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Influence of Key Parameters on the Load–Displacement Response of FRP-Confined Concrete Columns: A Finite Element Investigation

Mohammad Awad

M.Sc. Student, Civil Engineering Department, Faculty of Engineering,
The Hashemite University, P.O. box 330127, Zarqa 13133, Jordan;
Email: 2370308@std.hu.edu.jo.

Abstract:
This study investigates the influence of key parameters on the load–displacement response of fiber-reinforced polymer (FRP)-confined concrete columns through advanced finite element (FE) analysis. Building upon the previously developed numerical model for simulating the behavior of FRP-confined column[1],, the present work extends the investigation to assess the effects of critical parameters, namely the column diameter-to-length ratio, concrete compressive strength, FRP spiral pitch (spacing), and FRP type (CFRP or GFRP). The nonlinear response of concrete was represented using the Hognestad stress–strain relationship, while FRP confinement was modeled as a linear elastic–brittle material up to rupture. The FE results reveal that increasing the diameter-to-length ratio and concrete compressive strength enhances both axial load capacity and initial stiffness. In contrast, reducing the spiral pitch significantly improves ductility and energy dissipation. Furthermore, the type of FRP was shown to govern overall confinement efficiency, with CFRP generally providing superior stiffness and strength compared to GFRP. Overall, the findings provide valuable insights into the role of geometric and material parameters in shaping the structural performance of FRP-confined concrete columns, offering guidance for their design and optimization in engineering practice

Keywords— FRP-confined concrete columns; Finite element analysis; Load–displacement response; Spiral pitch; Column slenderness; FRP type; Concrete compressive strength

I. INTRODUCTION

The structural performance of reinforced concrete (RC) columns under axial compression remains a critical area in structural engineering due to their essential role in transferring vertical loads and maintaining stability. Traditional steel reinforcement has long served as the standard confinement strategy, but its susceptibility to corrosion in harsh environments undermines durability. Fiber-reinforced polymer (FRP) composites, such as CFRP and GFRP, have emerged as attractive alternatives owing to their high tensile strength, corrosion resistance, lightweight nature, and ease of installation. Recent experimental studies have confirmed that FRP confinement substantially improves the strength, ductility, and energy absorption of concrete columns. For example,[2] investigated the axial capacity of circular concrete columns reinforced with GFRP bars and spirals, establishing valuable benchmark data widely adopted in subsequent research. More recent works have built on this foundation: Axial Load Behavior of Concrete Columns Confined with GFRP Spirals highlighted the influence of spiral spacing on load–displacement capacity[3] Investigation of Circular Hollow Concrete Columns Reinforced with GFRP Bars and Spirals [4] showed how spiral configuration and GFRP type affect stiffness and strength; and Experimental and Numerical Studies on Compressive Behavior of Winding FRP Grid Spiral Stirrups Confined Circular Concrete Columns [5] demonstrated the sensitivity of ductility and ultimate load to spiral spacing and concrete strength. Additional contributions, such as Behavior of FRP-Confined Columns with Eco-friendly Concrete Under Combined Axial and Lateral Loading [6] and Compressive Behavior of Steel-FRP Composite Bars Confined with Low Elastic Modulus FRP Spirals in Concrete Columns[7], further emphasize the role of material properties and confinement configuration. Collectively, these studies underscore the growing interest in understanding how geometric and material parameters govern the confinement efficiency of FRP-reinforced columns. While experimental research has been pivotal, it is often limited by cost and logistical constraints, particularly when exploring large-scale specimens and multiple parameter variations. Finite element analysis (FEA) has therefore become a powerful complementary tool, enabling systematic investigation of nonlinear material behavior under controlled conditions. In the previous study, a finite element model was developed and validated against the benchmark tests of [2], confirming its accuracy in capturing the nonlinear response of FRP-confined columns. Building on this foundation, the present research shifts the focus from load–strain to load–displacement response, which provides a more comprehensive measure of column performance under axial compression. Four key parameters are examined: (i) FRP type (CFRP vs GFRP), (ii) diameter-to-length (D/L) ratio, (iii) concrete compressive strength, and (iv) spiral pitch (spacing). These parameters were selected because they govern confinement effectiveness, ductility, energy dissipation, and failure mode. The findings are intended to fill existing gaps in literature and to offer practical guidance for optimizing the design and performance of FRP-confined concrete columns.

