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ANALYSIS OF RC CIRCULAR BRIDGE COLUMNS RETROFITTED WITH FIBER REINFORCED POLYMER UNDER AXIAL AND LATERAL CYCLIC LOADING

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Abstract: From the last two decades non-metallic fiber reinforced polymer (FRP) composites have been used as a practical alternative material for the strengthening of concrete structures. The novelty of the composite materials lies in its outstanding mechanical properties such as, low weight and high tensile strength, and satisfactory durability properties even in an aggressive environment. These properties were effectively utilized to enhance the safety of various civil infrastructures. Although, under monotonic and cyclic lateral loadings, the behavior of FRP composite retrofitted reinforced concrete (RC) bridge columns has been investigated extensively in the lab, numerical knowledge needs to be further enhanced, especially in the area of different types of FRP composite retrofitted bridge columns under cyclic load. The objective of this study is to investigate numerically the effectiveness of different retrofitting techniques in upgrading the seismic performance of non-ductile RC bridge columns. The quasi-static cyclic analyses and non-linear static pushover analyses are conducted in this study. The seismic performance of the studied columns is evaluated in terms of load carrying capacity, flexural ductility, and hysteric behavior under quasi-static cyclic load along with constant axial load.

1. INTRODUCTION

The San Fernando earthquake 1971, Loma Prieta earthquake 1989, and Kobe earthquake, 1995 caused considerable damage on numerous of old reinforced concrete (RC) bridge columns. The main reason behind the failure of those bridges was due to poor reinforcement detailing which was designed before the consideration of new seismic design requirements (Saadatmanesh et al. 1994). The insufficient and poor reinforcement detailing of these structures has resulted in numerous bridges having columns with low flexural strength and stiffness or ductility capacity, and low shear strength to resist seismic loads as imposed by the recent codes and guidelines (ATC 1996, CSA S6 2014). The inadequate lap splice length at the plastic hinge zones and inadequate transverse reinforcement in these columns are the most contributors to their deficiency in resisting seismic force (Priestley and Seible 1995; Haroun and Elsanadedy 2005).

Numerous researchers have demonstrated that increasing the confinement in the potential plastic hinge zones of the column would enhance the compressive strength of the core concrete, ultimate compression strain and ductility (Mander et al. 1988, Ma and Xiao 1999). Hence, retrofitting techniques generally involve methods from improving the confining forces either in the potential plastic hinge zones or over the entire height of column (Chai et al. 1991). There are several rehabilitation methods available to upgrade the seismic performance of existing building and bridges. Recently, the uses of different fiber reinforced polymer (FRP) composites, such as glass fiber reinforced polymer (GFRP), carbon fiber reinforced polymer (CFRP), aramid fiber reinforced polymer (AFRP) and basalt fiber reinforced polymer (BFRP) jackets have been increasing rapidly, which can significantly improve the flexural and shear strengths and enhance the ductility of the column (Seible et al. 1997, Xiao and Wu 2000, and Gajdosova and Juraj 2013). Amongst all the FRP wraps, the CFRP jacketing technique is the most popular because of its higher modulus of elasticity and high tensile strength compared to other FRP composites.

The comprehensive review of the literature showed that the behavior of FRP-confined concrete specimens under monotonic load condition has been studied extensively (Mirmiran and Shahawy, 1997; Karbhari and Gao 1997; Samaan et al. 1998; Spoelstra and Monti, 1999; Demers and Neale 1999; Xiao and Wu, 2000; Moran and Pantelides, 2002). However, limited data are available in the existing literature for the FRP-confined RC column under simulated seismic load condition. Saadatmanesh et al. (1994) conducted an experimental investigation to study the seismic behavior of 1/5 scaled RC column strengthened with GFRP straps. Their results showed that the retrofitted columns significantly improved the seismic resistance capacity and prevented the longitudinal reinforcement bars from buckling under cyclic loading. Chang et al. (2004) performed pseudo-dynamic tests on the as-built and CFRP strengthened rectangular RC bridge columns under near-fault ground motions. They found that the seismic performance of damaged concrete bridge columns effectively improved the flexural strength capacity after retrofitting using CFRP composites. Haroun and Elsanadedy (2005) conducted tests on the as-built and FRP composite-wrapped scaled models of circular and square RC columns with inadequate lap-splice length under simulated seismic loading. Their results demonstrated that the as-built columns suffered brittle failure due to bond deterioration of the lap-splice of longitudinal reinforcement. The square retrofitted column exhibited limited improvement in clamping of the lap-splice region and for enhancing the ductility of columns, whereas the circular retrofitted columns had improved ductility, and it enhanced the seismic performance of the column. Ma and Xiao (1997) studied as-built and GFRP composite-wrapped ½-scaled models of circular bridge columns with poor lap splice detailing. They reported that the as-built model columns exhibited brittle failure due to bond deterioration of the lap-splice of longitudinal reinforcements. In addition, they observed that the brittle failure was prevented and dramatic improvement with enhanced ductility and energy dissipation capacity of the repaired and retrofitted columns was observed.

