An Experimental and Analytical Study on the Compressive Behavior of Glass Fiber Reinforced Concrete (GFRC) confined with GFRP Composites

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ABSTRACT

This study investigates the axial compression behavior of confined circular concrete columns through a combined experimental and analytical approach. It examines the influence of the concrete strength, 8.5, 16, and 25 MPa, internal glass fiber percentage, 0.3-1.2 %, and Glass Fiber Reinforced Polymer (GFRP) confinement thickness, 0.8, 1.6, and 2.4 mm. The Glass Fiber (GF) percentage and GFRP thickness have a significant impact on the results of the uniaxial compression tests exploring both the load-deformation behavior and crack propagation characteristics of the specimens, ranging from 90 to 110%. The proposed confinement model demonstrates excellent agreement with the experimental data for the ultimate axial strain and across the investigated range of concrete strengths.

Keywords-Glass Fiber Reinforced Polymer (GFRP); axial compression; concrete; strength; strain; confinement model

I. INTRODUCTION

Fiber-Reinforced Polymers (FRPs), such as carbon, glass, and aramid fibers, have experienced a surge in popularity for their contribution to the rehabilitation and strengthening of existing structures in the past decade. This is due to their numerous advantages, including high strength and durability, portability, ease of installation, and rapid implementation. GFRP is a composite material that has gained significant attention over the last few years owing to its superior mechanical properties and resistance to corrosion. Its use in confined concrete is particularly promising, as it can significantly enhance the structural performance of concrete elements [1-7].

Concrete is a versatile engineering material in the construction industry, prized for its high compressive strength, deformation resistance, durability, and cost-effectiveness. However, it is also brittle, lacks malleability, and is susceptible to cracking [8-12]. To overcome these limitations, researchers and engineers have developed Fiber-Reinforced Concrete (FRC), which exhibits excellent tensile strength, bending resistance, ductility, and elongation compared to the traditional concrete. FRC also reduces the shrinkage and cracking and improves the tensile strength in contrast to the conventional concrete due to the bridging and stress-transferring actions of the fibers, making it ideal for a wide range of applications.

Various types of fibers have been reported in the literature, including steel, polypropylene, carbon, glass, basalt, polyvinyl alcohol, and mixed fibers [13-20]. For instance, adding 0.5–1.5% of steel fibers by volume can increase the tensile strength of concrete by 37–177% [21].

Although incorporating fibers can improve mechanical resistance, it is crucial to consider the optimal fiber parameters to achieve the maximum mechanical strength. Not all fiber percentages and properties will lead to a continuous increase in mechanical resistance. Experiments were conducted using concrete specimens with varying GFRP contents of 0, 0.4, 0.8, and 1.2% by weight. The results showed that the compressive strength initially increased with the GFRP content up to 0.8% and then decreased. The optimal GFRP content depends on the type of fiber utilized. Fibers with high aspect ratios, characterized by shorter lengths relative to their diameter, exhibit superior capability in suppressing the initiation of micro-cracks. Conversely, fibers with lower aspect ratios, being those of greater length, demonstrate enhanced effectiveness in suspending the propagation of pre-existing micro-cracks [22].

Using multiple fibers in FRC could develop a result that combines features. For instance, the mixture of polyvinyl alcohol (PVA) and steel fibers has been proved to achieve the optimal tensile behavior [23]. Furthermore, the incorporation of tailored amounts of basalt fibers can reduce concrete porosity and enhance its durability [24].

While combining different fiber types has not yielded substantial improvements in the tensile strength of reinforced concrete, GFRP composites are a promising solution for external confinement, offering significant advantages in addressing this challenge [25-26]. Wrapping concrete with FRP jackets is an effective method for enhancing the compressive behavior of concrete. The lateral confining stress provided by FRP jackets increases the concrete's compressive strength and ductility due to the linear elastic behavior of FRP. The application of lateral confinement demonstrably alters the stress-strain response of conventional concrete to compression [27].

Prior studies have demonstrated that severely confined concrete exhibits minimal volumetric expansion [28-30]. The degree of concrete dilation, which triggers the FRP confining pressure, is strongly influenced by the stiffness of the confining material. Consequently, concrete specimens confined with stiffer FRP composites exhibit significantly less expansion compared to those confined with more flexible FRP composites. In applications which involve rehabilitation strengthening, ductility enhancement is a primary goal, so flexible FRP composites offer a significant advantage by promoting material ductility [31, 32].

GFRC encased in FRP jackets shows promise regarding the strengthening of structural components. However, more tests are needed to fully understand how these materials work together. Additionally, there is a lack of reliable models to predict the performance of GFRC [33].