II. FINITE ELEMENT MODEL

The finite element (FE) model was developed in ABAQUS to simulate the behavior of FRP-confined concrete columns subjected to axial compression. The modeling framework involved a detailed representation of material properties, boundary conditions, and loading schemes, ensuring a realistic approximation of experimental conditions.

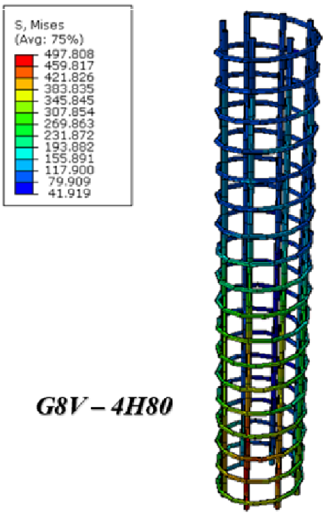

Figure 1 Influence of GFRP bar number and spacing on axial load capacity of columns

Figure 1 shows the longitudinal GFRP bar configuration and spiral spacing for specimen G8V-4H80, which served as a reference for the parametric study. The modeling framework involved a detailed representation of material properties, boundary conditions, and loading schemes, ensuring a realistic approximation of experimental conditions typically reported in the literature. This finite element model builds upon the framework developed and validated in the previous study [1],with its accuracy confirmed through benchmarking against the experimental results of Afifi, Mohamed et al [2], showing its ability to reliably capture the nonlinear response of FRP-confined concrete columns. In the present study, this validated model was extended to conduct a systematic parametric investigation into the effects of geometric and material parameters on the load–displacement response. Concrete was modeled as a nonlinear material to capture the behavior of FRP-confined columns under axial compression, including both strain-hardening before peak stress and strain-softening after peak stress. The Hognestad[8] stress–strain model was adopted due to its widespread use in finite element simulations of concrete and its ability to represent both the ascending and descending branches of the stress–strain curve, accounting for progressive cracking and crushing under compression. The stress–strain relationship for confined concrete is mathematically expressed as follows:

$$f_{c,1}= f_c'' \left[\frac{\epsilon_c}{\epsilon_0} - \left(\frac{-}{\epsilon_0}\right)^2\right] \quad (1)$$

$$f_{c,2}= f_c'' \left[1\text{-}0.15\left(\frac{\epsilon_c-\epsilon_0}{0.0038-\epsilon_0}\right)\right] \quad (2)$$

$$f_c'' = 0.9\,f'c \quad (3)$$

$$\epsilon_o = 1.8 f_c''/E_c \quad (4)$$

In the adopted constitutive model, the parameter f c" represents the effective compressive strength of concrete, which is conventionally taken as 90% of the cylinder strength f'c This reduction accounts for the difference between the idealized parabolic stress–strain relationship and the actual material response obtained from testing. The strain at peak stress is denoted by ϵ_0 which corresponds to the critical strain value where the maximum compressive strength of the concrete is reached. The elastic modulus of concrete, Ec defines the initial slope of the stress–strain curve and governs the material's stiffness in the linear elastic range.

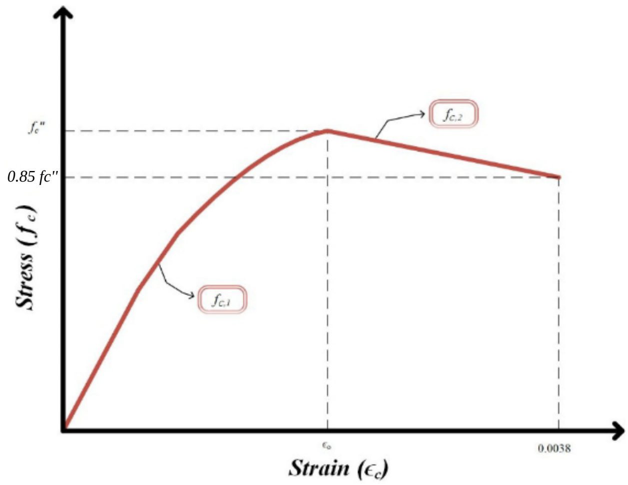

Figure 2 Stress–strain behavior of concrete modeled using the Hognestad relationship.