In the existing literature, most of the research works on FRP retrofitted RC bridge columns to date are related to experimental studies under seismic loads. Since experimental tests are costly and time consuming, it is beneficial to develop finite element models that can accurately simulate the behavior in terms of energy dissipation capacity and stiffness degradation characteristics of retrofitted columns. This study investigates the seismic performance of CFRP and GFRP retrofitted circular RC columns under quasi-static cyclic loading and non-linear static pushover analysis (NSPA) along with constant axial load using fiber-based finite element approach. The seismic performance of RC circular column is assessed in terms of different confinement ratios in order to study the load deformation behavior, ductility and stress-strain behavior of concrete and longitudinal steel under cyclic load.

2. NUMERICAL INVESTIGATION OF BRIDGE COLUMNS

2.1. Bridge Column Model

The finite element model of the bridge column approximated as a continuous 2-D finite element frame using nonlinear analysis program SeismoStruct (2015). In order to consider material nonlinearity, 3-D inelastic displacement-based frame elements have been used for the modeling of columns. In this research, to represent the distribution of material nonlinearity along the height and cross-sectional area of the member, the fiber modeling approach was employed. To model the cross-section of the column with its confined and unconfined concrete region as well as the longitudinal steel reinforcement of each fiber element has its own constitutive stress-strain relationship. In order to model the confined and unconfined concrete, the nonlinear variable confinement model proposed by Madas (1993) following the constitutive relationship by Mander et al. (1988) and the cyclic rules proposed by Martinez-Rueda (1997) with Madas and Elnashai (1992) model was implemented in the analysis. For the FRP confined concrete, Ferracuti and Savoia (2005) model following the constitutive relationship and cyclic rules proposed by Mander et al. (1988) and Yankelevsky and Reinhardt (1989) under compression and tension, respectively was used in the analysis. This model employs the Spoelstra and Monti (1999) model for the confining effect of FRP jacket. For the FRP materials, linear elastic behaviour up to rupture with zero compressive strength was considered in this study. Menegotto and Pinto (1973) steel model with Filippou (1983) isotropic strain hardening property has been adopted as the constitutive model of rebar to develop the finite element model. Fig. 1(C) characterizes the column fiber representation and its subsection into cover concrete, core concrete and steel reinforcements. When the column jacketed by FRP sheets, the cover concrete is considered as the concrete confined by the FRP jacket while core concrete is considered as concrete confined by FRP and the transverse reinforcements.

2.2. Numerical Model Validation

The numerical model is validated against the experimental results of circular RC column performed by Kawashima et al. (2000). The column specimen has a diameter of 400 mm, and an effective height of 1350 mm. The column is reinforced with 12-15M (dia. of 16 mm) longitudinal steel reinforcement ratio of 1.89%, and 0.128% transverse steel (dia. of 6 mm) with 300 mm center to center spacing, and the clear cover of concrete of 35 mm. The CFRP jackets were applied over a height of 1000 mm with the confinement ratio (ϕ) of 0.11 from the base of the column (Fig. 1(A)). To simulate the experimental results of the columns, they were idealized using a discrete finite element model (Fig. 1(B)). An axial compressive load of 188.4 kN representing 5% of the column axial capacity was applied at the top of the column. The compressive strength, the yield strength of longitudinal and transverse reinforcements were considered as 35 MPa, 374 MPa and 363 MPa, respectively. The CFRP and GFRP retrofitting techniques adopted in this study were adapted from Kawashima et al. (2000) and Shin (2012), respectively. The CFRP and GFRP composites have an initial stiffness of 266 GPa and 19.13 GPa, and an ultimate strain of 1.63% and 1.80%, respectively.

