A Theoretical Analysis Incorporating Empirical Formulas for Minimum GFRP Circular Spiral Reinforcement in Concrete Column Confinement

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ABSTRACT

This study investigates the influence of Glass Fiber Reinforced Polymer (GFRP) spirals on concrete column confinement. GFRP reinforcement is a useful alternative to traditional steel reinforcement because it offers certain advantages, like corrosion resistance and improved durability. GFRP spirals are lighter than the steel ones, providing higher tensile and fatigue strength. On the other hand, steel spirals are more affordable and offer higher compressive strength. While the traditional steel model aligns with the ACI code specifications, GFRP bars call for a different approach in determining the minimum spiral reinforcement. This study highlights the way that longitudinal reinforcement bars, which are conventionally neglected, influence the minimum spiral reinforcement requirements. The reinforced concrete models that may be applied in the future, should take into consideration both the confinement effectiveness of GFRP bars and the influence of longitudinal reinforcements to ensure structural integrity.

Keywords-spiral confinement; GFRP spirals; minimum spiral reinforcement; confinement effectiveness

I. INTRODUCTION

The utilization of GFRP reinforcement in concrete structures has gained considerable attention [1-5]. Traditional steel reinforcement is effective but also susceptible to corrosion, especially in environments near water or places exposed to chemicals. This leads to premature structural degradation, and therefore increases the maintenance costs.

GFRP reinforcement provides an alternative due to its inherent corrosion resistance, high tensile strength, and lightweight properties. Therefore, the behavior of concrete elements reinforced with GFRP has been extensively investigated. Also, efforts have been made to enhance the confinement mechanisms in order to improve the overall structural performance and endurance.

A critical aspect in the general design of reinforced concrete is the provision of adequate confinement to the concrete core. This is typically achieved by using transverse reinforcements, such as hoops and spirals.

When it comes to determining the minimum spiral reinforcement requirements, the conventional design practices for steel-reinforced concrete do not often take into consideration the use of longitudinal reinforcements. However, the mechanical properties of GFRP call for a reevaluation of this approach.

This study aims to investigate the influence of GFRP spirals on the confinement of concrete columns. An emphasis is also given for the results to be aligned with the current ACI code specifications and design practices that may arise in the near future.

II. LITERATURE REVIEW

Confinement is one of the most effective and widely implemented methods for increasing the axial compressive strength of concrete columns. Its application has been expanded with a variety of novel materials and has been modified by using new column geometries and confinement designs. Concrete confinement can be achieved through ties, hoops, and spirals. It can also be achieved with the use of fiber fabrics for wrapping, to enhance the compressive strength [6, 7]. Experiments on concrete columns reinforced with GFRP spirals have shown that using small GFRP spirals with close spacing can improve ductility and can compensate for the load of eccentric compression [8-10].

III. THEORETICAL ANALYSIS

A. Unconfined Axially Loaded Members

The ultimate capacity of an axially loaded compression member is determined by two primary factors: the compressive strength capacity of the concrete and the compressive strength capacity of the longitudinal steel reinforcement. The ultimate capacity of a short column that is loaded axially can be expressed as:

$$P_o = 0.85f'_c(A_g - A_{st}) + f_y A_{st} \quad (1)$$

where f'_c is the compressive strength of concrete, f_y is the yield strength of steel, A_g is the gross section area of the member, and A_{st} is the area of steel reinforcement.

B. Compressive Confinement

In concrete columns with transverse steel confinement, the concrete outside the confined core gets often fragmented. Consequently, the column's load-carrying capacity is reduced due to the smaller cross-sectional area. Nevertheless, the transverse reinforcement functions as passive confinement and can significantly enhance the compressive strength and deformation of the remaining concrete core [11-14]. The confined compressive concrete strength is represented by:

$$f'_{cc} = f'_c + k_l f_l \quad (2)$$

where f'_{cc} is the axial compressive strength of the confined column, f'_c is the compressive strength of concrete, f_l is the lateral confining pressure, and k_l is the lateral confining coefficient.

It has been shown that the lateral confining coefficient k_l typically ranges between 4.5 and 7.0 [15]. However, authors in [16] state that this range is between 2.1 and 4.0, while in a laboratory study, it was shown that k_l was 4.1 [17].

