Effect of Wrapping Thickness and Type on Reinforced Bridge Piers: A Numerical Study

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Abstract

This research paper investigates the impact of wrapping thickness and type on reinforced bridge piers through a numerical study. The Incesu bridge, located in the Ardanuç district of Artvin province, was selected as the case study, as it was completed with low concrete strength. Initially, the bridge was examined, revealing that the piers were inadequate against dynamic, dead, pedestrian, and covering loads. The study concentrated on employing carbon fiber reinforced polymer to reinforce the bridge piers. Various models were wrapped with carbon fiber reinforced polymer in full-length, half-length, and one-meter intervals. In the analysis, it is assumed that the wraps are linked to each other in both principal directions and not detached from one another. Along with the analyses conducted, stress and strain values are presented separately. It was observed that the wrapping effect obtained in small-sized elements in literature could not be obtained in large-sized elements. As the concrete quality improves, the influence of wrapping thickness diminishes. Moreover, the effects of full-length and half-length wrapping are very close to each other, suggesting that half-length wrapping of bridge piers is sufficient. The authors believe that the obtained analysis results will prove beneficial in achieving economic advantages in retrofitting projects within the construction sector.

Keywords

carbon fiber reinforced polymer, numerical modelling, polymer thickness, ANSYS

1 Introduction

Reinforcing the concrete elements by wrapping them with fibrous polymers (FRP) has become a very common strengthening technique in recent years [1–3]. Especially in the strength and ductility properties of small cylindrical specimens, a great improvement can be achieved with fiber reinforced polymer [4]. In insufficient reinforced concrete structural elements where, dynamic loads are also effective, it is known that the deformation capacity is increased with carbon fiber reinforced polymer wrapping [5]. When columns exposed to earthquake effects are wrapped with fiber reinforced polymer, although there is no significant increase in lateral rigidity and lateral load capacity, there is an improvement in displacement capacities [6]. In recent years, many studies have been carried out on the methods of full carbon fiber reinforced polymer cladding on reinforced concrete columns and carbon fiber reinforced polymer cladding by partial wrapping [7–12].

Researchers have discovered that some parameters have a significant impact on the benefit achieved with carbon fiber reinforced polymer. For example, the ovality of column corners is as important as the wrapping thickness and when the sample corners were ovalized at different rates, the load capacity of the samples wrapped with a single layer of carbon fiber reinforced polymer increased between 1.20 and 2.50 times. The load capacity of the samples wrapped with double carbon fiber reinforced polymer increased between 1.75 and 4 times [13, 14].

Many methods have been tried to wrap reinforced concrete columns with carbon fiber reinforced polymer fabric more effectively. Xu et al. [15] reinforced the bridge piers with 2mm and 4mm thick carbon fiber reinforced polymer in the horizontal direction and found that horizontal carbon fiber reinforced polymer wrapping increased the shear capacity of the reinforced concrete and strengthened

the reinforced concrete bridge piers by acting similarly to the transverse reinforcement behavior. Obaidat et al. [16] opened channels with an electric circular saw in a column with 700 mm length, 150 × 250 mm cross-section, and 4φ10 mm longitudinal reinforcement. Partial wrapping with carbon fiber reinforced polymer strips was applied to the channels opened close to the longitudinal reinforcements. Karaiya et al. [17] designed an experimental setup with a 2-story reinforced concrete frame in their study and showed that carbon fiber reinforced polymer wrapping significantly increases the shear and deformation capacity of the reinforced concrete frame. When similar studies are evaluated together; the increases in the axial load capacities of small members reinforced with carbon fiber reinforced polymer wrapping were satisfactory. In larger sized elements, while the axial load capacity improves to a limited extent, a more efficient performance is observed in lateral displacement capacity. Saljoughian and Mostofinejad [18] increased the displacement capacity by up to 20% and the load capacity by up to 50% with carbon fiber reinforced polymer wrapping if the axial load was applied cyclically to the column sample with dimensions of 150 × 150 × 900 mm. In the study conducted by Xu and Huang [19] on corroded short columns with dimensions of 300 × 300 × 500 mm, the increase in load capacity was determined as 10%. Zhang et al. [20] wrapped a prestressed reinforced concrete bridge column with a diameter of 350 mm with carbon fiber reinforced polymer fabric up to its middle region and a lateral load was applied. The moment capacity of the columns increased up to two times compared to the reference columns.

As a result, it is observed that the application of carbon fiber reinforced polymer wrapping improves the current performance. Various methods are suggested to predict the actual behavior of a structural system [21–23]. Studies show that the performance of carbon fiber reinforced polymer confined concrete and reinforced concrete elements can be predicted through finite element analysis [24]. Raza et al. [25] revealed the stress-strain relationship for fiber reinforced polymer-wrapped concretes through their experimental and analytical work on 678 standard cylindrical concrete samples. Accordingly, finite element analysis confirms the experimental results with an error margin of 13–38%. Most studies with small-sized elements are encountered in the experimental and theoretical studies in the literature. As the bearing element sizes increase, new problems will arise and the effect of the wrapping on the behavior of the reinforced concrete elements may decrease. This study includes the numerical analysis

of a bridge whose piers were wrapped with carbon fiber reinforced polymer because the concrete class was insufficient. The strengthening method applied on the existing bridge was analyzed numerically for different alternatives.

The company that carried out the strengthening work of the bridge claims that the stresses occurring in the bridge piers will be covered when 2 mm thick carbon fiber reinforced polymer wrapping is used. With the strengthening project implemented, the bridge is currently in service and in use. In this article, analysis was made for both the current situation and similar situations.

