Paper ID: 1195

Seismic Performance of Deficient RC Joints Retrofitted by CFRP for Enhancing Earthquake Resilience in Disaster-Prone Structures

S. M. Zahurul Islam*[1] , Mahdy Hassan Siddiki*[2], Mostakim Hossan[3], Eftakharul Islam[4]

[1]Department of Civil Engineering, RUET, Bangladesh (zahurul90@gmail.com)
[2]Department of Civil Engineering, RUET, Bangladesh (mahdihasansiddiki@gmail.com)
[3]Department of Civil Engineering, RUET, Bangladesh (mostakimh12@gmail.com)
[4]Department of Civil Engineering, RUET, Bangladesh (1900168@student.ruet.ac.bd)

Abstract

The structural engineering domain has exhibited growing interest in retrofitting techniques aimed at improving the seismic resilience and overall performance of existing reinforced concrete (RC) structures in recent years. A particular focus has been placed on beam-column joints, which are recognized as critical components in RC frames due to their exposure to substantial shear, moment, and torsional forces, especially under lateral loads such as those generated during seismic(earthquake) or wind events. Prior to the 1970s, a significant number of RC frame structures were constructed without proper design code requirements for transverse reinforcement within joint regions. This study investigates the seismic performance of reinforced concrete (RC) beam-column T-joints retrofitted with Carbon Fiber Reinforced Polymer (CFRP) under lateral loading. Seven T-joint specimens were tested experimentally with CFRP sheets applied in different orientations (0°, 45°, and 90°) on both the web and flange of the joint. Lateral loading was applied to evaluate load capacity with different CFRP orientation. It has been observed that for a defective T-joint, the load-bearing capacity increases by approximately 78.72% for a 90-degree CFRP orientation and 73.93% for a 45-degree CFRP orientation. This enhancement is attributed to the application of CFRP reinforcement to both the web and flange of the joint, with CFRP serving as the reinforcing material for the reinforced concrete (RC) structure.

Keywords: *Beam–column joints; Seismic retrofitting; CFRP strengthening; lateral loading; Earthquake*

1 Introduction

In recent years, structural engineering has placed increasing emphasis on retrofitting methods that enhance the seismic safety and overall performance of existing reinforced concrete (RC) structures. Among the most critical elements of RC frames are the beam-column joints, as they are subjected to high shear, moment, and torsional forces, particularly during earthquakes and strong wind events. Many RC frame buildings constructed before the 1970s did not follow modern design codes, especially regarding transverse reinforcement within the joint regions. As a result, these joints often display poor performance under lateral loads. Evidence from past earthquakes has shown that such deficiencies can cause reduced joint shear capacity and premature failures, such as buckling of column reinforcement, instead of the desired ductile plastic hinge formation in beams. Compounding this issue, the widely adopted “strong beam/weak column” design approach of the 1960s and early 1970s further increased the vulnerability of these structures. To address these shortcomings, specific design guidelines for RC beam-column joints were later developed to improve safety and reliability under seismic loading. FRP retrofitting of short RC columns significantly improves seismic performance by enhancing shear strength and energy dissipation while preventing concrete spalling and reinforcing bar corrosion (Attari et al., 2019). These studies demonstrated that CFRP composites, particularly when applied in configurations like X-shaped wraps, significantly enhance the lateral strength and seismic resilience of joints by reducing the likelihood of brittle shear failure (Le-Trung et al., 2010). As retrofitting advanced, hybrid FRP systems combining carbon and glass fibers emerged, effectively improving shear capacity and energy dissipation, particularly in pre-1970s buildings with deficient shear reinforcement. (Attari et al., 2019; Karayannis and Golias, 2022). Recent studies have shown that retrofitting corroded RC columns with Large Rupture Strain (LRS) FRP composites significantly improves ductility and seismic performance by providing better confinement and preventing premature failure under high axial loads (Bahraq et al., 2021; Todut et al., 2015). Full-scale tests show FRP retrofitting with CFRP, GFRP, or hybrid

