

Parametric Study on the Effect of Steel Confinement in Short Bridge Piers Retrofitted with Externally-Wrapped FRP

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Abstract. Confinement of reinforced concrete (RC) piers generally has a beneficial effect on both the compressive strength and the ductility of the confined member. Thus, externally-bonded fiber-reinforced polymer (FRP) wrapping is often used as a retrofit technique for bridge piers when additional compressive strength is needed. This study employs finite element analysis and a recently developed FRP-and-steel confined concrete model to investigate the influence of internal steel confinement on the response of circular RC columns confined with FRP and subject to concentric axial load. This new model leads to more accurate estimates of the response of these columns, what is particularly relevant for piers in short span bridges that are subjected mainly to vertical loads, for which it could lead to a more efficient and economical piers' retrofit, as well as a more accurate and less conservative bridge rating. A parametric study is conducted to examine the importance of some key parameters in the design of such columns.

1 Introduction

Retrofit of reinforced concrete (RC) bridge pier is an often-needed procedure, especially for piers of older bridges. The use of externally-bonded fiber-reinforced polymer (FRP) wrappings has been growing as a retrofitting and repairing technique of RC columns that are functionally deficient, e.g., due to deterioration attributed to aging and/or environmental factors, increased loads, damage by extreme events, or even inappropriate design. FRP jacketing became a relatively common retrofitting technique during the last three decades, due to the advantageous properties of FRP composites such as high strength and tensile modulus, excellent corrosion resistance, light-weight, and ease of transportation and application.

RC columns need to satisfy minimum code requirements for internal steel reinforcement and, in light of new design codes with even higher ductility requirements, the concrete in those columns is confined not only by external FRP sheets, but also by the internal reinforcing steel, which exerts a non-negligible additional confining pressure into the concrete core [1-4]. However, most of the FRP-confined concrete models that are available in the literature do not consider the confining mechanism of the existing transverse steel into the concrete [5-12, 24], or model the simultaneous confinement of FRP and steel via a linear superposition of their effects considered independently [1, 3, 13].

A constitutive model of concrete simultaneously confined by FRP and steel, recently developed by the authors [4], is employed in this study to model the combined confinement mechanisms of FRP and reinforcing steel within the cross-section of FRP-

confined RC columns. Zignago et al. [4] conducted an extensive comparison of numerical simulations performed using the Spoelstra-Monti and FRP-and-steel models to predict the load-carrying capacity of 46 axially-loaded FRP-confined RC columns, for which experimental results from nine different authors were available in the literature. It was shown that the FRP-and-steel model yields estimates of the structural behavior of those columns that are closer to the experimentally measured results. In particular, the ratio between the numerical estimates and the corresponding experimentally measured axial strengths assumed a mean value $\mu = 1.00$ and a coefficient of variation $COV = 0.10$ for the FRP-and-steel model, whereas the same statistics assumed the values $\mu = 0.88$ and $COV = 0.15$ for the Spoelstra-Monti model. It is noteworthy that the Spoelstra-Monti model was previously found to be among the most accurate models currently available in the literature to describe the structural response of RC columns retrofitted with FRP [5, 14]. Zignago et al. [4] also demonstrated that the FRP-and-steel model can achieve high accuracy in estimating the compressive strength of FRP-confined RC columns at a low computational cost when used in conjunction with fiber-section force-based elements. This model is particularly suited for the modeling of large-scale structures, such as bridges, due to its excellent combination of accuracy and low computational cost. This paper briefly describes the proposed FRP-and-steel confined concrete constitutive model and presents the results of a parametric study performed to investigate the effects of core concrete steel confinement on the axial strength of RC columns retrofitted with externally-bonded FRP wraps.

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2 FRP-and-steel confined concrete model

Spoelstra and Monti [5] proposed a material constitutive model for concrete confined with FRP or steel alone, which was based on an incremental-iterative approach that explicitly accounted for the continuous interaction with the confining device (FRP sheets or steel). In particular, this model considered the radial deformation of concrete due to dilation and the implicit relation between axial and lateral strains of concrete by enforcing equilibrium and compatibility at the interface.

