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# Strengthening of Non-Prismatic Concrete Bridge Piers Using Carbon, Glass, and Aramid FRP Under Lateral Loading

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## Abstract

Bridges are vital lifelines, and their seismic performance is critical. Many existing Reinforced Concrete (RC) bridges, especially those with non-prismatic columns, suffer from insufficient lateral strength and ductility due to outdated design codes or environmental degradation. This study investigates the effectiveness of three types of Fiber Reinforced Polymer (FRP) — Carbon Fiber Reinforced Polymer (CFRP), Glass Fiber Reinforced Polymer (GFRP), and Aramid Fiber Reinforced Polymer (AFRP) — in strengthening non-prismatic RC bridge piers under lateral loading. Using the nonlinear finite element method in ABAQUS (pushover analysis), four models were analyzed: Unstrengthened, and strengthened with CFRP, AFRP, and GFRP. Results show that CFRP wrapping provided the highest increase in ultimate strength (67%), energy dissipation (65%), and stiffness (34%), albeit with a 21% reduction in ductility. AFRP and GFRP also showed significant improvements. The study confirms that FRP wrapping is a highly effective retrofitting technique for non-prismatic bridge piers, with CFRP being the most efficient.

**Keywords:** Non-prismatic bridge pier, Fiber reinforced polymer, Carbon fiber reinforced polymer, Glass fiber reinforced polymer, Aramid fiber reinforced polymer, Lateral loading, Seismic retrofit, Pushover analysis.

## 1 | Introduction

Over the past decades, numerous Reinforced Concrete (RC) bridges have been designed based on older seismic codes that underestimated lateral loads [1], [2]. Earthquakes such as Northridge (1994) and Kobe (1995) revealed the vulnerability of RC bridge piers, especially those with non-prismatic geometry (variable cross-section) [3], [4]. These piers often fail in a brittle manner due to insufficient transverse reinforcement and low ductility. Strengthening using Fiber Reinforced Polymer (FRP) composites has emerged as a superior alternative to traditional steel jacketing due to its high strength-to-weight ratio, corrosion resistance, ease of installation, and minimal change in cross-section [5–7]. This study aims to evaluate and compare the

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performance of non-prismatic bridge piers strengthened with three types of FRP carbon, glass, and aramid under lateral monotonic loading.

## 2 | Research Objectives

- I. To determine the increase in lateral strength, stiffness, and energy dissipation
- II. To evaluate changes in ductility and yield displacement
- III. To compare Carbon Fiber Reinforced Polymer (CFRP) [8], Aramid Fiber Reinforced Polymer (AFRP) [9], and Glass Fiber Reinforced Polymer (GFRP) [10] effectiveness

## 3 | Numerical Modeling

### 3.1 | Reference Bridge and Geometry

The study focuses on the Arora Bridge (USA), a non-prismatic RC pier with a height of 1.7 m (scaled model). The cross-section varies from larger at the base to smaller at the top, as shown in *Fig. 1*.

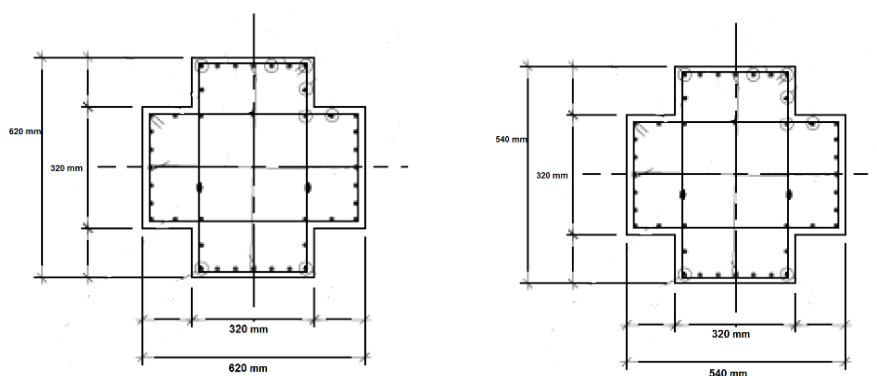


Fig. 1. Cross-section of non-prismatic pier (bottom and top).

### 3.2 | Material Properties

Concrete behavior was modeled using nonlinear stress-strain curves in compression and tension (*Figs. 2 and 3*). Steel reinforcement (longitudinal  $\text{Ø}12.7$  mm, transverse  $\text{Ø}6.7$  mm) was modeled elasto-plastically with yield strength of 400 MPa.