As a result of an extensive literature review, although there are numerous studies on small-sized reinforced concrete elements reinforced with carbon fiber reinforced polymer, the number of three-dimensional numerical studies in real dimensions is insufficient. The effectiveness of reinforcement with carbon fiber reinforced polymer wrapping in large-sized elements such as bridge columns was investigated and Incesu Bridge in Artvin was modeled by the ANSYS analysis program. Different types of wrapping models were applied to the analysis model and the performance of the different wrapping types under dynamic loads was evaluated.

2 Materials and method

27 core samples of 100 mm nominal diameter were taken from Artvin Incesu Bridge, whose model was created in ANSYS, shown in Fig. 1. The compressive strength shown in Table 1 without wrapping was measured as 24.8 MPa on samples with a length/diameter ratio of 1/1. This value was found to be quite low for the concrete strength class C30/37 of the bridge.

Core samples were wrapped with carbon fiber reinforced polymer as a single and double wrap to reinforce the bridge piers. Eight of the core samples taken from the bridge columns were unwrapped, 0.5 mm thick epoxy was applied, one layer of carbon fiber reinforced polymer was wrapped and 0.5 mm thick epoxy was applied, and then the compressive strengths seen in Table 1 were measured according to the TS EN 12390-3 standard [26]. In addition, unwrapped, single-wrapped, and double-wrapped samples were modeled using the ANSYS Workbench v17.2 analysis program and calculated in analytical results [27].

As seen in Table 1, the computer models described confirm the experimental data with an error margin of 1–3%. The similarity between the experimental and analytical results in the preliminary study shows that the structural performances of CFRP-wrapped elements can be analysed realistically.
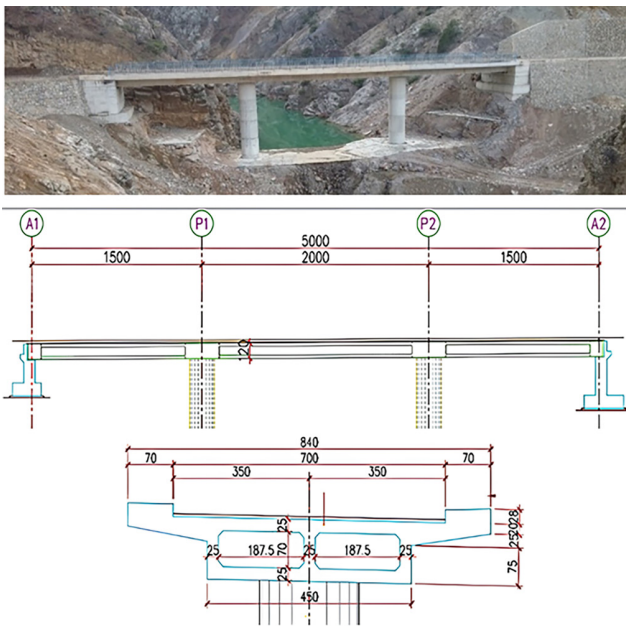
Fig. 1 Artvin Ardanuc Incesu Bridge

Table 1 Compressive strength of core samples

Sample	ANSYS (MPa)	Experiment (MPa)	Relative Error (%)
Unwrapped	24.50	24.80	1.20
A single layer of CFRP wrapping	47.90	49.40	3.04
Double CFRP wrapped	65.50	66.20	1.06

The strength class of the bridge columns, made according to the TS EN 12390-3 standard [26], has been determined to be C20/25. In the calculations in the project of the bridge, the concrete class has been taken as 30/37. This situation necessitated the detailed analysis of the bridge columns. A 3D model of the bridge was created. Dead loads, live loads, and constant ground acceleration were applied to the bridge model. The AASHTO (American Association of State Highway and Transportation Officials) regulation was used for fixed and live loads. For the acceleration value, the maximum ground acceleration value (a = 0.515g) seen in the Erzincan earthquake (1992) was used [28, 29].

The properties of the carbon fiber reinforced polymer used to strengthen the bridge columns are as in Table 2.

The analyses were carried out by modeling both bridge piers in different shapes and thicknesses varying from 1mm to 40 mm as shown in Fig. 2.

In Fig. 2, there are 5 different wrapping models for each column. The different wrapping models applied to the columns are shown as 0, I, II, III, and IV. The length of "a" was analyzed separately for the two different alternatives of 2 m

Table 2 Carbon fiber reinforced polymer fabric material properties [30]

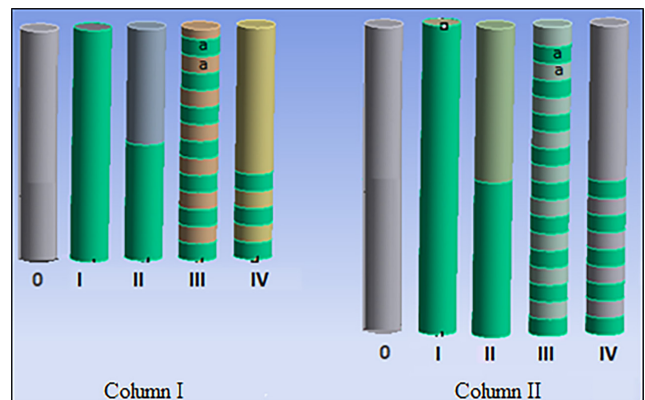| Properties	CFRP
Density	1544 kg/m³
Young's modulus	230000 MPa
Bulk modulus	191670 MPa
Shear modulus	88462 MPa
Poisson ratio	0.30
Critical mode I-Energy release rate	0.20
Critical mode II-Energy release rate	0.20
Critical mode III-Energy release rate	0.20

Fig. 2 The type of wrapping

and 1 m. Analyses were carried out by first taking the thickness of the dressing in the wrapped models as 1 mm. In subsequent analyses, the thickness of the dressing was increased to 2 mm, 4 mm, 8 mm, 16 mm, 20 mm, and 40 mm, respectively. In addition, all analyses were made for 3 different concrete classes (C20/25, C30/37, and C40/50). Thus, the bridge model was analyzed for a total of 129 different situations.