The FRP-and-steel confined concrete model proposed by Zignago et al. [4] modifies the Spoelstra-Monti model to consider the interaction effects due to the simultaneous confinement mechanisms of externally bonded FRP and transverse steel reinforcement. This model calculates the total lateral confinement pressure as the sum of the confining pressure exerted by FRP and internal reinforcing steel as follows:

$$f'_l = f_{l,steel} + f_{l,FRP} = \frac{1}{2} \cdot k_s \cdot \rho_s \cdot \sigma_s + \frac{1}{2} \cdot k_f \cdot \rho_f \cdot \sigma_f \quad (1)$$

In Eq. (1), $f_{l,steel}$ denotes the confinement action due to the transverse reinforcement steel, with k_s = steel confinement effectiveness coefficient [15], ρ_s = transverse steel reinforcement ratio, and σ_s = stress in the transverse reinforcing steel. The term $f_{l,FRP}$ represents the confinement action due to the externally bonded FRP, where k_f = FRP confinement effectiveness coefficient [16], ρ_f = FRP volume ratio, and σ_f = stress in FRP laminates in the hoop direction. **Error! Reference source not found.** shows the total confinement action, f'_l , the confinement action due to steel, $f_{l,steel}$, and the confinement action due to FRP, $f_{l,FRP}$, as functions of the concrete lateral strain for the most common case in which the rupture of the FRP happens at a strain level, $\epsilon_{f,u}$, that is intermediate between the transversal steel yielding strain, $\epsilon_{s,u}$, and fracture strain. It is observed that, after the lateral strain of concrete exceeds the yield strain of steel, the transverse reinforcement applies a constant confining pressure up to its ultimate strain, while FRP laminates exert a linearly increasing confining pressure up to rupture $\epsilon_{f,u}$. After the FRP fails, only the constant steel confinement is left acting on the concrete. The total lateral confining pressure f'_l is employed in the iterative procedure developed by Spoelstra and Monti [5] to generate a monotonic envelope for the stress-strain relation of the FRP-and-steel confined concrete model.

Error! Reference source not found. compares typical monotonic envelopes for the stress-strain relations of the Spoelstra-Monti and FRP-and-steel confined concrete models for the same underlying properties. It is noted that the Spoelstra-Monti model reduces to the Popovics-Saenz unconfined model [17, 18] once the concrete lateral strain ϵ_l reaches the FRP rupture strain $\epsilon_{f,u}$. On the other hand, when the confining FRP reaches its ultimate strain, the FRP-and-steel

confined concrete model by Zignago et al. [4] is reduced to the steel-confined concrete model proposed by Mander et al. [15] up to the transverse steel failure. The FRP-and-steel confined concrete model has also been extended for cyclic loading and, thus, can be used also for cyclic and dynamic analysis of structural systems [4].

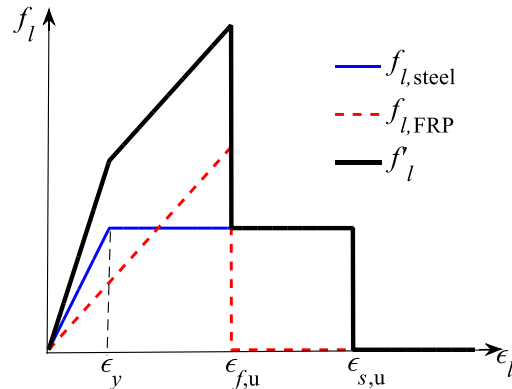


Fig. 1. Confinement pressure acting on concrete that is simultaneously confined by steel and FRP [4].

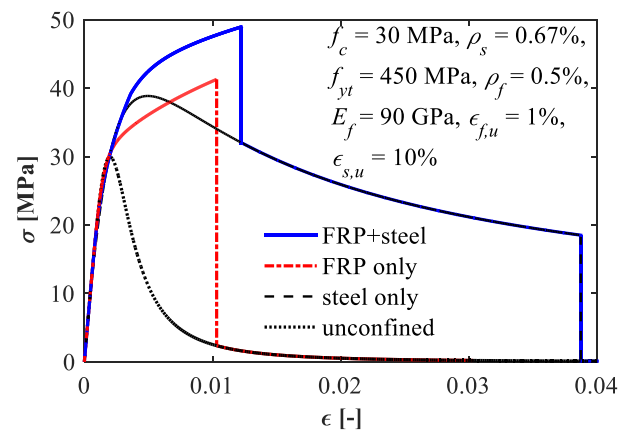


Fig. 2. Monotonic axial the stress-strain response curves obtained using different models and same underlying concrete properties [4].

