Examining Retrofit Techniques for Concrete Beam-Column Joints

Bhosale Dinish Dilip[1], Dr. Ajay Swarup[2]

Research Scholar, Department of Civil Engg., Sri Satya Sai University of Technology and Medical Sciences, Sehore, Madhya Pradesh.

Research Guide, Department of Civil Engg., Sri Satya Sai University of Technology and Medical Sciences, Sehore, Madhya Pradesh

Article Info
Page Number: 366 - 374
Publication Issue:
Vol 72 No. 2 (2023)

Article History:
Article Received: 15 July 2023
Revised: 24 September 2023
Accepted: 18 October 2023

Abstract

This study looks into reinforced concrete (RC) interior beam-column joints by testing four full-size samples with cyclic lateral loading in one direction. The specimens, mimicking real-scale joints in a four-story RC frame structure, include a control (C-SW), one retrofitted with Carbon Fiber Reinforced Polymer (CFRP) (C1-RT-B SW), one repaired with steel plates (C1-RP-Steel SW), and one retrofitted with steel plates (C1-RT-Steel SW). Analysis shows seismic flaws common in buildings built before the 1970s, such as columns not being able to bend as much as beams, not having enough shear strength because the core joint doesn't have any transverse reinforcement, and transverse reinforcements not being spaced out enough. The study aims to assess and develop retrofit solutions for realistic interior beam-column joints, focusing on improving seismic performance. Results indicate that retrofitting with steel plates significantly enhances energy dissipation and ductility, while CFRP retrofitting exhibits lower dissipation due to its linear properties.

Keywords: Reinforced concrete, beam-column joints, seismic retrofitting, cyclic loading, carbon fiber reinforced polymer (CFRP), steel plates,

---

Introduction

Before in-depth research on retrofitting and special design features for seismic stability, seismic design considerations were minimal. Retrofitting involves various measures to strengthen structural elements based on their lack of strength parameters. For instance, shear walls are now commonly incorporated at ground floors to resist lateral shear or base shear forces.[1] Retrofitting measures can include injecting grouts into cracks, improving bonding of roof-wall connections, and upgrading the strength of foundations.

Additionally, retrofitting may involve replacing existing elements or adding new elements made of the same material or composite materials. Factors such as seismic detailing, materials used, structural failure patterns, and the system of load-resisting elements need to be considered when deciding on retrofitting methodology.[2] The objective of retrofitting is to enhance the lateral strength of the structure, sometimes by adding extra elements or altering the properties of existing materials. However, modifying concrete properties after setting is challenging, so casting concrete with precision is crucial.[3]

The need for retrofitting can arise due to revisions in building codes over time or if a structure sustains damage from an earthquake. Retrofitting strategies may include following the principle of "strong column, weak beam," particularly in reinforced concrete structures where beam-column joints play a critical role in load transfer and resistance.[4]

Beam-column joints are susceptible to damage during seismic events, so retrofitting these joints is vital. This often involves incorporating corner rebars and ensuring the joints have sufficient load-resisting capacity.[5] When subjected to loads, beam-column joints experience moments and rotations, and their rigidity is crucial in structural analysis and design.

Unhealthy design and poor detailing of joints in structures have led to disastrous failures in the past. Extensive investigations in previous decades have focused on understanding the seismic response of these joints.[6] These investigations led to the upgrading of building codes to reflect the observed changes. Structures designed and constructed according to earlier versions of codes were often highly susceptible to damage during seismic activity. However, modifications to their structural composition and arrangement have improved their seismic behaviour.[7]

Observations regarding the superior performance of retrofitted buildings under seismic loads have increased the confidence of construction engineers and builders. Instead of demolishing and rebuilding seismically inferior buildings and structures, there is now a growing trend towards retrofitting and modification.[8]

When designing beam-column junctions to resist earthquake loads, it is critical to limit the joint's strength degradation until the beam reaches its full yield capacity as per design. Numerous studies conducted in the last few decades have focused on the seismic and non-seismic performance of beam-column joints, particularly regarding the mechanism for handling shear and moment, as well as the joint strength.[9-11]

Designing beam-column joints is considered to be a complex and demanding task for structural engineers. Efficient design of reinforced concrete (R.C.C.) seismic moment-resisting frames is critical for the safety of the structure. The size of the joint depends entirely on the size of the members of the frame. In addition to the loads considered during the initial design phase, we expect joints to handle complex combinations of loads. Therefore, the design and detailing of joints subjected to seismic forces should receive special considerations.