When collecting data from experiments/According to the data collected from the experiments, the confined strength in (2) can be represented as:

$$\frac{f'_{cc}}{f'_c} = 1 + a\left(\frac{f_l}{f'_c}\right)^b \quad (3)$$

The confined strain can be represented as:

$$\varepsilon_{cc} = \varepsilon_{co} + c\left(\frac{f_l}{f'_c}\right)^d \quad (4)$$

where a, b, c, and d are coefficients obtained by the experimental results.

C. Lateral Confining Pressure with Circular Transverse Steel

When a column is subjected to an axial load, its length shortens vertically, while it expands laterally. Assuming that such a reinforcement creates a uniform confining pressure and that the maximum lateral confining pressure is reached at the bending of the transverse steel, the equilibrium of a half-turn of the confinement cross-section can be expressed as:

$$2f_{yt}A_{sp} = d_s s f_l \quad (5)$$

or:

$$f_l = \frac{2f_{yt}A_{sp}}{d_s s} \quad (6)$$

where f_{yt} is the yield strength of the transverse steel, A_{sp} is the area of the circular transverse steel, d_s is the diameter of the circular transverse steel and s is the pitch of the circular transverse steel. Authors in [18-20] demonstrated that the lateral confining pressure could be reduced by several factors.

D. Confined Axially Loaded Column

From (6) and (2), the f'_{cc} can be expressed as:

$$f'_{cc} = f'_c + k_l\frac{2f_{yt}A_{sp}}{d_s s} \quad (7)$$

Equation (1) then becomes:

$$P_o = \left(0.85f'_c + k_l\frac{2f_{yt}A_{sp}}{d_s s}\right)A_{cc} + f_y A_{st} \quad (8)$$

where A_{cc} is the area of concrete in the column core and f'_c is replaced by $0.85f'_c$ in order to be aligned with the ACI code provisions for confined concrete.

If we substitute $A_{cc} = \frac{\pi d_s^2}{4} - A_{st}$, (8) becomes:

$$P_o = 0.85f'_c A_{cc} + k_l\frac{2f_{yt}A_{sp}}{d_s s}\left(\frac{\pi d_s^2}{4} - A_{st}\right) + f_y A_{st} \quad (9)$$

$$P_o = 0.85f'_c A_{cc} + k_l\frac{f_{yt}A_{sp}\pi d_s}{2s} - k_l\frac{2f_{yt}A_{sp}}{d_s s}A_{st} + f_y A_{st} \quad (10)$$

E. Minimum Spiral Reinforcement

1) General Solution

The confined axial load capacity of a column is defined by the principle that the column possesses sufficient transverse reinforcement to sustain loads beyond the limit and is capable of undergoing large compressive deformation. Consequently, the load-carrying capacity P_o of the column, which is given by (10), must be bigger than the P_o given by (1):

$$0.85f'_c A_{cc} + k_l\frac{f_{yt}A_{sp}\pi d_s}{2s} - k_l\frac{2f_{yt}A_{sp}}{d_s s}A_{st} + f_y A_{st} > 0.85f'_c(A_g - A_{st}) + f_y A_{st} \quad (11)$$

The minimum volumetric transverse reinforcement ratio can be expressed as:

$$\rho_s = \frac{A_{sp}\pi d_s}{sA_c} > \frac{1.7f'_c}{k_l f_{yt}}\left(\frac{A_g}{A_c} - 1\right) + \frac{4A_{sp}A_{st}}{d_s s A_c} \quad (12)$$

where $A_c = A_{cc} + A_{st}$ is the gross area of the column core.

The spiral area A_{sp} can be written as:

$$A_{sp} > \frac{1.7f'_c\left(\frac{A_g}{A_c} - 1\right)}{k_l f_{yt}\left(\frac{\pi d_s}{A_c} - \frac{4\rho_{cc}}{d_s}\right)}s = \frac{1.7f'_c(-A_g + A_c)d_s}{k_l f_{yt}(4\rho_{cc}A_c - \pi {d_s}^2)}s \quad (13)$$

where ρ_{cc} is the ratio of the longitudinal reinforcement area to the concrete core area.