Table 1. Concrete material properties (stress vs. strain).

Pure Stress		Pure Strain	
Strain (m)	Stress (N/m <sup>2</sup> )	Strain (m)	Stress (N/m <sup>2</sup> )
0.00000	20972037.3	0	15000000.00
0.00082	24525632.5	0.00082	16650000.00
0.00119	26215046.6	0.0063	12300000.00
0.00274	29186085.2	0.0177	6040000.00
0.00407	31038615.2	0.022	4540000.00
0.00707	33834886.8		
0.01070	350000000		
0.01270	33834886.8		
0.01570	31504660.5		
0.01970	26028628.5		
0.02170	22183755		
0.03000	9367509.99		

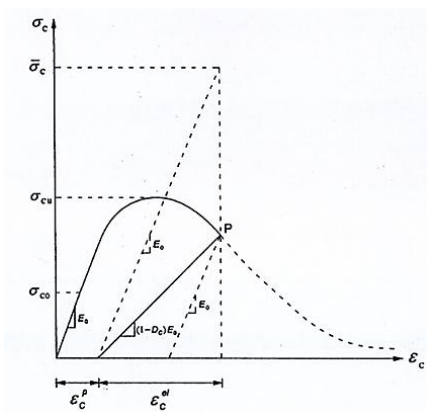


Fig. 2. Concrete behavior in compression.

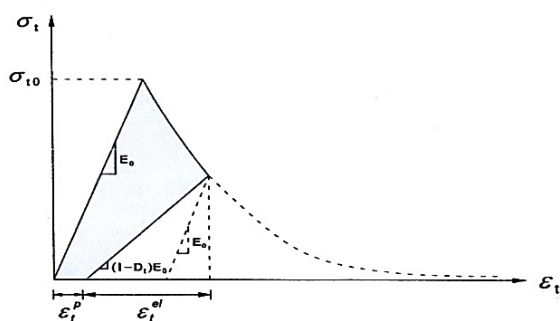


Fig. 3. Concrete behavior in tension.

FRP materials were modeled as linear elastic up to failure using surface elements (thickness 1.4 mm) [11]. The mechanical properties are shown in *Table 2* and *Fig. 4*.

Table 2. FRP material properties (elastic modulus, tensile strength).

Property	Carbon Fiber (CFRP)	Glass Fiber (GFRP)	Aramid Fiber (AFRP)
Fiber diameter (μm)	7	14	12
Density (g/cm <sup>3</sup> )	1.8	2.6	1.45
Tensile strength (MPa)	4900	2300	1650
Elastic modulus (GPa)	230	70	60
Ultimate strain (%)	1.5	2.5	2.8

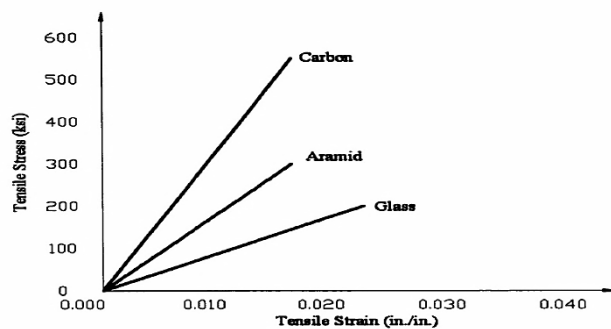


Fig. 4. Stress-strain curve for CFRP, AFRP, and GFRP.

### 3.3 | Finite Element Modeling (ABAQUS)

- I. Concrete and longitudinal steel: Solid elements (C3D8R).
- II. Transverse steel: Truss elements (T3D2).
- III. FRP wrap: Shell elements (S4R).
- IV. Perfect bond assumed between FRP and concrete.
- V. Boundary conditions: Fixed base, lateral load applied at top (displacement control).
- VI. Nonlinear pushover analysis (static, displacement-controlled).