3 Parametric study

A parametric study was performed to quantify the effects of internal steel confinement on the axial strength of circular RC columns confined with externally-bonded FRP laminates. The following parameters were considered: FRP type (carbon or glass FRP, i.e., CFRP or GFRP, respectively), FRP ratio (five different levels for each confining material), transverse steel reinforcement ratio (five different levels from 0%, i.e., no steel, to 2%, which is considered an upper bound for transverse steel reinforcement) and column diameter (three levels), for a total of 150 cases. Table 1 provides the values of the different parameters and their levels.

4 Finite element modeling

The finite element (FE) analyses were performed using a Matlab-based (MathWorks 1997) general purpose finite

element (FE) program suitable for linear and nonlinear, static and dynamic structural analyses. The columns were modelled using a fiber-discretized cross-section FE based on the force formulation [19] specialized for FE analysis of FRP-retrofitted RC members [14, 20]. The concrete fibers of each section were modeled using the FRP-and-steel confined concrete constitutive model by Zignago et al. [4]. It is noteworthy that, for the concrete cover fibers, which are confined only by FRP, the FRP-and-steel confined concrete model reduces to the Spoelstra-Monti model. The longitudinal steel reinforcement fibers were modelled using the Menegotto-Pinto model [21] as extended by Filippou et al. [22] to include isotropic hardening effects. The FRP efficiency factor, ζ_f , was described by the model proposed by Realfonzo and Napoli [23]. **Error! Reference source not found.** shows the constitutive material parameters assumed for this study. These material parameters were kept constant for all FE analyses.

Table 1. Parametric study: parameters and parameter levels.

Parameter	Range
FRP type	Carbon (C), Glass (G)
FRP ratio ρ_f - CFRP (%)	0, 0.25, 0.5, 1, 2
FRP ratio ρ_f - GFRP (%)	0, 0.5, 1, 2, 4
Steel ratio ρ_s (%)	0, 0.25, 0.5, 1, 2
Diameter (mm)	150, 300, 600

The load-carrying capacity of the cross-section of FRP-confined RC columns were evaluated through quasi-static analyses with monotonically increasing and concentrically applied axial loads. All columns had a length to diameter ratio $L/D = 8$ and were modelled using a single frame FE with five Gauss-Lobatto integration points. A constant value of concrete cover equal to 25 mm was assumed for all columns.

Table 2. Materials properties.

Material	Parameter	Value
Concrete	Compressive strength f_c (MPa)	30
	Strain at peak strength ϵ_{c0} (-)	0.02
	Initial tangent modulus E_c (MPa)	24648
Longitudinal steel reinforcement	Steel ratio ρ_l (%)	1
	Yield strength f_y (MPa)	450
	Young modulus E_s (GPa)	200
	Strain hardening ratio b (-)	0.005
Transverse steel reinforcement	Yield strength f_{yt} (MPa)	450
	Young modulus E_{st} (GPa)	200
CFRP	Tensile strength f_{tu} (MPa)	1000
	Young modulus E_f (GPa)	100
GFRP	Tensile strength f_{tu} (MPa)	400
	Young modulus E_f (GPa)	25

5 Results and discussion

The compressive strength results of the 150 nonlinear FE analyses are summarized in **Error! Reference source not found.** The vertical axes report the normalized axial strength defined as the ratio between the axial strength of

each column, P_{max} , and the axial strength of the column of same geometry without any confinement, P_0 (i.e., with $\rho_s = 0\%$ and $\rho_f = 0\%$). The horizontal axes report the transverse steel reinforcement ratio.

