Enhancing Seismic Performance through Rehabilitation: Analysis of Beam-Column Connections

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Abstract
This study focuses on the rehabilitation of beam-column connections weakened in flexure to restore their original seismic capacity. Two distinct repair approaches were deployed based on the severity of damage. For partial damage, involving loose concrete, compromised material was replaced with micro-concrete, followed by epoxy injection. In cases of severe damage, complete replacement of damaged concrete preceded epoxy injection. Voids created were filled with micro-concrete, and a bonding agent ensured strong adhesion. Epoxy was injected into drilled holes under high pressure. After a 7-day curing period, specimens were tested under various loading conditions. Data on crack location, pattern, and width were meticulously recorded. Post-processing analysis evaluated seismic capacity parameters and compared the effectiveness of repair techniques. The rehabilitation successfully restored seismic performance, enhancing ultimate strength, stiffness, energy dissipation, and ductility.
Keywords: Rehabilitation, Retrofitting, Structural integrity, Beam-column connections, Earthquake safety, Structural stability

Introduction

Seismic events have always posed a significant threat to the safety and stability of structures worldwide. With the increasing urbanization and expansion of cities into seismically active regions, the need for robust and resilient infrastructure has become more pressing than ever.[1] Structures, especially those constructed before modern seismic design codes were established, often lack the necessary strength and ductility to withstand the forces exerted during an earthquake. Consequently, there is a growing interest in retrofitting existing structures to enhance their seismic performance and ensure the safety of occupants [2].
Among the various elements of a structure, beam-column connections play a crucial role in its overall seismic performance. During an earthquake, these connections are subjected to significant forces and deformations, making them vulnerable points in the structure. As such, the rehabilitation and strengthening of beam-column connections have become a focal point in seismic retrofitting strategies[3].

Vital Role of Seismic Rehabilitation

Importance of Seismic Rehabilitation: Seismic rehabilitation involves the process of retrofitting existing structures to improve their ability to withstand seismic forces. It is a critical aspect of ensuring the safety and stability of buildings, particularly in areas prone to earthquakes[4]. Unlike new construction, where modern seismic design codes can be implemented from the outset, existing structures often require significant upgrades to meet current safety standards. Seismic rehabilitation not only enhances the structural integrity of buildings but also reduces the risk of casualties and property damage during an earthquake[5].

Role of Beam-Column Connections: Beam-column connections are vital structural elements that transfer loads between beams and columns. During an earthquake, these connections experience complex and often severe loading conditions, making them susceptible to damage and failure. Inadequate or poorly designed connections can lead to disproportionate structural damage and compromise the overall stability of the building. Therefore, the rehabilitation of beam-column connections is essential for improving the seismic performance of existing structures[6].

Challenges in Seismic Rehabilitation: Seismic rehabilitation presents several challenges, primarily due to the need to work within the constraints of existing structures. Unlike new construction, where design parameters can be optimized from the beginning, retrofitting projects must often contend with limited space, budgetary constraints, and the need to minimize disruption to building occupants[7]. Additionally, the heterogeneous nature of existing structures means that a one-size-fits-all approach to seismic rehabilitation is rarely feasible. Each building presents unique challenges that require customized solutions tailored to its specific characteristics and structural deficiencies.[8]

Methodology

The repair strategy was to restore the compromised connections to their original seismic capacity, encompassing strength, energy dissipation, and ductility. We deployed two distinct rehabilitation approaches based on the severity of the incurred damages.

Firstly, in cases of partial damage where concrete had become loose, the method involved the replacement of this compromised material with micro-concrete. We then performed an epoxy injection into the crack zone to reinforce the structure. Alternatively, for more severe damage, which involved the complete crushing of concrete, a similar process was followed but entailed the full replacement of the damaged concrete before the epoxy injection.

To address the voids created upon the removal of loose materials, micro-concrete was used to patch or fill these spaces. We applied a bonding agent beforehand to ensure a strong bond between the existing and fresh concrete. Additionally, we drilled holes along the cracks and inserted packers to facilitate the injection of epoxy. We injected this low viscosity resin under high pressure into the cracks to effectively reinforce the damaged areas.

