hooks) in the existing column and the seismically detailed transverse steel (with 135-degree hooks) inside the jacket.

$$f_{l,core} = f_{l,c} \, k_{pc} \, k_{vc} + f_{l,j} \, k_{ej} \, k_{vj} \tag{4}$$

Figure 2. Equilibrium of forces and confinement pressure in the transverse cross-section. (Self-Elaboration).
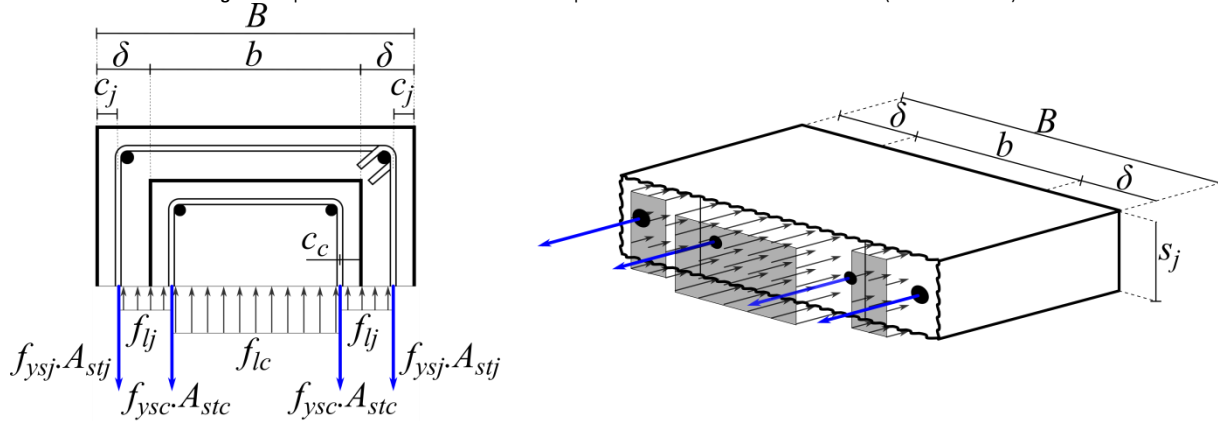
In Equation (4), the lateral confinement stresses from existing and jacket reinforcement ($f_{l,c}$ and $f_{l,j}$) are modified by coefficients to account for the non-uniformity of the confinement pressure in the plane and elevation sides. From equilibrium of forces in the transverse direction, confinement stresses can be calculated as:

$$f_{l,c} = \frac{2 f_{ysc} A_{stc}}{(b - c_c) s_c} \tag{5.a}$$

$$f_{l,j} = \frac{2. f_{ysj} A_{stj}}{(B - \delta) s_j} \tag{5.b}$$

where b is width of the existing column and B is width of the jacketed column. f_{ysc}, A_{stc}, s_c, and c_c are yield strength and area of existing column ties, vertical distance between ties, and concrete cover in the existing column cross section,

respectively. f_{ysj}, A_{stj}, s_j, and c_j are yield strength and area of ties inside jacket, vertical distance between ties, and concrete cover in the external jacket, respectively. δ, is the thickness of the external jacket.

From Campione et al. (2014), modification coefficients are calculated for the effect of internal ties in plane (k_{pc}) and in elevation (k_{vc}) as:

$$k_{pc} = 1 - \frac{4}{6} \frac{(b - 2\,c_c - 2\,d_{bc})^2}{(b - 2\,c_c)^2} \tag{6.a}$$

$$k_{vc} = \left(1 - \frac{s_c}{2\,(b - c_c)}\right)^2 \tag{6.b}$$

where d_{bc} is diameter of longitudinal bar in the core column. Also, effect of external ties in plane (k_{ej}) and in elevation (k_{vj}) is calculated as:

$$k_{ej} = 1 - \frac{2}{3b^2} \sqrt{(b + 2c_j - 2\delta)^3} \sqrt{b - 2c_j + 2\delta} \tag{7.a}$$

$$k_{vj} = \left(1 - \frac{s_j}{2(b + 2\delta - 2c_j)}\right)^2 \tag{7.b}$$

The ultimate strain of the confined concrete (ε_{cu}) was calculated using Equation (8) with considering the effects of the internal and the external transverse steel.