Material and Methods

Beam-column joint specimens detailing

In a study on reinforced concrete (RC) interior beam-column joints, four full-scale specimens were tested under uniaxial cyclic lateral loading. These specimens included a control (C-SW), one retrofitted with Carbon Fiber Reinforced Polymer (CFRP) (C1-RT-B SW), one repaired with steel plates (C1-RP-Steel SW), and one retrofitted with steel plates (C1-RT-Steel SW). Mimicking real-scale joints in a four-storey RC frame structure, each column represented a half-storey 1.50m column, each beam a 2.00m half-span beam, and the slab measured 1.95m wide with a depth of 150mm.

Analysis revealed seismic deficiencies typical of pre-1970s designs, including lower flexural capacity of columns compared to beams, insufficient shear capacity due to the absence of transverse reinforcement in the core joint, and inadequate spacing of transverse reinforcement. The selective weakening technique was adopted to reduce the stiffness provided by the slab, involving cuts parallel to the longitudinal and transversal beams. This study aims to assess and develop retrofit solutions for realistic interior beam-column joints, focusing on improving seismic performance.

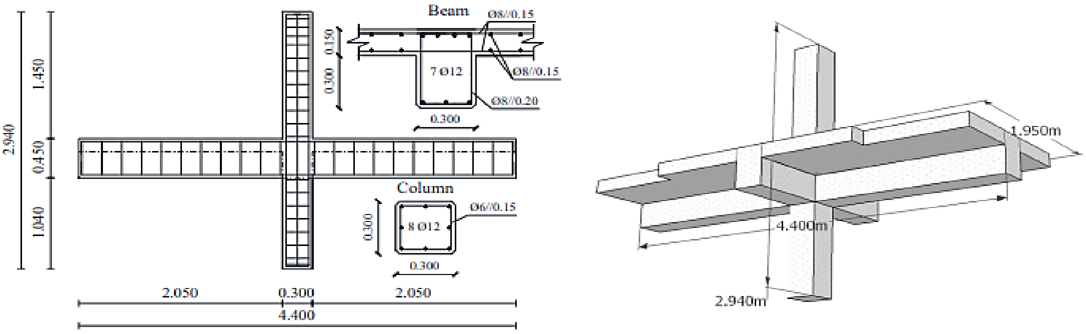

Figure 1. Specimen Configurations: Dimensions, Geometry, and Reinforcement Specifications

Concrete cylinder samples with dimensions of Ø150mmx300mm were casted on different days using the same formwork, positioned vertically. The purpose was to determine the properties of the concrete in each specimen.

Compressive tests were conducted on the concrete cylinder samples to evaluate their strength. Additionally, tensile strength tests were performed on both steel and Fiber Reinforced Polymer (FRP) S&P C-240 sheets to characterize the materials used in each specimen.

For the FRP tensile strength tests, the method outlined in ISO/DIS 10406-2:2013 was followed. This allowed for a standardized evaluation of the tensile strength of the FRP material used in the specimens.

Test setup and Loading History

The loading setup for the specimens is depicted in Figure 2. The specimens are tested horizontally, and six high-load carrying capacity and reduced friction rollers are positioned beneath the specimen to support its weight. The tests are conducted under displacement-controlled conditions.

Lateral displacements (dc) are induced by a hydraulic servo-actuator situated at the top of the upper column, 1.5m away from the center of the joint core. A constant axial load (N1) of 425 kN is applied to both the top and bottom of the columns. Additionally, an extra axial load

(N2) of 25 kN is applied at the bottom to create moments in the beams, simulating moments from gravity loading.

The cyclic lateral displacement history consists of three cycles for each of the following peak drift values (± %): 0.1, 0.2, 0.3, and then 0.5 to 6.0 with 0.5 increments. This same displacement history is used for all specimens.