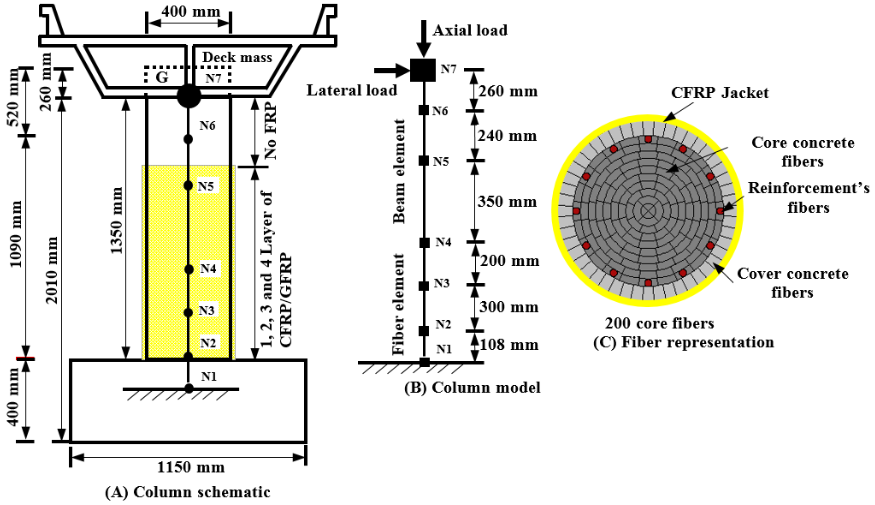


Figure 1: Schematic details of column and its finite element fiber model representation

In order to validate the numerical model, the CFRP retrofitted column is modelled and analyzed using a finite element (FE) program SeismoStruct (2015) under the same displacement-controlled reversed cyclic loading history. The RC cantilever column was displaced with an increment of 0.5% drift until reaching a maximum drift of 5%. The numerical model of column retrofitted with a single layer of CFRP sheet, which represents the volumetric confinement ratio, ϕ of 0.11% has been validated from the experimental results (Kawashima et al. 2000). Fig. 2(A) and Fig. 2(B) illustrate the hysteretic behavior of as-built column and CFRP retrofitted column, respectively. The current numerical results varied only with 3.5% and 3% in predicting the stiffness and capacity compared to those of the experimental results of as-built and retrofitted columns, respectively.

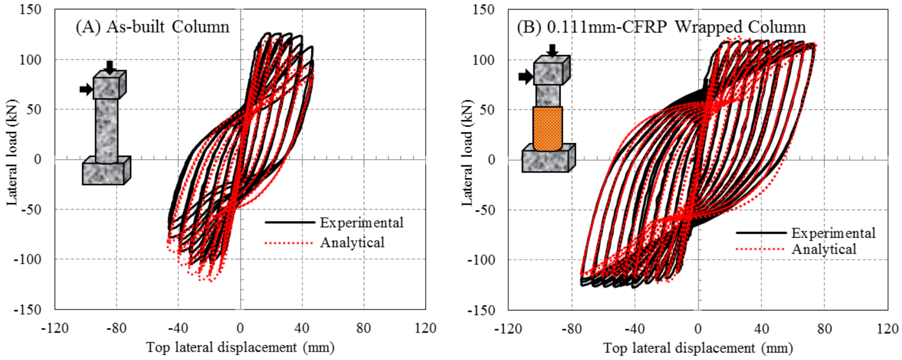


Figure 2:Comparison of the force displacement relationship of the numerical and experimental results (A) as-built column and (B) CFRP retrofitted column

2.3. Nonlinear Static Pushover Analysis and Flexural Limit States

In order to study the flexural limit states and lateral load capacity of the as-built column and FRP retrofitted columns, nonlinear static pushover analysis (NSPA) was carried out. The column had an axial load of 188.4

kN ($0.05.f_c'.A_g$, where f_c' is the compressive strength of concrete, and A_g is the gross cross-sectional area of the column). For the each confinement ratio, pushover analysis was conducted using incremental load in the form of displacement. Fig. 3(A) and Fig.3(B) show the total base shear *vs.* top lateral displacement curve for the as-built and CFRP/GFRP retrofitted columns, respectively (ϕ = 0.11, 0.22, 0.33 and 0.44 %). As seen from Fig. 3(A) and Fig. 3(B), the pushover response curve demonstrates that the CFRP retrofitted column increased the lateral load capacity of the columns considerably, whereas the GFRP retrofitted columns lateral load capacity was lower side compared to the CFRP retrofitted columns. The variation in the lateral load capacity was small in GFRP jacketed columns, whereas for CFRP jacketed columns was higher compared to the as-built column. In the case of CFRP retrofitted column the higher lateral load capacity attributed due to the higher tensile strength and elastic modules of CFRP composites. In general, the bridge column confined with FRP jackets achieves a higher displacement and ductility at a higher base shear compared to the as-built column.

