Current Science International
Volume: 15 | Issue: 01| Jan. - March| 2026

EISSN:2706-7920 ISSN: 2077-4435
DOI: 10.36632/csi/2026.15.1.3
Journal homepage: www.curresweb.com
Pages: 25-39

Behavior of Geopolymer Concrete Beams Strengthened using CFRP Sheets

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Received: 20 Nov. 2025 **Accepted:** 15 Jan. 2026 **Published:** 30 Mar. 2026

ABSTRACT
This study investigates the cyclic performance of beam–column joints fabricated with conventional reinforced concrete (RC) and metakaolin-based geopolymer concrete (GPC) with two distinct metakaolin replacement levels (15% and 100%), the beams are strengthened with external CFRP wrapping as a repair technique. The primary objective is to assess whether GPC can offer enhanced structural performance and sustainability compared to ordinary Portland cement (OPC) concrete, particularly under reversed cyclic loading conditions that simulate earthquake excitations. Specimens representing three anchorage systems Type A with 90° hooked bars, Type B with straight bars, and Type C with cross bars providing mechanical interlock were prepared with identical geometric dimensions and subjected to a constant axial load during testing. The experimental program involved detailed measurements of load–deflection behavior, ductility, energy absorption capacity, stiffness degradation, and failure modes. Results indicate that GPC beam–column joints exhibit improved energy dissipation and ductility compared to conventional RC joints, with the 100% metakaolin mix outperforming the 15% metakaolin mix in terms of both initial cracking resistance and ultimate load capacity. Additionally, anchorage systems incorporating 90° hooks and cross bars demonstrated superior performance over straight bars, reducing bond-slip issues and enhancing cyclic stability. The integration of CFRP wrapping enhanced the structural integrity of the joints by delaying the onset of macro-cracking and stabilizing internal reinforcement. However, the transition to high-displacement cycles eventually led to CFRP debonding, which limited the full potential of the strengthening scheme at peak drift levels. Microstructural analysis revealed that the denser matrix and enhanced bond characteristics of the optimized GPC mix contribute significantly to the improved cyclic behaviour. These findings suggest that metakaolin-based geopolymer concrete, particularly with 100% metakaolin replacement, is a promising sustainable alternative for seismic applications, offering potential reductions in CO_2 emissions while maintaining or even enhancing structural performance under cyclic loading.

Keywords: Geopolymer concrete, CFRP Sheets, metakaolin, cyclic loading, beam-column joints, seismic performance, anchorage systems.

1. Introduction
The seismic performance of beam–column joints is critical to the overall resilience of structures in earthquake-prone regions. Conventional reinforced concrete (RC) systems have long been the industry standard due to their well-established design practices; however, the high CO_2 emissions associated with Portland cement production and the inherent limitations in bond performance under cyclic loading have prompted researchers to explore alternative materials and detailing methods (ACI CODE-318-19(22), 2019). One promising alternative is geopolymer concrete, particularly those formulations based on metakaolin. Geopolymer concrete offers environmental advantages by reducing

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carbon emissions and exhibits unique microstructural characteristics due to its aluminosilicate network formation (Davidovits, 1991; Duxson *et al.,* 2007). In metakaolin-based geopolymer systems, the activation of metakaolin using alkaline solutions such as sodium hydroxide and sodium silicate leads to the formation of a three-dimensional binder that can rival or even surpass the performance of conventional binders (Provis, 2021).

Early research by Davidovits (1991) laid the groundwork by demonstrating that geopolymers could be designed to achieve high early strength and excellent durability. Subsequent studies have focused on the optimization of mix design parameters, including the Si/Al molar ratio, water-to-solids ratio, and the type and concentration of alkali activators (Duxson et al., 2007; Lahoti *et al.,* 2017), for instance, explored how variations in these parameters affect the compressive strength of metakaolin-based geopolymers, while other researchers have examined the influence of curing conditions and aggregate types on the resulting composite behavior. These studies collectively underscore that geopolymer concrete does not simply mimic the behavior of ordinary Portland cement (OPC) concrete, but instead offers distinct mechanical properties and microstructural features that may be better suited to certain structural applications.

In parallel with advances in material technology, significant attention has been given to the seismic detailing of beam–column joints. The performance of these joints under cyclic loading is heavily influenced by the anchorage details of the longitudinal reinforcement. Traditional RC designs often employ 90° hooked bars or rely on extended development lengths of straight bars to secure adequate bond strength, but these details must be revisited when considering the different bond characteristics of geopolymer concrete (ACI CODE-318-19(22), 2019). Studies have shown that proper confinement provided by transverse reinforcement is critical in both RC and geopolymer joints, as it helps to prevent premature bond failure and concrete spalling under cyclic loads (Mao *et al.,* 2022).

Recent experimental investigations have compared the seismic behavior of conventional RC joints with geopolymer concrete joints (Mao *et al.,* 2022) examined the bond and anchorage performance of beam flexural bars in geopolymer beam–column joints, finding that the use of slag-based geopolymer concrete can yield bond strengths comparable to or slightly exceeding those of OPC systems, provided that adequate detailing is employed. Similarly, studies such as those by Sahin *et al.* (2021) have evaluated the influence of aggregate type and mix design on the overall performance of geopolymer composites, reinforcing the notion that both material composition and reinforcement detailing must be considered in tandem.

