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A GENERAL ANALYTICAL APPROACH FOR PRESTRESSED AND NON-PRESTRESSED CONCRETE BEAM-COLUMNS REINFORCED WITH BONDED AND UNBONDED COMPOSITES: (I) THEORY

METODO ANALITICO GENERAL PARA VIGAS-COLUMNAS DE HORMIGON PREESFORZADO Y NO PREESFORZADO REFORZADAS CON "COMPOSITES" ADHERIDOS Y NO ADHERIDOS: (I) TEORIA

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ABSTRACT: An analytical method that determines the short and long-term response of prestressed and non-prestressed concrete beam-columns reinforced with any combination of FRP bars or/and plates, steel rebars, bonded and/or unbonded prestressed tendons is proposed. Beams and columns encased with FRP fabrics and FRP tubes filled with concrete are covered with the proposed model. The effects of tension stiffening, creep and shrinkage of the concrete, and the relaxation of the prestressed steel reinforcement are considered. The models proposed by Vecchio and Collins [1] and by Popovics [2, 3] for the stress-strain relationships of the concrete in tension and compression are adopted, respectively. The strain-stress relationships of the steel and FRP reinforcements are modeled using multiple straight lines (polygonal lines). The method of the fibers (modified) is used to calculate the moment-curvature diagrams at different levels of the applied axial load (i.e., the M-P-ϕ curves), and the Gauss method of integration (for the sum of the contributions of the fibers parallel to the neutral axis) to calculate the lateral rotations and deflections along the span of the beam-column. The validity of the proposed model and corresponding equations were tested against experimental data available in the technical literature (see part II of this publication).

KEYWORDS: Axial load, beam, column, composite materials, concrete-filled tube, high-strength concrete, deflections, fiber reinforced polymers (FRP), prestressed concrete

RESUMEN: Se propone un método de análisis que determina la respuesta a corto y largo plazo de vigas-columnas de hormigón pretensado y no pretensado reforzado con cualquier combinación de barras de FRP y/o placas, barras de acero, torones pretensados adheridos o no adheridos. El método de análisis propuesto incluye vigas y columnas revestidas con telas FRP y tubos de FRP rellenos de hormigón. También se incluyen los efectos de la rigidez a tracción, fluencia y retracción del hormigón y la relajación de la armadura de acero pretensado. Se adoptan los modelos de Vecchio y Collins [1] y de Popovics [2, 3] en las relaciones esfuerzo-deformación del hormigón a tracción y a compresión, respectivamente. Las relaciones esfuerzo-deformación de los refuerzos de acero y de FRP se modelan mediante líneas rectas múltiples (esto es, líneas poligonales). El método de las fibras (modificado) es utilizado para calcular los diagramas momento-curvatura a diferentes niveles de la carga axial aplicada (es decir, las curvas M-P-ϕ) y el método de Gauss de integración (para la suma de las contribuciones de los fibras paralelas al eje neutro) para calcular las rotaciones laterales y deflexiones a lo largo de la luz de la viga-columna. La validez del modelo propuesto y las ecuaciones correspondientes se pusieron a prueba con datos experimentales disponibles en la literatura técnica (véase la parte II de esta publicación).

PALABRAS CLAVE: Fuerza axial, viga, columna, materiales compuestos, tubos rellenos de hormigón, hormigón de alta resistencia, deflexiones, polímetros reforzados con fibras, hormigón pretensado.

1. INTRODUCTION

The use of FRP materials is of great importance in civil engineering, particularly in the retrofitting of existing structures. This is a consequence of current needs for lighter, more slender, corrosion resistant, and more economical structures. For instance, due to the deterioration, the relatively short life, and high-costs of the maintenance of existing highway structures, the Departments of Transportation (DOTs) all across the USA are very active in the use of composites in construction. In spite of the fact that there is still some reticence in the USA in using these materials, their use is growing little by little due to the low cost of maintenance in comparison with conventional materials. Piers made of FRP tubes filled with concrete, piers encased with FRP wraps, hybrid FRP beams and girders supporting decks also made of composites, rectangular and T-beams reinforced with FRP bars, beams prestressed with bonded or unbonded FRP tendons, and columns prestressed with FRP tendons, are now commonly used. A brief summary of the main uses and research of FRP composites in civil engineering structures is presented next.