In order to establish the curvature relationship of circular RC bridge column with limit states, Kowalsky (2000) proposed a simple relationship of curvature and displacement ductility (μ_Δ) and drift ratio (D) with serviceability and damage control limit states. In order to study the different confinement ratio of retrofitted circular bridge columns, two performance criteria considered herein are the displacement (Δ) and base shear (V) at the onset of first yielding (Δ_y, V_y) of longitudinal steel, and first crushing of core concrete (Δ_{crush}, V_{crush}). The yielding of longitudinal steel reinforcement was assumed to take place at a tensile strain of steel f_y/E_s. The crushing strain of unconfined concrete differs over a range from 0.0025 to 0.006 (MacGregor and Wight, 2005). Consequently, Paulay and Preistley (1992) recommended that the crushing strain of confined concrete is much higher and it varies from 0.015 to 0.05. In the present analysis, crushing of confined concrete assumed to take place when the concrete compressive strain reaches to 0.035.

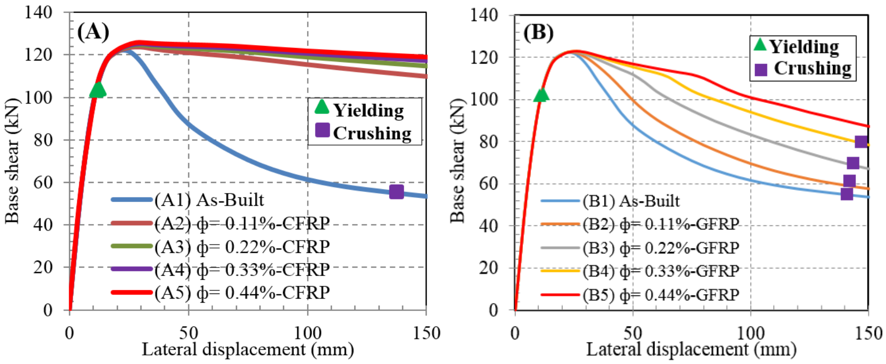


Figure 3: Comparison of pushover curves with different confinement ratios of (A) CFRP jacketed columns and (B) GFRP jacketed columns

The yielding of steel started at all the CFRP and GFRP jacketed columns almost at the same level of displacement and base shear. In the case of GFRP retrofitted columns, the crushing of core concrete found at the displacement and base shear in the range of 142.4 mm to 150.4 mm, and 56.35 kN to 67.25 kN, respectively for the confinement ratio, ϕ of 0.11 to 0.33. Whereas, in the case of CFRP retrofitted column no crushing occurred at the strain limit of 0.035 because of higher tensile strength and modulus of elasticity of CFRP jacket compared to GFRP jacket.

2.4. Moment-Curvature Response

Priestley et al. (1996) developed a simple relationship for the yield curvature (ϕ_y) of a circular RC column section. In order to compare the capacity of retrofitting techniques, the moment curvature analysis of the retrofitted sections and as-built section were also conducted which is depicted in Fig. 4(A) and Fig. 4(B) for CFRP and GFRP retrofitting techniques, respectively. The ultimate moment (M_u) and curvature (ϕ_u) are the ultimate state of sectional response of RC circular column section. In this study, the ultimate state of section is defined as the occurrence of extreme compression strain reaching the ultimate value at the jacket while rupturing steel hoops, or the strain in the extreme tension rebar reaching the "maximum tensile strain". In this analysis, the maximum tensile strain for steel reinforcement assumed at 60% of the ultimate strain. The ultimate strains of the CFRP and GFRP jackets were 0.0163 and 0.018, respectively. The higher load carrying capacity of the CFRP jacketed column attributed due to the high elastic modulus and tensile strength of CFRP jacket providing higher confinement to concrete whereas the lower load capacity attributed in the case of GFRP retrofitted column because of lower tensile and elastic modulus compared to CFRP jackets providing lower confinement to concrete compared to CFRP jacketing.

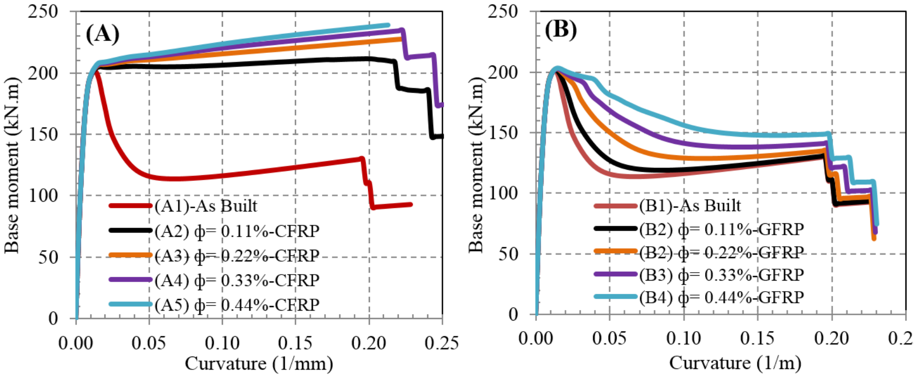


Figure 4: Comparison of moment-curvature with different confinement ratios of (A) CFRP jacketed columns and (B) GFRP jacketed columns