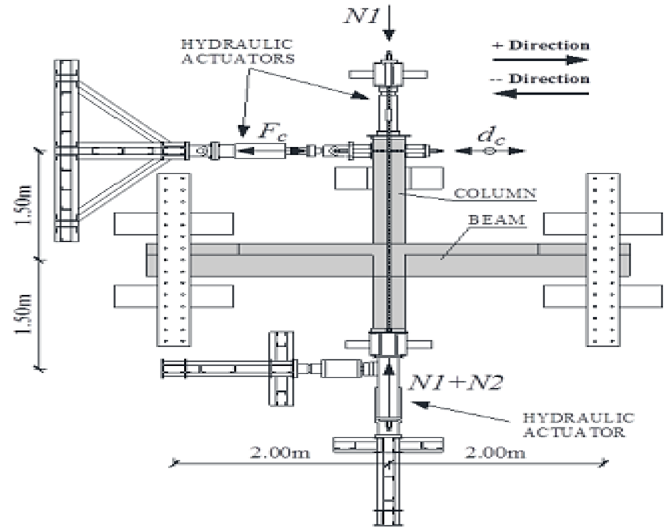

Figure 2. Test setup

Enhancing Structural Performance: Retrofit Schemes using CFRP and Steel Plates

The objective of the proposed retrofit scheme is to provide a comprehensive and practical solution to enhance the flexural capacity of beams without increasing their stiffness. This scheme ensures that plastic hinges form in the beam away from the joint, thereby improving the overall structural performance. Additionally, it aims to ensure that the flexural strength of the column is higher than that of the beams and to strengthen the joint by accommodating higher joint shear stresses.

Furthermore, a selective weakening technique is employed in the slab to weaken it close to the core joint. This weakening helps increase the rotation capacity of the beams, thereby improving the overall structural behavior.

The retrofit scheme, developed and implemented on specimen C1-RT-B SW, is detailed in Figure 3. This scheme offers a practical solution to enhance the structural performance of beams and joints, ensuring improved overall resilience and strength of the structure.

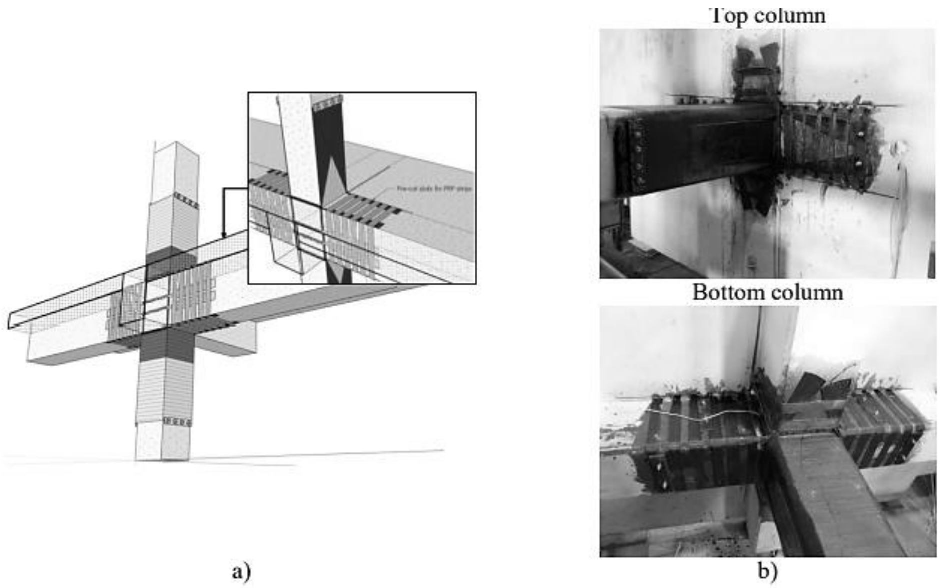

Figure 3. CFRP retrofit scheme: a) generic scheme; b) global view

Optimizing Structural Performance

The steel plates retrofit scheme is devised to bolster the strength and rigidity of the columns, ensuring that the beam becomes the weaker element. This strategy aims to prevent a weak-column strong-beam mechanism. Additionally, the retrofit enhances the ductility of the beam-column joint by applying suitable concrete confinement to the columns using external steel stirrups.