systems effectively strengthen RC beam-column joints, improving strength, lateral resistance, and ductility. (Allam et al., 2019). UHPFRC jacketing improves RC beam-column joint seismic performance by shifting brittle shear failures to ductile behavior due to its high strength and ductility (Bahraq et al., 2021). Models predict the seismic behavior of FRP-strengthened beam-column joints, evaluating configurations and aiding effective, cost-efficient retrofit design. (Allam et al., 2019; Bahraq et al., 2021). Beam-column joints, critical in RC structures, are often under-designed for lateral seismic forces, making FRP retrofitting essential to enhance their earthquake performance. (Adil et al., 2024). FRP composites, especially CFRP and GFRP, are widely used to strengthen RC beam-column joints, significantly improving shear strength and ductility due to their high strength-to-weight ratio and corrosion resistance (Beydokhty & Shariatmadar, 2016; Golias et al., 2022). In an innovative approach, flange-bonded CFRP sheets were used to relocate plastic hinges away from the critical joint area, improving the joint's capacity and ensuring a safer distribution of plastic deformations during seismic events (De Vita et al., 2017). Combining UHPFRC and CFRP composites has been shown to enhance strength, ductility, and energy dissipation in RC joints, effectively addressing confinement and debonding issues in seismic retrofitting (Fayaz et al., 2022). Seismic retrofitting of RC beam-column joints is essential, and CFRP wraps are favored over traditional methods for improving shear strength, ductility, and energy dissipation due to their high strength-to-weight ratio, corrosion resistance, and ease of application (Palanisamy & Kumarasamy, 2023).Recent research indicates that applying CFRP in full wraps, U-shaped wraps, or hybrid systems, and varying ply layers, significantly enhances joint confinement, mitigates debonding, and increases the load-bearing capacity of beam-column joints (Sayed Ahmed et al., 2025). While CFRP materials are commonly used for retrofitting, there has been limited research on how they perform in strengthening RC T-beam column joints under lateral loading, especially regarding how different CFRP orientations affect crack patterns and overall structural behavior. Studying the retrofitting of these joints with various CFRP orientations under lateral loads is therefore highly relevant.

2 Material Properties

Concrete, widely used in building construction, is made by mixing cement, sand, coarse aggregates, and water to create strong and durable structures like beams, columns, slabs, and foundations. Four materials have been used to prepare the tested specimens. These are mild steel (MS), CFRP wrap, adhesive and primer as shown in Figure 1. M20 concrete, a common grade, reaches a compressive strength of 20 MPa after 28 days and is typically mixed in a 1:1.5:3 ratio of cement, sand, and aggregate. Mild steel, a low-carbon steel with 0.15–0.30% carbon, is commonly used as reinforcement in concrete due to its ductility, weldability, and ease of fabrication. It has a yield strength of 250 MPa, ultimate tensile strength of 400–550 MPa, elongation of 20–25%, and a density of 7850 kg/m³, providing reliable tensile resistance in structural elements. In this research, carbon CFRP fabrics are used having a high tensile strength of 1500–2500 MPa, a modulus of elasticity of 120–150 GPa, ultimate tensile strain of 0.01–0.02, density between 1.4–1.8 g/cm³, shear strength of 70–100 MPa, and a Poisson's ratio of 0.25–0.35. It also exhibits good thermal conductivity (5–15 W/m·K), high fire resistance, and excellent chemical corrosion resistance. The material of adhesive is a clear to light yellow liquid with a density of 1.1 ± 0.05 g/cm³ and a viscosity of 500 ± 100 cP at 25°C. It has a tensile strength of 45 MPa, compressive strength of 85 MPa, and bond strength of 15 MPa. The recommended mix ratio of base to hardener is 2:1, with an initial cure time of 6–7 hours at 25°C and a pot life of 30–45 minutes. It can be applied at temperatures between 10°C and 35°C and remains stable in-service conditions ranging from -40°C to +80°C. The primer is a two-component epoxy resin with a mix ratio of 2:1 (base to hardener) and a pot life of 30–45 minutes at 25°C. It has a density of approximately 1.45 kg/L, a compressive strength of about 63 MPa, and a tensile adhesion strength of around 2 MPa on concrete. The primer requires an initial cure of 6–7 hours at 25°C, can be applied at temperatures between 10°C and 35°C, and performs well in service conditions ranging from -40°C to +80°C, providing a clean, uniform surface for better bonding of adhesives or CFRP layers.



Figure 1. MS Bar, CFRP and adhesive.

3 Experimental Program

This study focuses on an experimental investigation of reinforced concrete (RC) beam-column T-joints strengthened with carbon fiber reinforced polymer (CFRP) sheets. A total of seven specimens were prepared, including retrofitted joints with CFRP applied at different fiber orientations (0°, 45°, and 90°) as well as control specimens without CFRP for comparison. All specimens were cast and cured under identical conditions to maintain uniformity. The test setup was designed to replicate lateral force demands on the joint region. For this purpose, a monotonic lateral load was applied directly at the column part of the T-joint using a linear actuator. The beam was restrained to provide boundary conditions similar to in-situ structural behavior, while the column part was gradually pushed laterally until significant damage and failure were observed. This loading arrangement allowed assessment of the effectiveness of different CFRP configurations in enhancing the load-carrying capacity and deformation characteristics of RC beam-column joints under lateral loading. Dimensions, smoothing, deficient and CFRP strengthen test RC T joint is shown in Figure 2-3. Table 1 presents the configurations of CFRP orientations used in the experimental program. Figure 4 shows the experimental setup where an actuator applies lateral load to the column of the RC beam-column T-joint, instrumented with a load cell and LVDT.