This study delves into the impact of externally wrapped GFRP jackets on the mechanical behavior of GFRC cylinders containing varying glass fiber percentages. Additionally, the study examines the effectiveness of strength and strain models, primarily developed for specialized FRP composites, in predicting the behavior of GFRC. This would provide a more thorough understanding of how GFRP affects the behavior of confined GFRC columns under compressive load. To achieve these objectives, the current study experimentally analyzes 48 GFRC cylinders under monotonic axial compression. The testing program incorporates various parameters, such as concrete compressive strength, 8.5, 16, and 25 MPa, GF content, 0.3, 0.6, 0.9, and 1.2 wt%, and GFRP jacket thickness, 0.8, 1.6, and 2.4 mm. The collected data are used to evaluate the ability of a confinement proposed model to predict the ultimate axial strain and compressive strength of GFRC.

II. EXPERIMENTAL PROGRAM

A. *Materials and Casting Procedure*

To assess the practicality of this novel composite material, an experimental investigation of the axial compressive response of GFRC was carried out. For this purpose, forty-eight cylindrical concrete columns, with a diameter of 150 mm and a height of 300 mm, were fabricated and tested, as shown in Figure 1.

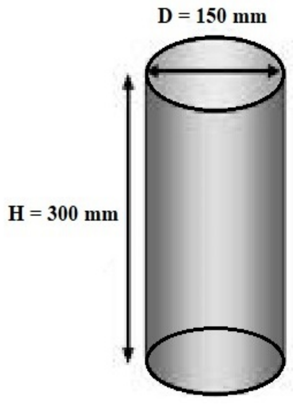

Fig. 1. Concrete test specimens.

The construction of cylindrical concrete columns involves three readily available materials. The first material is the concrete, which is available in three different strength classes, 8.5, 16, and 25 MPa. Table I summarizes the different mixture proportions of concrete. The second material is alkali-resistant GF (Figure 2(a)), incorporated into the concrete mix to enhance its toughness. These fibers are utilized at varying weight percentages, 0, 0.3, 0.6, 0.9, and 1.2%, to create GFRC.

The third material is a cost-effective GFRP composite specifically designed for column confinement (Figure 2(b)). It is manufactured locally using polyester resin and bidirectional fiberglass, with thicknesses 0.8, 1.6, and 2.4 mm tailored to specific needs. To assess their effectiveness, tensile strength testing is conducted on each thickness deploying a UTS-SHIMADZU universal machine, strictly adhering to the established guidelines outlined in [34]. The specifications of the materials are comprehensively detailed in Table II.

TABLE I. MIXTURE PROPORTIONS OF CONCRETE.

Strength classes of concrete	Cement (kg/m^3)	Sand (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Water (kg/m^3)	Superplasticizer
SC-8.5 MPa	200	853	853	481	100	As required
SC-16 MPa	300	810	520	520	132	As required
SC-25 MPa	400	773	496	496	163	As required

TABLE II. SPECIFICATIONS OF GLASS FIBER, EPOXY RESIN AND GFRP COMPOSITE.

Material		Length (mm)	Fiber diameter (mm)	Density (kg/m^3)	Tensile stress (MPa)	Ultimate strain (%)	Modulus of elasticity (GPa)	Standard deviation
GFRP composites	**Epoxy resin**	_	_	_	17.20	0.6322	2.72	1.08
	Glass FRP	_	_	_	377.64	2.04	18.70	1.91
Glass fiber (Alkali-resistant)		3 - 4.5	0.015	2600	1500 - 1700	_	72	_

The fabrication process begins with mixing cement, sand, gravel, fibers and the water which is gradually introduced to achieve a homogeneous mixture with thorough fiber dispersion. Subsequently, this mixture is cast into cylindrical molds. For the external confinement, the dust is meticulously removed from the concrete surface to ensure proper adhesion. Then, polyester resin is applied with a brush followed by the careful wrapping of a resin-soaked fiberglass board around the cylinder (Figure 2(c)). This process is repeated after 28 days of curing to finalize the strengthened specimen.

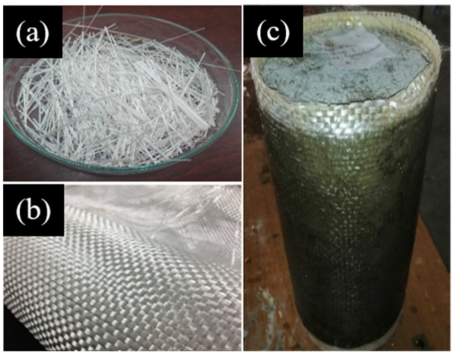

Fig. 2. (a) Alkali-resistant glass fiber, (b) GFRP composite, (c) GFRC strengthened specimens.