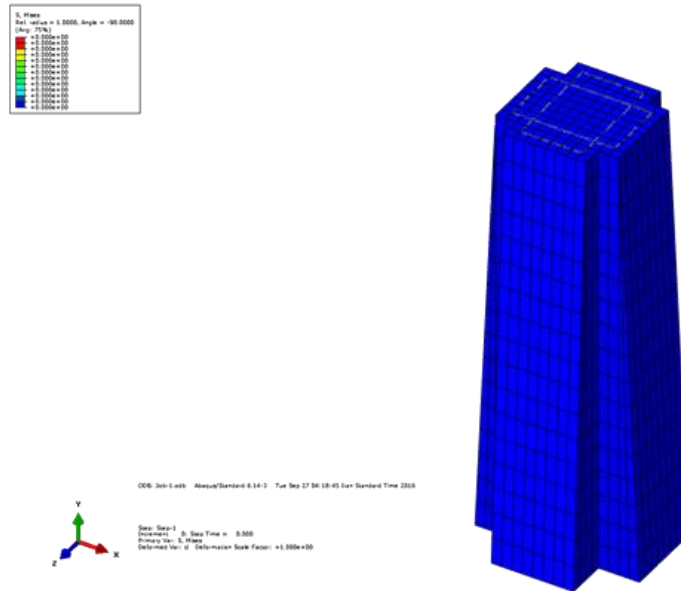
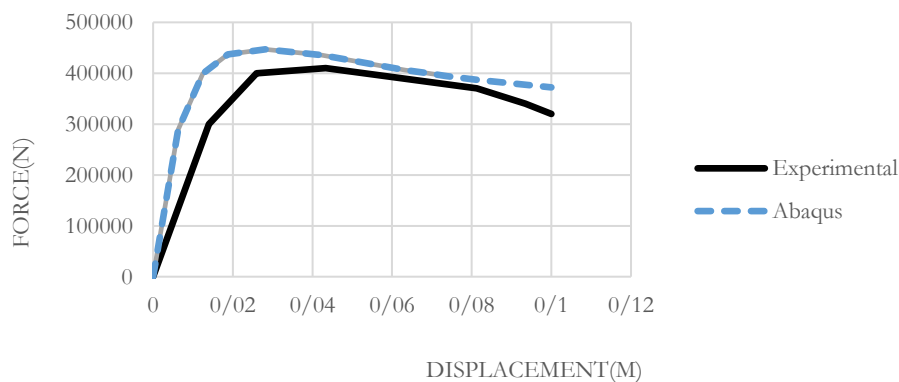


Fig. 5. 3D FE model meshing and boundary conditions.

### 3.4 | Validation

The FE model was validated against experimental data from a laboratory-scaled Arora bridge model. Good agreement was found (see *Fig. 6*).



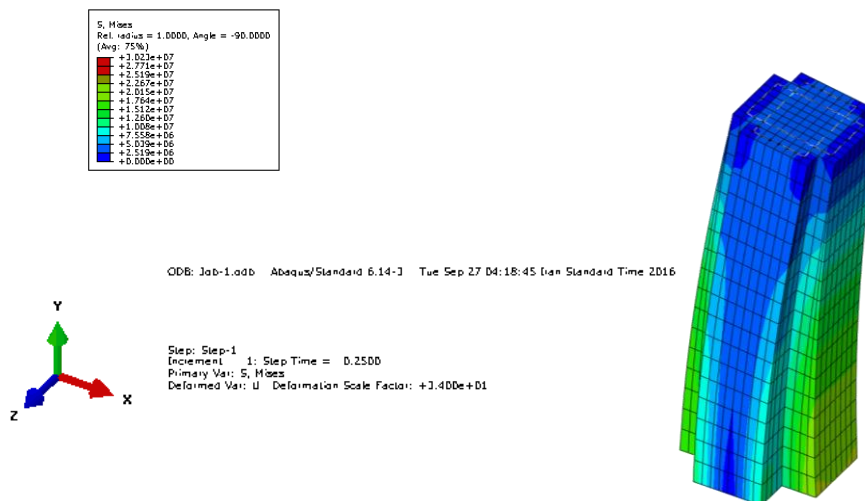


Fig. 6. Experimental vs. numerical pushover curve – validation.

## 4 | Strengthening Scenarios

Four models were analyzed:

Table 3. Analyzed models.

Model	FRP Type	Thickness
M1	None (reference)	—
M2	Carbon (CFRP)	1.4 mm
M3	Aramid (AFRP)	1.4 mm
M4	Glass (GFRP)	1.4 mm

## 5 | Results and Discussion

### 5.1 | Failure Sequence and Stresses

In the unstrengthened model (M1), cracking initiated at the pier base (plastic hinge zone) at a lateral displacement of  $\sim 0.0094$  m, followed by yielding of longitudinal steel and concrete crushing. Strengthened models showed delayed cracking and reduced tensile stress in concrete and steel due to confinement.