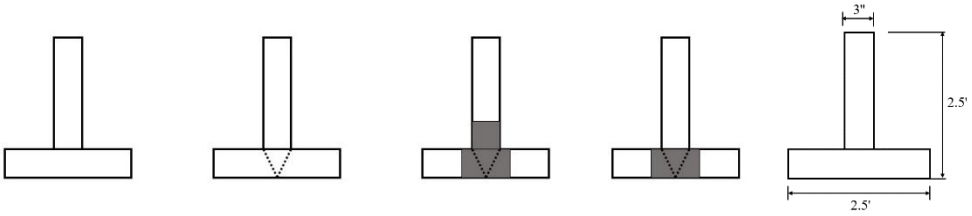


Figure 2. Details dimension of without and with CFRP of R.C T joint specimen.



Figure 3. Dimension of reinforcement details, smoothing and pre-cracking of R.C T joint specimen.

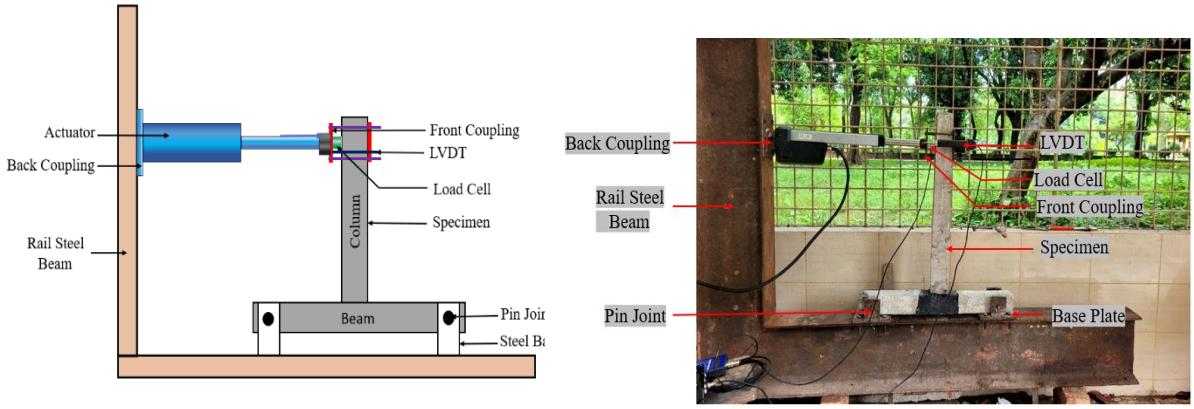


Figure 4. Test setup arrangement by electric actuator for push direction.

The specimens TCoFo, TCF0WF, TCF0F, TCF45WF, TCF45F, TCF90WF, and TCF90F represent tested R.C T joint specimen where C denotes deficiency introduced by cutting at the T-joint, Co indicates no cutting, F indicates CFRP applied at the flange only, W at the web only, and WF at both web and flange portion. The numbers 0, 45, and 90 specify the CFRP orientation in degrees.

Table 1. Labeling of specimens

Sample ID	Description
TCoFo	No CFRP (Control) and cut.
TCF0WF	CFRP applied at 0° orientation at both web and flange
TCF0F	CFRP applied at 0° orientation at flange only
TCF45WF	CFRP applied at 45° orientation at web and flange
TCF45F	CFRP applied at 45° orientation at flange only
TCF90WF	CFRP applied at 90° orientation at both web and flange
TCF90F	CFRP applied at 90° orientation at flange only

Figure 5 indicates the wrapping of CFRP at RC T joints at selected area.



Figure 5. Wrapping CFRP on the selected area of the joint.

4 Results and Discussions

Figures 6 to 8 present the load–displacement behavior and failure patterns of reinforced concrete T-joint specimens subjected to lateral loading. The control specimen, TCoFo, which had no CFRP strengthening, failed at an ultimate load of 47 kN. This confirmed its limited ability to resist lateral forces.