2.1 Analysis model
The three span Artvin Incesu bridge in the study is a 50 m and it has a width of 8.40 m. The bridge sits on two circular columns 2.20 m in diameter, 13.60 m and 18.15 m high, respectively. In addition, the upper deck of the bridge is held at both ends by supports that prevent vertical movement and rotation.

The ANSYS Workbench v17.2 program was used to create the computer model. The general view of the 3D model and the finite element network is as in Fig. 3. To obtain a result with sufficient precision, triangular finite element networks in the interval of 400 mm were created, and "quadratic element" was chosen. "Nonlinear Mechanical" solution was preferred as the "Physical Reference", while the element quality is a minimum of 0.14, it is created as a maximum of 1, and the "aspect ratio" is a maximum
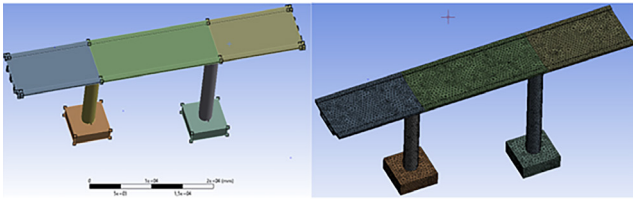
Fig. 3 Finite element model of the bridge and finite element network

of 14.088. For the modeling, the Hognestad concrete model used in the literature was used to consider the non-linear and plastic properties of concrete. The kinematic hardening model was chosen among the plasticity models.

The parameters of the concrete model used in the analysis are given in Table 3. Carbon fiber reinforced polymer is modeled as a linear-elastic isotropic material. "Bonded" is selected as the contact type at the points where the Carbon fiber reinforced polymer material touches itself and the concrete samples. The carbon fiber reinforced polymer rapping applications were applied only on the bridge piers. The bridge deck was not reinforced with carbon fiber reinforced polymer. Both bridge columns have the same size and reinforcement arrangement.

Many different loads are taken into consideration in the project design of bridges. These loads can be detailed as self-weight, live loads, earthquake loads, pedestrian loads, brake force, thrust due to the ground, and surcharge loads. Asphalt pavement, pavement, and guardrails were calculated as distributed loads. H30-S24 was selected as the standard truck type by making use of regulations such as ASSHTO as a moving load.

The pedestrian load of 3 kN/m^2 was impacted on the pedestrian road deck. Erzincan (1992) earthquake was considered as PSA$_{max}$ (g) = 0.525 g, and the

acceleration was 0.525 g perpendicular to the bridge and $0.3 \times 0.525 = 0.1575$ g in the direction of the bridge.

3 Analytical results
Fig. 5 shows the service condition of the bridge and the stress distributions of the model when the concrete class used in the bridge columns is C20/25.

The maximum stress occurred at the lower parts of the bridge columns. The highest stress and displacement values were realized at Pier-II, which has a long free length. For this reason, the effects of the wrapping and concrete class have been discussed based on pier-II. The stress value occurring at the base without any wrapping is 16.3 MPa (Fig. 4). When bridge pier number II is wrapped in 1 mm thickness at full length, the resulting stress decreases to 14.3 MPa. Fig. 5 shows the highest stresses in the bridge piers depending on the changing carbon fiber reinforced polymer thickness and size.

As seen in Fig. 5, as the thickness of the carbon fiber reinforced polymer is increased, the stress values on the bridge piers decrease. The stress values for 2 mm, 4 mm, 8 mm, 16 mm, 20 mm, and 40 mm wrapping thickness are
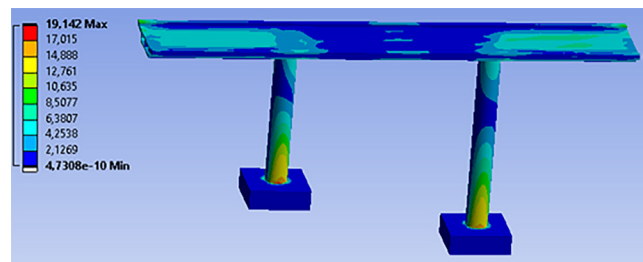

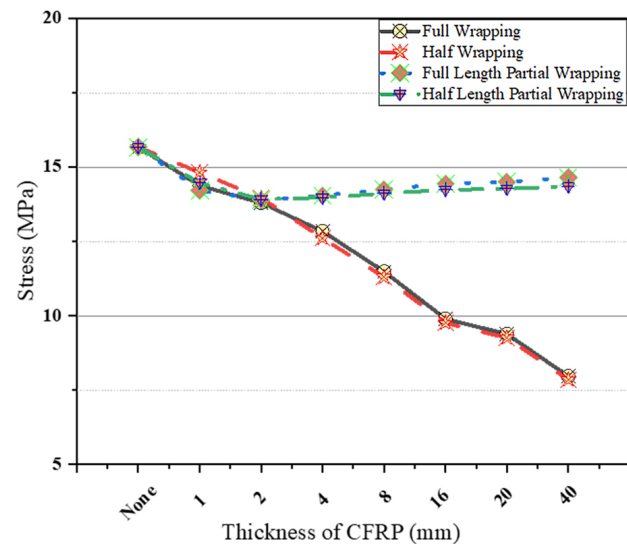Fig. 4 Stress distribution in the bridge lateral loading