2) Effective Lateral Confinement Coefficient

Authors in [14] showed that the coefficient for the effective lateral confining pressure was 4.1, which was the outcome of laboratory experiments in the early 1929. If this value is substituted into (13), the solution formula for the minimum transverse steel reinforcement is obtained:

$$A_{sp} > \frac{0.42f'_c(-A_g + A_c)d_s}{f_{yt}(4\rho_{cc}A_c - \pi {d_s}^2)}s \quad (14)$$

3) Modification Based on [22]

The axial compressive strength of the confined concrete proposed in [22] was calculated based on multiaxial tests [23, 24]. For the circular hoop and spiral transverse reinforcement, the formula is:

$$\mathrm{f}'_{\mathrm{cc}} = \mathrm{f}'_{\mathrm{co}}\left(-1.254 + 2.254\sqrt{1 + \frac{7.94\mathrm{f}'_{\mathrm{l}}}{\mathrm{f}'_{\mathrm{co}}}} - 2\frac{\mathrm{f}'_{\mathrm{l}}}{\mathrm{f}'_{\mathrm{co}}}\right) \quad (15)$$

The lateral confining pressure will not be perfectly maintained due to numerous factors and it should be reduced and modified by the confinement effectiveness coefficient $\mathrm{k_e}$.

For hoops:

$$\mathrm{k_e} = \frac{\left(1-\frac{s'}{2\mathrm{d_s}}\right)^2}{1-\rho_{\mathrm{cc}}} \quad (16)$$

For spiral:

$$\mathrm{k_e} = \frac{\left(1-\frac{s'}{2\mathrm{d_s}}\right)}{1-\rho_{\mathrm{cc}}} \quad (17)$$

where $\mathrm{d_s}$ is the diameter of the concrete core and s' is the spacing of the transverse steel hoops.

If we accept that the ultimate axially loaded confined strength must be greater than the unconfined strength, further calculations can be made and the final outcome of the spiral reinforcement $\mathrm{A_{sp}}$ can be simplified as:

The effective lateral confining pressure coefficient of (16) and (17) is substituted into (6). Then, this result is substituted into (15) and the outcome of (15) into (1). The spiral reinforcement $\mathrm{A_{sp}}$ can be, then, expressed as in (18):

$$\mathrm{A_{sp}} > \frac{\left(4.4154\mathrm{A_{cc}}-0.5\mathrm{A_g}+0.5\mathrm{A_{st}}+0.00001127\sqrt{1.604\times10^{11}\mathrm{A_{cc}}^2-3.97\times10^{10}\mathrm{A_{cc}A_g}+3.97\times10^{10}\mathrm{A_{cc}A_{st}}}\right)\mathrm{f}'_{\mathrm{c}}\mathrm{sd_s^2}}{(2\mathrm{d_s}-\mathrm{s})\mathrm{f_{yt}A_{cc}}} \quad (18)$$

4) Modification Based on [25]

Authors in [25] proposed a confinement model after they had experimentally tested 14 circular reinforced concrete columns with GFRP in both longitudinal and transverse bars. This model incorporates modifications from the model presented in [22] to predict the axial confined stress of concrete, using:

$$\frac{\mathrm{f}'_{\mathrm{cc}}}{\mathrm{f}'_{\mathrm{c}}} = 1 + 4.547\left(\frac{\mathrm{f_l}}{\mathrm{f}'_{\mathrm{c}}}\right)^{0.723} \quad (19)$$

The effective lateral confining pressure was directly adopted from [22]. By repeating the previous procedure, the complex relationship between $\frac{\mathrm{A_{sp}}}{\mathrm{s}}$ and ρ_{cc} is:

$$\mathrm{A_{sp}} > \frac{2\left(\frac{0.1185(\mathrm{A_g}-\mathrm{A_{st}})}{\mathrm{A_{cc}}}-0.1185\right)^{\frac{1}{0.723}}\mathrm{d_s}^2\mathrm{sf}'_{\mathrm{c}}}{(2\mathrm{d_s}-\mathrm{s})\mathrm{f_{yt}}} \quad (20)$$

5) Modification Based on [26]

