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A practical approach for the strength evaluation of RC columns reinforced with RC jackets

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ABSTRACT

Reinforced concrete (RC) jacketing is nowadays one of the most common techniques adopted for seismic retrofitting of existing RC columns. It is used to increase load-carrying capacity and ductility of weak existing members by means of a simple and cheap method. The structural efficiency is related to two main effects: – the enlargement of the transverse cross section; – the confinement action provided by the external jacket to the inner core. Several theoretical and experimental studies were addressed in the past to investigate on how it is possible to calculate the strength enhancement due to these effects and to highlight the main key parameters influencing the structural behavior of jacketed columns. Most of theoretical studies analyzed members subjected to axial compression while the case of axial force and bending moment was adapted only with complex formulations based on numerical approaches, which require the use of a suitable algorithm (e.g. non-linear finite element analyses, sectional fiber models). This paper presents a simplified approach, able to calculate the strength domains for jacketed columns subjected to axial force and uniaxial bending moment. The model takes into account the effects of confinement with proper stress-block parameters, the latter adapted for confined concrete, and of the composite action of jacket and core; buckling of longitudinal bars is considered and discussed with an appropriate stress–strain law for steel in compression. Results are compared with numerical analyses carried-out with the fiber model approach implemented in a commercial software (SAP2000), showing the accuracy of proposed method. Comparisons are also made with experimental results available in the literature in order to validate the model. Finally parametric considerations are made on the basis of adopted model, useful for design/verification purposes.

1. Introduction

Reinforced concrete (RC) jacketing is always more frequently adopted to retrofit existing RC columns with poor structural features. This method consists in casting a concrete layer around the existing member, and reinforcing the jacket with a properly designed amount of longitudinal and transverse reinforcement (Fig. 1). The efficacy of the technique on the structural behavior is related to the enlargement of the transverse cross section, which increases the load-carrying capacity and to the confinement pressure induced by the jacket in the inner column. This confining action allows to increase strength and ductility of the original concrete, and to restrain buckling of longitudinal bars, especially when stirrups in the column are largely spaced.

The efficiency of the RC jacketing is affected from different factors, which has to be taken into account when designing the strengthening technique. Particular attention has to be paid to old-new concrete interface, which could reduce the flexural capacity as observed in [1,2]. If concrete surface of the old member is not roughened, the reduction in the effectiveness of composite column, in terms of flexural capacity, is almost 10%, while if interfaces are well roughened these effects are negligible [3,4]. Furthermore, the long term effects, including shrinkage, have to be carefully taken into account, as stressed in [5].

From practical point of view some studies have proposed design rules for concrete jacketing techniques [6]; specifically, these can be summarized as follow: – the strength of the new materials utilized for the jacket must be greater than that of the column; – the thickness of the jacket should be at least 4 cm for shotcrete application and 10 cm for cast-in-situ concrete; – the reinforcement should be not less than four bars for four-side jacketing and minimum bar diameter 14 mm; – the ties should be minimum 8 mm and at least 1/3 of the vertical bar diameter; – the vertical spacing is at most 200 mm and close to the joint must not exceed 100 mm. In addition, the spacing of the ties should not exceed the

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thickness of the jackets. Furthermore, the surface should be moistened before placing shotcrete and the existing concrete must be heavily sandblasted and cleaned of all loose materials, dust and grease obtaining in this way a well-roughened surface.

Different researches were carried out in the last twenty years to evaluate experimentally the efficacy of the technique on the structural behavior of RC columns. Ersoy et al. [7] tested two series of jacketed columns under uniaxial compression or combined axial load and bending moment. They studied the effectiveness of repair and strengthening jackets and the differences between jackets made under load and after unloading.

Julio et al. [2] carried out an experimental study to analyze the influence of the interface treatment on the structural behavior of columns strengthened by RC jacketing. After testing seven full-scale models of column-footing, they concluded that for undamaged columns a monolithic behavior of the composite element can be achieved even without increasing their surface roughness, using bonding agents, or applying steel connectors before strengthening it by RC jacketing.

Takeuti et al. [8] tested twelve RC-jacketed columns under uniaxial compression with and without preloading. The authors found that the entire core contributes to the axial capacity of the jacketed column, as long as adequate confinement is provided. Also, preloading does not adversely affect the capacity of the jacketed column, while it may increase its deformability.

From a theoretical point of view several research works were addressed to this field. Among these Lampropoulos and Dritsos [5] analyzed the case of jacketed columns subjected to axial load and bending moment by means of non-linear finite element analyses. The authors studied the suitability of a proper formulation to model the old-new concrete interface by comparing numerical results with experimental data. More recently Campione et al. [9] proposed a theoretical model to calculate proper constitutive laws for old and new concrete and for steel, and validated their model with experimental data available in the literature. The case of eccentrically loaded columns was studied by considering a numerical approach based on the discretization of the section by means of the classic fiber model.

Concerning practical methods, different studies [10] focused on the use of "monolithicity coefficient factors", which are used for the design of the strengthened elements. The application of these factors is a 'design approach', proposed not only for the strength evaluation but also for stiffness, and deflection/rotation angle.