$$\varepsilon_{cu} = 0.004 + \frac{1.4}{f_{cc}} \left[\frac{f_{yc}\,\varepsilon_{suc}\,A_{sc}}{(b - c_c)\,s_c} + \frac{f_{yj}\,\varepsilon_{suj}\,A_{sj}}{(B - \delta)\,s_j}\right] \tag{8}$$

where f_{yc}, A_{sc}, ε_{suc} are yield strength of longitudinal steel, area of longitudinal steel bars, ultimate strain of longitudinal steel in the core section, respectively. f_{yj}, A_{sj}, ε_{suj} are yield strength of longitudinal steel, area of longitudinal steel bars, ultimate strain of longitudinal steel in the external jacket, respectively (Campione et al. 2014).

Methodology

**Model development and validation**

A new computer code is developed in Matlab (2011) to model the material properties of unconfined, partially confined and fully confined concrete in the column cross section (Figure 1b). The computer program is also used to determine axial load-moment interaction diagram of concrete jacketed RC columns.

Moment-curvature analysis is carried out using a uniaxial fiber model of the concrete jacketed RC columns. The analysis was carried out by using the Bernoulli assumption that plane sections remain plane under imposed axial load and moment actions. The cross section was discretized into multiple axial fibers. A linear strain distribution was imposed and the stress in each fiber was based on the uniaxial stress-strain relations for the material of that fiber, with the strain defined at the centroid of that fiber. The strain distribution was iterated until equilibrium was achieved under imposed moment and axial forces.

Specimen SBR is selected from literature (Ersoy et al., 1993) to compare the experimental data and numerical simulations of the concrete jacketed RC columns (Figure 3). In specimen SBR, the concrete compressive strengths were 40.3 MPa and 33.0 MPa in the original 160 mm square column and inside the concrete jacket, respectively.

Sectional analysis was carried out using the open-source software OpenSees (McKenna et al., 2004), and a model was developed based on the computed material properties of unconfined, partially confined and fully confined concrete in the Matlab code (2011). The moment-curvature analysis results from Matlab and OpenSees models are compared with the experimental data from Ersoy et al. (1993) to validate the material models and the developed code (Figure 3c). Numerical results and experimental data show very good agreement and the model could simulate the response of the concrete jacketed RC column SBR relatively closely.

Figure 3. Dimensions of the (a) core and (b) jacketed RC column for specimen SBR (Self-Elaboration), (c) Comparison of calculated and measured moment-curvature response. (Source: Ersoy et al., 1993).


(a)

(b)