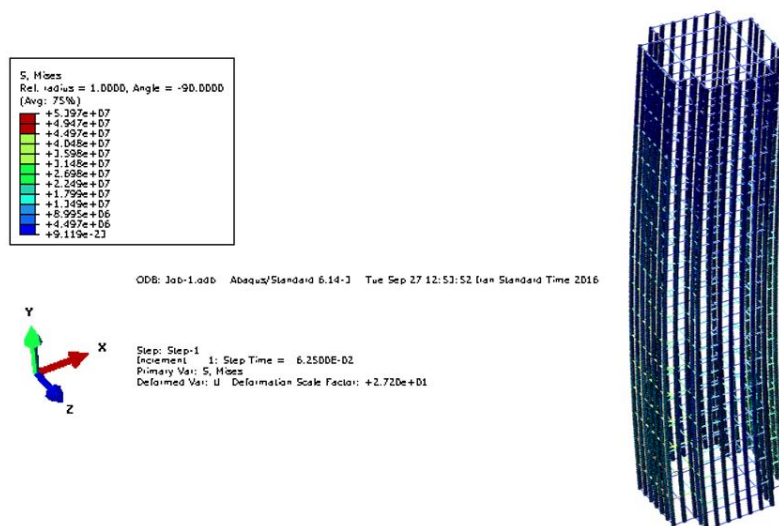


Fig. 7. Stress distribution in steel rebars – M1.

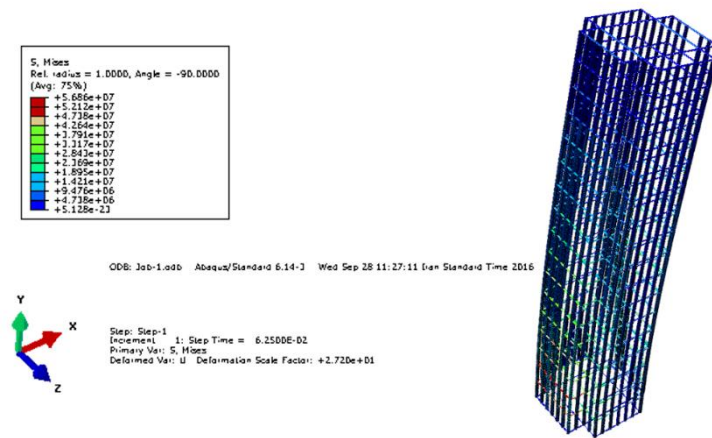


Fig. 8. Stress distribution in steel rebars – M2 (CFRP).

Table 4. Maximum stresses in concrete and steel at failure.

Model Name	FRP Type	Max Stress in Concrete (MPa)	Max Stress in FRP (MPa)	Max Stress in Steel (MPa)
Non-prismatic bridge column-1	Unstrengthened (Reference)	5.10	—	33.24
Non-prismatic bridge column-2	Carbon (CFRP)	4.14	62.31	28.76
Non-prismatic bridge column-3	Aramid (AFRP)	4.42	62.14	29.36
Non-prismatic bridge column-4	Glass (GFRP)	4.57	59.24	30.04

## 5.2 | Pushover Curves

The lateral load vs. displacement curves for all models are compared in Fig. 9.

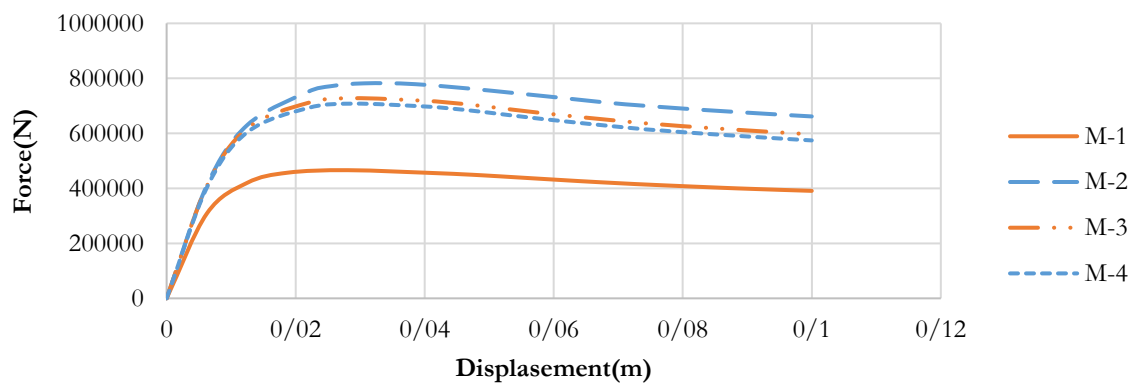


Fig. 9. Pushover curves – M1, M2, M3, M4.