It is clear that a combination of a simple calculation method with the use of "monolithicity coefficients" could be a useful tool

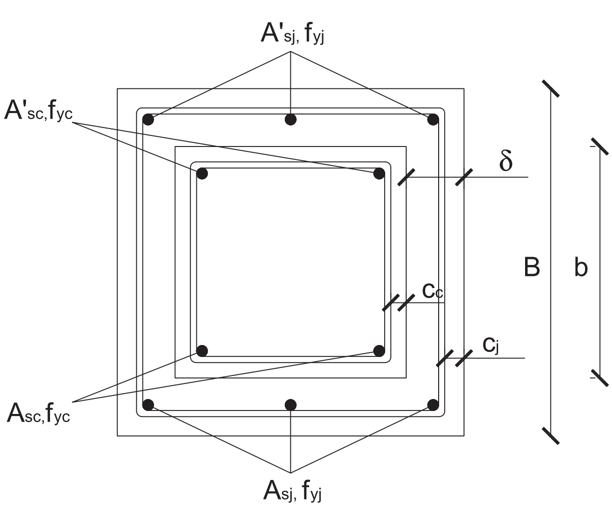

Fig. 1. Case study: square RC section reinforced with a RC jacket.

for practical engineering applications, which allows taking into account the effect of confinement and effective interaction between core and jacket.

The current paper aims to provide a simplified formulation for the calculation of strength domains of square columns reinforced with RC jackets. The proposed approach is based on the determination of some characteristic points defining the interaction domain. The corresponding values of axial force and bending moment are calculated by idealizing the constitutive laws of concrete in compression with stress-blocks, the latter to be calibrated on the basis of the confinement pressure.

It has to be noted that in the proposed model, perfect bond between the old and the new concrete is assumed and the effect of jacket's concrete shrinkage is neglected. It has been proved that both parameters affect the response of the jacketed columns, so they should be carefully addressed when adopting the proposed moment design chart.

In particular, considering the effective connection between old and new concrete, it is well-known that the response of the composite member is complex, thus a practical design procedure should take advantage of a monolithic approach, making use of properly defined "monolithicity factors" [10]. However, if the interface is well-roughened, bond between old and new concrete can be ensured, as experimentally demonstrated in [2].

Additionally, shrinkage effects play an important role on the strength of jacketed columns. In RC jacketed columns concrete shrinkage is restrained by the presence of the initial column [5], so tensile stresses could develop, inducing a biaxial state of stress in the jacket. The flexural capacity reductions due to these effects could be in the range between 23% and 46%, as discussed in [5].

The proposed approach discussed in the following should be adopted in addiction with "monolithicity factors", and with a reduction coefficient for taking into account shrinkage effects.

2. Constitutive laws of constituent materials

As discussed above, the adopted constitutive law has to take into account the effect of confinement. Campione et al. [9] have shown as the well-known model of Mander et al. [11] is suitable to model the compressive behavior of concrete of both jacket and core. Therefore the following relationship is adopted:

$$\sigma_c = \frac{\frac{\varepsilon}{\varepsilon_{cc}} \cdot f_{cc} \cdot r}{r - 1 + \left(\frac{\varepsilon}{\varepsilon_{cc}}\right)^r} \tag{1}$$

with

$$r = \frac{E_c}{E_c - E_{sec}} \tag{2}$$

where $E_c = 5000 \cdot \sqrt{f_c}$ in MPa and $E_{sec} = \frac{f_{cc}}{\varepsilon_{cc}}$.

As well-known, the peak stress f_{cc} and the peak strain ε_{cc} of confined concrete have to be calculated on the basis of the effective confinement pressure f_l by means of the following relations [11]:

$$f_{cc} = f_c \left[2.254\sqrt{1 + \frac{7.94 \cdot f_l}{f_c}} - 2 \cdot \frac{f_l}{f_c} - 1.254\right] \tag{3}$$

$$\varepsilon_{cc} = \varepsilon_{co} \cdot \left[1 + 5 \cdot \left(\frac{f_{cc}}{f_c} - 1\right)\right] \tag{4}$$

with f_c and ε_{co} the peak stress and strain of unconfined concrete.

The confining pressure is simply determinable from rigid body equilibrium of the section in the plane of the stirrup, the latter considered to be yielded. The expressions of confinement pressure induced from external and internal stirrups in the core assume the following form:

$$f_{l,c} = \frac{2 \cdot f_{ysc} \cdot A_{stc}}{(b - c_c) \cdot s_c} \quad \text{Due to internal stirrups} \tag{5}$$

$$f_{l,j} = \frac{2 \cdot f_{ysj} \cdot A_{stj}}{(B - \delta) \cdot s_j} \quad \text{Due to external stirrups} \tag{6}$$

being A_{stc} and A_{stj} the area of the legs in the core and jacket stirrups.

As well-known from the literature [11], appropriate efficiency coefficients have to be considered in order to take into account the effective confined concrete area in the section of transverse reinforcement and between two successive stirrups. Consequently, different coefficients are assumed respectively for core and jacket. Efficiency coefficients for the confining pressure exerted by the RC jacket are calculated as in [9]. Particularly, the in-plane coefficient for the pressure induced from the jacket's stirrups to the core is calculated as the ratio between the effectively confined concrete area of the core and the gross area of the core's transverse section. On these basis and considering that effectively confined concrete can be assumed as delimited from parabolic curves, the following expression of the efficiency coefficient reported in [9] can be considered:

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

for $\frac{\delta}{b} \leqslant \frac{1}{2\left(1 - \frac{c_j}{\delta}\right)}$

With the same assumptions expressed in [11], the vertical efficiency coefficient of confinement pressure exerted from the jacket assumes the following form:

$$k_{vj} = \left(1 - \frac{s_j}{2 \cdot (b + 2\delta - 2c_j)}\right)^2 \tag{8}$$

The equivalent confinement pressure is therefore obtained considering the effects of internal and external stirrups separately, giving the following:

$$\begin{aligned} f_{l,core} = {} & \frac{2 \cdot f_{ysc} \cdot A_{stc}}{(b - c_c) \cdot s_c} \cdot \left(1 - \frac{4}{6} \cdot \frac{(b - 2 \cdot c_c - 2 \cdot d_{bc})^2}{(b - 2 \cdot c_c)^2}\right) \\ & \cdot \left(1 - \frac{s_c}{2 \cdot (b - c_c)}\right)^2 + \frac{2 \cdot f_{ysj} \cdot A_{stj}}{(B - \delta) \cdot s_j} \\ & \cdot \left[1 - \frac{2}{3 \cdot b^2} \cdot \sqrt{(b + 2c_j - 2\delta)^3} \cdot \sqrt{b - 2c_j + 2\delta}\right] \\ & \cdot \left(1 - \frac{s_j}{2 \cdot (b + 2\delta - 2c_j)}\right)^2 \end{aligned} \tag{9}$$