Fig. 5 The highest stresses at pier-II for C20/25

Table 3 Concrete parameters

Linear Parameters	C20/25	C30/37	C40/50
Density (kg/m^3)	2300	2300	2300
Coefficient of thermal expansion (C^{-1})	1.40E-05	1.40E-05	1.40E-05
Young's modulus (MPa)	20500	24410	-
Poisson ratio	0.20	0.20	0.20
Bulk modulus (Pa)	1.14E + 10	1.36E+10	-
Shear modulus (Pa)	8.54E + 09	1.02E+10	-
Tensile yield strength (MPa)	0.00	0.00	0.00
Compressive yield strength (MPa)	6.42	9.80	12.69
Tensile strength (MPa)	3.00	3.00	3.00
Compressive strength (MPa)	17.00	25.50	34.00

calculated as 13.98, 12.59, 11.07, 9.52, 9.06, and 8.87 MPa, respectively. When the column in question is wrapped in 1 mm thickness from the lower end to half of the free height, the maximum stress formed is 14.89 MPa. When the thickness of the wrapping is increased to 2 mm, 4 mm, 8 mm, 16 mm, 20 mm, and 40 mm, the resulting stress values are 14.05, 12.69, 11.17, 9.58, 9.09, and 8.96 MPa, respectively. When the obtained tensile values are examined, no significant difference is observed between full-length gap wrapping and half-length gap wrapping. The same situation is detected between full-length partial wrapping and half-length partial wrapping. Similar values in terms of tension are obtained by wrapping the bridge columns in half-length instead of full-length carbon fiber reinforced polymer. The effect of the wrapping type and thickness on the maximum stress occurring in the columns varies according to the concrete class is shown in Figs. 6 and 7.

Figs. 5–7 show that no significant difference was observed between full-length wrapping and half-length wrapping applications in terms of stresses in any concrete class. When the performance of carbon fiber reinforced polymer wrapping compared to the unwrapped column is examined, the results of partial (gap) wrapping and gapless wrapping in 1 mm, 2 mm, and 4 mm thick carbon fiber reinforced polymer applications are very close to each other. When wrapping without gaps, as the thickness of the wrapping increases, the decrease in the maximum tension continues and reaches a decrease of 43% compared to unwrapped concrete. For partial wrapping, this decrease continues at the same rate with non-gap wrapping up to 4 mm. A lower stress drop can be achieved compared to
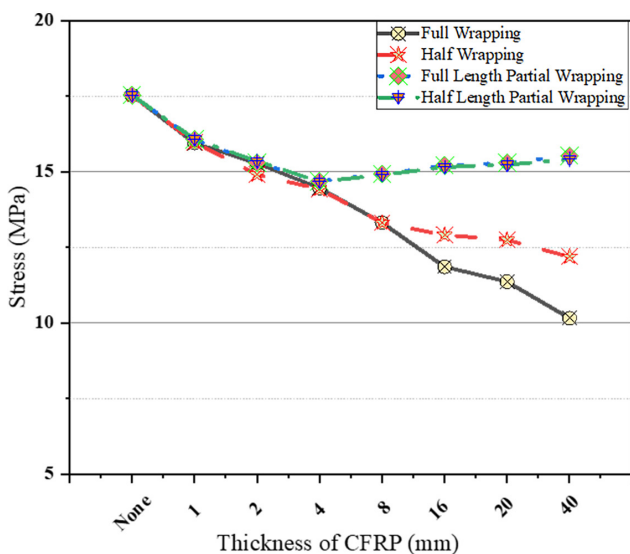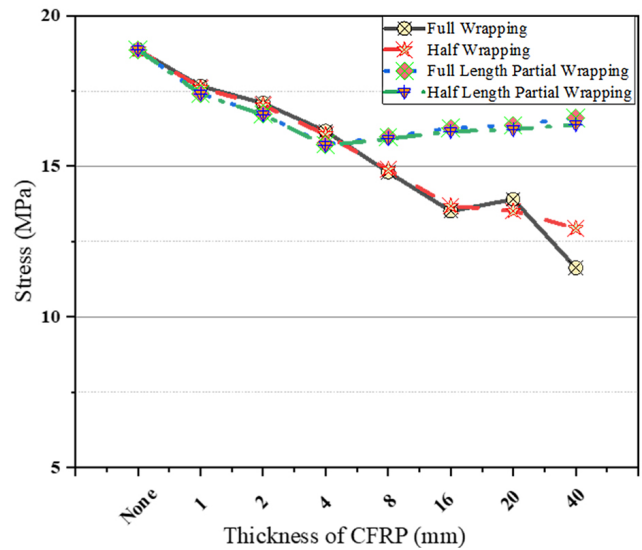

Fig. 7 The highest stresses at pier-II for C40/50

non-gap applications from 4 mm to 16 mm. When a partial wrapping thicker than 16 mm (20 and 40 mm) is applied, there is no difference compared to the 16 mm wrap.