Rebars made of FRP. The use of FRP bars as regular reinforcement has been investigated by many researchers. Saadatmanesh [4] studied the effects of the amount of FRP reinforcement and the type of bar shape and surface finish on the actual behavior and response of concrete beams. Thériault and Benmokrane [5] studied the effects of the amount of FRP reinforcement and the concrete strength on the crack width, bending moment resistance, and strains in the concrete and reinforcements. Bogdanovic [6] studied the lateral deflections in beams reinforced with aramid-fiber reinforced polymer (AFRP) bars. Thiagarajan [7] studied the moment-curvature response, bending moment strength, and strains in the concrete and reinforcements in beams reinforced with carbon-fiber reinforced polymer (CFRP) bars.

"Passive" FRP Laminates for Beam Retrofitting. This is perhaps the most common use of FRP composites in construction today. Saadatmanesh and Ehsani [8] and An et al. [9] carried out extensive theoretical and experimental studies on the behavior of rectangular and T-beams reinforced with GFRP laminates. Ross et al. [10] carried out theoretical and experimental studies on beams retrofitted with FRP laminates. Shahawy and Beitelman [11] and Ei-Tawil et al. [12] studied the static and fatigue response of T-beams reinforced with CFRP laminates. Borowicz [13] carried out theoretical and experimental studies on the behavior of rectangular and T-beams reinforced with mechanically applied FRP laminates. Ei-Refaie et al. [14] studied the behavior and response of continuous beams reinforced with FRP laminates. More recently, Rasheed et al. [15] proposed a method to calculate deflections in composite beams subjected to concentrated, uniform, and triangular distributed loads.

Prestressed FRP Laminates and Strands for Beam Retrofitting. Due to current needs for retrofitting existing prestressed concrete buildings and bridges, the use of prestressed FRP Laminates and Strands has received some attention. Sen et al. [16] showed that the actual behavior and response of beams prestressed with FRP strands and laminates are similar to those of prestressed with steel strands. Lees and Burgoyne [17] studied the effects of bonding in beams prestressed with AFRP strands. Grace et al. [18] investigated the behavior of box girders reinforced with bonded and unbonded prestressed CFRP bars and strands. Different techniques for the prestressing of FRP laminates have been proposed by Triantafillou et al. [19], Wight et al. [20], and Yu et al. [21].

FRP/Concrete Hybrid Beams. Deskovic et al. [22] studied the behavior of different forms of GFRP box girders with a concrete deck along the top surface and reinforced with CFRP laminates along the bottom of the girders. Fam and Rizkalla [23] studied the behavior of solid and hollow FRP tubes filled with concrete. Schnerch et al. [24] developed a method for the analysis of rectangular hybrid beam-columns.

Columns Reinforced with FRP. Kawaguchi [25] and Mirmiran et al. [26] experimentally studied the behavior of columns prestressed with FRP bars and strands. Issa et al. [27] studied the behavior of columns reinforced with GFRP tendons. Chaallal and Shahawy [28, 29] studied the behavior of rectangular columns encased with CFRP laminates.

Long Term Loads on Beams Reinforced with FRP. Plevris and Triantafillou [30] studied the long-term response of beams reinforced with FRP laminates. Deskovic et al. [31] studied the long-term response of hybrid beams subjected to sustained loads. Naguib and Mirmiran [32] studied the long-term response of a CFRP tube filled with concrete subjected to sustained loads. Zou [33, 34, 35, and 36] studied the long-term behavior of beams prestressed with FRP strands.

Objectives and Scope. The main objective of this paper is to present an analytical method and a numerical algorithm for the calculation of the short and long-term response of prestressed and non-prestressed concrete beam-columns reinforced with FRP bars or plates, steel rebars, bonded or/and unbonded prestressed tendons. In addition, beams and columns encased with FRP fabrics and FRP tubes filled with concrete are analyzed with the proposed model. The effects of tension stiffening, creep and shrinkage of the concrete, and the relaxation of the prestressed steel are considered. The models proposed by Vecchio and Collins [1] and by Popovics [2, 3] are adopted for the stress-strain relationships of the concrete in tension and compression, respectively. The strain-stress relationships of the steel and FRP reinforcements are modeled using multiple straight lines (polygonal lines). The method of the fibers (modified) is used to calculate the moment-curvature diagrams at different levels of the applied axial load (i.e., the M-P-ϕ curves), and Gauss' method of integration (for the sum of the contributions of the fibers parallel to the neutral axis) to calculate the rotations and lateral deflections along the span of the beam-column. The shear and torsion effects along the member are not included. Due to space limitations, the validity of the proposed method and numerical algorithm is presented in part II of this paper. (over 36 experimental test specimens reported by different researchers were used to verify the proposed method and the numerical algorithm).