Authors in [26] studied a small-scale concrete cylindrical column with a GFRP spiral without the longitudinal reinforcement. They proposed a prediction of the axial confined strength by having the parameter $\mathrm{k_l} = 1.31$. From the general solution in (13) the outcome is $\mathrm{A_{st}} = 0$. The minimum spiral reinforcement is:

$$\mathrm{A_{sp}} > \frac{1.30\mathrm{f}'_{\mathrm{c}}(\mathrm{A_g}-\mathrm{A_c})}{\mathrm{f_{yt}}\pi\mathrm{d_s}}\mathrm{s} \quad (21)$$

6) ACI Code

Based on the theoretical solution from (12), the ACI 318-19 specifies the minimum spiral steel reinforcement, in terms of the circular transverse steel volume ratio to the gross area of the column core [27]. The value of the later confining coefficient $\mathrm{k_l}$ was taken approximately as 3.77. The second term related to the longitudinal steel reinforcement was omitted. The equation was adopted from [28], where a study was carried out based on previous tests and several new researches [29, 30]. The minimum spiral reinforcement given by the ACI code is expressed as:

$$\mathrm{A_{sp}} > \frac{0.45\mathrm{f}'_{\mathrm{c}}}{\mathrm{f_{yt}}\pi\mathrm{d_s}}\left(\mathrm{A_g}-\mathrm{A_c}\right)\mathrm{s} \quad (22)$$

7) Modification Based on [21]

Authors in [21] proposed a model to evaluate the confined stress of concrete columns by using linear regression on the collected dataset from the research on GFRP spiral confinement:

$$\frac{\mathrm{f}'_{\mathrm{cc}}}{\mathrm{f}'_{\mathrm{c}}} = 1 + 1.7389\left(\frac{\mathrm{f_l}}{\mathrm{f}'_{\mathrm{c}}}\right) \quad (23)$$

The minimum spiral reinforcement based on (17) can be expressed as:

$$\mathrm{A_{sp}} > \frac{0.4888\mathrm{f}'_{\mathrm{c}}(\mathrm{A_g}-\mathrm{A_{st}}-\mathrm{A_{cc}})\mathrm{d_s^2}s}{(2\mathrm{d_s}-\mathrm{s})\mathrm{f_{yt}A_{cc}}} \quad (24)$$

IV. DISCUSSION OF MINIMUM SPIRAL REINFORCEMENT

A. GFRP and Traditional Steel Bars

In order to discuss the results of this study, a cylindrical concrete column was utilized as an example. Its parameters were:

- Concrete strength $\mathrm{f}'_{\mathrm{c}} = 30$ N.
- Column diameter $\mathrm{d} = 150$ mm.

  Concrete core diameter $\mathrm{d_s} = 100$ mm.

The spiral steel bar strength was set to be equal to the average GFRP bar rupture strength, which according to the ACI 440.1R code [31], is $\mathrm{f_{yt}} = 586.5$ N.

Figure 1 shows the results of the minimum spiral reinforcement area $\mathrm{A_{sp}}$ ($\mathrm{mm^2}$) as a function of spiral spacing s (mm). The traditional steel model presented in [14] produces a linear and conservative result that is consistent with the ACI code. On the contrary, the GFRP bar model presented in [26], which accounts for a less effective confinement, requires a higher minimum spiral reinforcement than that specified by the ACI code.

The models presented in [21, 22, 25] result in complex, nonlinear functions for minimum spiral reinforcement. This makes them less appropriate for defining the minimum spiral bar requirements. Therefore, when utilizing GFRP bars, the reduced confinement effectiveness must be considered and the appropriate specifications should be included in the reinforced concrete structure codes.

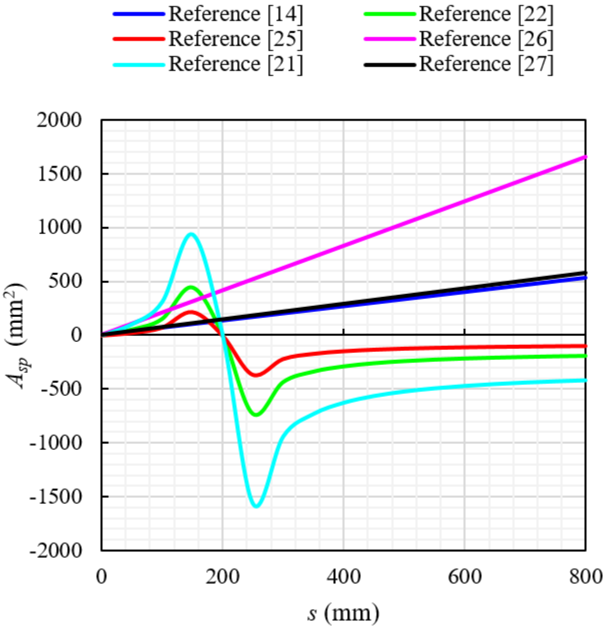

Fig. 1. Minimum spiral reinforcement: GFRP and traditional steel bars.