2.5. Ductility

The displacement ductility factor (μ_Δ) is one of the important parameters in the seismic design criteria. The displacement ductility factor is defined as $\mu_\Delta = \Delta_u/\Delta_y$, where Δ_y is the yield lateral displacement and Δ_u is the ultimate lateral displacement. In order to define the displacement ductility factor for each retrofitted column, the ultimate displacement point considered on the pushover curve as the corresponding displacement when the specimen strength capacity decreases to 85% of the peak strength of the column.

A comparison of ductility factor of retrofitted columns with different confinement ratios (ϕ = 0.11 to 0.44 %) of FRPs is depicted in Fig.5. The specimens with a larger μ_Δ exhibited a better ductility. The displacement ductility ratio of as-built column was observed of 2.7, and the retrofitted specimen using CFRP and GFRP with a confinement level of 0.44 had a ductility ratio of 20.8 and 7, respectively. From Fig. 5, the ductility of the retrofitted specimen increases as the level of confinement increases. In the case of CFRP jacketed columns, its ductility factor was found much higher compared to that of the GFRP jacketed columns. The high ductility factor in the case of CFRP retrofitted column attributed due to the higher modulus of elasticity of CFRP jacket contributing to increased level of confinement.

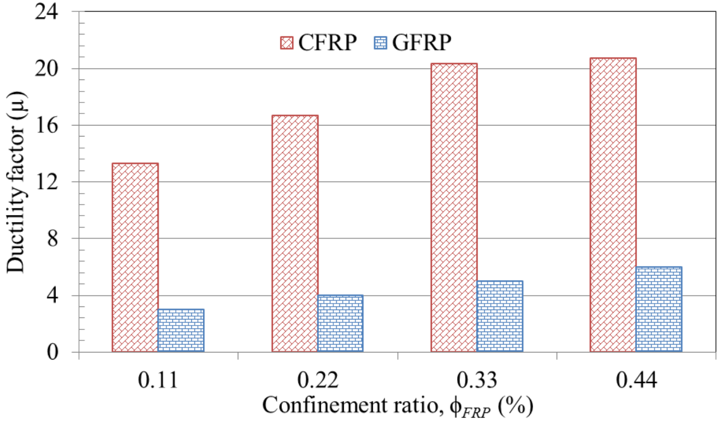
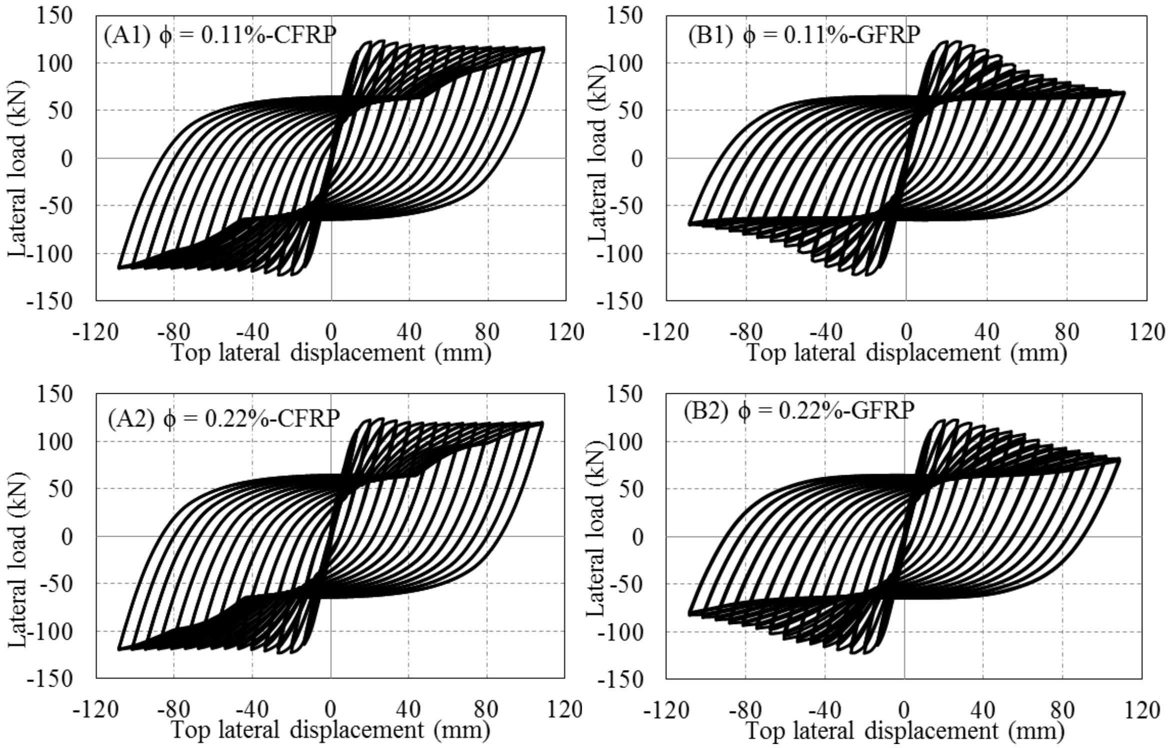