The compressive behavior of confined concrete is finally defined by calculating the ultimate strain ε_{cu}. This can be computed as suggested in [6] and considering both the effects of internal and external stirrups:

$$\varepsilon_{cu} = \varepsilon_{co} + \frac{2.8}{f_{cc}} \cdot \left[\frac{\varepsilon_{suj} \cdot A_{sj}}{s_j \cdot (B - \delta)} + \frac{\varepsilon_{suc} \cdot A_{sc}}{s_c \cdot (b - c_c)}\right] \tag{10}$$

It has to be noted that in general the in-plane efficiency coefficient of the jacket is quite low [9], especially if only four bars are placed and for the common values of concrete cover. Therefore, for design/verification purposes the jacket's concrete can be considered as unconfined.

As it could be noted, the constitutive law of confined concrete expressed by Eq. (1) is not suitable for a straightforward calculation, due to the arising difficulty in performing its integration. However, Karthik and Mander [12] proposed a new analytical form of the constitutive law, valid for both confined and unconfined concrete, and able to approximate the stress–strain relationship expressed by Eq. (1). This can be written in the following form:

$$0 \leqslant x < 1; \;\; \sigma_c = K \cdot f_c(1 - |1 - x|^n) \tag{11a}$$

$$1 \leqslant x < x_u; \;\; \sigma_c = K \cdot f_c - \left(\frac{K \cdot f_c - f_{cu}}{x_u - 1}\right)(x - 1) \tag{11b}$$

in which f_{cu} = stress corresponding to stirrup fracture strain; $K = f_{cc}/f_c$ confinement ratio, x = normalized strain where $x = \varepsilon_c/\varepsilon_{cc}$, $x_u = \varepsilon_{cu}/\varepsilon_{cc}$, $n = E_c\varepsilon_{co}/f_c$ and $n = E_c\varepsilon_{cc}/f_{cc}$ for unconfined and confined concrete, respectively.

Eq. (11) can be applied to model concrete in compression for both jacket and core and they are here adopted due to their suitability to be used for simplified sectional analyses. In particular, for concrete of the core the value of $f_{c,core}$ has to be introduced in Eq. (11) instead of f_c, while the confinement ratio K, the peak ε_{cc} and the ultimate ε_{cu} strains have to be evaluated as discussed above. Analogously for the jacket, if considered as unconfined concrete, Eq. (11) can be used by introducing the jacket's concrete strength $f_{c,jacket}$, and by considering $\varepsilon_{c0} = 0.0036$ as suggested by Collins and Mitchell [13].

Fig. 2a shows the comparison between the constitutive laws in compression for both concrete of core and jacket. In particular the exact (Eq. (1)) and the simplified (Eq. (11)) form of the stress–strain law in compression is plotted. The considered unconfined compressive strength is $f_{c,core}$ = 18 MPa and $f_{c,jacket}$ = 30 MPa for core and jacket respectively. Good accordance can be noted between the two curves, except for the limited softening branch of unconfined concrete. Fig. 2b shows the plots of the stress–strain relationships for steel of longitudinal bars in both tension and compression. It has to be noted that for an exact calculation the constitutive law of steel in tension has to consider the strain-hardening effect, while that in compression has to include the buckling effects, especially when stirrups are largely spaced. In this case the constitutive model proposed by Dhakal and Maekawa [14] is able to consider the effect of buckling, and it is not here reported for the sake of brevity. As recalled in [9], the key parameter to evaluate

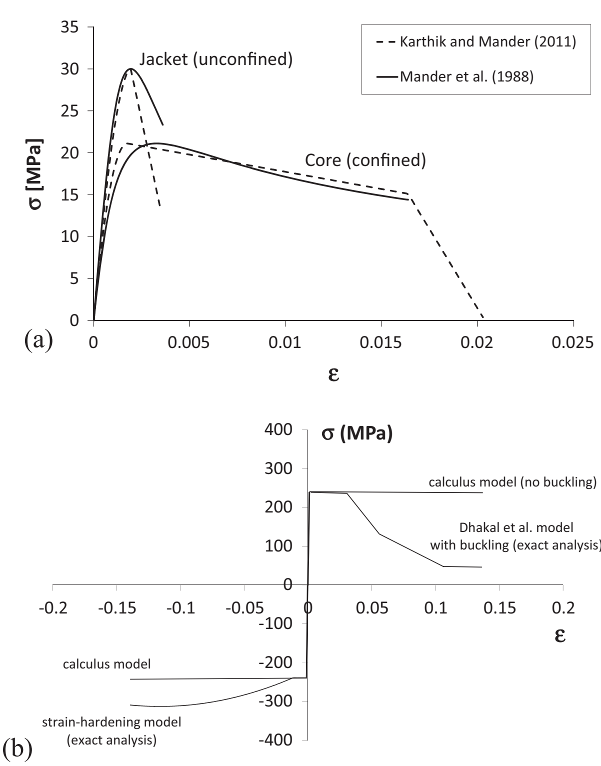

Fig. 2. Detailed and simplified stress strain laws. (a) Compressive constitutive laws for concrete of core and jacket. (b) Constitutive laws for steel of longitudinal bars.

the buckling behavior of longitudinal bars is the critical length-to-diameter ratio $L/\O_l$, which can be calculated with a simple model of elastic beam on elastic soil. With this assumptions, Campione et al. [9] also demonstrated that second order effects are negligible for pitch-to-diameter $s/\O_l$ ratios less than 4.5, consequently this value is recommended as design reference for stirrups for the jacket. In the following, elastoplastic behavior of steel is assumed for reinforcement of both core and jacket, in tension and in compression for the sake of simplicity. However, it has to be stressed that a preliminary verification of the critical length of bars in the concrete core [9] is necessary to confirm this assumption.