(c)
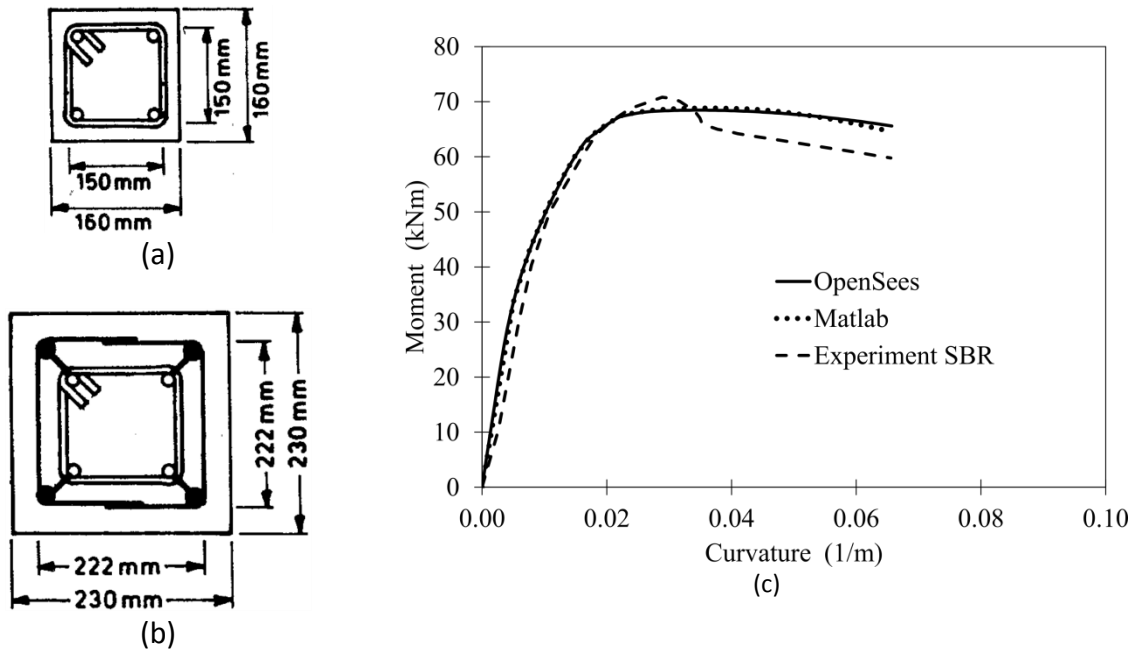
Parametric Analysis

In this study, a parametric study is performed to examine the effect of core concrete quality on the total lateral response of the concrete jacketed RC columns. The behavior of a concrete jacketed RC column is calculated by using OpenSees (McKenna et al., 2004). In OpenSees, cross sectional models of concrete jacketed RC columns were modeled using four different uniaxial materials representing longitudinal steel, and unconfined, partially confined and fully confined concrete (Figure 4). Confined and unconfined concrete are modeled based on Mander et al. (1988), and fully confined concrete is modeled based on Campione et al. (2014). From OpenSees library, *Concrete01, Concrete04* and *Steel01* are used for unconfined concrete, confined concrete and steel materials, respectively.

Figure 4. Concrete and steel materials models. (Self-Elaboration).
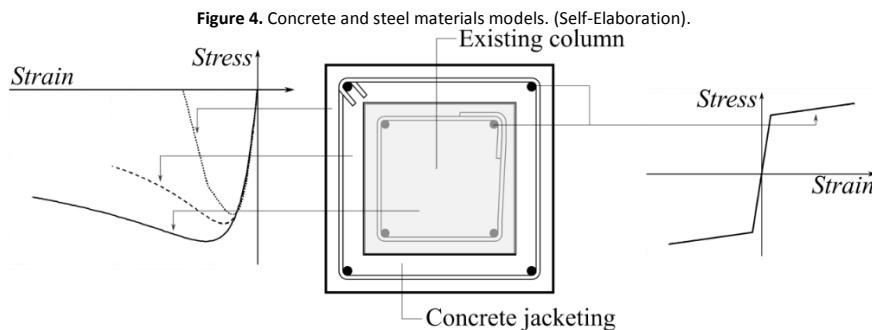
For the parametric study, the concrete jacketed RC column section shown in Figure 5 is used. The existing column of the jacketed column has a 300 mm square cross section. The longitudinal reinforcement includes four 14 mm diameter bars. Transverse reinforcement includes 8 mm diameter hoops with a vertical spacing of 200 mm. Concrete cover from the center of the transverse steel is 30 mm. Inside the jacket, the clear cover from exterior face of ties to edge of jacketed column was 10 mm to provide a minimum cover for the steel. The jacket had four 18 mm diameter longitudinal bars, and 8 mm ties spaced at 100 mm. Yield strength for both longitudinal and transverse steel is 220 MPa in the existing column, and 420 MPa for both steels in the jacket.