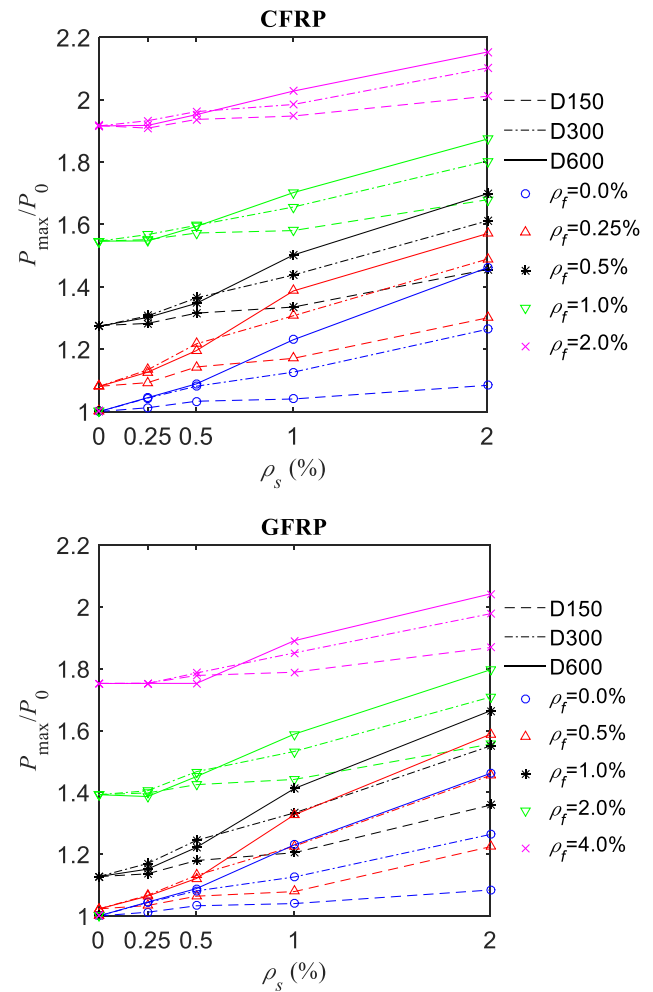


Fig. 3. Normalized axial strength for RC columns confined with: CFRP (top) and GFRP (bottom).

From the results reported in **Error! Reference source not found.**, it is observed that confinement with FRP has a significant effect on the compressive strength of the columns. As expected, this effect increases for increasing values of ρ_f , with a strength increase of more than 90% for $\rho_f = 2\%$ and CFRP, and slightly less than 80% or $\rho_f = 4\%$ and GFRP. Also, the confinement effect provided by the internal steel has a positive effect on the compressive strength of the columns. This effect also increases for increasing values of ρ_s and for increasing column diameters, with a 50% increase in strength for columns without FRP wrapping (i.e., $\rho_f = 0\%$) and diameter equal to 600 mm when $\rho_s = 2\%$. The higher relative increase in compressive strength for larger diameters is due to the realistic assumption of a constant concrete cover for columns of different dimensions, which implies that the proportion of core concrete subject to steel confinement increases for larger column diameters. A similar behavior is also observed for columns wrapped with FRP, with the relative increase in compressive strength due to the steel confinement that

reduces for increasing values of ρ_f . This observation confirms that the simultaneous FRP-and-steel confinement effects are non-linear and, thus, cannot be obtained through a simple linear superposition of the separate effects considered as independent.

In order to quantify the effects of internal steel confinement on FRP-confined RC columns, the FE analysis results are also reported as a function of the relative confinement effect of steel and FRP, c_f , which can be described as follows [4]:

$$c_f = \frac{f_{l,steel} \cdot A_{c,core}}{f_{l,FRP} \cdot A_g} \quad (2)$$

in which $A_{c,core}$ denotes the area of the concrete core, and A_g represents the gross cross-sectional area. **Error! Reference source not found.** plots the increment in compressive strength due to steel confinement, ΔP (i.e., the gain in strength obtained by considering the contribution of internal steel confinement on the concrete core when compared to the compressive strength obtained by neglecting the internal steel confinement effects), as a function of the relative confinement effect, c_f .