The stress variation between full-length carbon fiber reinforced polymer wraps and half-length carbon fiber reinforced polymer wraps is much higher than in low concrete grades. With the increase in the concrete class, the full-length carbon fiber reinforced polymer wrapping application performs significantly better than other applications. It is seen that partial wrapping performs similarly to half-length gapless wrapping up to 8 mm. With a 16 mm thick partial wrapping, some further stress reduction was achieved, but no extra benefit was achieved at 20 mm and 40 mm wrapping thicknesses. This shows that as the concrete class improves, the partial thickness of the dressing provides benefits. Although the stress values vary according to the concrete class, the stress distributions given for the C40/50 concrete class in Fig. 8(a) and Fig. 8(b) occur similarly in all concrete classes. While the stress distribution in the unwrapped models shows a relatively uniform increase, in circles that expand from the core to the outer fibers, the stress distribution in the wrapped models is more complex. In the reinforced concrete element whose deformation is
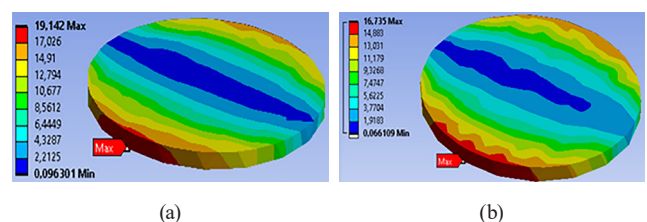

Fig. 6 The highest stresses at pier-II for C30/37

(a)   (b)

Fig. 8 Stress distribution at unwrapped column cross-section and 1 mm full-length wrapped model (a) Unwrapped; (b) 1mm full wrapped

limited by the effect of the wrapping (especially in the outer fibers), the tension layers interlock with each other.

For the column with the C20/25 concrete class, Fig. 9 shows the maximum displacement values at the upper end of the element because of the applied load combinations depending on the thickness of the wrapping and the concrete class. The effect of limiting the displacements in the bridge piers where the reinforcement is applied increases in proportion to the thickness of the wrapping.

For the C20/25 concrete class, the maximum lateral displacement in the column without confinement is 107.26 mm. The maximum displacement value drops to 99 mm when the entire free length of the column is wrapped with 1 mm carbon fiber reinforced polymer. When 1 mm carbon fiber reinforced polymer wrapping was applied only to the lower half of the column instead of the full length of the column, it decreased to 98 mm. When carbon fiber reinforced polymer wrapping is done from the bottom to the column half instead of the full length of the column, there is little improvement in the lateral displacement values, although 50% less wrapping material is used. The maximum displacement was calculated as 102 mm in the case of 1 m full and 1 m gap partial wrapping using the same thickness carbon fiber reinforced polymer fabric. If partial wrapping is applied only to the lower half of the column, this value increases to 103 mm. When the thickness of the wrapping is increased to better observe the performance differences between the application types and when the column is wrapped with 8 mm thick carbon fiber reinforced polymer fabric, the maximum lateral displacement decreases to 75 mm. This value dropped to 77 mm through half-length wrapping. The maximum lateral displacement
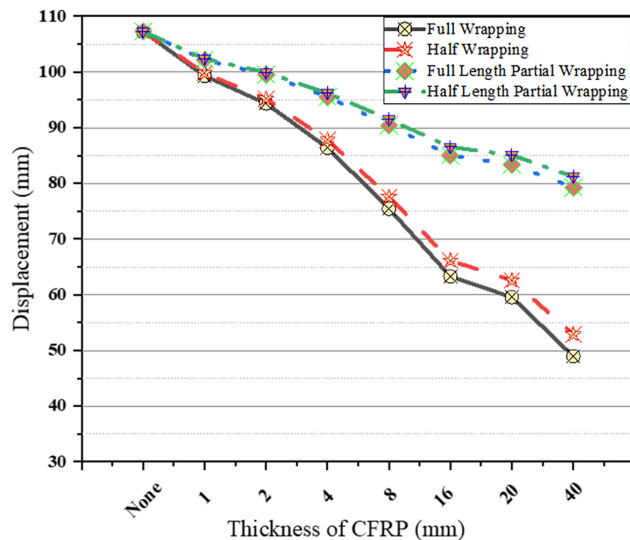
was calculated as 91 mm with full-length partial wrapping at the same thickness and 90 mm with half-length partial wrapping. As can be seen from the results, applying the reinforcement application only in the lower half of the bridge piers performs close to the application in the full length. Another point seen in Fig. 9 is that non-gap wrapping performs better than partial application.

When the concrete class was increased to C30/37, it was displaced by 76 mm without applying carbon fiber reinforced polymer reinforcement. When full-length reinforcement was applied with 1 mm thick carbon fiber reinforced polymer, the displacement value decreased to 72 mm. The displacement values for wrap thicknesses of 2 mm, 4 mm, 8 mm, 16 mm, 20 mm, and 40 mm were calculated as 70 mm, 67 mm, 61 mm, 55 mm, 52 mm, and 44 mm, respectively (Fig. 10). Fig. 11 shows the displacements of the bridge piers reinforced with carbon
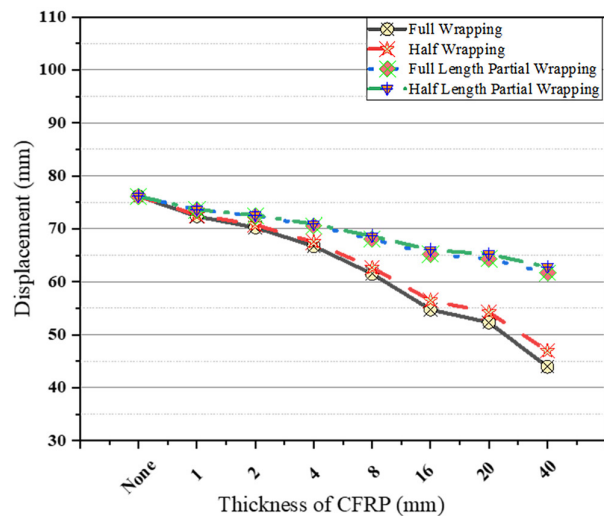