Figure 5. Cross sectional dimensions of the (a) core and (b) jacketed RC column. (Self-Elaboration).
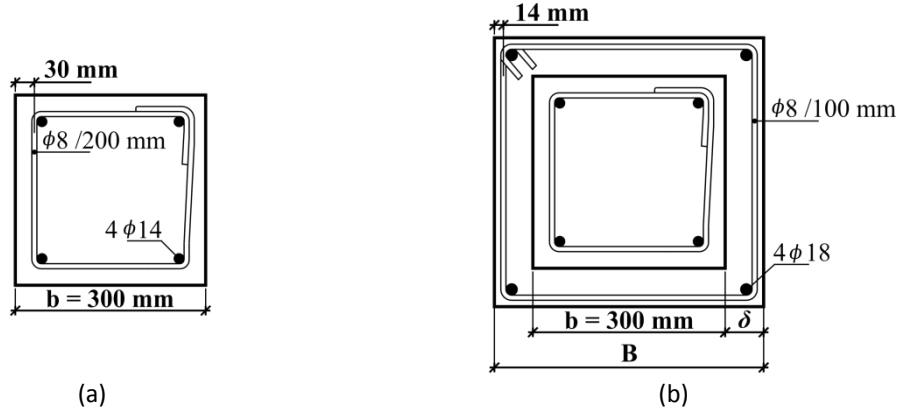
In the parametric study, compressive strength of concrete inside the jacket was kept constant as 25 MPa. The thickness of the jacket, δ, and core concrete quality were selected as variables. The ratio of thickness of the jacket to existing column width, δ/b, were chosen as 0.15, 0.30 and 0.50. Core concrete inside the existing column had 10, 14, 16, 18, 20 and 25 MPa compressive strength (Table 1.).

Axial load ratios (ALR) were calculated for the chosen lower and higher axial load levels, N_1 and N_2, respectively.

$$ALR = \frac{N}{f_{c\_core} * b^2 + f_{c\_jacket} * (B^2 - b^2)} \tag{9}$$

where f_{c_core} and f_{c_jacket} are the concrete compressive strength for the core and jacket, respectively.

Table 1. Main parameters used for the analysis.

b (mm)	f_{c_core} (MPa)	f_{c_jacket} (MPa)	$\dfrac{\delta}{b}$	B (mm)	N1 (kN)	N2 (kN)	ALR1 (%)	ALR2 (%)
300	25	10	0.15	390	500	2000	20.4	81.5
300	25	10	0.3	480	1000	3500	22.7	79.4
300	25	10	0.5	600	1500	5500	19.6	71.9
300	25	14	0.15	390	500	2000	17.8	71.1
300	25	14	0.3	480	1000	3500	21.0	73.4
300	25	14	0.5	600	1500	5500	18.7	68.7
300	25	16	0.15	390	500	2000	16.7	66.8
300	25	16	0.3	480	1000	3500	20.2	70.7
300	25	16	0.5	600	1500	5500	18.3	67.2
300	25	18	0.15	390	500	2000	15.8	63.0
300	25	18	0.3	480	1000	3500	19.5	68.2
300	25	18	0.5	600	1500	5500	17.9	65.7
300	25	20	0.15	390	500	2000	14.9	59.7
300	25	20	0.3	480	1000	3500	18.8	65.9
300	25	20	0.5	600	1500	5500	17.5	64.3
300	25	25	0.15	390	500	2000	13.1	52.6
300	25	25	0.3	480	1000	3500	17.4	60.8
300	25	25	0.5	600	1500	5500	16.7	61.1

Axial stress-strain relationships were calculated for the fully confined concrete fibers with strengths varying from 10 to 25 MPa, and unconfined and partially confined concrete materials for varying values of δ/b using the developed computer code (Figure 6). Figure 6 shows that as the jacket thickness, δ, increases the jacket provides better confinement for the existing column. As a result, the concrete strength increases and deformation capacity decreases. For example, when the δ/b ratio increases from 0.15 to 0.50 the confined concrete strength increases from 23.37 MPa to 25.29 MPa when the compressive strength of the existing column is 20 MPa. However, the failure strain is reduced from 0.027 to 0.021 when the δ/b ratio increased from 0.15 to 0.50 for 20 MPa core concrete strength.