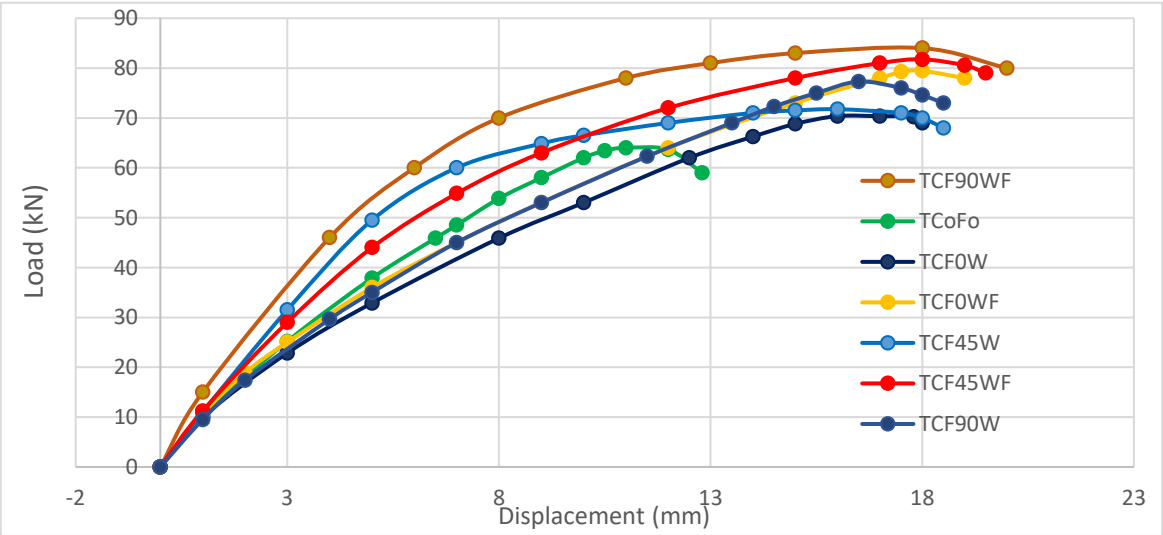


Figure 6. Comparison of load-displacement behavior for reference and CFRP strengthening deficient RC T joint.

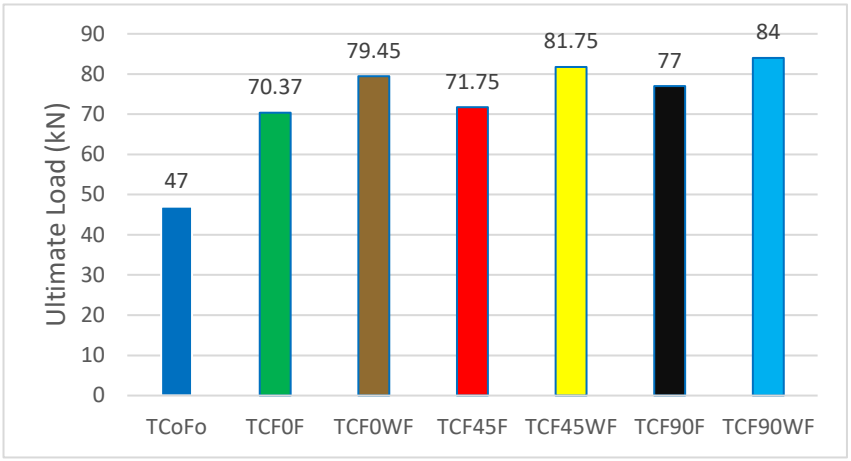


Figure 7. Enhanced load carrying capacity of deficient RC T joint strengthening by CFRP.



Figure 8. Failure mode of CFRP strengthening RC T joint specimens.

All CFRP-strengthened specimens showed substantial improvement in load-carrying capacity, with performance varying based on both the location and orientation of the CFRP application. Specimens strengthened on both the web and flange consistently outperformed those strengthened only at the flange. The TCF0WF, TCF45WF, and TCF90WF specimens achieved ultimate loads of 79.45 kN, 81.75 kN, and 84 kN respectively. These values represent increases of 69.1%, 73.9%, and 78.7% over the control. In contrast, flange-only strengthening showed more moderate gains. The TCF0F specimen reached 70.37 kN, TCF45F reached 71.75 kN, and TCF90F reached 77 kN, corresponding to improvements of 49.7%, 52.7%, and 63.8%. CFRP orientation had a strong influence on performance. The 90° orientation provided the best confinement and load resistance, especially when applied to both web and flange. The 45° orientation also contributed to increased strength and improved ductility, while the 0° layout showed a noticeable but comparatively lower level of enhancement. In addition to improving strength, CFRP retrofitting altered the failure mechanism. The strengthened joint exhibited major cracking at the beam–column joint, leading to brittle shear failure. However, in CFRP-strengthened specimens, the cracking shifted toward the adjoining column. This shift indicates that CFRP confinement effectively strengthened the joint core, delayed crack formation, and redistributed stresses more favorably. As a result, failure became more ductile, which is highly beneficial for structures exposed to seismic forces. Overall, the results demonstrate that CFRP retrofitting is an effective method to improve the lateral load capacity and ductility of RC T-joints. The best performance was achieved by applying CFRP to both the web and flange in a 90° orientation.