Finally, ϵ_c represents the axial strain in the concrete, which varies throughout the loading history and serves as the primary variable describing the state of deformation in the model. Collectively, these parameters ensure that the stress–strain relationship captures both the ascending and descending branches of the curve, providing a realistic representation of the nonlinear compressive behavior of confined concrete..

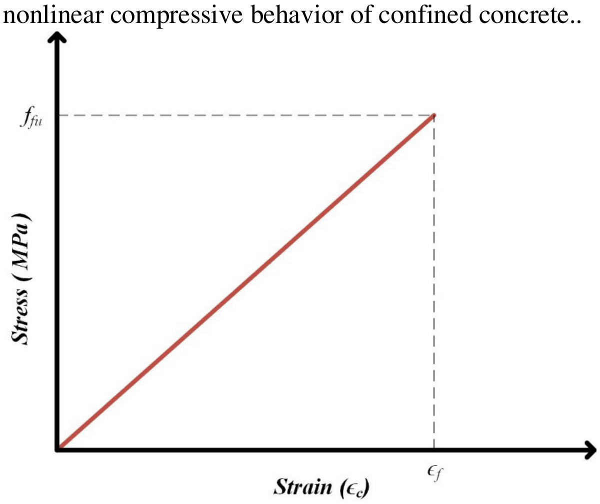

Figure 3 Stress–strain behavior of FRP reinforcement showing linear-elastic brittle response.

These equations ensure that the stress–strain curve is properly calibrated to match experimental data, providing a smooth representation of both peak and post-peak behavior As illustrated in Figure 2, the model enables accurate simulation of the nonlinear response of FRP-confined concrete, capturing essential features such as peak load, descending branch, and post-peak ductility. FRP reinforcement was represented as a linear elastic brittle material, consistent with its experimentally observed behavior. Unlike steel, FRP does not exhibit yielding or strain hardening; once the ultimate tensile strength is reached, rupture occurs suddenly, resulting in an immediate loss of confinement. The adopted stress–strain model for FRP reinforcement is shown in Figure 3, highlighting the absence of a plastic plateau and emphasizing the importance of precisely defining the elastic modulus and tensile strength.

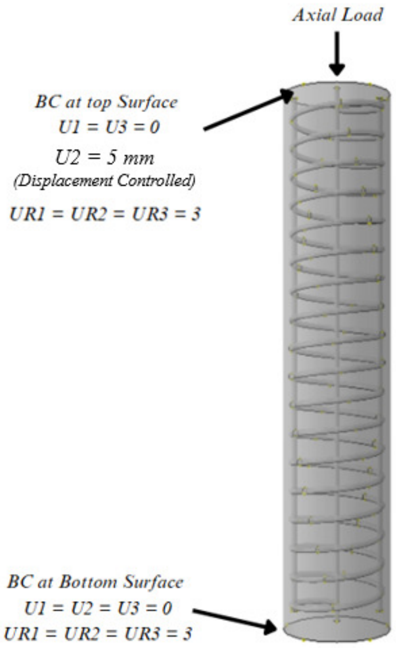

Figure 4 Boundary conditions and axial load application in the finite element model

This approach ensures that the brittle nature of FRP is fully captured in the numerical model, in alignment with experimental observations. The columns were modeled with fixed support at the base and free translation at the loaded end, where axial displacement was imposed. To enhance numerical stability and ensure accurate tracing of the post-peak response, a displacement-controlled loading scheme was employed. The adopted boundary conditions are illustrated in Figure 4, while the displacement-controlled loading method is presented in Figure 5. This modeling approach enabled the FE simulations to capture the entire load–displacement curve, including the descending branch after peak load—an essential feature for evaluating ductility, energy dissipation, and confinement efficiency.