Axial load-moment interaction diagrams for concrete jacketed RC columns with different core concrete strengths are determined using the developed computer code. As shown in Figure 6, core concrete quality has virtually no effect on the response of concrete jacketed RC columns under low axial loads below the balance point. On the contrary, under higher axial loads the axial load and flexure capacity of concrete jacketed RC columns increases with increasing core concrete quality. Figure 6 also shows that δ/b ratio has a significant effect on the overall axial load and moment strength of the jacketed columns. For example, at balanced point, moment and axial load capacity of jacketed column are 267.8 kNm and 1649.2 kN, respectively, for $\delta/b = 0.15$ when the core concrete strength is 25 MPa. The moment and axial load capacity are 789.3 kNm and 4070.2 kN at balanced point for the jacketed column with 25 MPa core concrete strength and $\delta/b = 0.50$.

Figure 6. Jacket and core concrete material models and axial load-moment interaction diagrams of concrete jacketed RC columns with varying core concrete strengths. (Self-Elaboration).

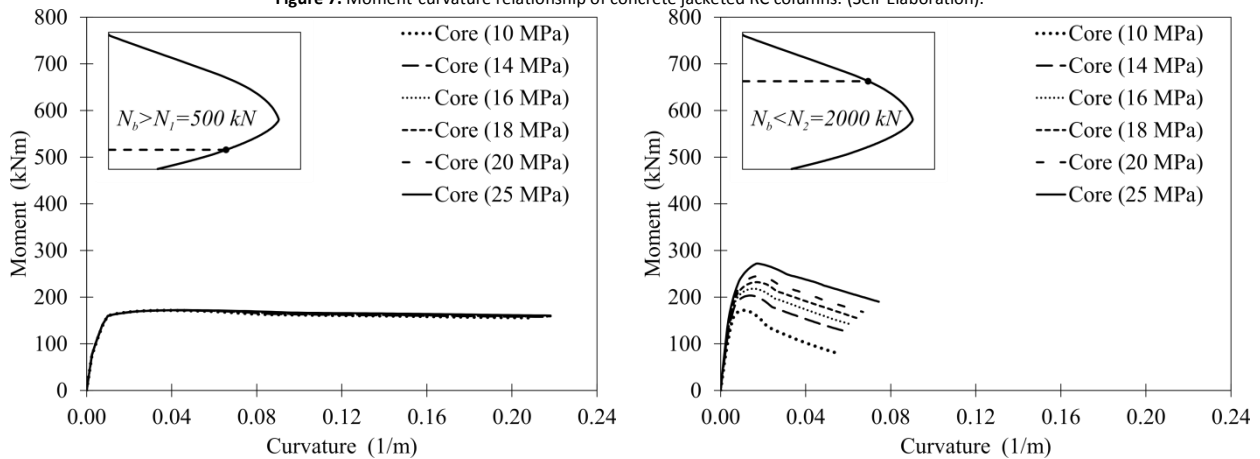(a) $\frac{\delta}{b} = 0.15$

(b) $\frac{\delta}{b} = 0.30$
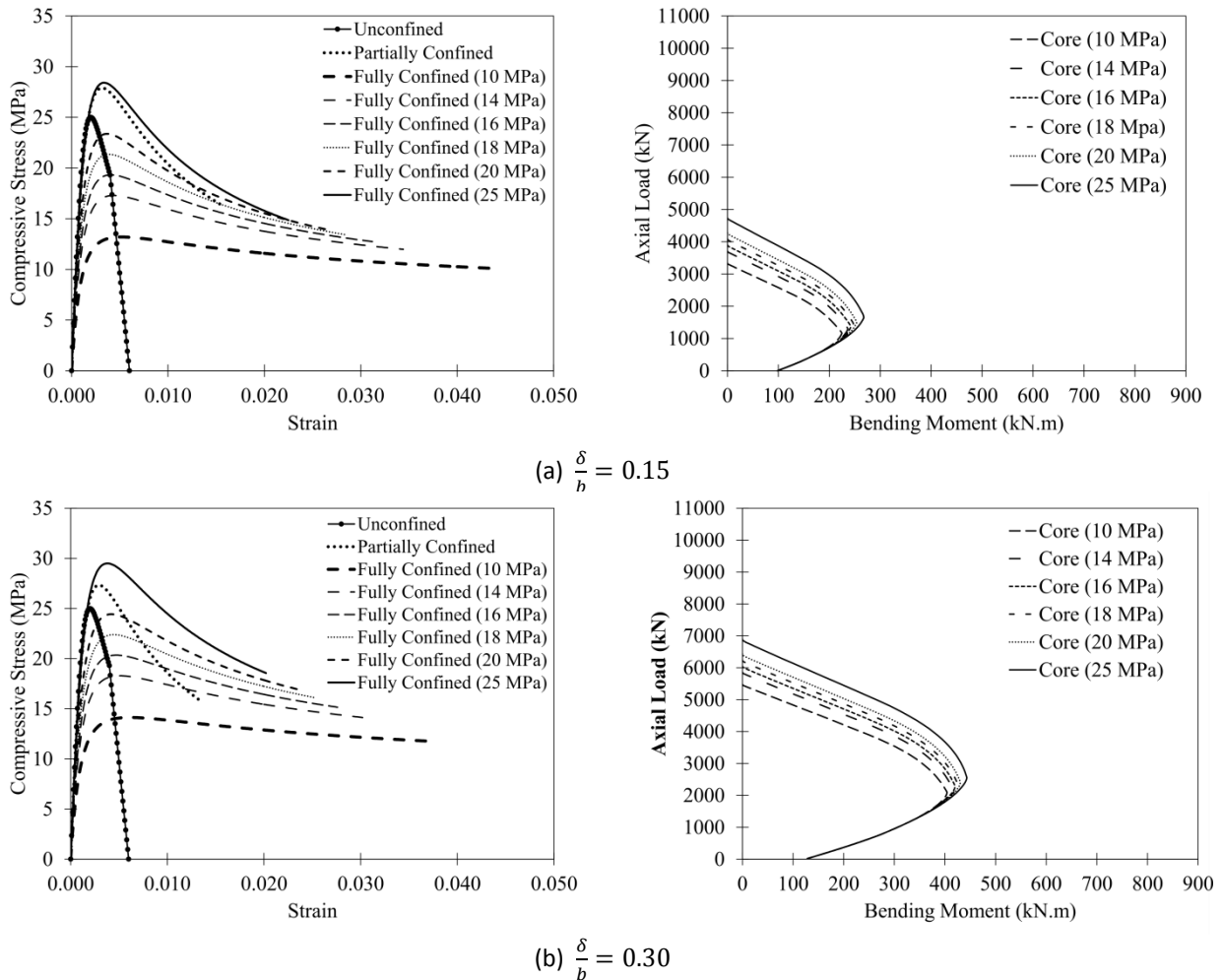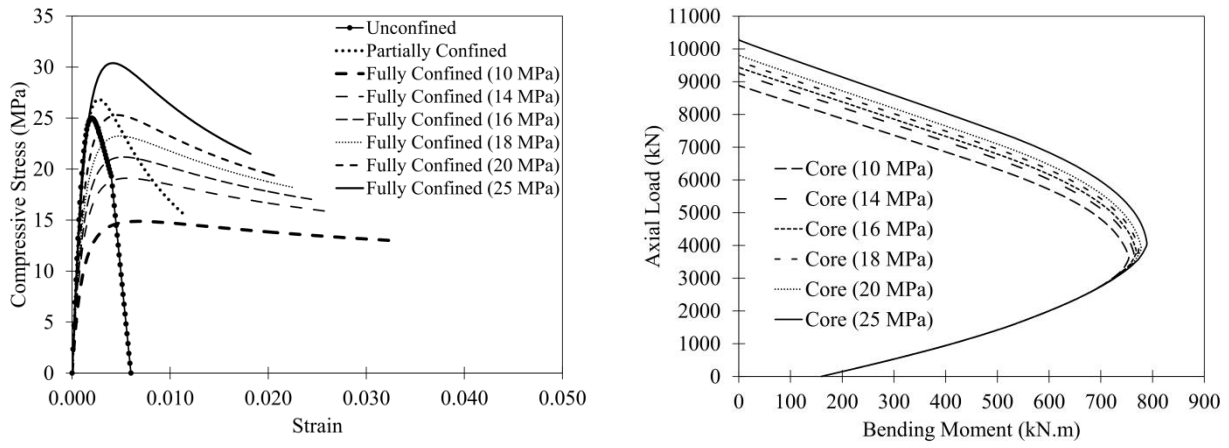
(c) $\frac{\delta}{b} = 0.50$