CFRP (M2) shows the highest load capacity and post-yield stiffness.

### 5.3 | Stiffness

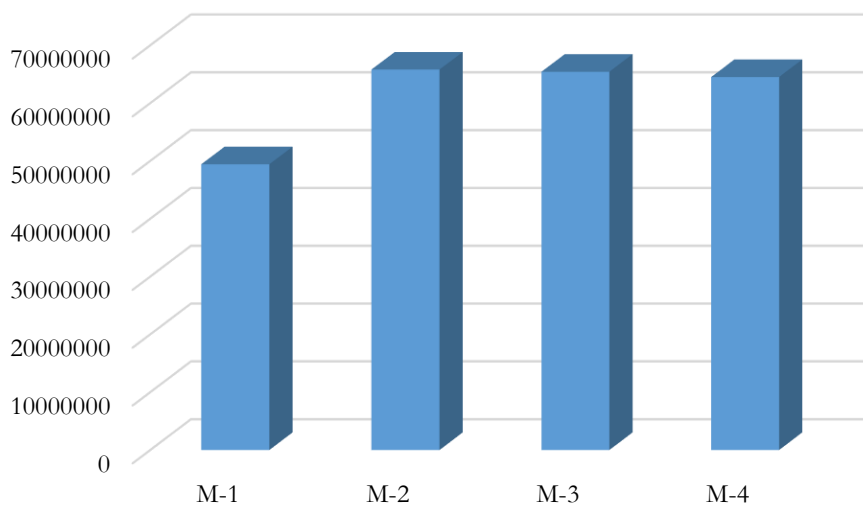


Fig. 10. Stiffness comparison (bar chart).

- I. CFRP: +34%.
- II. AFRP: +32%.
- III. GFRP: +30%.

### 5.4 | Energy Dissipation (Area under Pushover Curve)

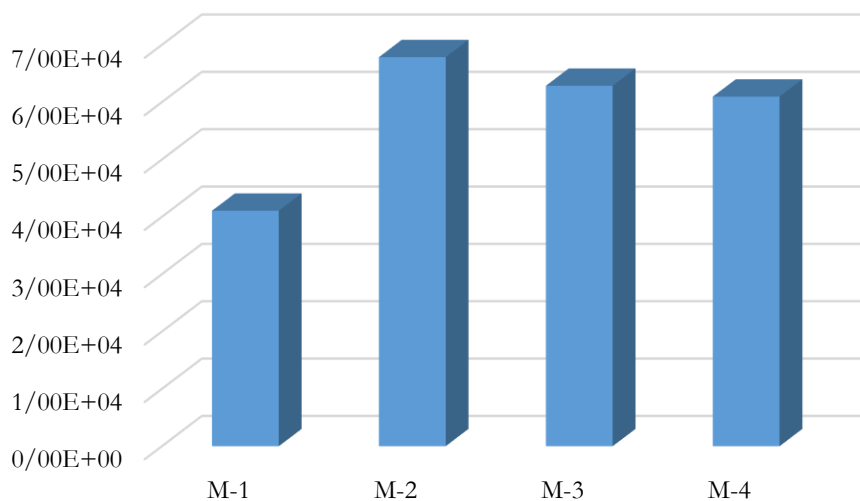


Fig. 11. Energy dissipation comparison (bar chart).

- I. CFRP: +65%.
- II. AFRP: +53%.
- III. GFRP: +48%.