Fig. 10 Maximum displacements for C30/37 concrete grade

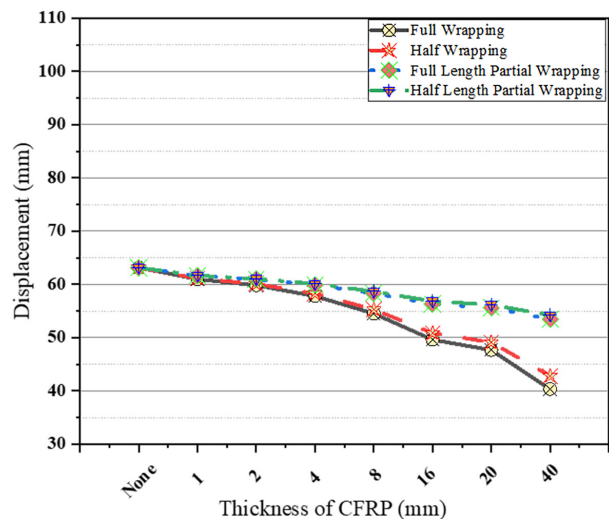Fig. 9 Maximum displacements for C20/25 concrete grade

Fig. 11 Maximum displacements for C40/50 concrete grade

fiber reinforced polymer in different types for the C40/50 concrete class, for which the maximum displacement in the unconfined column has been calculated as 63 mm. The displacement values for 1 mm, 2 mm, 4 mm, 8 mm, 16 mm, 20 mm, and 40 mm full-length wrapping thickness are 61 mm, 60 mm, 59 mm, 58 mm, 55 mm, 50 mm, 48 mm, and 40 mm, respectively. When carbon fiber reinforced polymer wrapping is applied in strips with one-meter gaps, the displacement values decrease compared to the column without wrapping. No significant difference was observed between the application of the strips with gaps in full-length or half-length.

4 Discussion

In this study, it is seen that reinforcement with carbon fiber reinforced polymer is more successful in limiting lateral displacements. Compared to this study, higher strength increases are observed in similar studies in the literature. Kim and Gao [11] wrapped the surfaces of cylindrical samples of different sizes from the bottom to the top with carbon fiber reinforced polymer, increasing the surface area from 0% to 100%, and applied pressure tests to the samples. The wrapping applied to the upper half of the reinforced concrete column did not make a significant contribution. It is sufficient to wrap 50% of the sample surface.

Many studies in the literature have applied only axial load to columns, such as Kim and Gao [11]. Full-length wrapping is more effective in experiments where the sample capacity is consumed only by axial pressure. In a real structure, it is not realistic for a reinforced concrete column to consume all its capacity under axial pressure. In addition, the cross-sections of reinforced concrete elements in real buildings are much larger than many academic studies. When the results of the experiments conducted by Kim andGao [11] are examined carefully, it is seen that the rate of compressive strength gained by the carbon fiber reinforced polymer wrapping decreases as the sample size increases. If the wrapping thickness is kept constant, the carbon fiber reinforced polymer fabric will remain weaker than the increasing cross-section ratio. Reinforcement in spaced strips is often used to save carbon fiber reinforced polymer fabric by reducing the wrapping area. However, the collapse mechanisms encountered with partial wrapping and gapless wrapping are different from each other [16]. Zeng et al. [13] suggest that if D is column diameter and S_f is distance between the wrapping strips, S_f/D ratio should be 0.5 to achieve better performance. In the partial wrapping in this study, 1 m strips

were applied with a gap of 1m each and the column diameter is 2.20 m. The S_f/D ratio is close to but slightly below the recommended value, at about 0.46. The gap wrapping applications analyzed in this study confirm the results of Zeng et al [13].

Mai et al. [4] suggest that full-length carbon fiber reinforced polymer wrapping in reinforced concrete columns increases the axial load capacity 1.6 times more than partial wrapping. They reached these results by applying axial load on a column of $150 \times 150 \times 800$ mm^3. The average compressive strength of the concrete used in the study in question is 36 MPa. The total thickness of the 0.167 mm carbon fiber reinforced polymer wrapping applied in 3 layers was approximately 0.5 mm. To compare the results of the study with the results of Mai et al. [4], this article has the closest characteristics; 1 mm thick carbon fiber reinforced polymer wrap applications. The column sizes in this article study are quite large compared to the experimental samples. However, considering the proportional wrapping performances, the stress variation rates of full-length wrapping and partial wrapping for the C30/37 concrete class (1.7 times higher than the partial wrapping performance) confirm the results of Mai et al. [4].

