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EXPERIMENTAL AND NUMERICAL SIMULATION OF GFRP CONFINED CYLINDRICAL CONCRETE UNDER COMPRESSION

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ABSTRACT: Fiber Reinforced Polymer (FRP) wrap stands as one of the most popular methods for retrofitting deteriorated reinforced concrete structural elements. Among the available options, Glass Fiber Reinforced Polymer (GFRP) presents itself as a cost-effective alternative, although with fewer technical advantages. While GFRP wrapping is commonly applied to columns, the extent of its confinement effect on altering the mechanical properties of concrete remains unclear. To address this gap, an experimental and numerical analysis was conducted. Concrete cylinder specimens wrapped with GFRP layers were axially tested under compression until failure. The resulting stress-strain relationship was used to validate numerical simulations carried out using numerical simulation with finite elements method. The experimental findings suggest that concrete confinement using only a low number of GFRP wraps may not be effective in providing adequate lateral restraint for concrete under compression. GFRP for concrete confinement clearly transforms the material from being brittle to becoming ductile, resulting in a deformation capacity that can be up to 2-5 times greater. A numerical model of the confined concrete cylinder with GFRP specimens could show the confinement effect to increase the ultimate stress and strain. In addition, the numerical model could investigate the failure pattern with good agreement with the experimental results.

Keywords: GFRP retrofitting, Confined concrete, Concrete column, Deteriorated concrete building, Compression test

1. INTRODUCTION

Building structures deteriorate over time due to various factors. To maintain the performance of a building, it is often necessary to retrofit its structural elements [1]. Concrete jacketing is a common method of retrofitting [2,3], while another popular approach involves wrapping using Fiber Reinforced Polymer (FRP). Various types of fibers are used for retrofitting, including glass, carbon, and aramid [3], [4]. FRP sheets have gained significant attention in the construction industry due to their economic, efficient, and time-saving application on-site [5-8]. There are two main types of FRP: Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP). CFRP is preferred over GFRP for its higher moduli and lower density, as shown in Table 1 [5]. On the other hand, GFRP offers a more economical option for retrofitting [9].

Many researchers worked on the GFRP application for strengthening reinforced concrete (RC) beams [10-14] and columns [15,16]. GFRP confinement was reported to give better concrete performance than CFRP in harsh environments [17]. Chiew et al. [18] carried out a test on RC beams flexurally strengthened using GFRP layers where significant increases in strength and stiffness were observed. Sinha et al. [12] applied GFRP bars for the possible replacement of steel in the RC beam and reported a decrease in the strength of the beam with the increase in GFRP percentage. The application of GFRP in columns improved the ductility of the concrete [13]. The application of FRP on critical structural elements of buildings can enhance their seismic capacity [7]. In an earlier study, Ronagh and Eslami [19] investigated the effect of CFRP/GFRP on flexural strengthening and yielded similar results. They further stated that CFRP provided twice the strength of GFRP, but the latter offered greater ductility.

A study on the effect of GFRP confinement on the mechanical properties of low-strength concrete indicates that compressive strength is a more effective criterion than the level of confinement [20]. Numerical simulations on the behavior of concrete confined with GFRP demonstrate an increase in strength due to confinement effect [21]. Another study shows that the effect of GFRP confinement significantly increases the compressive strength and modulus of elasticity when applied in GFRP wrapping infill material [22]. The stress-strain behavior of a concrete cylinder confined by FRP was proposed by the predecessor studies [23,24]. Despite numerous research efforts on GFRP applications, many issues remain unknown and require further investigation [12].

Table 1 Properties of common fibers [5]

Material	Density (gr/cm^3)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Max Elongation (%)
E-Glass	2.57	3400	72.5	2.5
S-Glass	2.47	4600	88.0	2.5
Carbon (High modulus)	1.90	3000	500.0	0.5
Aramid	1.40	2800-4100	70-190	0.2

2. RESEARCH SIGNIFICANCE

Glass Fiber Reinforced Polymer (GFRP) is emerging as a cost-effective option for retrofitting concrete columns. However, the impact of GFRP confinement on concrete mechanical properties remains uncertain, with conflicting reports on improvement. Considering the relatively low elastic moduli of GFRP, a thorough investigation into the effects of confinement is crucial. This study specifically explores changes in the mechanical properties of GFRP confined concrete under compression. A numerical analysis has been devised to simulate the alterations in the mechanical characteristics of concrete with GFRP confinement.

3. EXPERIMENTAL PROGRAM

3.1 Characteristics of Samples

A total of 7 cylindrical concrete samples of 150 mm in diameter and 300 mm in height were cast and tested for compression. The samples originated with target strengths of 25 MPa. Other 7 data of concrete cylindrical specimens from the earlier study [25] were also discussed as the comparator. For each strength level, control samples or unconfined concrete (UC) and wrapped specimens or confined concrete (CC) were prepared. The labels CC-1 and CC-2 represent the number of GFRP layers applied to the samples, with CC-1 indicating one layer and CC-2 indicating two layers of GFRP. The GFRP layer was applied to form confined concrete samples approximately one week before testing.