To achieve this, the retrofit solution focuses on boosting the flexural capacity of the columns along a 750mm length from the joint. This involves the use of three ø20mm steel rods per column corner to connect the steel devices through the slab. Furthermore, four ø10mm mechanical anchors are positioned on the last two external steel stirrups per column face. Epoxy resin is utilized to fill the gap between the steel profiles and the concrete, ensuring a secure connection.

By employing this retrofit solution, the moment capacity and moment demands predictions on the retrofitted specimen indicate that the weak element becomes the bottom face of the beam. This strategic approach effectively enhances the overall structural integrity and performance of the system.

The steel device is constructed using 40x40x3 steel L-profiles at the corners, each with a length of 750mm. Additionally, six stirrups with a thickness of 3mm and a width of 40mm are used, along with eight angles that are 10mm thick and have sides measuring 320mm for the columns and 160mm for the beams.

To ensure the strength of the joints, the steel components are welded in place, mimicking real-world conditions. Moreover, the joint core is reinforced with two ø12mm bars per joint face. These bars pass through the beams and are secured to 50x50x5 steel L-profiles positioned at the intersection of the beams. This construction method enhances the overall stability and durability of the steel device.

Result and Discussion

The study looks into how structures change when they are loaded and unloaded repeatedly, focusing on the hysteretic response and how energy is lost during the process. It presents a comprehensive analysis of how the dissipated energy evolves in relation to the drift level, shedding light on the structural damping characteristics.

One notable aspect of the investigation is the establishment of equivalent damping-displacement ductility relationships. These relationships offer valuable insights into the structural behavior under varying levels of displacement, providing a basis for comparison between different retrofit solutions and between control and retrofitted specimens.

The comparison of cyclic results, particularly in terms of force-displacement relationships, serves to highlight the efficacy of retrofitting solutions. By juxtaposing these relationships, the study elucidates the differences in outcomes between various retrofit strategies and their impact on structural performance.

Furthermore, the examination of the final damage pattern offers a holistic view of the structural response to cyclic loading. The study quantifies the energy absorption capacity of the structures under consideration through the analysis of the hysteretic dissipated energy, computed as the cumulative area under force-displacement diagrams.

The calculation of equivalent damping and displacement ductility provides quantitative measures to assess structural performance and resilience. To figure out how well retrofitting strategies work and how structures react to cyclic loading, equivalent damping (ξ_{eq}) and displacement ductility are useful measurements.

The control specimen C-SW showed an expected failure at a low drift value (1.6% ultimate drift), primarily in the superior column, demonstrating a weak-column strong-beam mechanism despite the selective weakening technique applied to the slab.

When comparing the retrofitted specimens, those reinforced with steel plates exhibited lower pinching effects compared to the specimen retrofitted with CFRP. This difference in behavior can be attributed to the elastic properties of CFRP, which contribute less to dissipating energy compared to steel plates.

Specimen C1-RT-B SW reached larger drift levels due to lower stiffness and a more extensive distribution of damage compared to specimens retrofitted with steel plates.

While specimens C1-RP-Steel SW and C1-RT-Steel SW showed similar cyclic behavior, the test on C1-RT-Steel SW was stopped at 2.5% drift due to the tension failure of rebars located at the bottom of the right beam.

The strengthening solution adopted for C1-RT-Steel SW increased the ultimate drift by delaying buckling of the beam rebars. However, the connection between the longitudinal steel plate of the beam and the steel retrofit device was lost at 1.5% drift.