Moment curvature relationships were calculated to have a better understanding of response of concrete jacketed RC columns at lower and higher axial load levels (Figure 7). Lower axial load (N_1) levels were selected as 500, 1000 and 1500 kN below the balanced axial load (N_b) for $\delta/b = 0.15, 0.30$ and 0.50, respectively. Higher axial load (N_2) levels were selected as 2000, 3500 and 5500 kN above the balanced point in the axial load-moment interaction diagram for $\delta/b = 0.15, 0.30$ and 0.50, respectively. Figure 7 shows that the core concrete quality has virtually no effect on the flexural response of concrete jacketed RC columns subjected to low axial forces for all jacket thicknesses or δ/b ratios. This is mainly because the natural axis is typically inside the jacket and most of existing column or core concrete is in tension and does not contribute to the flexural strength. On the contrary, core concrete quality has a significant effect on the bending response of concrete jacketed RC columns subjected to constant high axial forces above the balance point. As the core concrete quality increases the flexural response of concrete jacketed RC columns improve in terms of both flexural strength and curvature ductility capacity.

As the δ/b ratio increases, the distance between adjacent longitudinal bars in the jacket also increases, therefore effectively confined concrete area inside jacket decreases. For this reason, as shown in Figure 7, by increasing δ/b ratio the ductility of concrete jacketed RC columns also decreases. For example, when the δ/b ratio increases from 0.15 to 0.50 the ductility of concrete jacketed RC columns decreases from 0.218 to 0.091 for lower axial load levels and compressive strength of the core column is 25 MPa. In addition, for higher axial load levels the ductility of concrete jacketed RC columns decreases from 0.074 to 0.032 when the δ/b ratio increases from 0.15 to 0.50 and core concrete strength is 25 MPa.

The moment strength increases with increasing δ/b ratio because of the increase in the amount of higher strength concrete inside the jacket. Moreover, the effect and contribution of jacket concrete on the flexural response of concrete jacketed RC columns may be reduced due to potential slip along the interface between the new and existing concrete. Therefore, the effect of the concrete strength of existing column is likely to become more evident on the response of concrete jacketed RC columns when the axial load magnitude is high and interface slip is also taken into account.

Figure 7. Moment-curvature relationship of concrete jacketed RC columns. (Self-Elaboration).