3.2 GFRP wraps and epoxy resin

Glass Fiber Reinforced Polymer (GFRP) is a composite material of woven E-glass fibers and polyester material bonded together. The woven plastic is hardened using thermosetting polymers such as epoxy resin or thermoplastics [26]. In this study, the epoxy polymer used was bisphenol A epichlorohydrin resin. The hardener was EPH 555 cycloaliphatic amine, with a mixture ratio of 3:1. The GFRP wrap was applied using the wet lay-up method with tangential orientation (Fig. 1). The GFRP used in the experiment was a unidirectional fiber sheet with a thickness of 0.5 mm that has orthotropic behavior. The properties of the GFRP wrapping were obtained from a previous study [27], as outlined in Table 2. These GFRP properties were also utilized in the development of numerical analysis.

Table 2 Mechanical properties of GFRP [27]

Property	Magnitude
Young's modulus in the longitudinal direction	28 GPa
In-plane shear modulus	0.946 GPa
Through-thickness shear modulus	1.2 GPa
Longitudinal tensile strength	750 MPa
Density	1500 kg/m^3

3.3 Instrumentation and Test Setup

A compressive strength test of concrete cylinders was conducted in accordance with ASTM C39. For confined concrete samples, the GFRP was applied about one week before testing. Axial loading was performed on both unconfined and confined concrete samples using a Universal Testing Machine (UTM) with a capacity of 2000 kN at a loading rate of 265 kN/min until failure. Concrete capping with layers of sulfur was applied at both ends of the cylinder (Figure 1) to ensure an evenly distributed load. Prior to placing the wrapped concrete samples into the UTM, a set of rings and a dial gauge were installed in the cylinder samples to monitor the strain development under the applied load. It was crucial to position the wrapped concrete cylinder sample precisely at the center of the loaded base of the UTM. The final compression test setup is depicted in Figure 1 (d).

4. DISCUSSION OF THE TEST RESULTS AND DEVELOPMENT OF NUMERICAL SIMULATION

4.1 Behavior of unconfined and confined concrete under compression

The results of the compressive strength test for the unconfined concrete samples of 25 MPa and 40 MPa [13] are presented in Figure 2. These findings confirm the theory that the elastic modulus of concrete is influenced by its density, and lower-strength concrete exhibits greater ultimate strain [13].

Figures 3 and 4 present the compressive test results for concrete samples confined with one and two layers of GFRP, respectively. For concrete specimens with a compressive strength of 40 MPa,

(a) (b) (c) (d)

Fig. 1. Concrete cylinder sample of specimens: (a) unconfined, (b) single wrap, (c) double wrap and (d) instrumentation set up during compression test.

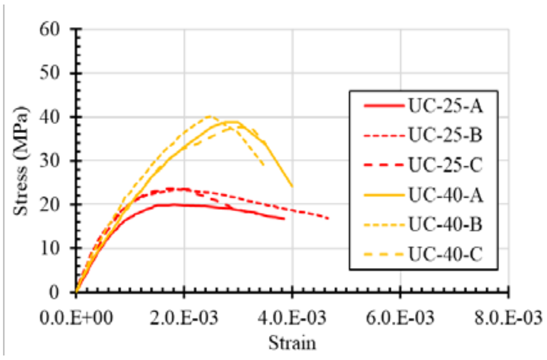


Fig. 2 Unconfined concrete compressive strength test for samples of 20 MPa and 40 Ma.

several tests encountered setup issues [25]. The displacement recording was stopped to prevent the dial gauge damaged from the probable explosion failure of the specimens. Despite these issues, the test data are still utilized as the trend results demonstrate certain validity.

Theoretically, when concrete is confined, its lateral internal deformation is restricted. The test results for both concrete strengths of 25 MPa and 40 MPa exhibit a similar pattern. Several behaviors can be observed from the results as follows:

a) The initial trend of the stress-strain curve for all the test results is close or even aligned with one another. This suggests effective bonding between the GFRP and concrete surfaces to form a composite material (Figure 3). It indicates that the elastic modulus for both unconfined and confined concrete remain unchanged. This suggests that the addition of GFRP wrapping of one and two layers will not yield significant effects on concrete elastic modulus. Similar findings were observed by previous researchers [9,13,23,24].

b) The confinement effect of one layer of GFRP significantly increases the ultimate strain of concrete, leading to a two to fivefold increase in the absorption energy of the material compared to the unconfined sample (Figures 3 and 4). With two layers of GFRP wrapping, the increase in ultimate strain becomes even more pronounced [13]. It appears that the increase in ductility corresponds to the addition of GFRP wrapping layers, as reported from the predecessor studies [23,24].