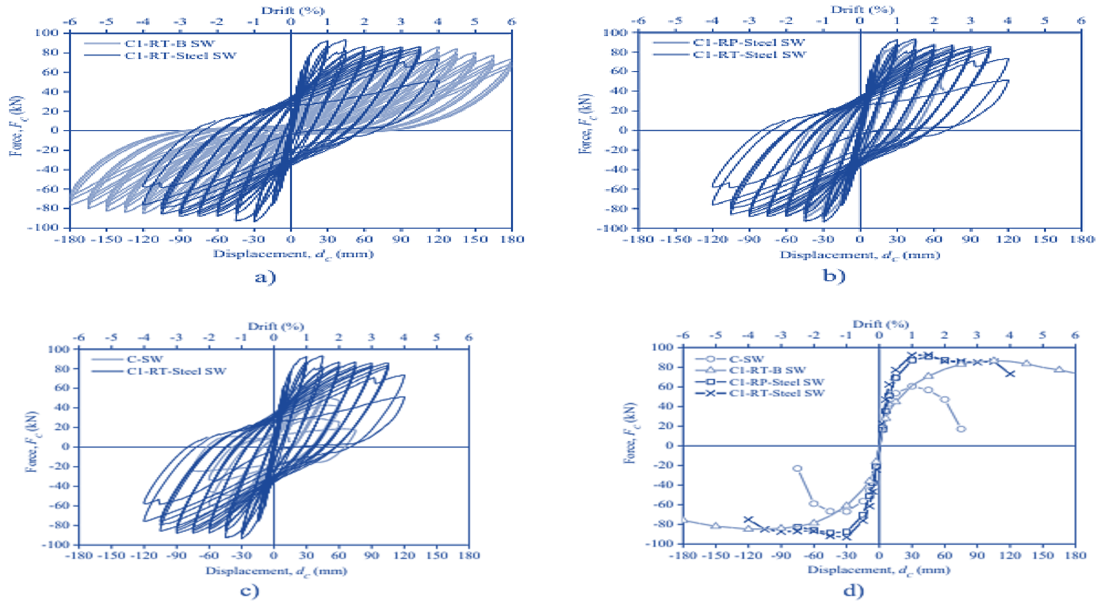

Figure 4. Strength-Displacement Graphs

The evolution of dissipated energy and the equivalent damping-displacement ductility is illustrated in Figure. 5. It's observed that specimens retrofitted with steel plates exhibit the highest energy dissipation at each drift level. This is because the global behavior is primarily governed by the rebars on the beams. These steel-retrofitted specimens reach hardening, resulting in enlarged load-unload-reload loops.

However, in the case of specimen C1-RT-B SW, the increase in cumulative dissipated energy is not as pronounced due to the linear properties of the CFRP. Despite specimen C1-RT-B SW showing a larger ultimate drift than specimen C1-RT-Steel SW, the latter exhibits the largest ductility. This is because the yield drift in specimen C1-RT-Steel SW is almost twice that of specimen C1-RT-B SW.

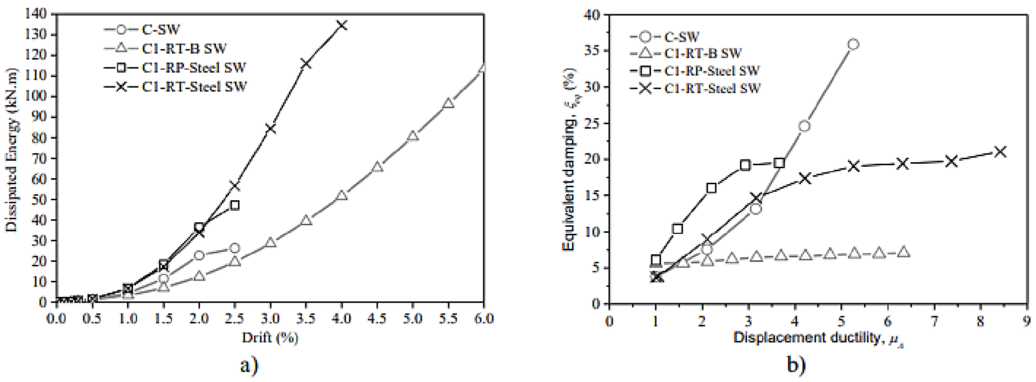

Figure 5. a) Energy Dissipation Evolution, b) Ductility Relationship

Conclusion

The study presents comprehensive findings on retrofitting RC interior beam-column joints for enhanced seismic performance. Results indicate that retrofitting with steel plates effectively enhances energy dissipation and ductility, outperforming CFRP retrofitting. Steel plate retrofitting ensures that plastic hinges are formed away from the joint, improving structural performance. Additionally, selective weakening of the slab increases the rotation capacity of the beams.

Comparative analysis reveals that steel-retrofitted specimens exhibit higher energy dissipation and ductility than CFRP-retrofitted specimens. While CFRP retrofitting allows for a larger ultimate drift, steel retrofitting provides more ductility. These findings offer valuable insights for retrofitting strategies aimed at improving the seismic resilience of RC structures.

