



Compressive behavior of FRP externally wrapped R.C. column with buckling effects of longitudinal bars

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ABSTRACT

In this paper, a calculation model to simulate the compressive behavior of R.C. columns with square cross-sections externally wrapped with FRP, including buckling effects of the longitudinal bars and reduction of the confinement pressure induced by the buckled compressed bars, is presented and discussed. The model distinguishes the cases of corner and side bars, calculating the different critical lengths and the critical loads. The Teng et al. (2009) model was adopted to predict the compressive behavior of FRP-confined concrete, and the Dhakal and Maekawa (2002) model was taken into account to predict the compressive behavior of longitudinal bars. The critical length and critical stress of compressed bars including interaction effects between concrete cover, stirrups and FRP wraps were calculated, distinguishing between corner and side bars. Based on the model mentioned, analytical expressions were derived to calculate the critical strain at the onset of bar buckling and the minimum thickness of FRP to prevent instability of the compressed bars. Finally, a theoretical–experimental comparison was made to validate the model.

1. Introduction

Starting from about two decades ago, the external wrapping of R.C. columns with FRP materials became a very popular retrofitting technique analyzed in depth from both the experimental and theoretical points of view; it also became the object of fairly recent international codes [1,2]. In the researches carried out, FRP wrapping techniques, in which fabric fibers work in traction in the direction of the cross-sectional expansion of the concrete element, were identified as an effective technique for reinforcing or retrofitting R.C. columns subject to axial and lateral actions with corroded reinforcement [Campione Cannella Minafò, Campione Cannella Ferrotto Cavaleri].

Theoretical and experimental studies [3,4] stressed the effectiveness of external wrapping technique to mitigate the fragility of the compressed concrete with increased strength and ductility. These effects depend on the reinforcing material (carbon, glass, aramidic, basalt, etc.), the number of layers used in the wrapping, the connection technique (epoxy resins or cement mortars), and the fabric overlapping connections. Research on durability and composite stability has led to research on the use of materials that could also ensure long-term resistance and high performance under exceptional actions (fire, earthquake, explosions, etc.).

Many of the compression tests [5–9] on concrete cylinders or prisms were carried out with almost quasi-static loads (slow tests), which were

mainly monotonic or cyclic, but without inversion of sign. These tests were conducted with variation in the strength class of concrete on concrete elements externally wrapped with FRP in the absence of traditional reinforcement (longitudinal bars and transverse stirrups). Attention was focused above all on the effect of the wrapping in relation to the shape of the cross-section of the element (circular, square, rectangular, and elliptical). It emerged from these studies that in members with sharp corners or rounded with a low fillet radius, due to stress concentration at the corner premature failure occurs under medium stress in the fiber at a much lower value than at ultimate stress (values between 0.1 and 0.3 of the ultimate stress). It was thus found that to avoid this phenomenon at the edges of the section, before wrapping it is necessary to utilize an adequate radius of the corners with suggested values between 15 and 30 mm. With the same number of FRP layers, the cross-sectional shape plays a fundamental role. The most effective shapes are in circular specimens, followed by square and then rectangular ones, where, however, when the ratio of the sides is higher than two, the bandage has little effect (only the ductility increases and not the resistance).

The maximum strain on the FRP when confined concrete reaches the peak stress is another key parameter for understanding the effectiveness of the reinforcement and for predicting the strength and ductility of the wrapped element. Its value depends on many factors, including some properties of the concrete and other reinforcement

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materials including elastic modulus and number of layers. The behavior of FRP composite is almost linear elastic. The maximum strain achievable on FRP wrap depends on the limit state, which is reached when a buckling effect arises, at which time the maximum dilatation occurs in the confined concrete, or when there is delamination of the FRP from the concrete. The maximum strain in FRP at concrete failure is also related to the effect of the concentration of stresses due to the shape of the sections. In accordance with [10,1], the ultimate strain can be assumed to be 0.004, or 0.4 or 0.6 of the ultimate strain value provided by the manufacturer respectively.

Therefore, the material can be ductile when it is effectively confined. In this case, strain-hardening behavior is observed. The material can be brittle when it is weakly confined. In this case, strain-softening behavior is observed [8].

Other recent experimental works investigated on the effect of pre-existing loads in the columns at the moment of strengthening with FRP sheets and how the presence of previous sustained loads influences the compressive behavior after wrapping in terms of strength and deformational capacity [11–13].

From the analytical point of view, several models in the literature [14–16] can capture the salient aspects experimentally found.

Lam and Teng [16,17] suggest that the dimensionless confinement pressure on the compressive strength of unconfined concrete should not be less than 0.08, which is indicated as the minimum level of confinement required to avoid a strain-softening behavior.

More recently, attention has been paid to structural elements such as medium-scale or full-scale columns with longitudinal bars and transverse stirrups and externally wrapped with FRP [18–20]. The authors mentioned evaluated the effect of the reinforcement technique regarding both material confinement and ductility and the stability conditions of the compressed bars, a phenomenon that occurs after the separation of the cover and when the reinforcements are close to enervation. As with the material, the column behavior is affected by the confinement of the concrete. But, as it is often observed on real-scale elements, the behavior of the element is also related to the instability of the compressed bars and the interaction of FRP and steel reinforcements. In the case of square-to-rectangular cross-sections, effective confinement does not make it possible to obtain hardening behavior and the main effects due to FRP are a reduction in the buckling phenomenon and an increase in the ductility of the compressed element without an increase in strength.