2. PROPOSED ANALYTICAL MODEL

The proposed model is an extended and improved version of an algorithm presented previously by Rodriguez-Gutierrez and Aristizabal-Ochoa [37, 38] for the analysis, design, and behavior of slender concrete columns subjected to biaxial bending and axial load. The M-P-ϕ diagrams along the member are calculated using the method presented by Rodriguez-Gutierrez and Aristizabal-Ochoa [37] with the exception of the stress-strain curve of the concrete which is the one presented by Popovics [2, 3] and expressed by Eq. (1a), instead of the parabola of Hognestad (for the ascending part) and the straight line (for the descending part; i.e., Eqs. (3a) and (3b) listed in ref. [37]). It was found that the stress-strain curve given by Eq. (1a) is more appropriate for beam-columns made of high-strength concrete. Expression (1a) includes the simultaneous long-term effects of shrinkage $\varepsilon_{sh}(t)$ and creep $\varepsilon_o(t)$ both of which must be determined beforehand either experimentally or theoretically by the user.

$$f_c = \frac{f''_c(t)\beta_c\left[\frac{\varepsilon_c - \varepsilon_{sh}(t)}{\varepsilon_o(t)}\right]}{\beta_c - 1 + \left[\frac{\varepsilon_c - \varepsilon_{sh}(t)}{\varepsilon_o(t)}\right]^{\beta_c}} \quad (1a)$$

$$\beta_c = \frac{1}{\left(1 - \frac{f''_c(t)}{E_c(t)\,\varepsilon_o(t)}\right)} \quad (1b)$$

Where:

$$\varepsilon_o(t) = \varepsilon_o(0)[1+\phi(t, t_i)] \quad (1c)$$

$$E_c(t) = E_c(0)/[1+\chi\phi(t, t_i)] \quad (1d)$$

$f''_c(t)$ = maximum stress in the concrete at time t;

$E_c(t)$ = elastic modulus of the concrete at time t;

$\varepsilon_{sh}(t)$ = shrinkage strain of the concrete at time t;

$\varepsilon_o(t)$ = strain in the concrete corresponding to the maximum stress in concrete $f''_c(t)$ at time t;

$\phi(t, t_i)$ = creep factor of the concrete;

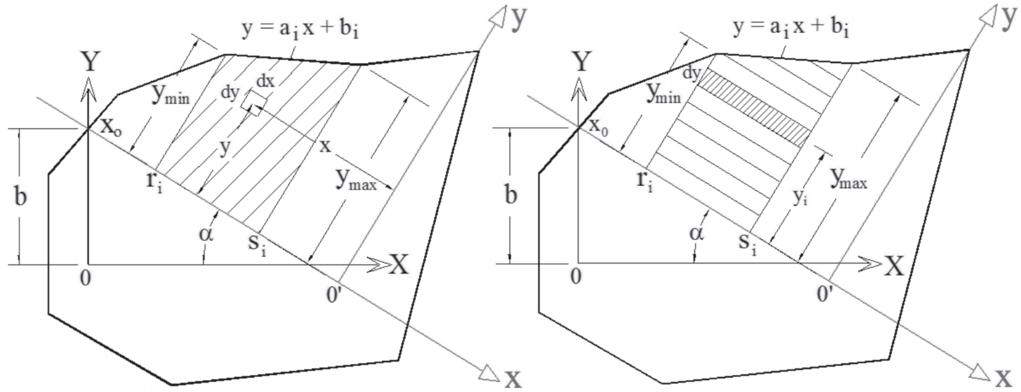
t_i = initial time of application of loading in days;

χ = age factor of the concrete.