After the repair process, we left the specimens undisturbed for 7 days to allow the injected epoxy resin to reach sufficient strength. After achieving this strength, we struck the packers' heads to remove them, and used a grinding machine to eliminate any remaining sealing materials. This meticulous process ensured that the repaired structures regained their original seismic capacity, ensuring durability and safety.

In this investigation, the focus was on beam-column connections with beams weakened in flexure. The study involved testing connections of different sizes: large, medium, and small, under various loading conditions designated as type-1 and type-2. The control specimens were subjected to these loading types to assess their behavior.
During testing, the degree of damage was monitored, and the specimens were subsequently rehabilitated using either repair method-1 or method-2, depending on the observed damage. Throughout the experiment, data regarding crack location, pattern, and width were meticulously recorded at each stage of loading until the experiment concluded.
Post-processing of the recorded data was performed to analyze several critical parameters associated with the seismic capacity of these connections. The effectiveness of the repair techniques applied was evaluated by comparing the seismic performance of the rehabilitated specimens with that of their respective control specimens.

Result and Discussion

The effectiveness of various repair techniques was assessed by comparing the seismic performance of rehabilitated specimens with control specimens. The previous section presented the hysteretic responses of all the connections. From these responses, parameters related to seismic capacity, such as ultimate strength, stiffness degradation, energy dissipation, and ductility of the specimens, were evaluated. This evaluation allowed for a comprehensive understanding of the effectiveness of the adopted repair techniques in enhancing the seismic performance of the specimens.

Hysteretic Response and Ultimate Strength Analysis

The hysteresis loops obtained under loading type-1 revealed that the highest load carrying capacity was observed during the first cycle for each displacement amplitude. Consequently, the peak values of the capacity from the first cycle were selected to plot the envelope of the hysteresis loops. Figures 1to 3illustrate the envelope of hysteresis loops for both control and rehabilitated specimens under all loading types.
Upon comparing the curves of control and rehabilitated specimens at each displacement, it was observed that all the rehabilitated specimens exhibited a similar trend of load recovery, albeit with a relatively low recovery rate. The envelope of hysteresis loops for the rehabilitated specimens indicated a slightly higher load carrying capacity in both push and pull directions compared to the control specimens. However, a comparison of the ultimate load carrying capacity achieved by the rehabilitated specimens under loading type-1 and type-2 was not possible due to the implementation of different rehabilitation strategies based on the extent of damage. It was observed that appropriately chosen repair strategies were capable of restoring the lost capacity, even in severely damaged connections.