3. Stress block approach for strength calculation

Under the hypotheses of plane section and perfect bond between steel and concrete, the calculation of the flexural capacity of a square RC jacketed section for a generic neutral axis depth can be written by means of the following equilibrium equations (Fig. 3):

$$C_j + C_c + F'_j + F'_c + F_c + F_j = N \tag{12a}$$

$$C_j \cdot d_j + C_c \cdot d_c + F'_j(x_c - c_j) + F'_c(x_c - \delta - c_c) + F_c(b + \delta - x_c - c_c) + F_j(B - x_c - c_c) = M - N\left(\frac{B}{2} - x_c\right) \tag{12b}$$

where

$$C_j = \alpha_j\beta_j \cdot f_{c,jacket}x_cB - (\beta_jx_c - \delta)b\alpha_jf_{c,jacket} \tag{13}$$

compressive force in the concrete jacket

$$C_c = \alpha_c\beta_c \cdot f_{cc,core}(x_c - \delta)b \tag{14}$$

compressive force in the concrete core

$$F_j = \sigma_{sj}A_{sj} = \gamma_j \cdot f_{yj} \cdot A_{sj} \quad F'_j = \sigma'_{sj}A'_{sj} = \gamma'_j \cdot f_{yj} \cdot A'_{sj} \tag{15}$$

forces in steel of the jacket, being $\gamma_j = \frac{\sigma_{sj}}{f_{yj}}$ and $\gamma'_j = \frac{\sigma'_j}{f_{yj}}$

$$F_c = \sigma_{sc}A_{sc} = \gamma_c \cdot f_{yc} \cdot A_{sc} \quad F'_c = \sigma'_cA'_{sc} = \gamma'_c \cdot f_{yc} \cdot A'_{sc} \tag{16}$$

forces in steel of the core, being $\gamma_c = \frac{\sigma_{sc}}{f_{yc}}$ and $\gamma'_c = \frac{\sigma'_c}{f_{yc}}$

$$d_j = \frac{B \cdot \beta_j \cdot x_c\left(x_c - \frac{\beta_jx_c}{2}\right)}{B \cdot \beta_j \cdot x_c - b \cdot (\beta_jx_c - \delta)} - (\beta_jx_c - \delta) \cdot b \cdot \frac{\left(x_c - \delta - \frac{(\beta_jx_c - \delta)}{2}\right)}{B \cdot \beta_j \cdot x_c - b \cdot (\beta_jx_c - \delta)} \tag{17}$$

distance of the resultant compressive force in the concrete jacket from the neutral axis

$$d_c = x_c - \delta - \frac{\alpha_c\beta_c}{2}(x_c - \delta) \tag{18}$$

distance of the resultant compressive force in the concrete core from the neutral axis

It has to be noted that when $\beta_jx_c < \delta$ the second terms in Eqs. (13) and (17) has to be set equal to zero, and furthermore if $x_c < \delta$ Eqs. (14) and (18) are also equal to zero.

Once that the constitutive law of concrete in compression is defined, the stress block parameters α and β have to be calculated to be used for the calculation of the flexural capacity of the jacketed section.

For the generic known value of maximum strain, the stress-block parameters can be found from taking the first and second moments of area of the stress–strain law expressed by Eq. (11). The following expressions result:

$$\alpha\beta = \frac{\int_0^{\varepsilon_c}\sigma_c d\varepsilon_c}{f_c\varepsilon_c} \tag{19a}$$

$$\beta = 2 - 2 \cdot \frac{\int_0^{\varepsilon_c}\sigma_c\varepsilon_c d\varepsilon_c}{\varepsilon_c\int_0^{\varepsilon_c}\sigma_c d\varepsilon_c} \tag{19b}$$

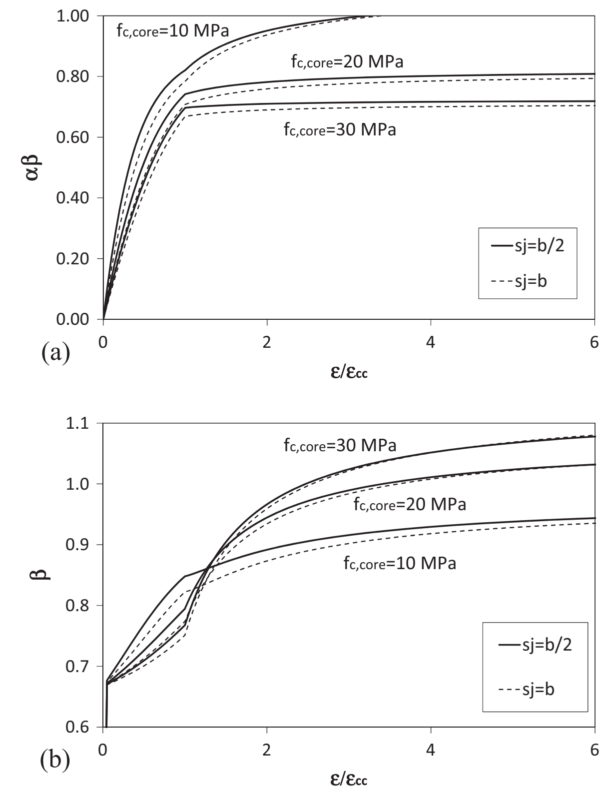

Fig. 4. Stress-block parameters for concrete of the core as a function of axial strain (δ/b = 0.33, c_j/δ = 0.5).