References

1. ACI 318M-08 (2008). “Building Code Requirements for Reinforced Concrete”, American ConcreteInstitute, Detroit, Michigan.
2. ACI 440 2R (2008). “Guide for the design and construction of externally bonded FRP systems forstrengthening concrete structures.” ACI 440 2R, ACI Committee 440, Farmington Hills, Michigan.
3. Al-Salloum, A. Y., and Almusallam, T. H., (2007). “Seismic response of interior RC beam-columnjoints upgraded with FRP sheets. I: Experimental study,” J. Compos. Constr., 11 (6), 575-589.
4. Antonopoulos, C. P., and Triantafillou, T. C., (2003). “Experimental investigation of FRP - strengthenedRC beam-column joints,” J. Compos. Constr., 7 (1), 39-49.
5. Bousselham, A., (2010). “State of Research on Seismic Retrofit of RC Beam-Column Joints withExternally Bonded FRP,” Jour composites for construction ASCE January-February 2010, 49-61
6. Dhakal, R.P., Pan, T.C. and Tsai, K.C., (2003). “Enhancement of Beam-Column Joint by RCJacketing”, online citation http://hdl.handle.net/10092/4198
7. Eligehausen, R., Mallée, R., Silva, J. (2006). Anchorage in Concrete Construction. Ernst & Son, Berlin,Germany.
8. Eligehausen, R., Genesio, G. Ožbolt, J. Pampanin, S. (2008). 3D Analysis of Seismic Response of RCBeam-Column Exterior Joints before and after retrofit. In: 2nd ICCRRR, Vol. I:407-408.
9. Eurocode 8, (1998). “Earthquake resistant design of structures – part 1: General rules and rules forbuildings” ENV 1998-1-1/2/3, CEN Technical Committee 250/SC8, Berlin, Germany.

10. FIB Bulletin 14 (2001). “Externally bonded FRP reinforcement for RC structures.”, FédérationInternationale du Béton, Lausanne, Switzerland.

11. Genesio, G., Akgüzel, U. (2009). Seismic retrofit for reinforced concrete exterior beam-column joints using a fully fastened metallic haunch solution, Part 1: Feasibility study - Test report, No. WS 212/23-09/02. University of Stuttgart, Germany.

12. Genesio, G., Sharma, A. (2010). Seismic retrofit solution for reinforced concrete exterior beam-columnjoints using a fully fastened haunch - Part 2-2: Retrofitted joints - Test report, No. WS 221/08 - 10/02, University of Stuttgart, Germany.

13. Genesio, G, Eligehausen, R., Pampanin (2010-1). Seismic assessment of pre-1970s RC beam-columnjoints. 14th European Conference on Earthquake Engineering, Ohrid, Macedonia.

14. Genesio, G, Eligehausen, R., Akgüzel, U., Pampanin (2010-2). Application of post-installed anchors for seismic retrofit of RC frames. 14th European Conference on Earthquake Engineering, Ohrid, Macedonia.

15. Ghobarah, A. and Said, A., (2002). “Shear strengthening of beam-column joints,” EngineeringStructures, 24, 881-888.

16. Ghobarah, A., and El-Amoury, T., (2005). “Seismic rehabilitation of deficient exterior concrete frame joints,” Jour Compos. Constr., 9 (5), 408-416.

17. Hakuto, S., Park, R. and Tanaka, H., (2000). “Seismic load tests on interior and exterior beam-columnjoints with substandard reinforcing details,” ACI Structural journal, 97(1), 11-25.

18. IS 13920:1993 (2002). “Indian Standard ductile detailing of reinforced concrete structures subjected toseismic forces — Code of Practice,” Edition 1.2, Bureau of Indian Standards, New Delhi.

19. IS 13935:1993 (2002). “Indian Standard repair and seismic strengthening of buildings – Guidelines”Edition 1.1, Bureau of Indian Standards, New Delhi.

20. Liu, C., (2006). “Seismic Behaviour of Beam-Column Joint Subassemblies Reinforced With Steel Fibers,” Master of Engineering Thesis, University of Canterbury, Christchurch, New Zealand.