B. Instumentation and Test Setup

A detailed setup with specialized instruments measured the axial strain and the lateral expansion of GFRP-confined GFRC cylinders during compressive strength evaluation using a 2000 kN testing machine. Three Linear Variable Differential Transformers (LVDTs) were strategically mounted on a specially designed steel frame utilizing threaded bolts, creating a robust setup for measuring the lateral dilation of the concrete cylinders. Furthermore, as depicted in Figure 3, two precisely positioned strain gauges measured the lateral expansion of the confined sample at the mid-height of the concrete cylinders. A pre-calibrated hydraulic jack applied a constant monotonic axial load at a rate of 0.1 kN/s.

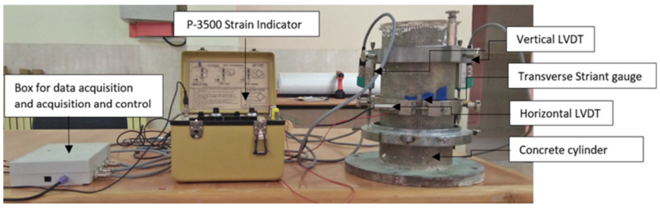

Fig. 3. Experimental configuration and data acquisition system for uniaxial compression testing of GFRP-reinforced concrete columns.

III. EXPERIMENTAL RESULTS

Figures 4-6 illustrate the effect of the GFRP layer thickness on the axial compressive strength of concrete cylinders reinforced with varying glass fiber percentages. The concrete specimens were cast with three different compressive strengths: 8.5, 16, and 25 MPa. The GFRP jacket thicknesses applied to the cylinders were 0.8, 1.6, and 2.4 mm. The fiber volume percentages in the GFRC cylinders were 0.3, 0.6, 0.9, and 1.2 wt%.

A direct and positive correlation is observed between the thickness of the GFRP layer and the axial strength achieved by the concrete cylinders across all four glass fiber weight percentages. Regarding specimens without a GFRP layer, for each concrete strength and fiber content, the axial strength values, ranging from 9.35 to 33.01 MPa, are lower compared to the specimens confined with GFRP jackets with 0.8, 1.6, or 2.4 mm thickness, and axial strength values ranging from 12.5 to 66.02 MPa. As a result, the axial strength of specimens confined with GFRP jackets exhibited a notable enhancement of approximately 90-110% in comparison to those without

GFRP layers. This is because the GFRP jackets provide confinement that strengthens the GFRC cylinders. This observation confirms the effectiveness of the GFRP jackets in confining and strengthening the concrete elements.

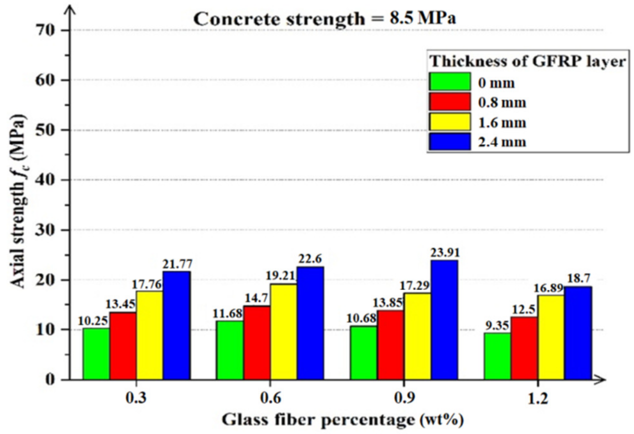

Fig. 4. Effect of GFRP jacket thickness and glass fiber content on the axial compressive behavior for concrete strength: 8.5 MPa.

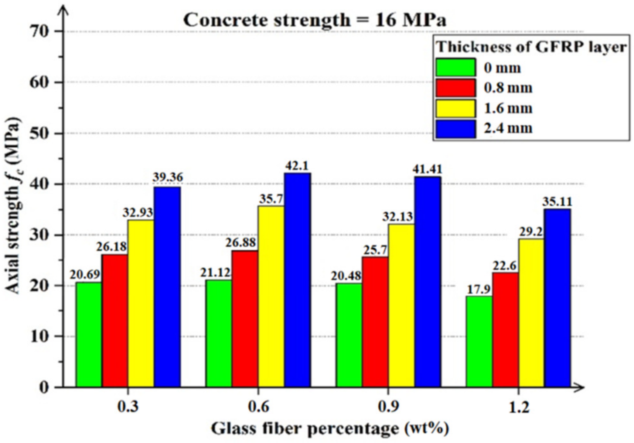

Fig. 5. Effect of GFRP jacket thickness and glass fiber content on the axial compressive behavior for concrete strength: 16 MPa.