Xu et al. [15] applied half-length carbon fiber reinforced polymer wrapping in two layers of 0.17 mm (total thickness of 0.34 mm) to columns 330 mm in diameter and 1700 mm in length in the experimental setup they established. When lateral loads were applied to wrapped and unwrapped columns, it was measured that the wrapped sample had 24% more tensile capacity. With the carbon fiber reinforced polymer wrapping, an increase of 10% was achieved in the maximum displacement value. The column in the experimental setup of Xu et al [15]. has a D/L ratio of 0.194 and a t/D ratio of 0.001, where t is the wrapping thickness, D is the column diameter and L is the column-free length. To be able to compare the current results with those of the study by Xu et al. [15], the results of column-I, where the ratios between width, length, and wrapping thickness are closer, should be considered. In this study, the D/L ratio of the 13.60 m long bridge pier number I is 0.16, and the t/D ratio is 0.0009 when it is wrapped with 2 mm carbon fiber reinforced polymer. 14% decrease was calculated in the stress value affecting the column with 2 mm wrapping thickness. This value is lower than the 24% rate in the study by Xu et al. [15]. However, it should be kept in mind that the aspect ratio is slightly higher and there is no additional axial load on the column in the experiment by Xu et al. [15]. There are a bridge deck and service

loads on the column in this study. The horizontal displacement values obtained in both studies confirm this hypothesis. Xu et al. [15] observed an increase of 10% in the displacement capacity of the wrapped column. On the other hand, it was observed that the displacement demand was reduced by 12% in the equivalent column in this study. As can be seen, the lateral displacement is somewhat more limited due to the additional axial load on the column.

5 Conclusions

In this study, carbon fiber reinforced polymer wrapping applications and the effect of the thickness of the wrapping have been evaluated based on a bridge pier whose strength is lower than predicted. As a result of the analysis made in the study, the following conclusions have been reached:

1. Significant strength can be gained with the application of carbon fiber reinforced polymer wrapping to reinforced concrete columns and successful results are obtained in limiting the lateral displacements in the column.
2. Although it provides a high rate of increase in the strength of small-sized elements wrapped with carbon fiber reinforced polymer, no significant increase is observed in the compressive strength of large-sized elements.

3. In order to provide large strength increases in a real structure, it is necessary to increase the thickness of the wrapping in proportion to the element sizes.
4. The concrete quality directly affects the performance of carbon fiber reinforced polymer wrap application. While increasing the thickness of the wrap in low-strength concretes gives more successful results, the effect of the thickness of the wrap decreases as the concrete quality increases.
5. The half-length and full-length wrapping results are very close to each other in both partial and gapless wrapping applications. It is sufficient to apply carbon fiber reinforced polymer wrapping on bridge piers only in the lower half of the column.
6. The reinforcement application with carbon fiber reinforced polymer in the reinforced concrete column has yielded more successful results in limiting the displacements.

Future Studies

In this study, it was assumed that CFRP fabrics would not move on each other. The contact type used does not allow movement in both directions. In future studies, this situation can be modelled with a more realistic contact model.

References

[1] Haj Seiyed Taghia, S. A., Darvishvand, H. R., Asadi, S., Pourhasan, M. "A comparative study on the implementation of carbon and glass fibers wrappings to improve the compressive strength and seismic behavior of concrete", Asian Journal of Civil Engineering, 21, pp. 1389–1398, 2020.
https://doi.org/10.1007/s42107-020-00285-5

[2] Zeng, J.-J., Guo, Y.-C., Gao, W.-Y., Chen, W.-P., Li, L.-J. "Stress-strain behavior of concrete in circular concrete columns partially wrapped with FRP strips", Composite Structures, 200, pp. 810–828, 2018.
https://doi.org/10.1016/j.compstruct.2018.05.001

[3] Chen, C.-C., Chen, S.-L. "Strengthening of reinforced concrete slab-column connections with carbon fiber reinforced polymer laminates", Applied Sciences, 10(1), 265, 2019.
https://doi.org/10.3390/app10010265

[4] Mai, A. D., Sheikh, M. N., Hadi, M. N. "Experimental and analytical investigations on the effectiveness of non-uniform CFRP wrapping on circularised RC columns", Structure and Infrastructure Engineering, 17(8), pp. 1125–1140, 2021.
https://doi.org/10.1080/15732479.2020.1800756

[5] Van Cao, V., Quoc Nguyen, T. "Effects of CFRP/GFRP flexural retrofitting on reducing seismic damage of reinforced concrete frames: a comparative study", Asian Journal of Civil Engineering, 20, pp. 1071–1087, 2019.
https://doi.org/10.1007/s42107-019-00173-7

[6] Özcan, O., Binici, B., Özcebe, G. "Yetersiz betonarme kolonlar için lifli polimer güçlendirme tasarım kurallarının irdelenmesi", (investigation of fibrous polymer reinforcement design rules for inadequate reinforced concrete columns), Turkish Journal of Civil Engineering, 21(104), pp. 5219–5239, 2010. (in Turkish) [online] Available at: https://dergipark.org.tr/tr/pub/tekderg/issue/12755/155214 [Accessed: 15 August 2023]

[7] Yurdakul, O., Tunaboyu, O., Routila, L., Avşar, O. "Parameter sensitivity of CFRP retrofitted substandard joints by stochastic computational mechanics", Composite Structures, 238, 112003, 2020.
https://doi.org/10.1016/j.compstruct.2020.112003

[8] Abdesselam, A., Merdas, A., Fiorio, B., Chikh, N. E. "Experimental and numerical study on RC beams strengthened by NSM using CFRP reinforcements", Periodica Polytechnica Civil Engineering, 67(4), pp. 1214–1233, 2023.
https://doi.org/10.3311/PPci.21309

[9] Cao, Y., Liu, M., Wu, Y. F. "Effect of low strain rate on the axial behavior of concrete in CFRP-confined circular cylinders", Construction and Building Materials, 255, 119351, 2020.
https://doi.org/10.1016/j.conbuildmat.2020.119351

[10] Gahmousse, Z., Djebbar, M.-S., Djebbar, N. "Seismic performance of RC columns retrofitted by CFRP wrapping 'Study of the influencing parameters'", Asian Journal of Civil Engineering, 22, pp. 911–928, 2021.
https://doi.org/10.1007/s42107-021-00354-3