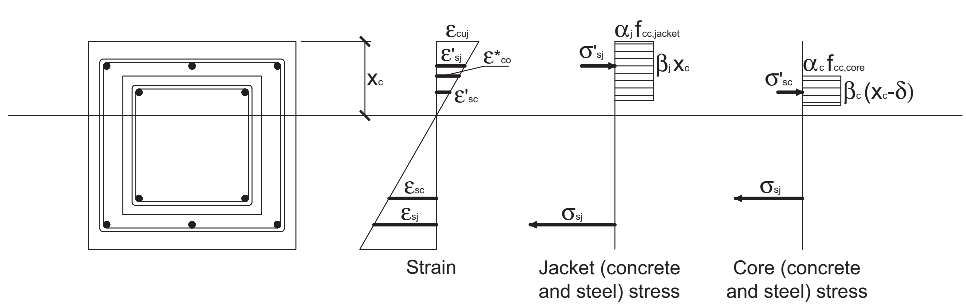

Fig. 3. Stress block approach for the evaluation of failure condition in a RC jacketed section.

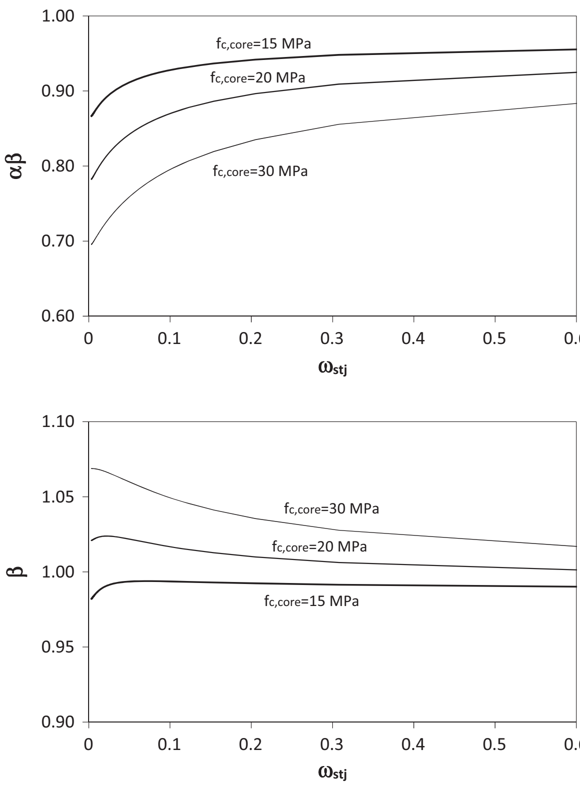

Fig. 5. Stress-block parameters at failure for the core concrete as a function of the geometrical ratio of jacket's transverse reinforcement.

Fig. 4 shows the variation of the stress-block parameters as a function of the normalized strain for the core concrete. The normalized jacket's thickness is $\delta/b = 0.33$ while the cover-to-jacket thickness ratio is $c_j/\delta = 0.5$. Curves are drawn for three different compressive strengths of concrete and for two values of stirrup's pitch, equal respectively to b and $b/2$. As it could be noted, both parameters depend mainly from the concrete strength and low variation can be observed from the amount of transverse reinforcement. Moreover the first parameter ($\alpha\beta$) reaches a constant value after the peak strain, while the second parameter (β) tends to become constant near the ultimate strain.

Fig. 5 shows the variation of the stress-block parameters at failure as a function of the geometrical ratio of stirrups. It has to be noted that also at failure the stress-block parameters are a function of the unconfined concrete strength; the variation is more marked for the first parameter and for higher concrete strengths.

4. Definition of the m–n interaction domain

As discussed above, the evaluation of the axial force-bending moment domain for RC jacketed sections is a difficult task. Most of studies proposed to calculate the load-carrying capacity of a jacketed section subjected to axial force and bending moment by means of complex algorithms which require the use of a computer software. The proposed model is based on the determination of the M-N interaction domain with five points, the latter to be calculated with simple relationships on the basis of the ultimate conditions of the considered section, as analogously done for un-retrofitted RC columns. Fig. 6 shows the assumed strain profiles at failure. In particular profile 1 corresponds to failure due to tensile axial force and bending moment, being all steel bars yielded in tension in both core and jacket ($\gamma_j = \gamma'_j = \gamma_c = \gamma'_c = -1$ if elastoplastic behavior is assumed in both tension and compression). The corresponding neutral axis has the depth equal to:

$$x_{c,1-2} = \frac{\varepsilon_{cuj}}{\varepsilon_{cuj} + \varepsilon_{yj}} \cdot c_j \tag{20}$$

where ε_{cuj} is the ultimate compressive strain of the concrete of the jacket and ε_{yj} is the yield stress of longitudinal bars in the jacket.