Figure 5: Ductility comparison of different confinement ratio (Φ) of CFRP and GFRP retrofitted columns from NSPA

2.6. Nonlinear Reversed Cyclic Analysis

A displacement controlled-quasi-static cyclic load with an increment of 0.5% drift until reaching a maximum drift of 8% was applied on the retrofitted circular RC bridge columns. The effect of confinement ratio on the hysteretic behavior of columns wrapped with CFRP and GFRP was investigated in this study. The hysteretic behaviors of CFRP, and GFRP composites retrofitted columns with varying confinement ratios are depicted in Fig. 6. In all the cases, the column jacketed with CFRP shows superior load carrying capacity compared to the GFRP jacketed columns. In the case of CFRP sheet retrofitted columns were able to maintain their load-carrying capacity until the end of the loading protocol, whereas in the case of GFRP sheet jacketed columns the increase in the lateral load resistance force was found more pronounced up to 4% drift, but this effect reduced in the subsequent cycles.

The numerical results show that improved flexural strength and ductility can be achieved with an increased confinement ratio of CFRP and GFRP wraps. For illustration purpose, the comparative lateral load versus top lateral displacement envelope curves for all the retrofitted specimens are depicted in Fig. 7. Fig. 7 shows that the effect of retrofitting materials which considerably increases the ductility on the envelope curve. The increased lateral force and top lateral displacement attributed because of the concrete confinement exerted by the CFRP and GFRP wraps. A significant reduction on the displacement ductility was observed for the as-built specimen. In both the case (CFRP and GFRP jacketed columns) the retrofitted column shows higher ductility compared to the as-built columns. The CFRP retrofitted column shows greater ductility compared to the GFRP retrofitted columns. In the case of CFRP jacketed column with the increase of confinement ratio from 0.11% to 0.44%, no much variation was found (Fig. 7). Thus, it can be concluded that one or two layer of CFPR jacket is sufficient to increase the flexural strength and ductility of the deficient columns. But, in the case of GFRP jacketed columns, four layer of GFRP jackets (ϕ = 0.44 %) is needed to achieve the similar level of displacement ductility.