## 5.5 | Ultimate Lateral Strength

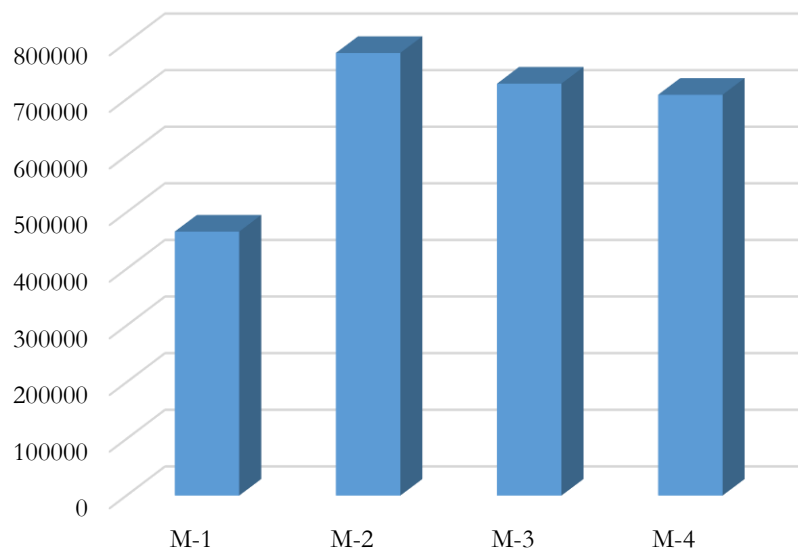


Fig. 12. Ultimate strength comparison (bar chart).

- I. CFRP: +67%.
- II. AFRP: +56%.
- III. GFRP: +51%.

## 5.6 | Ductility

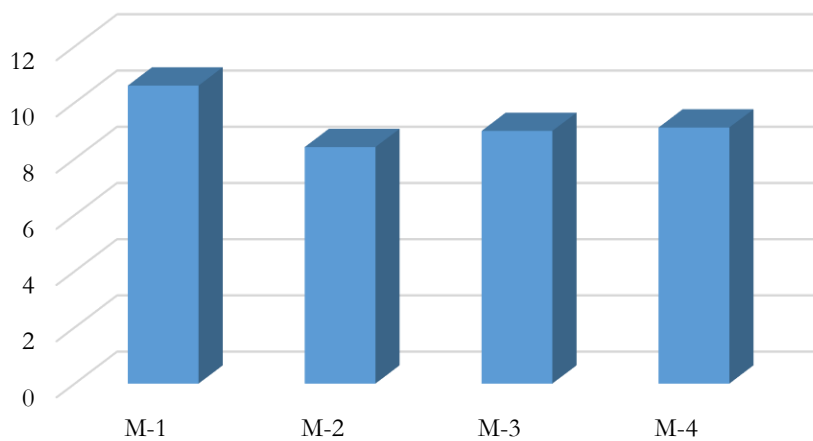
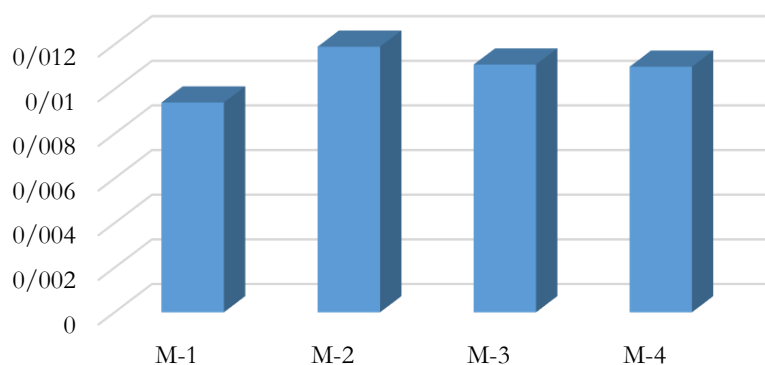


Fig. 13. Ductility comparison (bar chart).

- I. CFRP: -21%.
- II. AFRP: -15%.
- III. GFRP: -14%.

FRP wrapping increases strength but reduces ductility — a known trade-off in confinement.

## 5.7 | Yield Displacement



**Fig. 14. Yield displacement comparison (bar chart).**

- I. CFRP: -26%.
- II. AFRP: -18%.
- III. GFRP: -17%.

Strengthened models yield at smaller displacements due to earlier activation of FRP confinement.

## 6 | Discussion

All FRP types significantly improved seismic performance. CFRP consistently outperformed AFRP and GFRP in strength, stiffness, and energy absorption, due to its higher elastic modulus and tensile strength. However, the reduction in ductility must be considered in design, especially for high seismic zones. The confinement effect is more pronounced in non-prismatic piers because of the varying cross-section, which creates stress concentration at the smaller top section — effectively mitigated by FRP wrapping.