c) Close examination of the stress-strain curve shows that while unconfined concrete exhibits a certain peak (ε_c, f_c) and then descends constantly till crushing (ε_{cu}, f_{cu}), confined concrete, after reaching the unconfined compressive strength (ε_t, f_t), deviates and continues with a slightly positive slope, finally dropped when fracture of the GFRP layers occurred (ε_{cuc}, f_{cuc}) (Figures 3 and 4). In contrast to unconfined concrete which has peak stress before crushing occurs (*ultimate* state), the confining effect of GFRP creates the peak stress of the concrete at a large strain which is before the rapture of GFRP (ultimate condition). It appears that the post-compression strength slope tends to increase with the addition of each GFRP layer. This finding differs slightly from that of [11], where for low confinement (one layer of GFRP), the curve starts to deviate and then has a descending branch with a relatively small slope. However, for more than one layer of GFRP, the pattern of this finding aligns with the results of previous researchers [11,29].

d) The difference in compressive stress resistance magnitude for unconfined concrete and the stress level at which the curve starts to deviate for confined concrete is relatively small (Figures 3 and 4). For the single layer of GFRP, the stress difference is nearly zero. This result confirms the other findings from previous researchers [9,22], providing further confirmation of the observed trend.

This result suggests that GFRP confinement may not have a significant impact on concrete unconfined compressive strength improvement. The confinement provided by a single layer of GFRP wrapping appears ineffective in restraining the lateral deformation of concrete under compressive loading. The findings

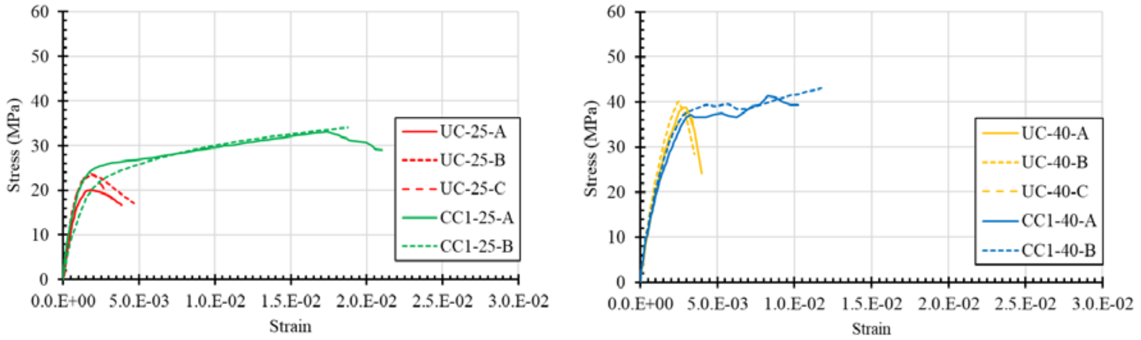


Fig. 3. The results of compressive strength test of 25 MPa (left) and 40 MPa (right) for both unconfined concrete and confined concrete with one layer of GFRP

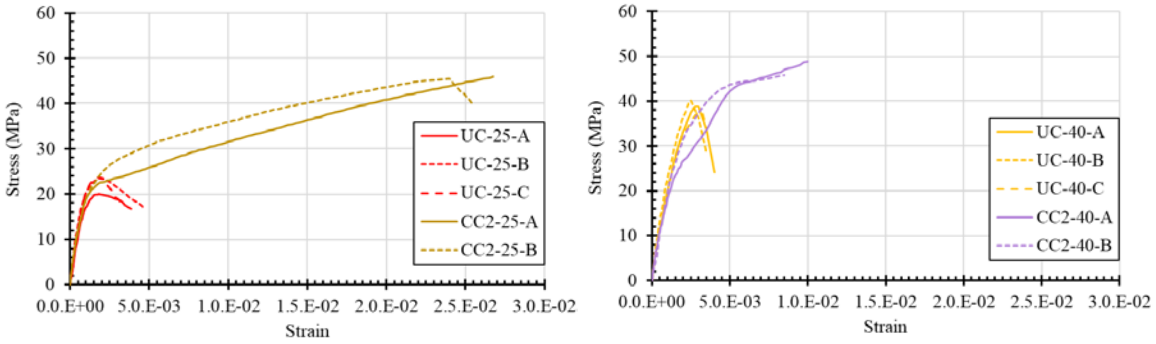


Fig. 4. The results of compressive strength test: (a) 25 MPa and (b) 40 MPa for unconfined concrete and confined concrete with two layers of GFRP.

indicate that the strength and stiffness of confined concrete remain relatively unchanged, suggesting that with only one layer of GFRP wrapping, lateral deformation of concrete under compression may still fully occur within the concrete. This finding aligns with the results of previous researchers [9,16]. While their study investigated the combined effect of adding GFRP layers for lateral confinement and CFRP layers for longitudinal strengthening, one of their key findings indicates that two layers of GFRP may not be sufficient to provide adequate lateral confinement.