5 Conclusion

CFRP strengthening significantly improves the lateral load capacity and failure behavior of reinforced concrete T-joints. The control specimen failed at 47 kN, showing limited resistance. Specimens strengthened with CFRP showed notable load capacity gains, especially when CFRP was applied to both the web and flange, achieving up to 79% higher loads. The 90° CFRP orientation provided the best performance, followed by 45°, while 0° showed moderate improvement. CFRP also shifted cracking from the joint core to the adjoining column, delaying brittle failure and promoting ductility, which is important for seismic safety. Overall, applying CFRP to both web and flange at 90° orientation is the most effective way to enhance strength, ductility, and seismic resilience of RC T-joints.

Acknowledgement

The authors gratefully have acknowledged the financial support of the University Grants Commission of Bangladesh under the Project No.: DRE/08/RUET/764(52)/Pro/2025-2026/01.

References

Adil, W., Rahman, F. U., Ali, Q., & Papakonstantinou, C. G. (2024). An Improved Anchorage System for L-Shaped FRP Composites to Enhance the Seismic Response of Beam-Column Joints in a Low-Strength Substandard Reinforced Concrete (RC) Frame. *Buildings*, *14*(3). https://doi.org/10.3390/buildings14030721

Allam, K., Mosallam, A. S., & Salama, M. A. (2019). Experimental evaluation of seismic performance of interior RC beam-column joints strengthened with FRP composites. *Engineering Structures*, *196*. https://doi.org/10.1016/j.engstruct.2019.109308

Attari, N., Youcef, Y. S., & Amziane, S. (2019). Seismic performance of reinforced concrete beam–column joint strengthening by frp sheets. *Structures*, *20*, 353–364. https://doi.org/10.1016/j.istruc.2019.04.007

Bahraq, A. A., Al-Osta, M. A., Khan, M. I., & Ahmad, S. (2021). Numerical and analytical modeling of seismic behavior of beam-column joints retrofitted with ultra-high performance fiber reinforced concrete. *Structures*, *32*, 1986–2003. https://doi.org/10.1016/j.istruc.2021.04.004

Beydokhty, E. Z., & Shariatmadar, H. (2016). Behavior of damaged exterior RC beam-column joints strengthened by CFRP composites. *Latin American Journal of Solids and Structures*, *13*(5), 880–896. https://doi.org/10.1590/1679-78252258

De Vita, A., Napoli, A., & Realfonzo, R. (2017). Full scale reinforced concrete beam-column joints strengthened with steel reinforced polymer systems. *Frontiers in Materials*, *4*. https://doi.org/10.3389/fmats.2017.00018

Fayaz, Q., Kaur, G., & Bansal, P. P. (2022). Numerical Modelling of an Exterior RC Beam Column Joint Subjected to Cyclic Loading Strengthened Using UHPFRC and CFRP. *ASPS Conference Proceedings*, *1*(1), 891–900. https://doi.org/10.38208/acp.v1.599

Le-Trung, K., Lee, K., Lee, J., Lee, D. H., & Woo, S. (2010). Experimental study of RC beam-column joints strengthened using CFRP composites. *Composites Part B: Engineering*, *41*(1), 76–85. https://doi.org/10.1016/j.compositesb.2009.06.005

Palanisamy, G., & Kumarasamy, V. (2023). Rehabilitation of damaged RC exterior beam-column joint using various configurations of CFRP laminates subjected to cyclic excitations. *Revista Materia*, *28*(2). https://doi.org/10.1590/1517-7076-RMAT-2023-0110

Sayed Ahmed, M. M., El-Zoughiby, M. E., & Abdelwahed, B. S. (2025). Numerical investigation of retrofitting techniques for substandard exterior reinforced concrete beam–column joints. *Innovative Infrastructure Solutions*, *10*(6). https://doi.org/10.1007/s41062-025-02017-7