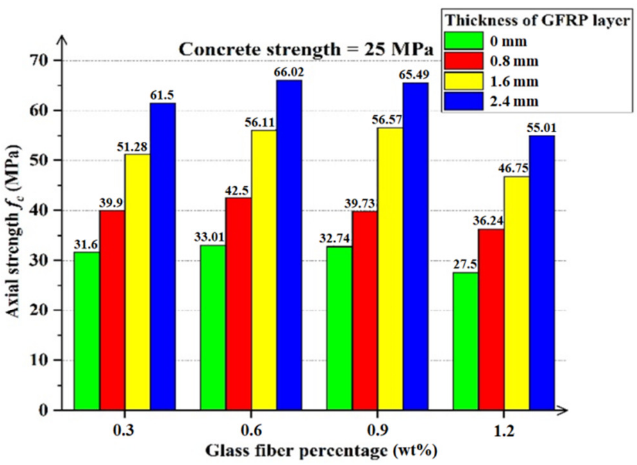

Fig. 6. Effect of GFRP jacket thickness and glass fiber content on the axial compressive behavior for concrete strength: 25 MPa.

IV. ANALYTICAL STUDY

In engineering, codes of practice might provide valuable guidance, but their limitations should be acknowledged. Simplified models and outdated provisions can lead to conservative or inaccurate designs. Engineers should supplement code-based approaches with additional analyses or testing, especially for GFRC elements. The development of an accurate stress-strain model for GFRP-confined GFRC cylinders necessitates focusing on the ultimate axial stress, f_{cc} (Mpa), and the unitless strain, ε_{cc}.

A. Strength Prediction Model of GFRC Columns Confined With GFRP

The analysis of the experimental data from testing campaigns revealed a significant linear relationship between the ratio f_{cc}/f_{co} and the ratio f_l/f_{co}, where f_{co} (Mpa) is the ultimate axial stress of unconfined concrete and f_l (Mpa) is the confining pressure. Specifically, the increase in the values of f_{cc}/f_{co} showed a decrease in the values of f_l/f_{co}. As a consequence, the ultimate stress and strain capacity were primarily governed by the efficacy of lateral confinement, provided by the GFRP wrap and hoop reinforcement. A multi-parameter regression analysis was conducted on 48 data points from the test database for predicting the ultimate stress f_{cc}, defined by (1), with an exceptional correlation coefficient (R^2) of 0.9993:

$$f_{cc} = 0.847 f_{co} - 0.14 f_l + 0.1 f_l \cdot f_{co} \qquad (1)$$

where f_l is defined by (2):

$$f_l = \frac{2 f_f \cdot t}{d} \qquad (2)$$

where f_f (MPa) is the tensile strength of FRP determined through flat coupon tests, t (mm) is the thickness of FRP, and d (mm) is the section diameter.

B. Strength Model Verification

Figure 7 presents a comparison between the predictions of for the proposed strength model of GFR-confined GFRC f'_{cc}/f'_c, with the experimental results f_{cc}/f_{co}. This comparison helps to assess the validity of the proposed model. The result demonstrates that the model offers robust and accurate predictions across the entire strength spectrum, with a low maximum error of –1 %.

C. Strain Prediction Model of GFRC Columns Confined With GFRP

This study presents a refined model (3) for the ultimate axial strain prediction based on the analysis of 48 test results in the database. This model explicitly accounts for the critical factors of confinement stiffness and GF content, providing valuable insights for material design and optimization:

$$\frac{\varepsilon'_{cc}}{\varepsilon_c} = -6.5\left(\frac{f'_c}{\varepsilon_c}\right)^{0.1} + 1.37\left(\frac{f_l}{\varepsilon_c}\right)^{0.3} + 5.07\left(\frac{\varepsilon'_{cch}}{\varepsilon_c}\right)^{0.3} - 1.17 \qquad (3)$$

where ε_c is the confined concrete compressive strain, ε'_{cc} is the predicted ultimate strain, and ε'_{cch} is the predicted horizontal strain of confined concrete.

Strong linear correlations were identified between $\varepsilon_{cc}/\varepsilon_{co}$, f_l/ε_c, f_c/ε_c, and $\varepsilon_{cch}/\varepsilon_c$, primarily through tests performed on GFRP-confined GFRC cylinders.