The lack of stiffness improvement in confined concrete using limited GFRP layers deserves further consideration. Referring to Table 1 [5], although the tensile strength of glass fiber is comparable to carbon, the elastic modulus of glass fiber-based materials (88 GPa) is markedly lower than that of carbon (500 GPa). Consequently, glass fiber-based materials experience greater deformation under similar stress conditions. It was evident from the significant deformation observed in GFRP-confined concrete under compression. This finding appears to contradict the results reported in previous study [10]. Another study reported a significant increase in strength and stiffness based on the results of flexural tests conducted on reinforced concrete beams strengthened with GFRP layers [18]. However, it is crucial to note that GFRP fibers possess very high tensile strength, with type E glass fiber having a strength of 3400 MPa and type S glass fiber having a strength of 4600 MPa [5]. In the experiments conducted by Chiew et al. [18], the GFRP layers were applied to the tension zone of the beam, allowing the GFRP fibers to work in tension effectively. This difference in application method likely contributes to the disparity in results compared to the findings of this study.

The notable contribution of adding GFRP wrapping in RC structural elements is the significant increase in concrete ultimate stress and strain compared to unconfined concrete. Overall, the addition of GFRP has significantly enhanced the ultimate stress and strain of concrete, far surpassing that of unconfined concrete by several orders of magnitude (Figure 3). The addition of GFRP wrapping clearly transforms the concrete characteristics from brittle to ductile material [13,20].

For both types of concrete strength, confined concrete exhibits larger deformations (ultimate strain), about 2-5 times greater than that of unconfined concrete. However, for higher-strength types of concrete, the results might be slightly lower due to their inherent brittleness [9]. Confined concrete with two layers of GFRP shows greater ultimate strain and experiences larger strength gains compared to when one layer of GFRP. The number of GFRP layers appears to influence the confinement effect on concrete, indicating that the quantity of GFRP layers in concrete could impact its inelastic modulus.

In assessing the seismic performance of building structures, it's frequently observed that certain structural elements, especially reinforced concrete columns, fail to meet shear capacity requirements, prompting the need for retrofitting. It makes the building structure vulnerable to seismic events due to the brittle nature of these structural elements, which may lead to catastrophic failure. One effective solution for enhancing column shear strength involves utilizing FRP. By applying FRP, the column gains restraint against lateral deformation when subjected to compression [3]. This restraining effect is expected to improve both the strength and stiffness of the confined concrete. Consequently, with the improvement in concrete strength and stiffness, the shear capacity of the RC column is also enhanced. However, this research indicates that the use of a low number of GFRP layers may not be effective, as it provides inadequate lateral restraint. Close observation of the failed specimens reveals that the GFRP layers tend to delaminate, with many of the GFRP fibers being partially or fully fractured on the surface of tested confined specimens (Figure 9).

4.2 Numerical Simulation

Numerical simulation was conducted to develop a finite element model based on the data from experimental results. The simulation process involved the appropriate constitutive material model of confined concrete and GFRP wrapping using finite element analysis with Abaqus Software. The aim of the numerical simulation was to create models that closely resemble the characteristics stress-strain relationship observed in the experimental results. Based on the numerical model, the stress-strain characteristics of the interaction between concrete and GFRP can be described. It is widely acknowledged that creating an accurate numerical model requires a precise selection of element type, boundary conditions, and meshing of the model.

4.2.1 Development of numerical model

Before the modeling of concrete confined with the GFRP layer specimen, the constitutive material input of the unconfined concrete specimen model needs to be verified with the experimental results and also theoretical constitutive model of concrete developed by Pour et al. (2018) [30]. Therefore, the numerical model of the unconfined concrete also need to be developed.

In the development of numerical model, the unconfined concrete constitutive material follows previous study [13]. In achieving an appropriate result for the confined concrete model, the modified concrete damage plasticity constitutive model developed by Teng et al. (2007) [30] was adopted. The mechanical properties parameter input of GFRP follows the predecessor study by Du et al (2017) [27]. All parameters of concrete constitutive models were employed as input in Abaqus software as concrete damage plasticity model (CDP) [31].

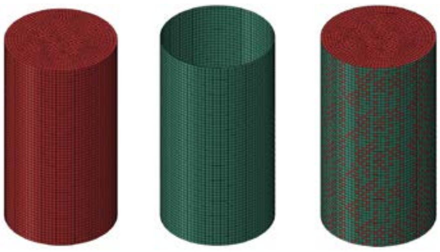

(a) (b) (c)

Fig. 5 Meshing of the specimen numerical model: (a) concrete cylinder, (b) GFRP layer, and (c) concrete cylinder with GFRP

The unconfined and confined models of the concrete cylinder were configured with solid elements (Fig. 5 (a)). The GFRP layers of wrapping are to be idealized as shell elements (0.5 mm of measured thickness), as shown in Fig. 5 (b). A mesh convergence analysis was conducted to determine the appropriate mesh size. After careful evaluation, a mesh size of 5 mm was selected, yielding the best results with only a 3.67% deviation from the experimental results. Boundary conditions were applied to the top and bottom surfaces of the concrete cylinders. The bottom boundary condition was assumed to be restrained for all translations, while the top boundary condition was unrestricted for the longitudinal Z direction as displacement control.