Ultimate strain profile 2 is characterized from upper steel yielded in compression, with stress equal to the yield strength. The following neutral axis depth holds

$$x_{c,2-3} = \frac{\varepsilon_{cuj}}{\varepsilon_{cuj} - \varepsilon_{yj}} \cdot c_j \tag{21}$$

The following steel stress ratios results

$$\gamma'_j = 1; \ \gamma_j = -1; \tag{22}$$

$$\gamma'_c = \begin{cases} \text{if } |\varepsilon'_{sc}| > \varepsilon_{yc} \rightarrow \ \gamma'_c = \text{sign}(\varepsilon'_{sc}) \\ \text{if } |\varepsilon'_{sc}| < \varepsilon_{yc} \rightarrow \ \gamma'_c = \frac{\varepsilon'_{sc} E_s}{f_{yc}} \end{cases}; \quad \gamma_c = \begin{cases} \text{if } |\varepsilon_{sc}| > \varepsilon_{yc} \rightarrow \ \gamma_c = \text{sign}(\varepsilon_{sc}) \\ \text{if } |\varepsilon_{sc}| < \varepsilon_{yc} \rightarrow \ \gamma_c = \frac{\varepsilon_{sc} E_s}{f_{yc}} \end{cases} \tag{23}$$

where ε_{sc} and ε'_{sc} are the strains in the top and bottom steel of the core, which can be evaluated with the following expressions:

$$\varepsilon'_{sc} = \frac{\delta + c_c - x_{c,2-3}}{x_{c,2-3}} \cdot \varepsilon_{cuj} \quad \varepsilon_{sc} = -\frac{\delta + b - c_c - x_{c,2-3}}{x_{c,2-3}} \cdot \varepsilon_{cuj} \tag{24}$$

The strain profile 3 presents bottom steel stress equal to the yield stress. The neutral axis depth is equal to

$$x_{c,3-4} = \frac{\varepsilon_{cuj}}{\varepsilon_{cuj} + \varepsilon_{yj}} \cdot (B - c_j) \tag{25}$$

The steel stress ratios are

$$\gamma'_j = \begin{cases} \text{if } |\varepsilon'_{sj}| > \varepsilon_{yj} \rightarrow \ \gamma'_j = \text{sign}(\varepsilon'_{sj}) \\ \text{if } |\varepsilon'_{sj}| < \varepsilon_{yj} \rightarrow \ \gamma'_j = \frac{\varepsilon'_{sj} E_s}{f_{yj}} \end{cases} \quad \gamma_j = -1 \tag{26}$$

$$\gamma'_c = \begin{cases} \text{if } |\varepsilon'_{sc}| > \varepsilon_{yc} \rightarrow \ \gamma'_c = \text{sign}(\varepsilon'_{sc}) \\ \text{if } |\varepsilon'_{sc}| < \varepsilon_{yc} \rightarrow \ \gamma'_c = \frac{\varepsilon'_{sc} E_s}{f_{yc}} \end{cases} \quad \gamma_c = \begin{cases} \text{if } |\varepsilon_{sc}| > \varepsilon_{yc} \rightarrow \ \gamma_c = \text{sign}(\varepsilon_{sc}) \\ \text{if } |\varepsilon_{sc}| < \varepsilon_{yc} \rightarrow \ \gamma_c = \frac{\varepsilon_{sc} E_s}{f_{yc}} \end{cases} \tag{27}$$

being the steel strains equal respectively to

$$\varepsilon'_{sj} = \frac{x_{c,3-4} - c_j}{x_{c,3-4}} \cdot \varepsilon_{cuj} \quad \varepsilon'_{sc} = -\frac{\delta + c_c - x_{c,3-4}}{x_{c,3-4}} \cdot \varepsilon_{cuj} \quad \varepsilon_{sc} = -\frac{\delta + b - c_c - x_{c,3-4}}{x_{c,3-4}} \cdot \varepsilon_{cuj} \tag{28}$$

In every case the strain at the top fiber of the core can be calculated as follows:

$$\varepsilon^*_{co} = \frac{x_c - \delta}{x_c} \cdot \varepsilon_{cuj} \tag{29}$$

The domain is finally completed with two further points (0 and 4), which corresponds respectively to the theoretical cases of pure tensile and pure compressive axial force. The minimum axial force is calculated as the yield tensile force carried out by longitudinal bars, while the maximum is equal to the concrete axial capacity of the column in correspondence of the peak strain value.

Fig. 7 shows the comparison between the M–N interaction domain of an unreinforced member and those relative to jacketed sections with normalized jacket thicknesses δ/b equal to 0.13 and 0.33 respectively. The ratio between the concrete compressive

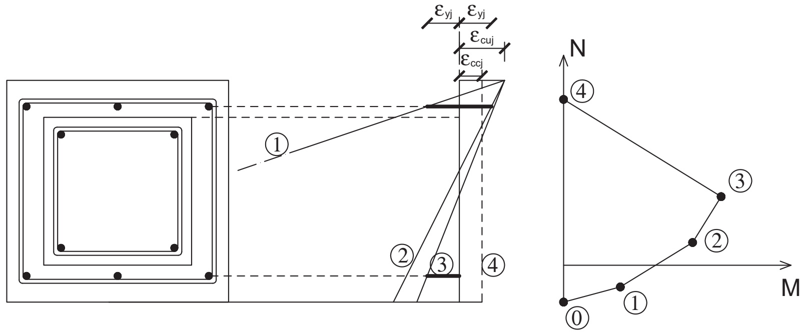

Fig. 6. Proposed model for calculation of strength domains of RC jacketed sections.