B. *Inclusion of Longitudinal Steel Reinforcement Effects*

The influence of longitudinal reinforcement bars is disregarded when determining the minimum spiral reinforcement. However, this analysis demonstrates that they have a measurable effect on the required minimum spiral reinforcement. As illustrated in Figure 2, the general solution reveals a correlation between the required minimum spiral reinforcement, expressed as $\frac{A_{sp}}{s}$, and the quantity of the longitudinal reinforcing bars ρ_{cc}.

For the traditional steel spiral confinement, with a lateral confining coefficient of 4.1 established in [14], the minimum spiral reinforcement requirements of the ACI code are satisfied within a longitudinal reinforcement percentage range of 0.01-0.08.

When the confinement effectiveness is reduced because of the use of GFRP bars, the effective confinement coefficient is reduced below 4.1. This has an effect on the minimum spiral reinforcement requirements stipulated by the ACI code. These requirements, then, become progressively insufficient.

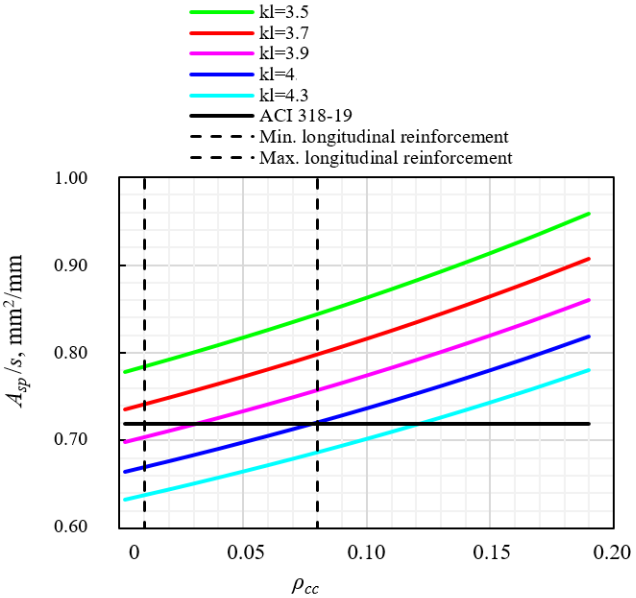

Fig. 2. Minimum spiral reinforcement versus the ratio of longitudinal reinforcement area to concrete core area.

V. CONCLUSION

This study utilizes a concrete column confined by spiral reinforcement, based on proposed confinement models and in accordance with the ACI code specifications. The procedure of the theoretical analysis that integrates the empirical formulas proposed in [14, 22] for conventional steel spiral reinforcement, has been thoroughly presented. Furthermore, the models presented in [21, 25, 26] for GFRP spiral reinforcement have been analyzed.

The results show that the ultimate strength of the concrete columns can be enhanced by providing more spiral reinforcement. However, the results have further revealed that if the theoretical analysis is blended with the traditional steel model proposed in [14], the outcome complies with the ACI code predictions.

Furthermore, the longitudinal reinforcement bars which are conventionally neglected in the theoretical analysis formula, significantly influence the minimum spiral reinforcement requirements. This is evident from the correlation between the spiral area to the spacing ratio and longitudinal bar quantity.

Consequently, future reinforced concrete codes should exploit both the reduced confinement efficiency of the Glass Fiber Reinforced Polymer (GFRP) bars and the influence of the longitudinal reinforcement to accurately evaluate the strength capacity of the confined concrete columns, and thus ensure structural integrity.

DECLARATION OF COMPLETING INTEREST

The authors declare that they have no financial interests or personal relationships that could have influenced the work reported in this paper.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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