One of the important steps in developing the numerical model was defining the interaction between adjacent layers, particularly between the GFRP layer and the concrete surface. The contact-with-friction interaction was used in these finite element models. The friction coefficient with a value of 0.3 was used, according to the reference [29]. On the normal interaction, hard contact was adopted.

4.2.2 Numerical simulation results

According to the numerical simulation, the stress-strain relation of the unconfined concrete specimens model has a good agreement with the experimental results and theoretical, as shown in Figure 6. Both elastic modulus and compressive strength (peak stress) achieved coincidence results with the experimental and theoretical. For specimen UC-40, the numerical model shows a more gradual softening curve than the experimental and theoretical.

The additional GFRP layer confinement exhibited an enhancement of deformation capacity of the numerical model as the experimental results and theoretical (Figures 7 and 8) from the Pour et al. [29]. In two layers of GRP numerical model results showed accordance result with the experimental and theoretical in the terms elastic and inelastic deformation state. However, in one layer of GFRP confinement, the inelastic modulus of numerical

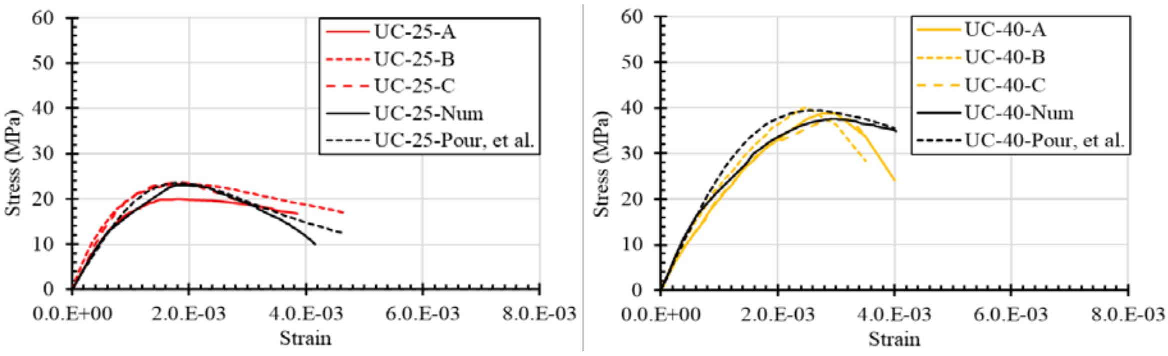


Fig. 6 Stress-strain from experimental, theoretical, and numerical model for unconfined concrete with compression strength 25 MPa (left) and 40 MPa (right)

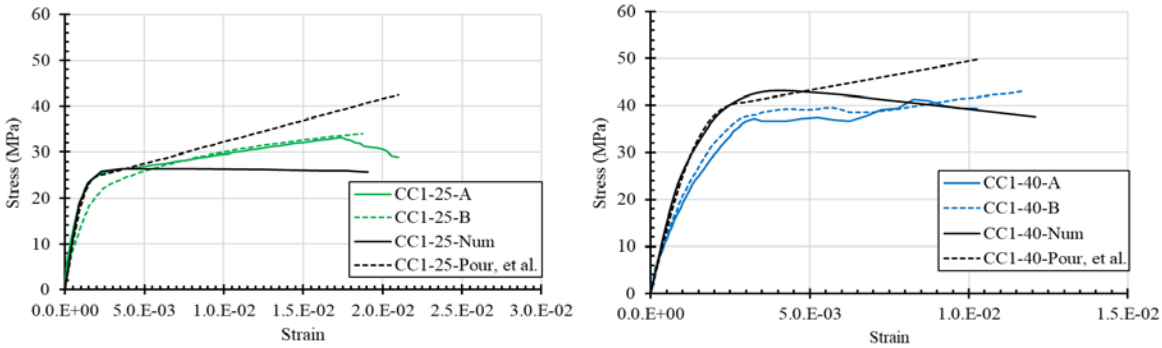


Fig. 7 Stress-strain from experimental, theoretical, and numerical model for 1 GFRP layer confined concrete with compression strength 25 MPa (left) and 40 MPa (right)