[11] Kim, Y. J., Gao, J. "Hollow concrete cylinders confined with CFRP: Strength and size effect", Construction and Building Materials, 250, 118839, 2020.
https://doi.org/10.1016/j.conbuildmat.2020.118839

[12] Dadmand, B., Pourbaba, M., Riahi, R. "Experimental and numerical investigation of different types of jacketing effect on retrofitting RC short columns using ECC concrete", Periodica Polytechnica Civil Engineering, 66(2), pp. 603–613, 2022.
https://doi.org/10.3311/PPci.19114

[13] Zeng, J. J., Lin, G., Teng, J. G., Li, L. J. "Behavior of large-scale FRP-confined rectangular RC columns under axial compression", Engineering Structures, 174, pp. 629–645, 2018.
https://doi.org/10.1016/j.engstruct.2018.07.086

[14] Jiang, C., Wu, Y.-F. "Axial strength of eccentrically loaded FRP-confined short concrete columns", Polymers, 12(6), 1261, 2020.
https://doi.org/10.3390/polym12061261

[15] Xu, J. J., Demartino, C., Shan, B., Heo, Y. A., Xiao, Y. "Experimental investigation on the performance of cantilever CFRP-wrapped circular RC columns under the lateral low-velocity impact", Composite Structures, 242, 112143, 2020.
https://doi.org/10.1016/j.compstruct.2020.112143

[16] Obaidat, Y. T., Ashteyat, A. M., Obaidat, A. T., Alfaris, S. F. "A new technique for repairing reinforced concrete columns", Journal of Building Engineering", 30, 101256, 2020.
https://doi.org/10.1016/j.jobe.2020.101256

[17] Karaiya, B. K., Oinam, R. M., Sahoo, D. R., Gupta, A. "Lateral cyclic performance of a CFRP retrofitted two-story RC frame with open ground story", Bulletin of Earthquake Engineering, 18, pp. 5919–5939, 2020.
https://doi.org/10.1007/s10518-020-00913-0

[18] Saljoughian, A., Mostofinejad, D. "The behavior of RC columns confined with CFRP using CSB method under cyclic axial compression", Construction and Building Materials, 235, 117786, 2020.
https://doi.org/10.1016/j.conbuildmat.2019.117786

[19] Xu, Y.Y., Huang, Q. "Cyclic performance of corroded reinforced concrete short columns strengthened using carbon fiber-reinforced polymer", Construction and Building Materials, 247, 118548, 2020.
https://doi.org/10.1016/j.conbuildmat.2020.118548

[20] Zhang, Y., Tabandeh, A., Ma, Y., Gardoni, P. "Seismic performance of precast segmental bridge columns repaired with CFRP wraps", Composite Structures, 243, 112218, 2020.
https://doi.org/10.1016/j.compstruct.2020.112218

[21] Chang, W., Hao, M., Zheng, W. "Compressive behavior of UHPC confined by both spiral stirrups and carbon fiber-reinforced polymer (CFRP)", Construction and Building Materials, 230, 117007, 2020.
https://doi.org/10.1016/j.conbuildmat.2019.117007

[22] Gurbuz, A., Tekin, M. "Farklı tip betonarme binalar için geliştirilmiş hasar tahmin yöntemleri", (Developing damage estimation methods for different types of reinforced concrete buildings), Teknik Dergi, 28(4), pp. 8051–8076, 2017. (in Turkish)
https://doi.org/10.18400/tekderg.334196

[23] Bruggi, M., Ismail, H., Lógó, J. "Topology optimization with graded infill accounting for loading uncertainty", Composite Structures, 311, 116807, 2023.
https://doi.org/10.1016/j.compstruct.2023.116807

[24] Gambarelli, S., Ožbolt, J. "MESO-Scale modeling of CFRP-confined concrete: microplane-based approach", Fibers, 8(6), 38, 2020.
https://doi.org/10.3390/fib8060038

[25] Raza, A., Shah, S. A. R., Khan, A. R., Aslam, M. A., Khan, T. A., Arshad, K., Hussan, S., Sultan, A., Shahzadi, G., Waseem, M. "Sustainable FRP-confined symmetric concrete structures: an application experimental and numerical validation process for reference data", Applied Sciences, 10(1), 333, 2020.
https://doi.org/10.3390/app10010333

[26] Slovenski Standard "TS EN 12390-3 (2019): Testing hardened concrete-Part 3: compressive strength of test specimens", Slovenian Institute for Standardization, Ljubljana, Slovenia, 2019.

[27] ANSYS "Reference manual, (v17.2)", [computer program] Available at: https://www.ansys.com [Accessed: 12 March 2020]

[28] PEER "PEER Ground Motion Database", [online] Available at: http://ngawest2.berkeley.edu/ [Accessed: 15 August 2023]

[29] Kurt, Z., Tonyali, Z. "Performance analysis of a reinforced concrete frame system according to TBEC-2018", Sciennovation a Journal of Structural Science and Innovation, 1(2), pp. 6–22, 2020. [online] Available at: https://dergipark.org.tr/en/download/article-file/1001097 [15 August 2023]

[30] Ustabaş, I., Gürbüz, A., Kurt, Z., Deşik, F. "Betonda CFRP sargı uygulamasinin deneysel ve analitik olarak krasilaştirilmaşi", (Experimental and analytical comparison of CFRP wrap application in concrete), Journal of Engineering Sciences and Design, 8(3), pp. 921–930. (in Turkish)
https://doi.org/10.21923/jesd.777814