In this paper, attention is focused on the behavior of compressed columns with square cross-sections externally wrapped with FRP, also considering buckling effects of longitudinal bars and a resulting loss of confinement effects.

An assessment concept is therefore presented and discussed regarding the main aspects of the steel transverse reinforcement as well as the steel longitudinal bars contribution in the overall compressive response of FRP-confined RC columns including buckling effects. As a consequence of the physical and mechanical considerations on the behavior of the different materials of the RC members, an analytical model is proposed for a realistic prediction of the confinement action affected by an effectiveness reduction due to the buckling of the longitudinal bars.

A procedure for the determination of the lateral confinement pressure to be used for the evaluation of the strength of the confined concrete is presented, comparing the results of the compressive Stress-strain response with a wide range of experimental data available in the literature.

2. Behavior of compressed steel bars

Several experimental-theoretical works studied the compressive behavior of steel bars [21–23]. The tests performed showed that the compression behavior of the bars and buckling in compression, if they occur, depend on the type of steel (elastic modulus, yield stress,

hardening ratio, etc.), load eccentricity, the diameter (ϕ) of the bars and the distance between two supports (L). In particular, when the ratio L/ϕ increases steel bars buckle in the hardening, plastic or elastic ranges.

Monti and Nuti [21] studied the experimental compression behavior of deformed steel bars with varying diameters (16, 20 and 24 mm) and with L/ϕ ratios between 5 and 11. The bars had a yielding stress f_y of 440 MPa.

Bae et al. [22] investigated the experimental behavior of deformed steel bars under an axial load, assuming the diameter of steel bars equal to 32.3 and 25.5 mm, with L/ϕ ratios between 4 and 12. The yielding stress and corresponding strain were 437 and 444 MPa and 0.0022 for 32.3 and 25.5 mm bars and ultimate stress 728 and 636 MPa load for 32.3 and 25.5 mm bars.

Cosenza and Prota [23] studied the experimental compressive behavior of smooth bars varying the diameter of the bars (8, 12, 14 and 16 mm) with L/ϕ , ratios between 5 and 70. The steel used had yielding stress $f_y = 410.8$ MPa and corresponding strain $\epsilon_y = 0.0021$, respectively; ultimate stress $f_u = 540.9$ MPa and elastic modulus $E_s = 195$ GPa, respectively.

All authors agree that increasing the L/ϕ ratio the behavior of the steel bar is close to that detected in traction. Such a crisis may occur in the elastic or plastic phase for a high or intermediate L/ϕ ratio.

From a theoretical point of view, several models describe the behavior of compression bars including buckling phenomena. Among these, it was chosen to adopt the σ - ϵ relation of Dhakal and Maekawa [24] proposed in the analytical form:

$$\sigma_s = \begin{cases} E_s \cdot \epsilon_s & \epsilon_s \leq \epsilon_y \\ f_y & \epsilon_y \leq \epsilon_s \leq \epsilon_h \\ f_y + (\epsilon_s - \epsilon_h) \cdot E_h & \epsilon_h \leq \epsilon_s \leq \epsilon_u \end{cases} \quad (1)$$

with f_u being the ultimate stress, E_s the elastic modulus of the steel, ϵ_h the strain at the beginning of the hardening, ϵ_u the ultimate strain and E_h the hardening modulus.

In the case of compressed bars, the Stress-strain curve in compression takes the form:

$$\frac{\sigma}{\sigma_l} = 1 - \left(1 - \frac{\sigma^*}{\sigma_l^*}\right) \cdot \left(\frac{\epsilon - \epsilon_y}{\epsilon^* - \epsilon_y}\right) \quad \epsilon_y < \epsilon \leq \epsilon^* \quad (2)$$

$$\sigma \geq 0.2 \cdot f_y; \quad \sigma = \sigma^* - 0.02 \cdot E_s \cdot (\epsilon - \epsilon^*) \quad \epsilon > \epsilon^* \quad (3)$$

$$\frac{\epsilon^*}{\epsilon_y} = 55 - 2.3 \cdot \sqrt{\frac{f_y}{100}} \cdot \frac{L}{\phi} \quad \frac{\epsilon^*}{\epsilon_y} \geq 7 \quad (4)$$

$$\frac{\sigma^*}{\sigma_l^*} = \alpha \cdot \left(1.1 - 0.0116 \cdot \sqrt{\frac{f_y}{100}} \cdot \frac{L}{\phi}\right) \quad \frac{\sigma^*}{f_y} \geq 0.2 \quad (5)$$

with $\alpha = 1$.

Application of the model of Dhakal and Maekawa [24] to the experimental cases of [21–23] allows one to derive the Stress-strain curves shown in Fig. 1. The model of Dhakal and Maekawa [24] describes with a good level of approximation the behavior of the compressed bars observed experimentally. If the L/ϕ ratio is higher than 5, buckling occurs in the hardening or plastic phase and buckling occurs only for deformation values greater than 30 times the yielding strain. It was also noted that for L/ϕ lower than 5, the compressive behavior is only slightly influenced by buckling effects.

2.1. Critical load and critical length of restrained longitudinal bars

In the case of internal reinforcing bars of R.C. columns, when the cover is spalled off the risk of bars buckling arises, occurring at a lower or higher critical stress than the yielding stress on a critical length L higher or lower than the pitch of the stirrups, depending on the reciprocal flexibility of the restraint with respect to that of the

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