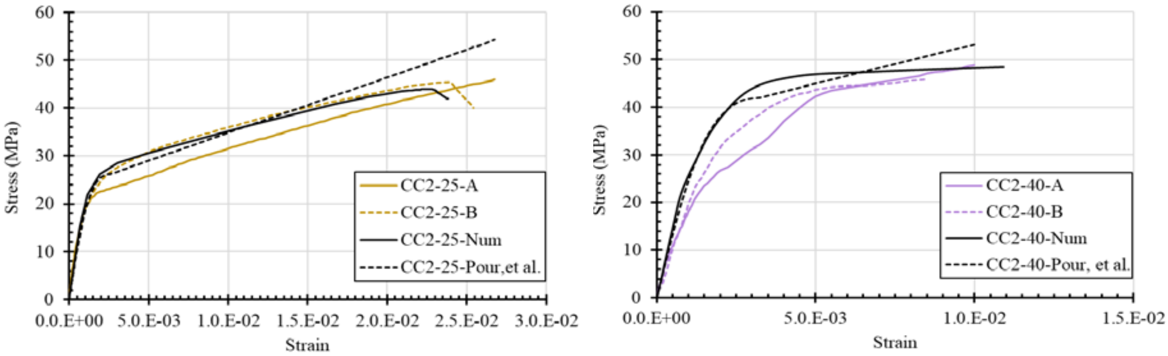


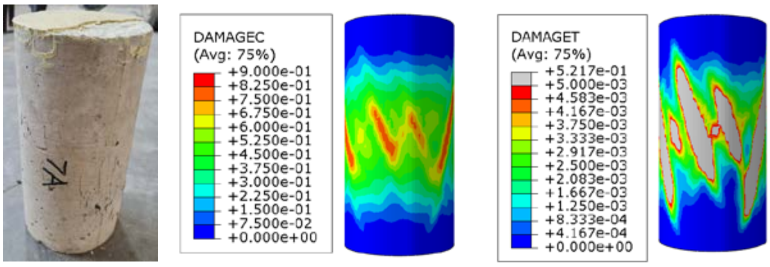
Fig. 8 Stress-strain from experimental, theoretical, and numerical model for 2 GFRP layer confined concrete with compression strength 25 MPa (left) and 40 MPa (right)

model (UC-25) showed flat trend, while the UC-40 showed softening trend. The limitation of the parameter input properties of GFRP material model might generate the different mechanical behavior of confined concrete in the inelastic modulus.

4.3 Failure mode

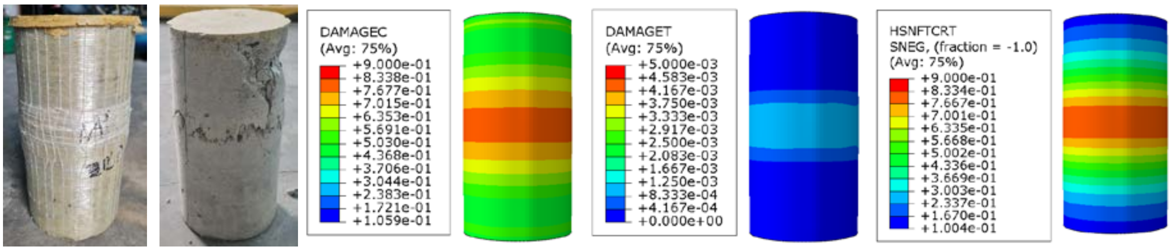
The experimental results revealed that for unconfined concrete, the samples suffered severe tension and compression cracks. In contrast, for confined concrete, the failure occurred due to the breaking of GFRP fibers followed by compression crushing of the concrete at the middle part of cylinder specimens. The breakage of GFRP fibers indicates significant lateral deformation occurred when the specimen was loaded close to its maximum load, nearly resulting in collapse. The comparison of the damage pattern of the specimens in the final state of the testing is shown in Figure 9 (a).

Comparing the characteristics of failure from the experiments to the numerical results, as indicated by the outputs of compression damage (DAMAGEC) and tension damage (DAMAGET), and fracture damage of GFRP (HSNFTCRT), as shown in Figure 9 (b, c, d), reveals interesting insights. Examination of the damage model of the unconfined concrete reveals that tension and compression cracks accumulated in the middle of the concrete cylinder. The simulation of unconfined concrete, the crack



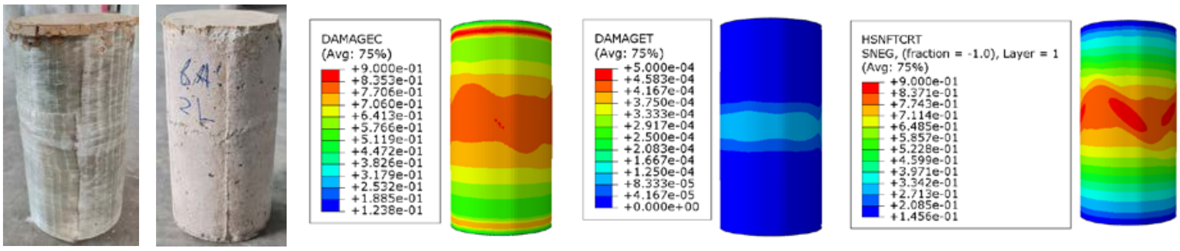
(a) (b) (c)

Unconfined concrete



(a) (b) (c) (d)

Confined concrete with one layer of GFRP



(a) (b) (c) (d)