Any theoretical or experimental expression for $\phi(t, t_i)$ and $\varepsilon_{sh}(t)$ may be used.

The beam-column can be reinforced with combinations of FRP bars or plates, steel rebars, bonded or/and unbonded prestressed tendons all with different stress-strain relationships. Beam-columns made of circular tube sections are modeled as 16-sided polygons (since a larger number of sides does not increase the accuracy significantly).

Calculation of Displacements and Rotations. The method of the fibers (modified) is used to calculate the moment-curvature diagrams at different levels of the applied axial load (i.e., the M-P-ϕ curves), and Gauss' method of integration (for the sum of the contributions of the fibers parallel to the neutral axis) to calculate the rotations and the lateral deflections along the span of the beam-column, as shown in Fig. 1.



(a) Gauss Integration (b) Integration by fibers

FIG. 1. Cross-section of beam-column subjected to biaxial bending

Consider the beam column AB (shown in Fig. 2) with generalized boundary conditions subjected to an axial load P (with eccentricities e_a and e_b at A and B, respectively), and subjected to concentrated or distributed transverse loads. The bending moment M(Z) along the member span is as follows:

$$M(Z) = \hat{a}_a \ddot{A}_a Z - P\left(\ddot{A}_a + v(Z) - e_a\right) - \hat{e}_a \grave{e}_a - M_q(Z) - M_p(Z) - \frac{Z}{L}\left(Pe_a - Pe_b\right) \tag{2a}$$

Where: $M_q(Z)$ and $M_p(Z)$ = bending moment at Z (along the column with pinned-pinned end conditions) caused by the distributed and concentrated loads, respectively; and v(Z) = lateral deflection at Z.

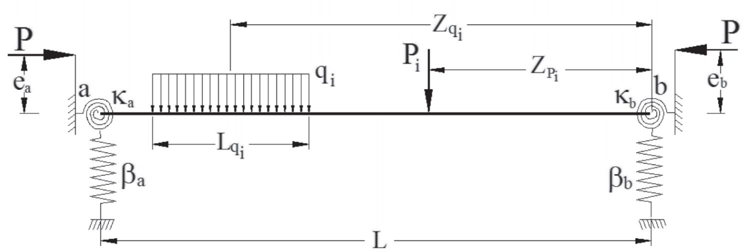


FIG. 2. Model of beam-column with generalized boundary conditions

To obtain M(Z) and v(Z) along the member, both the rotations and lateral deflections at the ends A and B (i.e., θ_a, θ_b, Δ_a, Δ_b, respectively) must be determined first. To achieve this, the following four non-linear equations must be solved:

$$M(\varphi_b) - \ddot{A}_a + \ddot{A}_b - \grave{e}_a L = 0 \tag{2b}$$

$$M(\varphi_a) + \ddot{A}_a - \ddot{A}_b + \grave{e}_b L = 0 \tag{2b}$$

$$\ddot{A}_a \hat{a}_a L + Pe_a - \hat{e}_a \grave{e}_a - \hat{e}_b \grave{e}_b - \sum_{i=1}^{Np} p_i Z_{p_i} - \sum_{i=1}^{Nq} q_i l_i Z_{q_i} - P\left(\ddot{A}_a - \ddot{A}_b\right) \tag{2d}$$

$$\ddot{A}_a \hat{a}_a + \ddot{A}_b \hat{a}_b - \sum_{i=1}^{Np} p_i - \sum_{i=1}^{Nq} q_i l_i = \mathbf{0} \tag{2e}$$

Where: $M(\varphi_a)$, $M(\varphi_b)$ = moments at ends A and B obtained from the moment-curvature diagrams, respectively; and Δ_a, θ_a, Δ_b and θ_b = deflections and rotations at ends A and B, respectively.