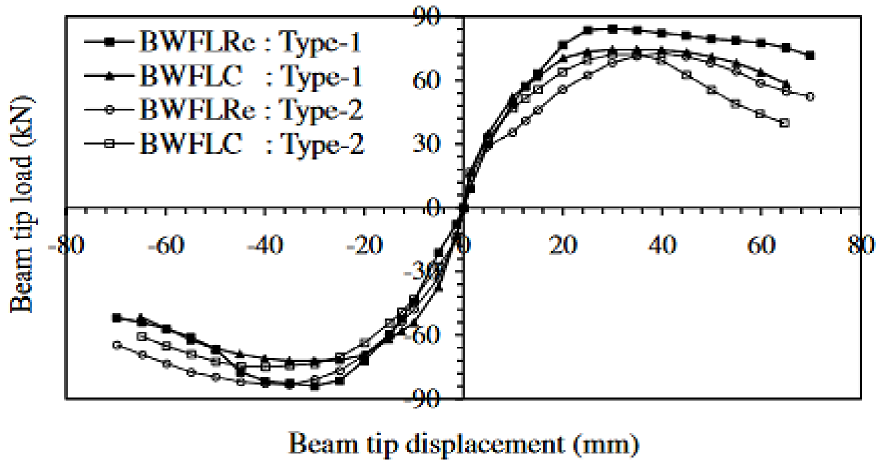

Figure 1. Performance Comparison of BWFL Specimens

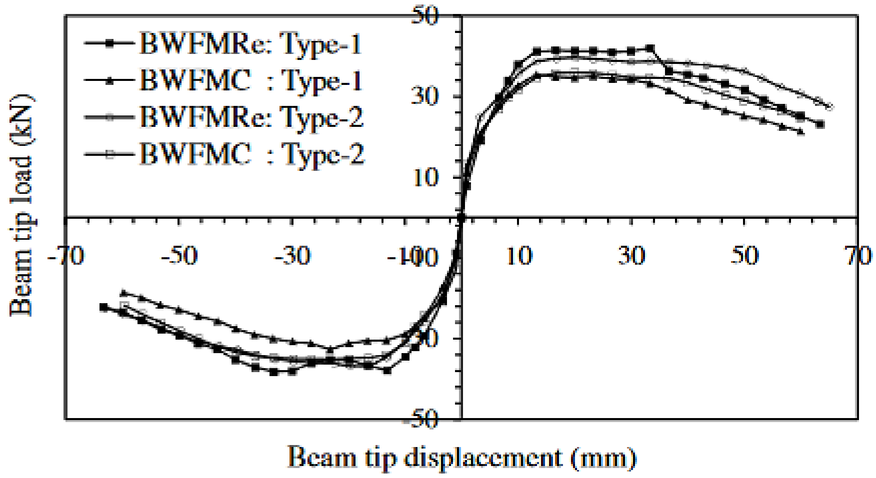

Figure 2. Performance Comparison of BWFM Specimens

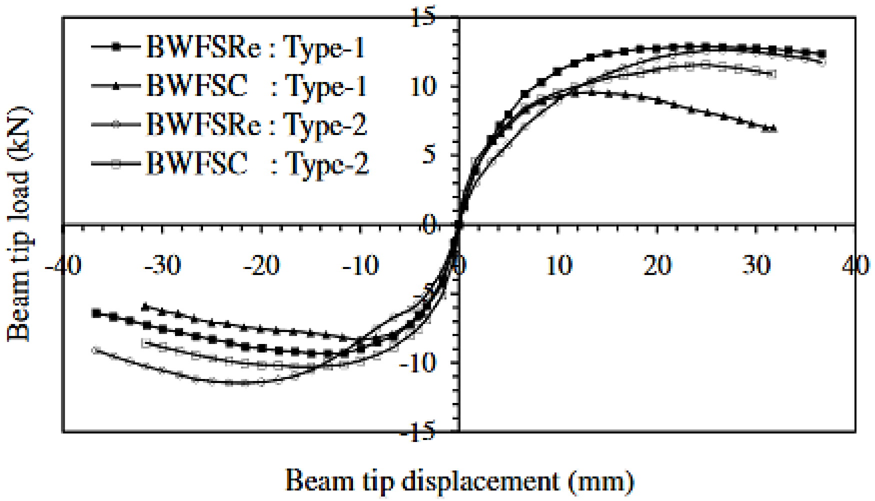

Figure 3. Performance Comparison of BWFS Specimens

Evaluation of Energy Dissipation in Rehabilitated Specimens

The ability of a structural element to withstand earthquake loads significantly depends on its capacity to dissipate energy. The area enclosed by the hysteresis loop serves as a measure of energy dissipation. Cumulative energy dissipation at a specific amplitude was calculated by summing up the energy dissipated in all preceding cycles, including that amplitude.

Figures 4 to 6 illustrate the plots of cumulative energy dissipation versus drift angle for both control and rehabilitated specimens. While energy dissipation for loading type-1 and type-2 is presented in the same figure, comparison between the two cannot be made due to different loading characteristics.