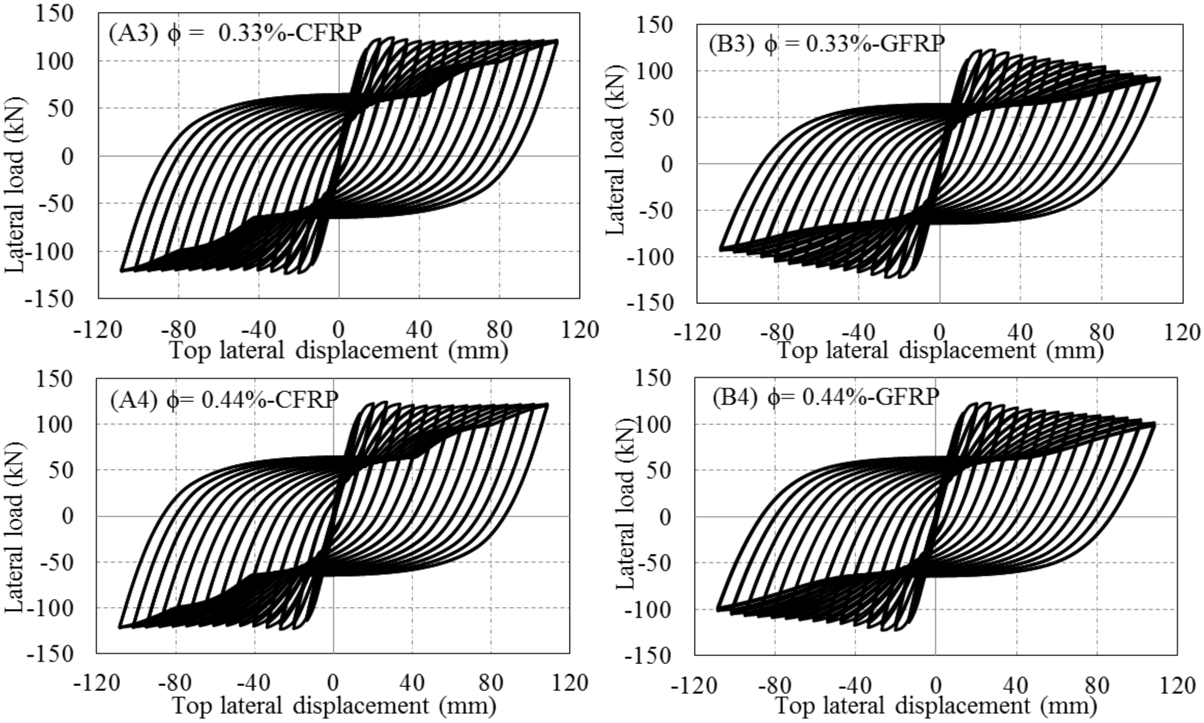


Figure 6: Force displacement relationship of CFRP/GFRP retrofitted column under cyclic loading (A1) CFRP column (ϕ = 0.11), (A2) CFRP column (ϕ = 0.22), (A3) CFRP column (ϕ = 0.33), (A4) CFRP column (ϕ = 0.44), (B1) GFRP column (ϕ = 0.11), (B2) GFRP column (ϕ = 0.22), (B3) GFRP column (ϕ = 0.33), and (B4) GFRP column (ϕ = 0.44)

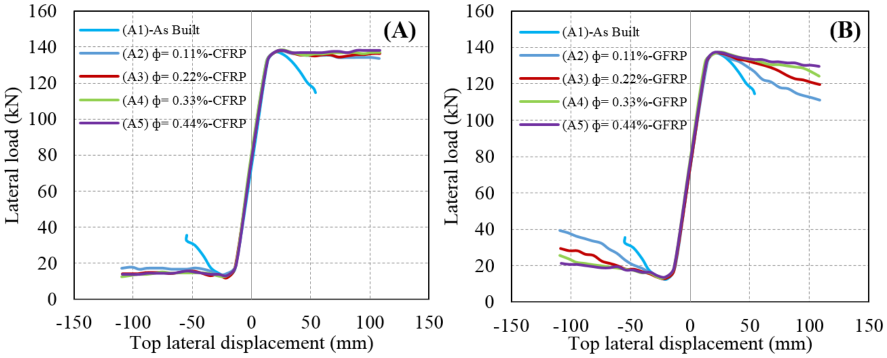


Figure 7: Comparison of the envelope curve of (A) CFRP and (B) GFRP retrofitted column

In order to get better understanding on the level of damage occurred during cyclic analysis of the column, a comparison between the concrete and longitudinal steel stress-strain behavior of CFRP and GFRP jacketed columns are presented in Fig. 8. The CFRP jacketed column in all four cases resulted in an early increase in the compressive strength compared to the GFRP jacketed column. The increased strength of column can be attributed to a significant reduction in the level of concrete damage, which shows the reduction in the maximum compressive strain. The reduction in concrete maximum strain of 0.11, 0.22, 0.33 and 0.44 % confinement ratio was found 59, 64, 62 and 59%, respectively. The results of axial strain in longitudinal steel are portrayed in Fig. 8, which also shows that in the case of CFRP confinement there is a reduction in deformation demand on the longitudinal steel reinforcement by 11, 10, 8 and 6 % with the confinement ratio of 0.11, 0.22, 0.33 and 0.44 %, respectively.

The numerical result shows that the deficient bridge RC columns retrofitted with CFRP and GFRP can enhance the load carrying capacity and ductility compared to the as-built column under nonlinear pushover and cyclic loading. In addition, less damage observed in concrete core and longitudinal reinforcement when the columns jacketed with CFRP and GFRP composites. On the other hand, the column retrofitted using

CFRP wraps improved the seismic behavior of the column significantly compared to the GFRP wraps in terms of load carrying capacity and ductility. The CFRP jacketed columns revealed better strength and ductility due to the early increase in concrete strength that reduces the damage experienced by both concrete and steel.