(a) $\frac{\delta}{b} = 0.15$

(b) $\frac{\delta}{b} = 0.30$

(c) $\frac{\delta}{b} = 0.50$
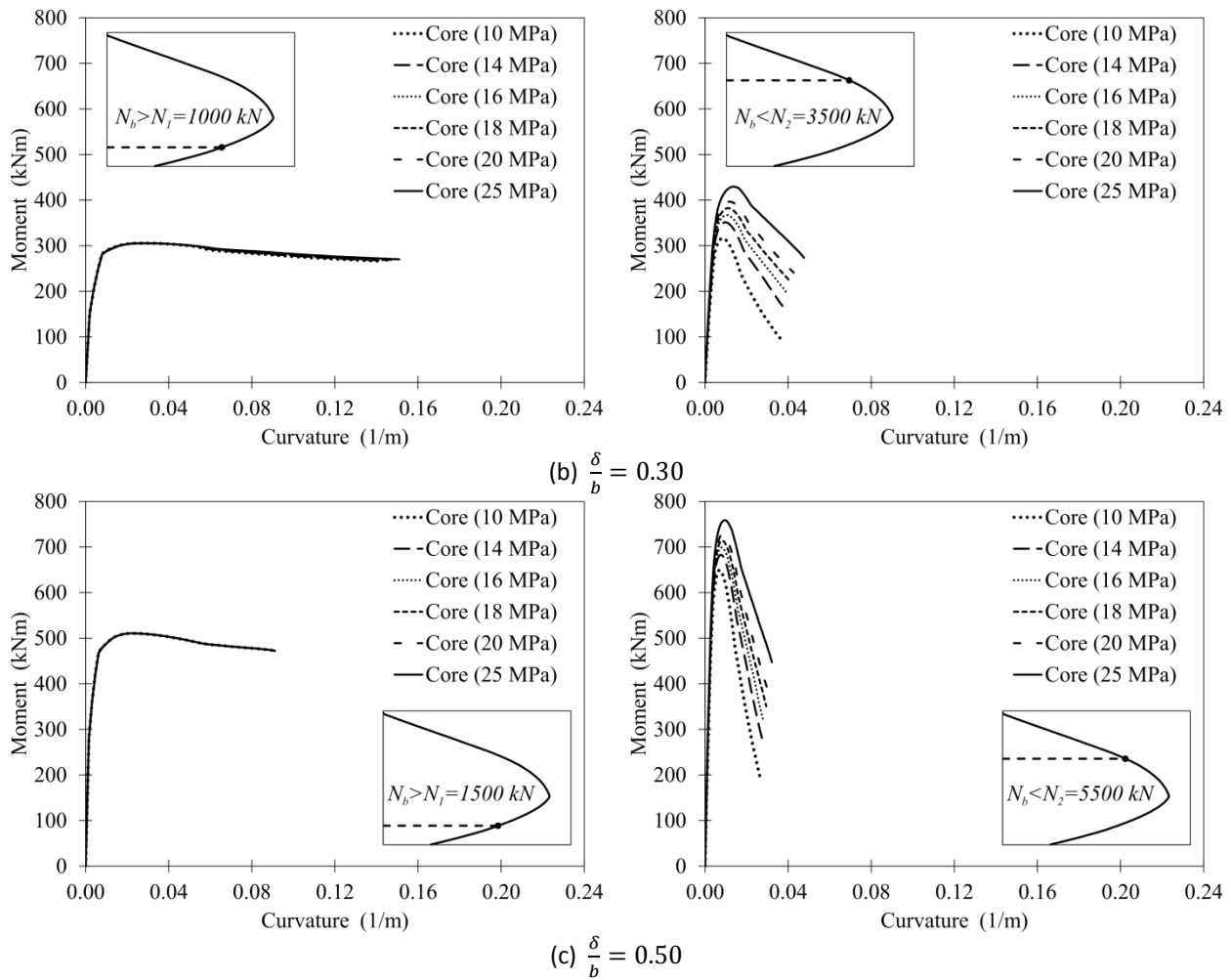
Conclusions

Based on the results of the numerical simulations and comparison with the experimental response of concrete jacketed RC columns the following conclusions are reached. It was determined that the effect of concrete quality of the existing column on response of jacketed column highly depend on the axial load level. As could be seen clearly (Figures 9 and 10), the existing column's concrete quality has no effect on concrete jacketed RC column behavior when the axial load is less than the balanced axial load ($N < N_b$). However, when the applied axial load is larger than the balanced axial load ($N > N_b$) the concrete strength of existing column significantly increases the strength of concrete jacketed RC column. Moreover, and as expected, the response of concrete jacketed RC column has a ductile behavior when $N < N_b$, and more brittle behavior when $N > N_b$. Therefore, this study demonstrates that the concrete quality of the existing column has no influence on ductile behavior of concrete jacketed RC column under lower axial loads while under higher axial load core concrete increases the strength but reduces the ductility.

Acknowledgment

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