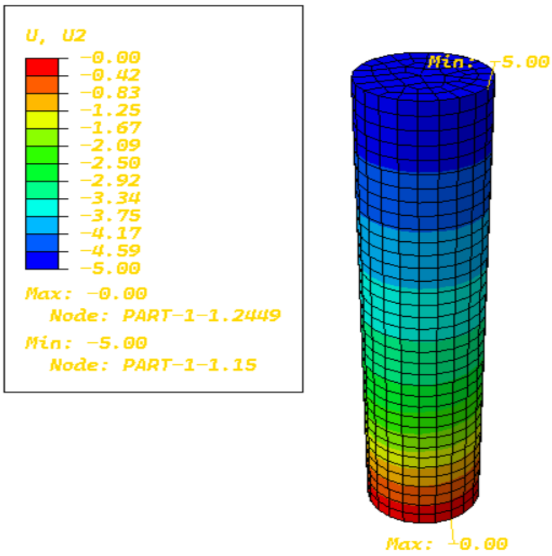

Figure 5 Displacement-controlled loading scheme adopted in the FE analysis

III. Key Parameters Studied

To investigate the influence of design and material variables on the structural response of FRP-confined concrete columns, a comprehensive parametric study was carried out. The key parameters were selected based on their critical role in governing confinement effectiveness, stiffness, ductility, and ultimate load capacity. The four parameters examined in this study are detailed below. Columns with varying diameter-to-length (D/L) ratios were analyzed to evaluate the effect of column slenderness on load-carrying capacity, stiffness, and overall stability. Different geometrical configurations considered in this study are illustrated in Figure 6, showing the variation in column height relative to diameter. Changes in the D/L ratio influence the confinement effectiveness of FRP spirals, as slender columns tend to exhibit more pronounced buckling tendencies.

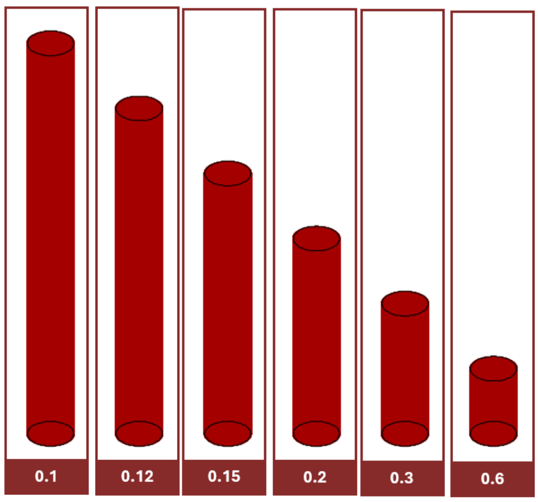

Figure 6 Column geometries with different diameter-to-length (D/L) ratios considered in the study.

The impact of concrete material properties was assessed by considering compressive strengths ranging from 28 MPa to 50 MPa. Higher-strength concrete is generally associated with increased axial load capacity but may exhibit reduced ductility, making the interaction between concrete and FRP confinement critical for post-peak performance. The role of confinement intensity was examined by varying the spiral pitch of FRP reinforcement from 40 mm to 120 mm. A smaller spiral pitch increases confinement effectiveness, enhancing both ductility and energy dissipation while delaying the onset of crushing. A schematic representation of the spiral arrangement is shown in Figure 7, highlighting how transverse reinforcement spacing governs the lateral restraint provided to the concrete core. The effect of FRP material type was investigated by comparing CFRP and GFRP spirals. CFRP typically exhibits higher tensile strength and stiffness, whereas GFRP offers cost-effectiveness and corrosion resistance. The comparison aimed to quantify the influence of material properties on axial load capacity, stiffness, and post-peak ductility

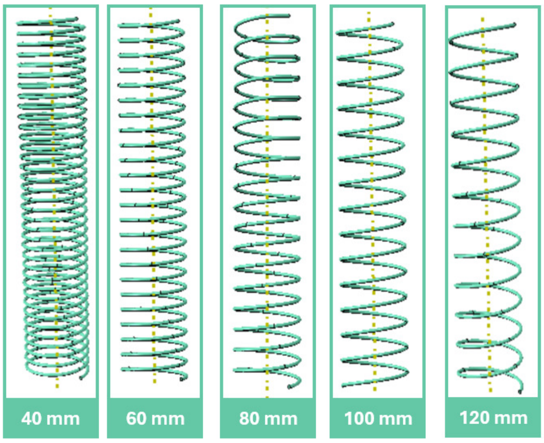

Figure 7 Schematic representation of FRP spiral pitch configurations in the FE model