Confined concrete with two layers of GFRP

Fig. 9 The failure mode of unconfined and confined concrete: (a) experimental, (b) compression damage of concrete (numerical), (c) tension damage of concrete (numerical), and (d) tension damage of GFRP (numerical)

initiation and the progressive tension crack development can be easily monitored. The critical characteristic of unconfined concrete failure mode is the immense progressive cracks that took place within the concrete before failure, and the sample failed only in a few minutes. For confined concrete, tension crack development could not be observed. Only when loading reached close to the maximum stage were some signs of fibers extension where noticeable. More fiber deformation was observed, and suddenly, some fibers were broken (high value of HSNFTCRT). As the load gradually increased, more and more fibers were finally broken (Figure 9 (a), (d)). The formation of compression concrete crushing (DAMAGEC) shows an increase in maximum stress, but this is not critical stress where the curve starts to deviate; this is the maximum stress achieved before it collapses (Figures 7 and 8). Numerical analysis confirms that unconfined and confined concrete are failures under tension and compression damage, while the confined concrete failure under breaking of the GFRP layer than followed by the concrete compression crushing.

5. CONCLUSIONS

Concrete confinement using only a low number of GFRP wraps may not be effective, as it provides inadequate lateral restraint for concrete under compression. Additionally, a limited number of GFRP wraps yield only a slight increase in strength development. Furthermore, the elastic modulus of unconfined and confined concrete remains unchanged, indicating that there is no improvement in elastic moduli of confined concrete using GFRP. Hence, a low number of GFRP wraps is not effective for retrofitting shear deficiencies in RC structural elements.

Using GFRP for concrete confinement clearly transforms the material properties from being brittle to becoming ductile, resulting in a deformation capacity (ultimate strain) that can reach up to 2-5 times greater than that of unconfined concrete.

A numerical simulation could exhibit the mechanical behavior of the unconfined and confined concrete with GFRP under a compression load well.

The damage pattern in the failure state of unconfined concrete due to tension and compression cracks could be visualized well. In addition, the numerical model could also capture the damage pattern of confined concrete in a failure state caused by the fracture of GFRP layers and induce the compression crushing damage.

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7. REFERENCES

[1] Hutton H. G., Dhakal P., Eatherton M. R., and Jacques E., Development of FRP Retrofit Guidelines for Deficient Reinforced Concrete Horizontal Lateral Force Resisting Systems, Virginia Tech Research Report No. CE/VPI-ST-23/07. Blacksburg, VA, 2023. pp.1-207.

[2] Lejano B. A., Evaluation of Different Fiber Reinforced Mortar as Retrofitting Materials for RC Columns, International Journal of GEOMATE, 13(35): July 2017, pp.40-47.

[3] Kalogeropoulos G. and Tsonos A.-D., Seismic Performance Enhancement of RC Columns Using Thin High-Strength RC Jackets and CFRP Jackets, Fibers, Vol. 9, No. 5, 2021, p.1-24.

[4] Yuhazri M. Y., Zulfikar A. J., and Ginting A., Fiber Reinforced Polymer Composite as a Strengthening of Concrete Structures: A Review, in IOP Conference Series: Materials Science and Engineering, Dec. 2020, pp.1-12.

[5] Qureshi J., A Review of Fibre Reinforced Polymer Structures, Fibers, Vol. 10, No. 3, 2022, pp.1-29.

[6] Goodwin D., Sattar S., Dukes J., Kim J. H., Ferraris C., and Sung L.-P., Research Needs Concerning the Performance of Fiber Reinforced (FR) Composite Retrofit Systems for Buildings and Infrastructure, Gaithersburg, MD, 2019. pp.1-116.

[7] Vecchio C. Del, Ludovico M. Di, and Prota A., Cost and Effectiveness of Fiber-Reinforced Polymer Solutions for the Large-Scale Mitigation of Seismic Risk in Reinforced Concrete Buildings, Polymers, Vol. 13, No. 17, 2021, pp. 1-15.

[8] Ling J. H., Lim Y. T., and Jusli E., Methods to Determine Ductility of Structural Members: A Review, Journal of the Civil Engineering Forum, 2023, pp. 181–194.

[9] Alrshoudi F., Abbas H., Abadel A., Albidah A., Altheeb A., and Al-Salloum Y., Compression Behavior and Modeling of FRP-Confined High Strength Geopolymer Concrete, Construction and Building Materials, Vol. 283, 2021, 122759. pp.1-11.

[10] Nguyen V. N. and Cao V. Van, NSM GFRP Strengthening of Reinforced Concrete Beams after Exposure to Fire: Experiments and Theoretical Model, Journal of Composites for Construction, Vol. 27, No. 1, 2023. p.27.

[11] Fazli H., Yassin A. Y. M., Shafiq N., and Wee T., The Behavior of Carbon Fiber Reinforced Polymer (CFRP) Strengthened Beams Under a Marine Environment, International Journal of GEOMATE, Vol. 13, No. 39, 2017.pp. 179-184.