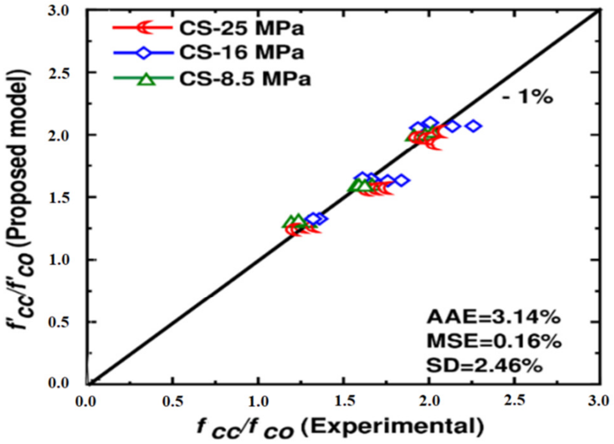

Fig. 7. Strength proposed model results in comparison with the experimental results.

D. Strain Model Verification

In Figure 8, the strain proposed model $\varepsilon'_{cc}/\varepsilon'_{co}$ and experimental strain $\varepsilon_{cc}/\varepsilon_{co}$ curves for GFRC cylinders confined with GFRP are compared. The proposed model's predictions for the ultimate strain exhibited significant variability, ranging from -25 to +18% compared to the experimental values. A significant disparity was observed between the experimental results and the proposed analytical model for the samples with a compressive strength of 8.5 MPa, particularly when the strain exceeded 10.

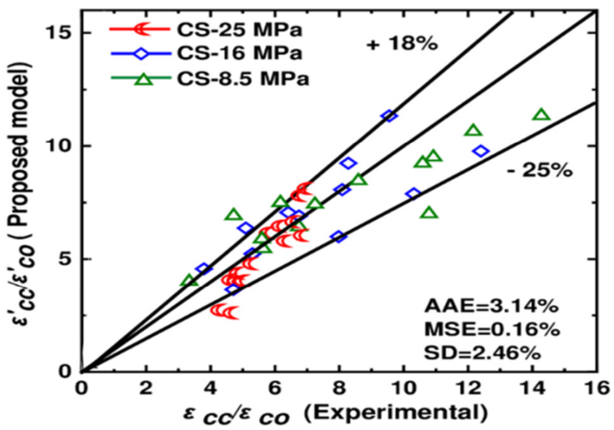

Fig. 8. Comparison of the experimental and proposed model results for strain.

V. CONCLUSION

This study seeks to comprehensively assess the effect of Glass Fiber-Reinforced Polymer (GFRP) composites on the confinement behavior of circular concrete columns containing internal Glass Fibers (GF). This investigation employs a combined approach, using experimental testing of 48 circular concrete columns with varying concrete strengths, 8.5, 16, and 25 MPa, GFRP layer thicknesses, 0.8, 1.6, and 2.4 mm, and internal fiber percentages, 0.3, 0.6, 0.9, and 1.2 wt%, under monotonic axial compression. Moreover, the research analyzes the predictive performance of the existing and proposed models regarding the ultimate strength and strain of the investigated specimens. Based on the experimental and analytical results, the following conclusions can be drawn:

- Incorporation of a GFRP jacket around Glass Fiber-Reinforced Concrete (GFRC) specimens can decrease the lateral strain, highlighting the efficacy of this composite in enhancing the overall mechanical performance of RC structures.
- The post-peak response of GFRC specimens exhibited compression softening, while GFRP confinement transformed material behavior into a bilinear response. This suggests that GFRP reinforcement effectively enhances the post-failure behavior of the material.
- Concrete cylinders reinforced with GFRP jackets consistently exhibited significantly higher axial strength values compared to those without GFRP, for all compressive strengths, ranging from 90 to 110%.
- Concrete samples containing 0.6 wt% glass fiber exhibited a significantly higher confinement effect from the GFRP compared to samples with other fiber percentages.
- The proposed confinement model demonstrates excellent agreement with the experimental data for ultimate axial strain and stress for GFRC specimens confined with GFRP with a low maximum error, –1%, for the strength spectrum, and -25 to +18% for the strain spectrum. This suggests that the model is able to predict with accuracy the behavior of confined concrete columns under compression.
- This work extends previous research by providing a more comprehensive understanding of the interaction between concrete, glass fibers, and GFRP confinement in enhancing the performance of confined columns. The findings are particularly relevant for applications in structures requiring high load-bearing capacity and durability, such as bridges, buildings, and infrastructure.

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