IV. RESULT

The finite element simulations provide detailed insights into how the selected parameters influence the load–displacement response of FRP-confined concrete columns. The effects of each parameter are summarized below. As illustrated in Figure 8, columns with larger D/L ratios exhibited increased axial strength and initial stiffness. Stockier columns (lower D/L) demonstrated more effective confinement and a delayed onset of instability, whereas slender columns (higher D/L) showed reduced axial capacity and were more susceptible to buckling and premature failure. These results highlight the importance of column slenderness in defining confinement efficiency and overall stability.

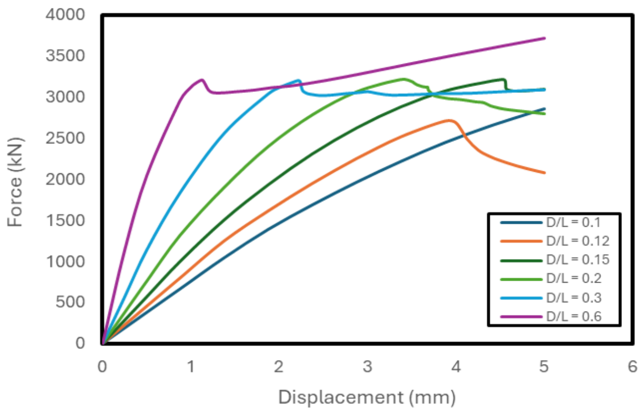

Figure 8 Comparison of FE results for columns with varying D/L ratios

The impact of concrete compressive strength is presented in Figure 9. Columns made with higher-strength concrete (e.g., 50 MPa) achieved greater axial load capacity; however, this was accompanied by reduced ductility. Conversely, columns with lower-strength concrete exhibited higher deformation capacity before failure. This indicates a trade-off between strength and ductility, emphasizing the need to balance these properties when selecting concrete grades for FRP-confined columns.

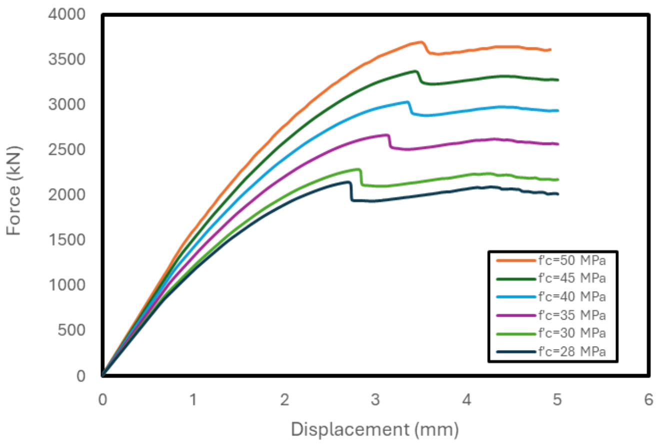

Figure 9 Comparison of FE results for columns with different concrete compressive strengths.

The influence of transverse reinforcement spacing is shown in Figure 10. Columns with tighter spiral spacing (e.g., 40 mm) display enhanced ductility and higher energy absorption, attributed to stronger confinement. Wider spiral pitches (100–120 mm) resulted in diminished confinement effectiveness, lower ductility, and more brittle failure modes. These observations confirm that spiral pitch is a key parameter controlling post-peak behavior and energy dissipation in FRP-confined concrete columns.