## 7 | Conclusion

Based on the numerical study, the following conclusions are drawn:

- I. CFRP wrapping increases ultimate lateral strength by 67%, energy dissipation by 65%, and stiffness by 34%.
- II. AFRP and GFRP also provide substantial improvements but to a lesser degree.
- III. Ductility decreases by 21% for CFRP, 15% for AFRP, and 14% for GFRP — an acceptable trade-off for strength gain.
- IV. FRP strengthening is highly effective for non-prismatic RC bridge piers under lateral loading.
- V. CFRP is recommended for maximum performance; GFRP is a cost-effective alternative.

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## Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data Availability

All data generated or analyzed during this study are included in this published article. Additional data supporting the findings of this study are available from the corresponding author upon reasonable request.

## Authors' Contributions

R.R.: Conceptualization, Methodology, Software, Formal Analysis, Investigation, Data Curation, Visualization, Writing—Original Draft Preparation.

R.M.: Validation, Supervision, Writing—Review and Editing, Technical Guidance, Project Administration.

All authors have read and agreed to the published version of the manuscript.

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## Consent for Publication

All authors have read and approved the final version of the manuscript and consent to its publication.

## Ethics Approval and Consent to Participate

This study did not involve human participants or animals. Therefore, ethics approval and informed consent to participate were not required.

## References

- [1] Zhao, R., Zheng, K., Wei, X., Jia, H., Li, X., Zhang, Q., ... & Yu, C. (2022). State-of-the-art and annual progress of bridge engineering in 2021. *Advances in bridge engineering*, 3(1), 29. <https://doi.org/10.1186/s43251-022-00070-1>
- [2] Ahmad, M. W., Rizwan, M., & Tahir, M. F. (2025). Retrofitting of seismically deficient RC bridge pier using HSP concrete jacket and FRP rebars. *Engineering science and technology, an international journal*, 70, 102146. <https://doi.org/10.1016/j.jestch.2025.102146>
- [3] Afsar Dizaj, E., Salami, M. R., & Kashani, M. M. (2022). Nonlinear dynamic behaviour and seismic fragility analysis of irregular multi-span RC bridges. *Structures*, 44, 1730–1750. <https://doi.org/10.1016/j.istruc.2022.08.112>
- [4] Miano, A., Iacovazzo, P., Mele, A., Di Ludovico, M., & Prota, A. (2024). Seismic fragility of circular piers in simply supported RC bridges: A proposal for capacity assessment. *Engineering structures*, 302, 117426. <https://doi.org/10.1016/j.engstruct.2023.117426>
- [5] Hu, W., Li, Y., & Yuan, H. (2020). Review of experimental studies on application of FRP for strengthening of bridge structures. *Advances in materials science and engineering*, 2020(1), 8682163. <https://doi.org/10.1155/2020/8682163>
- [6] Wang, Q., Zhu, H., Zhang, B., Tong, Y., Teng, F., & Su, W. (2020). Anchorage systems for reinforced concrete structures strengthened with fiber-reinforced polymer composites: State-of-the-art review. *Journal of reinforced plastics and composites*, 39(9–10), 327–344. <https://doi.org/10.1177/0731684420905010>
- [7] Megahed, F. A., Seleem, M. H., Badawy, A. A. M., & Sharaky, I. A. (2023). The flexural response of RC beams strengthened by EB/NSM techniques using FRP and metal materials: A state-of-the-art review. *Innovative infrastructure solutions*, 8(11), 289. <https://doi.org/10.1007/s41062-023-01245-z>
- [8] Jahami, A., & Issa, C. A. (2024). An updated review on the effect of CFRP on flexural performance of reinforced concrete beams. *International journal of concrete structures and materials*, 18(1), 14. <https://doi.org/10.1186/s40069-023-00651-y>
- [9] To, Q. B., Lee, K., Cuong, N. H., & Shin, J. (2024). Development of machine learning based seismic retrofit scheme for AFRP retrofitted RC column. *Structures*, 69, 107279. <https://doi.org/10.1016/j.istruc.2024.107279>
- [10] Ye, H., Zhou, H., Peng, H., Ye, J., & Bu, Z. (2025). Experimental study on improving the strength and ductility of prefabricated concrete bridge piers using GFRP tube confinement. *Buildings*, 15(17), 1–32. <https://doi.org/10.3390/buildings15172981>
- [11] Hammad, M., Bahrami, A., Khokhar, S. A., & Khushnood, R. A. (2024). A state-of-the-art review on structural strengthening techniques with FRPs: Effectiveness, shortcomings, and future research directions. *Materials*, 17(6), 1–38. <https://doi.org/10.3390/ma17061408>