[12] Sinha A. R., Prakash S., Singh K., Kumar S., and Kumar C., Feasibility and Utilization of GFRP in Concrete Structures, International Journal of Engineering Research and, Vol. V9, No. 08, 2020. pp.610-616.

[13] Mander J. B., Priestley M. J. N., and Park R., Theoretical Stress-Strain Model for Confined Concrete, Journal of Structural Engineering, Vol. 114, No. 8, 1988. pp.1804-1826.

[14] Attia M. M., Abdelsalam B. A., Tobbala D. E., and Rageh B. O., Flexural Behavior of Strengthened Concrete Beams with Multiple Retrofitting Systems, Case Studies in Construction Materials, Vol. 18, 2023. pp.1-19.

[15] Tu J., Gao K., He L., and Li X., Experimental study on the axial compression performance of GFRP-reinforced concrete square columns, Advances in Structural Engineering, Vol. 22, No. 7, 2019, pp. 1554–1565.

[16] Khorramian K. and Sadeghian P., Hybrid System of Longitudinal CFRP Laminates and GFRP Wraps for Strengthening of Existing Circular Concrete Columns, Engineering Structures, Vol. 235, 2021, pp.1-14.

[17] Kashwani G., Al-Tamimi A., and Riyadh A.-A., Evaluation of FRP Concrete Compression Member Under Repeated Load and Harsh Environment, International Journal of GEOMATE, Vol. 9, No. 2, 2016, pp. 1460–1466.

[18] Chiew S.-P., Sun Q., and Yu Y., Flexural Strength of RC Beams with GFRP Laminates, Journal of Composites for Construction,Vol.11,No.5,2007, pp.497–506.

[19] Ronagh H. R. and Eslami A., Flexural Retrofitting of RC Buildings Using GFRP/CFRP – A Comparative Study, Composites Part B: Engineering, Vol. 46, 2013, pp. 188–196.

[20] Khaloo A., Tabatabaeian M., and Khaloo H., The Axial and Lateral Behavior of Low Strength Concrete Confined by GFRP Wraps: An

Experimental Investigation, Structures, Vol. 27, 2020, pp. 747–766.

[21] Moussaoui B., Bouamra Y., Tahar K. A., Amrouche M. O., and Ouabed D., Behavior of Short Concrete Cylinders Partially Confined with GFRP Composites, Procedia Structurl Integrity,Vol.17,2019, pp.979–985.

[22] Otoom O. F., Lokuge W., Karunasena W., Manalo A. C., Ozbakkaloglu T., and Thambiratnam D., Experimental and Numerical Evaluation of The Compression Behaviour of GFRP-Wrapped Infill Materials, Case Studies in Construction Materials, Vol. 15, 2021, pp.1-24.

[23] Cao Y. G., Jiang C., and Wu Y. F., Cross-sectional unification on the stress-strain model of concrete subjected to high passive confinement by fiber-reinforced polymer, Polymers, Vol. 8, No. 5, 2016. pp. 1-17.

[24] Youssef M. N., Feng M. Q., and Mosallam A. S., Stress-strain model for concrete confined by FRP composites, Composites Part B: Eng, Vol.38, No.5–6, 2007, pp. 614-628.

[25] Zacharias A. I., Experimental and Numerical Study on the Influence of Glass Fiber Reinforced Polymer (GFRP) Reinforcement on the Compressive Strength of Concrete Cylinders, graduate thesis, Civil and Environmental Engineering Department, Universitas Gadjah Mada, 2022. pp. 1-122.

[26] Srivastava J. P. and Kumar P., Introduction to Glass Fiber-Based Composites and Structures, in Natural and Synthetic Fiber Reinforced Composites,Wiley,2022, pp.1–16.

[27] Du B., Chen L.M., Zhou H., Guo Y.G., Zhang J., Peng S.W., Liu H.C., Li W.G., and Fang D.N., Fabrication and Flatwise Compression Property of Glass Fiber-Reinforced Polypropylene Corrugated Sandwich Panel, International Journal of Applied Mechanics, Vol. 09, No. 08, 2017, pp.1-19.

[28] Carreira D. J. and Chu K.-H., Stress-Strain Relationship for Plain Concrete in Compression, ACI Journal Proceedings, Vol. 82, No. 6, 1985.

[29] Pour A. F., Ozbakkaloglu T., and Vincent T., Simplified design-oriented axial stress-strain model for FRP-confined normal- and high-strength concrete, Engineering Structures, Vol. 175, 2018, pp. 501–516.

[30] Teng J. G., Huang Y. L., Lam L., and Ye L. P., Theoretical Model for Fiber-Reinforced Polymer-Confined Concrete, Journal of Composites for Construction, Vol. 11, No. 2, 2007, pp. 201–210.

[31] Abaqus, Abaqus 6.11 Analysis User’s Manual, Vol. 5., Prescribed Conditions, Constraints & Interactions, Product of Dassault Systèmes Simulia Corp, Providence, 2011, pp. 1-931.