An iterative process is proposed to solve Eqs. (2a-e) for θ_a, θ_b, Δ_a and Δ_b as follows:

1) Select a set of trial (initial) values for the unknowns θ_a, θ_b, Δ_a, and Δ_b;

2) Divide the beam-column into N_e elements (at least 10) and the bending moments are calculated at the N_e+1 sections;

3) Determine the curvatures at the N_e+1 sections using the corresponding M-P-ϕ curves;

4) Calculate $M(\varphi_a)$ and $M(\varphi_b)$;

5) The four non-linear equations (2b-e) are solved; if the solution is not obtained, the values of the unknowns θ_a, θ_b, Δ_a, and Δ_b are corrected using a numerical method (like Newton-Raphson or Runge-Kutta);

6) Return to step 2 and repeat the process until Eqs. (2b-e) are solved;

7) Once Eqs. (2b-e) are solved to a desired level of accuracy, the rotations and lateral deflections of each node are calculated as follows:

$$\theta_1 = \theta_a \tag{3a}$$

$$\theta_{N_e+1} = \theta_b \tag{3b}$$

$$v_1 = -\Delta_a \tag{3c}$$

$$v_{N_e+1} = -\Delta_b \tag{3d}$$

$$\theta_2 = \theta_a - \frac{L_e}{2}(\phi_1 + \phi_2) \tag{3e}$$

$$\theta_i = \theta_a - \frac{L_e}{2}(\phi_1 + \phi_i) - L_e \sum_{j=2}^{i-1} \phi_j \quad (3 \le i \le N_e) \tag{3f}$$

$$v_i = \frac{e_i}{6}[L - L_e(i-1)]^3 + \frac{f_i}{2}[L - L_e(i-1)]^2 + g_i[L - L_e(i-1)] + h_i \quad (2 \le i \le N_e) \tag{3g}$$

Where: $$e_i = \frac{1}{L_e}(\phi_{i-1} - \phi_i) \tag{3h}$$

$$f_i = \phi_i - e_i[L - L_e(i-1)] \tag{3i}$$

$$g_i = \phi_i - \frac{e_i}{2}[L - L_e(i-1)]^2 - f_i[L - L_e(i-1)] \tag{3j}$$

$$h_i = v_{i-1} - \frac{e_i}{6}[L - L_e(i-2)]^3 - \frac{f_i}{2}[L - L_e(i-2)]^2 - g_i[L - L_e(i-2)] \tag{3k}$$

8) Calculate the second-order moments along the member (P-Delta effects) and return to Step 3. The iterative process is halted when the maximum lateral displacement along the column remains practically unchanged between two consecutive iterations. When this happens, the column is stable under the applied loads; otherwise, the column becomes unstable under the applied loads when the maximum lateral displacement along the column keeps on increasing between two consecutive iterations. The number of iterations required is generally less than 5 but it increases as the beam-column is less stiff and lateral displacements become large.

Notice that the proposed method does not require any assumed curve of the deflected shape of the member like in most other methods.

For the particular case of a simple supported beam-column with zero moments at both ends only Eqs. (2a) and (2b) have to be solved by making $\Delta_a = \Delta_b = 0$ with Eq. (2a) reduced to:

$$M(Z) = P\left[v(Z) + e_a\right] - M_q(Z) - M_p(Z) - \frac{Z}{L}\left(Pe_a - Pe_b - \sum_{i=1}^{N_q} q_i l_i Zq_i - \sum_{i=1}^{N_p} p_i Zp_i\right) \tag{4}$$

For beam-columns reinforced with steel shapes or composites plates, the contributions to the axial load and bending moments with respect to the local xy-axes of the shape or plate-j are given by the following expression:

$$P_{rj} = \int_{y_{min}}^{y_{max}} f_s dA \tag{5a}$$

$$M_{rxj} = \int_{y_{min}}^{y_{max}} f_s y dA \tag{5b}$$

$$M_{ryj} = \int_{y_{min}}^{y_{max}} f_s x dA \tag{5c}$$

Using Fig. 3a: $dA = h_j ds = \dfrac{h_j dy}{\sin\varphi}$ and $x = \dfrac{1}{a_{rj}}(y - b_{rj})$.