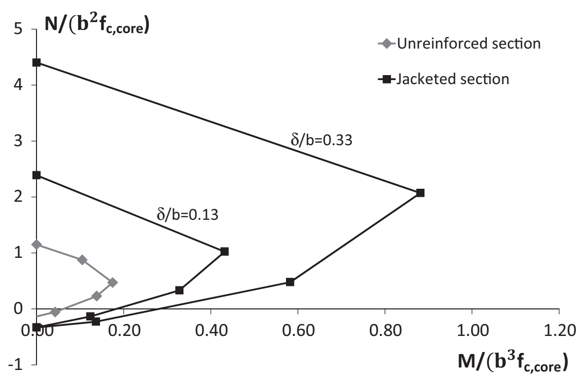

Fig. 7. Simplified strength domains for RC jacketed sections.

strengths of core and jacket is equal to $f_{c,core}/f_{c,jacket}$ = 0.57, the geometrical ratio of longitudinal steel in the core is equal to $(A_{sc} + A'_{sc})/b^2$ = 1%, while the same for the jacket is equal to 2%. The transverse reinforcement ratio is equal to ω_{stc} = 2% for the core and ω_{stj} = 6% for the jacket. Axial force and bending moment values are normalized with respect to $b^2 f_{c,core}$ and $b^3 f_{c,core}$ respectively, in order to stress the effect of retrofitting on the strength of the original column. It can be noted as the capacity is noticeably increased, especially for higher values of axial force. Furthermore the enlargement of the jacket's thickness induces the enhancement of the flexural capacity, the latter increasing for great values of axial force. Large thicknesses are therefore required only when the column is subjected to great axial load values. For low levels of normal force, that is a common case for buildings in seismic regions, thin jacket's thicknesses could be more convenient, although this solution would require the use of special admixtures with reduced coarse aggregate size.

Particular care has to be addressed to the effect of axial preloading on the existing column. As discussed by Del Rio Bueno [15] the effective enhancement of the structural performances by concrete jacketing strictly depends on the existing axial load. In particular, if the axial load value corresponds to the peak compressive strain of unconfined concrete or greater, a very small increase of the axial capacity and a limited enhancement of ductility could be obtained. Therefore the proposed method has to be applied only when the axial load on the inner column is lower than that corresponding to the peak strain of unconfined concrete. Proposed stress block parameters could take into account of the existing axial shortening ε_{ex} of the column, simply by changing the integration limits in Eq. (19) as it follows:

$$\alpha\beta = \frac{\int_{\varepsilon_{ex}}^{\varepsilon_c} \sigma_c d\varepsilon_c}{f_c \varepsilon_c} \tag{30a}$$

$$\beta = 2 - 2 \cdot \frac{\int_{\varepsilon_{ex}}^{\varepsilon_c} \sigma_c \varepsilon_c d\varepsilon_c}{\varepsilon_c \int_{\varepsilon_{ex}}^{\varepsilon_c} \sigma_c d\varepsilon_c} \tag{30b}$$

However, further studies will be addressed on this aspect to clarify analytically and experimentally on the effect of the axial preloading on the overall flexural capacity of the reinforced member.

5. Comparisons with numerical analyses and experimental data

The proposed model is validated with experimental data available in the literature [7] and with numerical analyses carried out with the software SAP2000 [16]. This software is chosen because it allows one complete modeling of the analyzed case study, and additionally it is one of the most diffused computer program worldwide for structural analysis. In particular the "Section Designer" package allows to analyze complex cross-sectional sections with user-defined features by means of the classic fiber method. For the examined case the jacket was divided in 100 square fibers while the confined region was modeled with 400 square cells. Rebars were considered as points, and overlapping with the square concrete cells was considered by neglecting the single cell coincident with a bar location. Constitutive laws of confined, unconfined concrete and steel were preliminary calculated and introduced in the software as user-defined laws by points. The software takes advantage of a step-by-step numerical algorithm (Newton-Raphson) for the solution of the non-linear system to calculate the interaction domain. The required precision is achievable by setting the number of points defining the domain. In the present analysis the number of points was assumed equal to 200.

Fig. 8 shows the comparison between the analytical results obtained with the proposed model and those computed numerically. The case study refers to a column with side b = 300 mm, cover thickness c_c = 20 mm, having concrete compressive strength

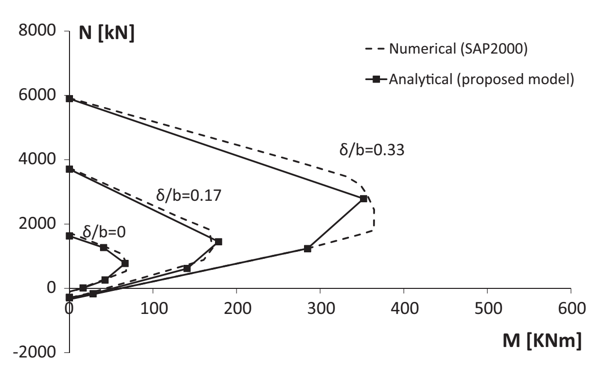

Fig. 8. Comparison between numerical and analytical results.