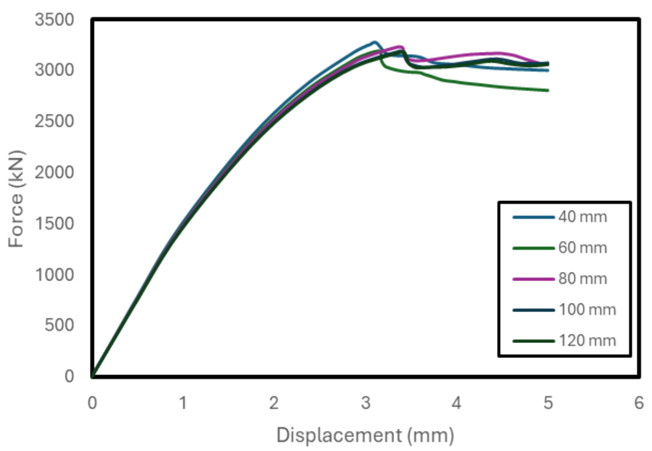

Figure 10 Comparison of FE results for columns with varying spiral pitches

In addition to geometric and material parameters, the type of FRP reinforcement was found to significantly affect the axial behavior of confined concrete columns. Figure 11 presents a comparison between columns confined with glass FRP (GFRP) and carbon FRP (CFRP). The results show that CFRP-confined columns achieved higher axial load capacity and exhibited greater post-peak stability compared to GFRP-confined columns. Specifically, CFRP provided improved stiffness along the ascending branch of the load–displacement curve and maintained a higher plateau in the descending branch, reflecting enhanced confinement efficiency and delayed strength degradation.

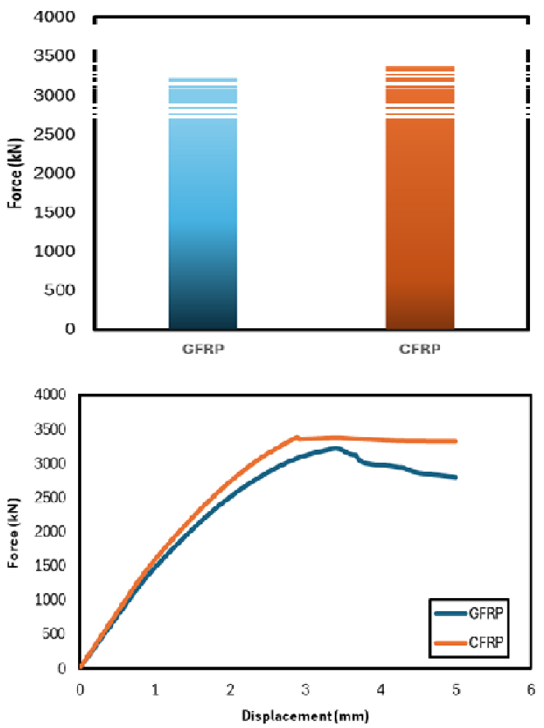

Figure 11 Effect of FRP type (CFRP vs. GFRP) on the load–displacement response of confined columns.

In contrast, GFRP-confined columns demonstrated lower peak loads and a more pronounced post-peak strength reduction, which is consistent with the lower elastic modulus and tensile strength of GFRP relative to CFRP. These findings indicate that the choice of FRP type has a direct impact on both load capacity and ductility, with CFRP outperforming GFRP in terms of structural efficiency, albeit at a higher material cost.

V. Conclusion

This study presented a comprehensive finite element investigation of FRP-confined concrete columns to examine the influence of key geometric and material parameters on their load–displacement response. The results indicate that column slenderness, represented by the diameter-to-length (D/L) ratio, significantly affects both strength and stability, with stockier columns exhibiting enhanced confinement efficiency and delayed onset of instability, while slender columns are more prone to premature failure. Concrete compressive strength was also found to play a critical role: higher-strength concrete increased axial load capacity but reduced ductility, highlighting the need to balance strength and deformation capacity when selecting concrete grades. The spacing of FRP spirals was shown to govern confinement effectiveness, as tighter spiral pitches improved ductility and energy absorption, whereas wider spacing led to reduced confinement and more brittle post-peak behavior. Finally, the type of FRP material influenced the overall structural performance, with CFRP providing superior stiffness, higher peak loads, and greater post-peak stability compared to GFRP, although GFRP offers advantages in cost and corrosion resistance. Collectively, these findings demonstrate that the interaction between column geometry, concrete properties, spiral arrangement, and FRP type controls both peak and post-peak behavior of confined columns, providing practical guidance for the design and optimization of FRP-confined concrete members in engineering applications.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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