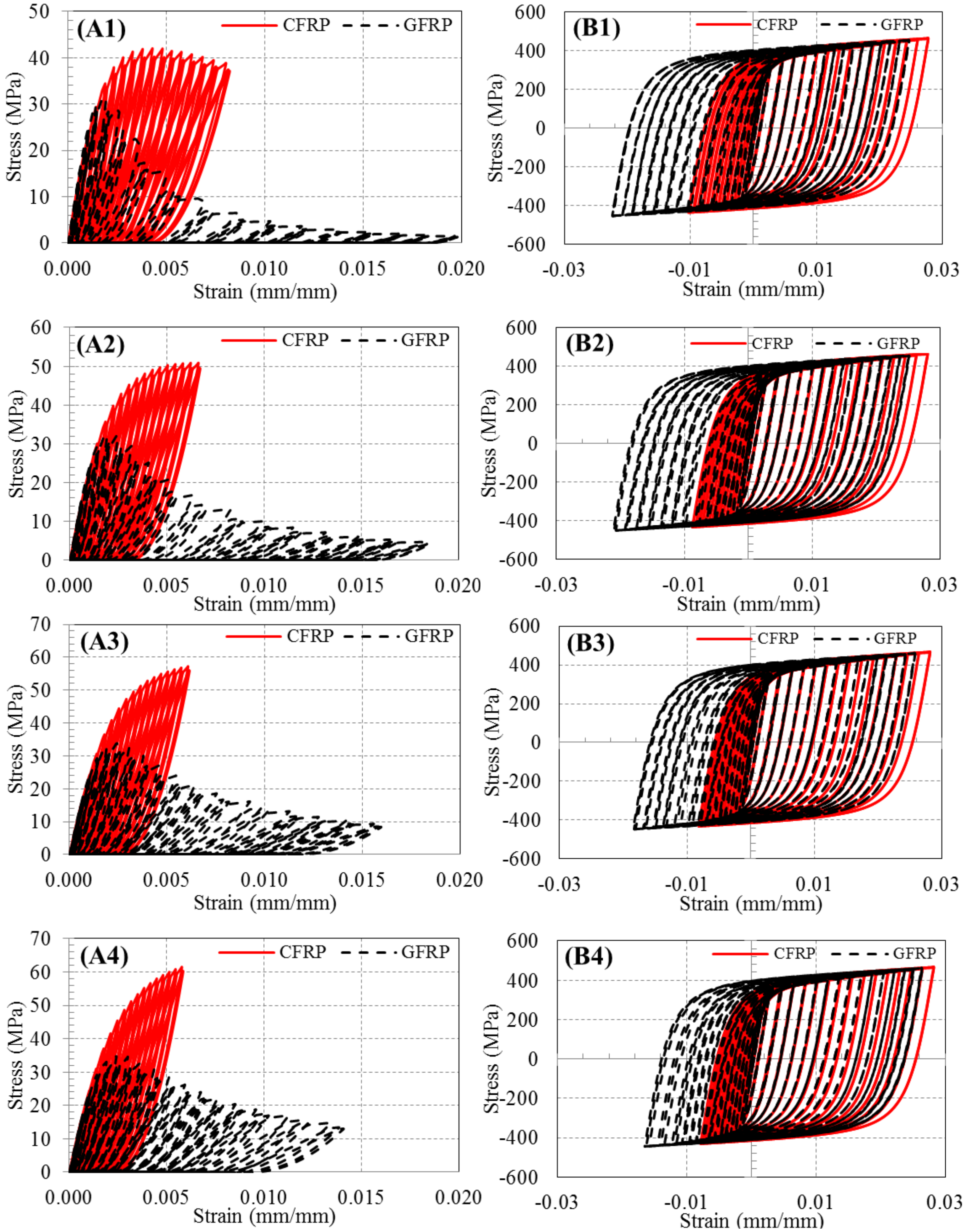


Figure 8: Axial Stress vs. strain of core concrete and longitudinal steel of CFRP/GFRP retrofitted column under cyclic loading (A1) Core concrete (ϕ = 0.11), (A2) Core concrete (ϕ = 0.22), (A3) Core concrete (ϕ = 0.33), (A4) concrete (ϕ = 0.44), (B1) Steel (ϕ = 0.11), (B2) Steel (ϕ = 0.22), (B3) Steel (ϕ = 0.33), and (B4) Steel (ϕ = 0.44)

3. CONCLUSIONS

In the present research, extensive nonlinear finite element analyses (FEA) were conducted to understand the behavior of non-ductile RC circular columns retrofitted with different confinement ratio of CFRP and GFRP jackets under monotonic and reversed cyclic loading. The nonlinear fiber elements were used in FEA, which are based on cyclic constitutive models of longitudinal reinforcement and concrete confined with lateral tie and FRP composites. Constitutive models of concrete confined with advanced composites and lateral ties provide good agreement with numerical simulation results. From the numerical investigation, the hysteretic results showed that column retrofit techniques with advanced composites can improve the seismic performance of substandard RC columns in term of flexural strength and ductility.

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