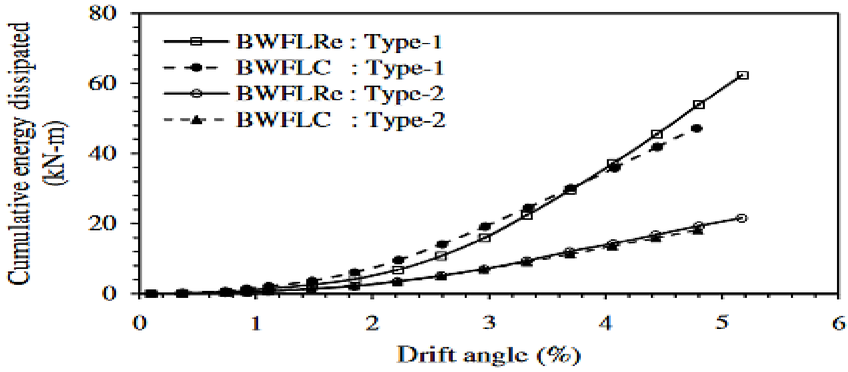

Figure 4. Energy Dissipation Comparison in BWFL Specimens

Upon examination of these plots, it's evident that the cumulative energy dissipated by the rehabilitated specimens is relatively lower during the initial stages of loading. However, in subsequent loading cycles, the energy dissipated by the rehabilitated specimens matches that of the corresponding control specimens. The increase in stiffness at the end of the imposed displacement history resulted in the rehabilitated specimens bearing more load corresponding to any drift angle compared to the control specimens. Consequently, the total area enclosed by the plot of beam tip load versus beam tip displacement was greater for rehabilitated specimens than for control specimens. This increase in enclosed area possibly contributed to the improvement in cumulative energy dissipation in subsequent loading cycles. Up to the drift level tested, the energy dissipated by the rehabilitated specimens was slightly higher than that of the respective control specimens.

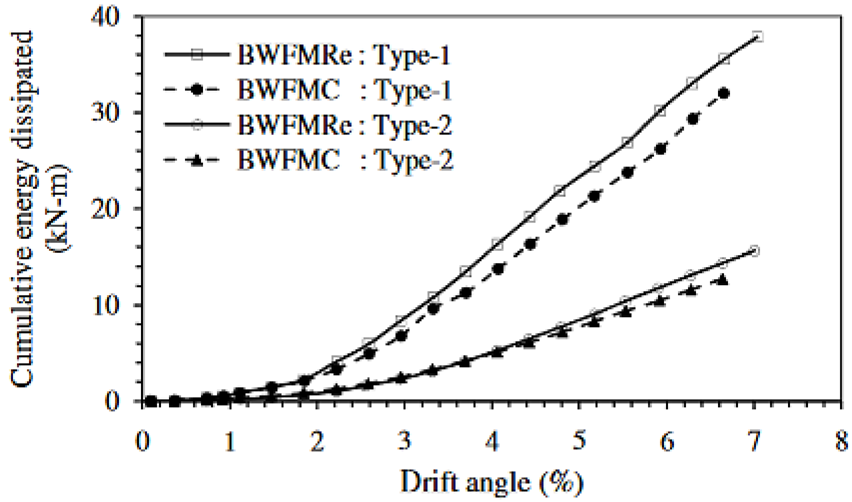

Figure 5. Energy Dissipation Comparison in BWFM Specimens

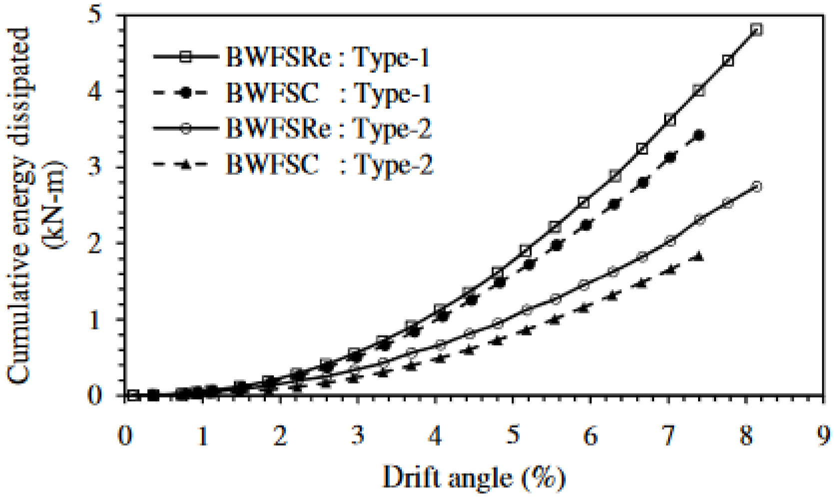

Figure 6. Energy Dissipation Comparison in BWFS Specimens

Conclusion

The rehabilitation of beam-column connections demonstrated effective restoration of seismic capacity through meticulous repair techniques tailored to the extent of damage. Comparisons between control and rehabilitated specimens revealed improved seismic performance, evidenced by enhanced ultimate strength, stiffness, and energy dissipation. Despite initial differences in energy dissipation, rehabilitated specimens exhibited comparable performance to control specimens in subsequent loading cycles. The study underscores the importance of appropriate repair strategies in restoring structural integrity and ensuring safety against seismic forces.

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