If the strain-stress relationship of the composite plate-j is modeled using straight lines, the integrals (5a)-(5c) can be expressed as follows:

$$P_{rj} = \sum_{i=1}^{N_{pl}} \frac{h_j}{\sin\varphi_j}\left\{\frac{f_{ri}\,\varepsilon}{2c}(y_{i+1}^2 - y_i^2) + k_{ri}(y_{i+1} - y_i)\right\} \tag{6a}$$

$$M_{rxj} = \sum_{i=1}^{N_{pl}} \frac{h_j}{\sin\varphi_j}\left\{\frac{f_{ri}\,\varepsilon}{3c}(y_{i+1}^3 - y_i^3) + \frac{k_{ri}}{2}(y_{i+1}^2 - y_i^2)\right\} \tag{6b}$$

$$M_{ryj} = \sum_{i=1}^{N_{pl}} \frac{h_j}{\sin\varphi_j}\left\{\frac{f_{ri}\,\varepsilon}{3ca_{rj}}(y_{i+1}^3 - y_i^3) + \frac{(y_{i+1}^2 - y_i^2)}{2a_{rj}}\left(k_{ri} - \frac{f_{ri}\, b_{rj}\,\varepsilon}{c}\right) - \frac{k_{ri}\, b_{rj}}{a_{rj}}(y_{i+1} - y_i)\right\} \tag{6c}$$

Where:

N_{pl} = number of straight segments used to represent the stress-strain curve of the composite material, as shown by Fig. 2b;

φ_j = angle made by the mid-plane of plate-j with the neutral axis of the beam;

$a_{rj} = \tan\varphi_j$;

h_j = thickness of plate-j; and

f_{ri} and k_{ri} = slope and intersection of a line that describes the stresses along the composite plate-j, respectively.

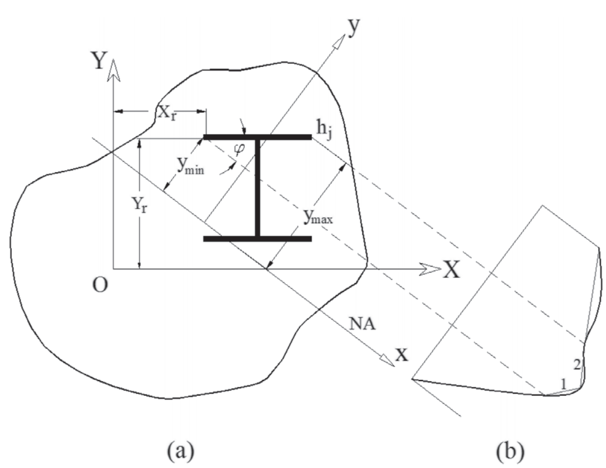


FIG. 3. Stress distribution across an embedded shape

The model by Vecchio and Collins [1] is adopted for the stress-strain relationship for the concrete in tension as described by the following two expressions:

$$f_{ct} = \frac{y}{c}\varepsilon E_t \quad (\text{for } \frac{y}{c}\varepsilon \le \varepsilon_{cr}) \qquad (7a)$$

$$f_{ct} = \frac{\alpha_1 \alpha_2}{1+\sqrt{500\frac{y}{c}\varepsilon}} f_{cr} \quad (\text{for } \frac{y}{c}\varepsilon > \varepsilon_{cr}) \qquad (7b)$$

Where:

f_{cr} = stress of the concrete at cracking (assumed to be equal to $0.6\sqrt{f_c^{'}}$ with $f_c^{'}$ in MPa);

y = distance from the extreme fiber in tension to the neutral axis;

c = depth of the neutral axis;

ε = strain of the concrete at the extreme fiber in tension;

ε_{cr} = strain of the concrete at cracking;

α_1 = factor that takes into account the effects of the bonding characteristics of the reinforcement. (= 1 for regular corrugated rebars; = 0.7 for plain bars, wires or bonded strands; = 0.5 for FRP reinforcement; and = 0 for unbonded reinforcement); and

α_2 = factor that takes into account the effects of the type of applied loads (= 1 short-term load; and = 0 for long-term and cyclic loads).

3. CONCLUSIONS

A model is developed that is capable of predicting the short and long-term response of prestressed and non-prestressed concrete beam-columns of any cross section reinforced with FRP bars and/or plates, steel rebars, bonded and/or unbonded prestressed tendons. In addition, beams and columns encased with FRP fabrics and FRP tubes filled with concrete can be analyzed. The effects of tension stiffening, creep and shrinkage of the concrete, and the relaxation of the prestressed steel are considered. The validity of the proposed model and corresponding equations were tested against experimental data available in the technical literature (see part II of this article).

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