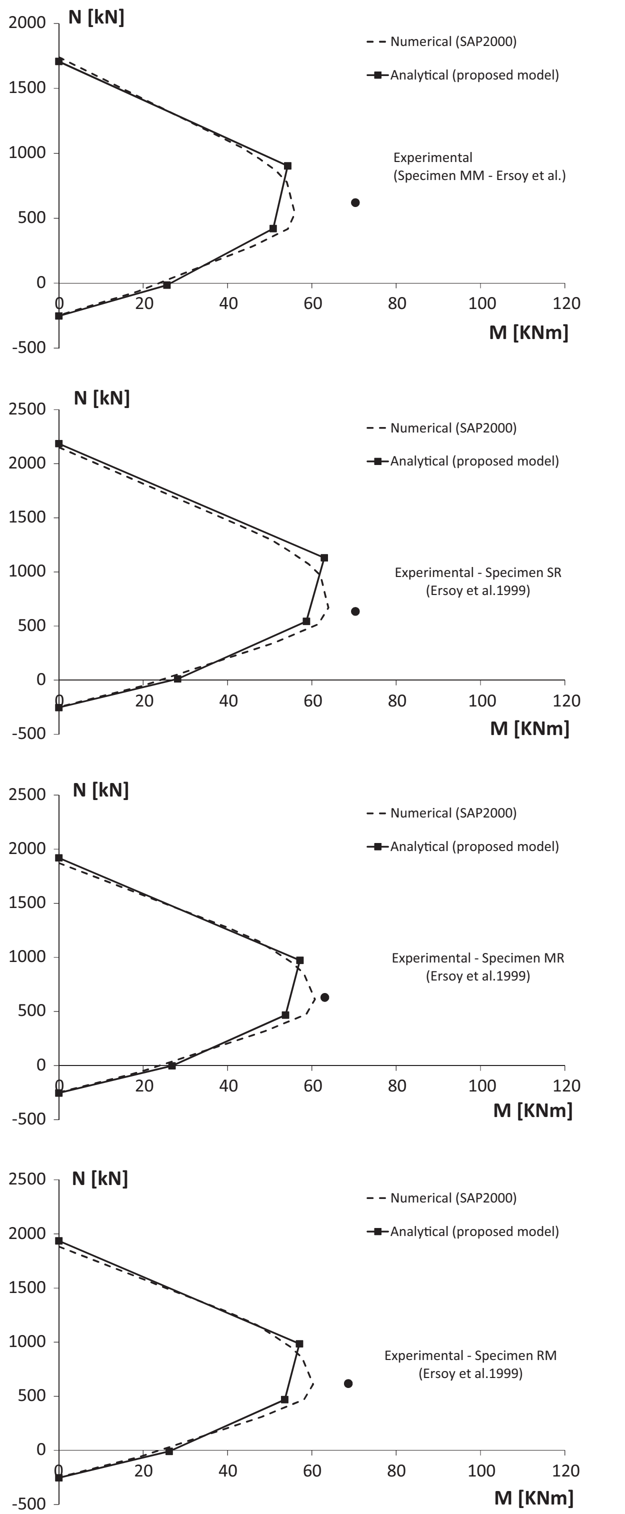

Fig. 9. Comparison between analytical, numerical solutions and experimental results of Ersoy et al. [7].

equal to $f_{c,core}$ = 18 MPa, reinforced with four longitudinal bars having diameter 12 mm and yield strength equal to f_{yc} = 280 MPa. The RC jacket is supposed to have concrete compressive strength $f_{c,jacket}$ = 25 MPa, cover thickness c_j = 25 mm and four longitudinal bars with diameter 12 mm placed at the corners with yield stress f_{yj} = 450 MPa. Stirrups of the core have 8 mm diameter, pitch equal to 200 mm and yield stress 280 MPa; stirrups of the jacket have 8 mm diameter at pitch 100 mm and yield stress 450 MPa. These features are chosen in order to simulate a poor existing RC columns designed only for gravity loads and reinforced with the RC jacketing technique.

Three analysis case are plotted, referring to the unreinforced section ($\delta/b = 0$), and the two limit cases of jacket's thickness suggested [6], equal respectively to $\delta/b = 0.17$ and $\delta/b = 0.33$. Good accordance can be noted between the numerical and the analytical solution, highlighting also that proposed method is slightly conservative with respect to the numerical model due to the stress-block approximation. The comparison stresses again that the increase of the strength enhancement with the jacket's thickness is negligible for low levels of axial force.

A further comparison is shown in Fig. 9, which shows the interaction domains obtained theoretically (numerical and analytical solutions) together with the experimental results determined in [7]. The column has b = 160 mm, cover thickness c_c = 5 mm and it is reinforced with four longitudinal bars having diameter 12 mm. The RC jacket has thickness equal to δ = 35 mm, cover thickness c_j = 5 mm and four longitudinal bars with diameter 12 mm. The yield strength of longitudinal reinforcement is equal to f_{yc} = 300 MPa and f_{yj} = 280 MPa for core and jacket respectively. Stirrups in the core have 4 mm diameter and pitch equal to 100 mm, while stirrups in the jacket have 8 mm diameter and pitch 100 mm. The concrete compressive strength varies for each case analyzed and further details can be found in [7].

Also in this case the analytical solution achieved with the proposed model fits the numerical solutions with good accuracy and with differences less than 5%. In all examined cases the experimental result is close to the theoretical predictions with the exception of specimen MM, where a difference can be observed. This deviation could be addressed to different aspects concerning the test specimen, such as the effective strength of materials (especially steel), since the two theoretical approaches (numerical and analytical) lead to similar results. However it has to be noted that the result is quite conservative with respect to safety in all examined cases. From this preliminary verification the model could be considered as an useful tool for design purposes of RC jacketed columns. Further experimental investigation should be addressed to verify in deep the suitability of the model.

6. Conclusions

In this paper, a simplified analytical method is presented able to calculate the strength domains for RC jacketed columns. The model is based on the determination of some characteristic points of the interaction domains, and it is based on the stress-block approach. From derived results and from comparisons with numerical analyses carried-out with a commercial software (SAP2000), the following conclusions can be drawn:

- the stress-block approach is applicable to RC jacketed sections if parameters are well-calibrated;
- for common confinement levels, stress block parameters are mainly a function of concrete compressive strength and their value tends to be constant after that peak strain is reached;
- results derived with the proposed method are in good accordance with those obtained numerically. Also comparisons with experimental data have shown good agreement, even if with a limited number of comparisons. Further experimental investigations need to be addressed to verify the applicability of this approach;
- the proposed model allows one to calculate strength domains in easy manner (calculation by hand) for RC jacketed sections. A combination of this method with the use of "monolithicity

coefficient" and safety factors considering shrinkage effects, could represent an useful tool for practical engineering applications.

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