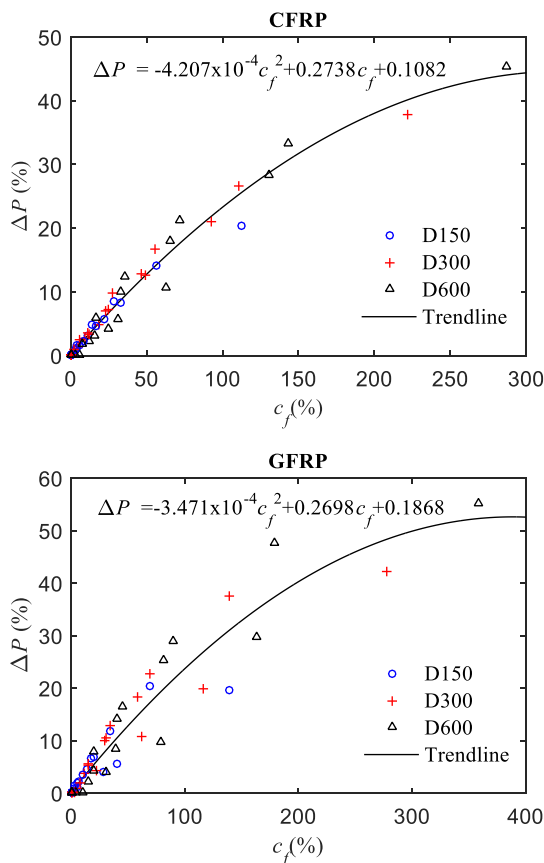


Fig. 4. Compressive strength increment, ΔP , versus relative confinement effect, c_f , for columns confined with: CFRP (top) and GFRP (bottom).

As expected, the results shown in **Error! Reference source not found.** indicate that the compressive strength increment due to internal steel confinement increases (in a less than proportional manner) with the relative confinement effect. It is also observed that the internal

steel confinement can produce a compressive strength increment as high as 55% for extreme cases with very large transversal steel amounts (GFRP with $c_f \approx 360\%$), and as high as 20% for a more realistic condition in which the confining forces exerted into the concrete core by the internal steel and by the FRP wrapping are of the same order of magnitude ($c_f \approx 100\%$). For CFRP, the compressive strength increments exhibit a small variability for a given value of c_f , whereas for GFRP, the compressive strength increments exhibit a larger variability than for GFRP, but reach similar values for comparable values of c_f . Therefore, the consideration of the simultaneous confinement action of externally-bonded FRP and internal steel is crucial for obtaining accurate estimates of the compressive strength of circular RC columns confined with FRP.

6 Conclusions

This paper investigated the effects of internal steel confinement on the compressive strength of circular RC columns confined with externally-bonded FRP. A parametric study was carried out in order to quantify the influence of key parameters (i.e., type of FRP, FRP ratio, transversal steel ratio, and column diameter) on the column's compressive strength. It was found that the FRP confinement alone can increase the cross-sectional capacity by up to 100% when compared to a column without any confinement, whereas the internal steel confinement alone can increase the compressive strength of the column by up to 50% when compared to a column without any confinement. It was also found that the simultaneous FRP-and-steel confinement is in general not negligible and can be significant, depending on the relative confinement effect between steel and FRP, as measured by a previously proposed coefficient c_f [4]. In particular, the internal steel confinement effect increases for increasing values of the parameter c_f , and compressive strength increments of 10% to 20% can be achieved for realistic values of c_f contained between 50% and 100%.

It is concluded that, for $c_f \geq 10\%$, the confinement effects of transverse reinforcement steel on the concrete core should be included in the estimation of columns' compressive strength. The consideration of the simultaneous confinement of steel and FRP produces more accurate estimates of the compressive strength of circular RC columns confined with externally-bonded FRP. In addition, the compressive strength increment produced by the internal steel confinement could have important consequences on the retrofit of bridge piers, for which the diameters are large and the amount of internal steel is usually also high. Considering this effect could significantly reduce the amount of FRP wrapping needed to obtain a target compressive strength and, thus, could lead to a more efficient and economical bridge piers' retrofit, as well as to a more accurate and less conservative bridge rating, particularly for piers in short span bridges that are subjected mainly to vertical loads.

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