Performance parameters such as stiffness degradation, energy dissipation capacity, ductility, and residual deformations have been widely recognized as key indicators of seismic resilience. For instance, studies by Duxson *et al.* (2007) and Provis, (2021) have provided insight into the material behavior of geopolymer concretes under monotonic loading, yet less is known about their cyclic performance. More recent work by Mao *et al.* (2022) has begun to fill this gap by systematically investigating bond performance and the resulting hysteretic response of geopolymer joints. However, a direct comparison between conventional RC joints and geopolymer joints, especially with variations in metakaolin content, remains underexplored.

The literature indicates that while geopolymer concrete has the potential to achieve comparable or superior performance relative to OPC concrete under static loading conditions, its behavior under repeated cyclic loading may differ significantly due to differences in microstructure, bond characteristics, and the interaction with reinforcement detailing (Sahin *et al.,* 2021). Moreover, the role of metakaolin content in modifying the geopolymer matrix by influencing factors such as gel formation and porosity—adds another layer of complexity to the seismic performance of these joints. For example, a 15% replacement level might offer improved workability and bond conditions, whereas a 100% metakaolin mix could yield higher compressive strengths but may also exhibit different fracture characteristics under cyclic loading.

Ultimately, the evolution of geopolymer concrete from a laboratory curiosity to a viable structural material has been marked by significant research efforts (Davidovits, 1991; Provis 2021).

Recent investigations have further demonstrated its potential in critical applications such as beam–column joints (15, Sahin *et al*., 2021), although further comparative studies are needed—particularly those that explore the impact of metakaolin content and anchorage detailing on cyclic performance. This study is intended to bridge that gap by providing a systematic comparison of conventional and geopolymer joint performance under seismic loading, thereby contributing to the broader field of sustainable and resilient structural design.

2. Research significance

This study holds significant importance in advancing both the technical and environmental aspects of modern structural engineering. By systematically comparing the cyclic performance of conventional reinforced concrete beam–column joints with those fabricated using metakaolin-based geopolymer concrete, the research directly addresses critical issues in seismic design. Beam–column joints are recognized as pivotal elements in the structural integrity of multi-storey frames, and their failure under cyclic loading during seismic events can precipitate catastrophic collapse. Enhancing the performance of these joints, therefore, is of paramount importance.

From a technical standpoint, the investigation delineates the effects of varying metakaolin replacement levels specifically, 15% versus 100% on the mechanical behavior of geopolymer concrete joints. Additionally, by evaluating different anchorage detailing schemes (Types A, B, and C), the study contributes to a deeper understanding of how reinforcement geometry and anchorage configurations influence bond performance, ductility, energy dissipation, and stiffness degradation under reversed cyclic loads. This nuanced examination is expected to yield design insights that can be directly incorporated into seismic performance models and future building codes, thus promoting safer structural systems.

Environmentally, the research is particularly significant as it explores geopolymer concrete as a sustainable alternative to ordinary Portland cement (OPC) concrete. The production of OPC is energy-intensive and associated with high carbon dioxide emissions. In contrast, metakaolin-based geopolymer concrete utilizes industrial by-products and exhibits a substantially lower carbon footprint, thereby aligning with global efforts to reduce greenhouse gas emissions. Demonstrating that geopolymer concrete can achieve comparable or superior seismic performance while simultaneously mitigating environmental impact could catalyze a paradigm shift in construction practices.

3. Experimental Program

This section delineates the comprehensive experimental investigation undertaken to evaluate the cyclic performance of beam–column joints fabricated with conventional reinforced concrete (RC) and metakaolin-based geopolymer concrete (GPC). The study specifically examines two distinct metakaolin replacement levels (15% and 100%) and three anchorage configurations (Types A, B, and C) under reversed cyclic loading, thereby simulating seismic excitation.

3.1. Design of specimens

All specimens were fabricated to replicate the critical connection zones found in multi-storey structures. Beams were cast with a cross-sectional area of 200 × 300 mm and a length of 1500 mm, while columns measured 300 × 200 mm in cross-section and 1900 mm in length (Fig.1). Reinforcement detailing was implemented according to the strong-column, weak-beam philosophy. The specimens were subdivided into groups based on the anchorage detailing: Type A employed 90° hooked bars to enhance end-bearing, Type B utilized straight bars relying solely on bond over an extended development length, and Type C featured cross bars designed to create a mechanical interlock within the joint (see Fig. 2 for the schematic view of the employed anchorage systems).

EISSN: 2706-7920 ISSN: 2077-4435 **DOI: 10.36632/csi/2026.15.1.3**

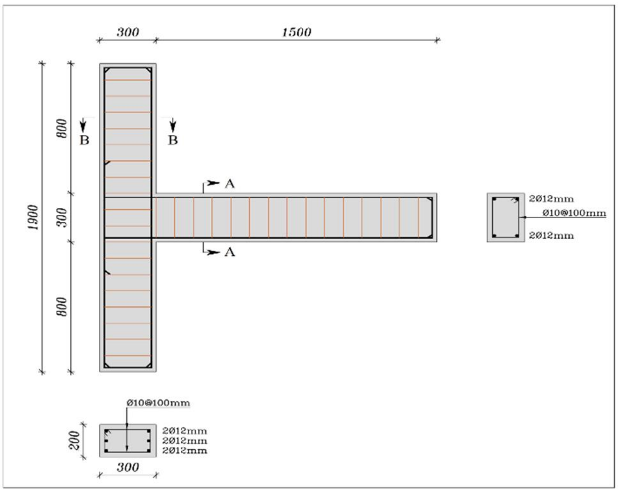


Fig. 1: Geometry (in mm) and reinforcement detail of test specimens

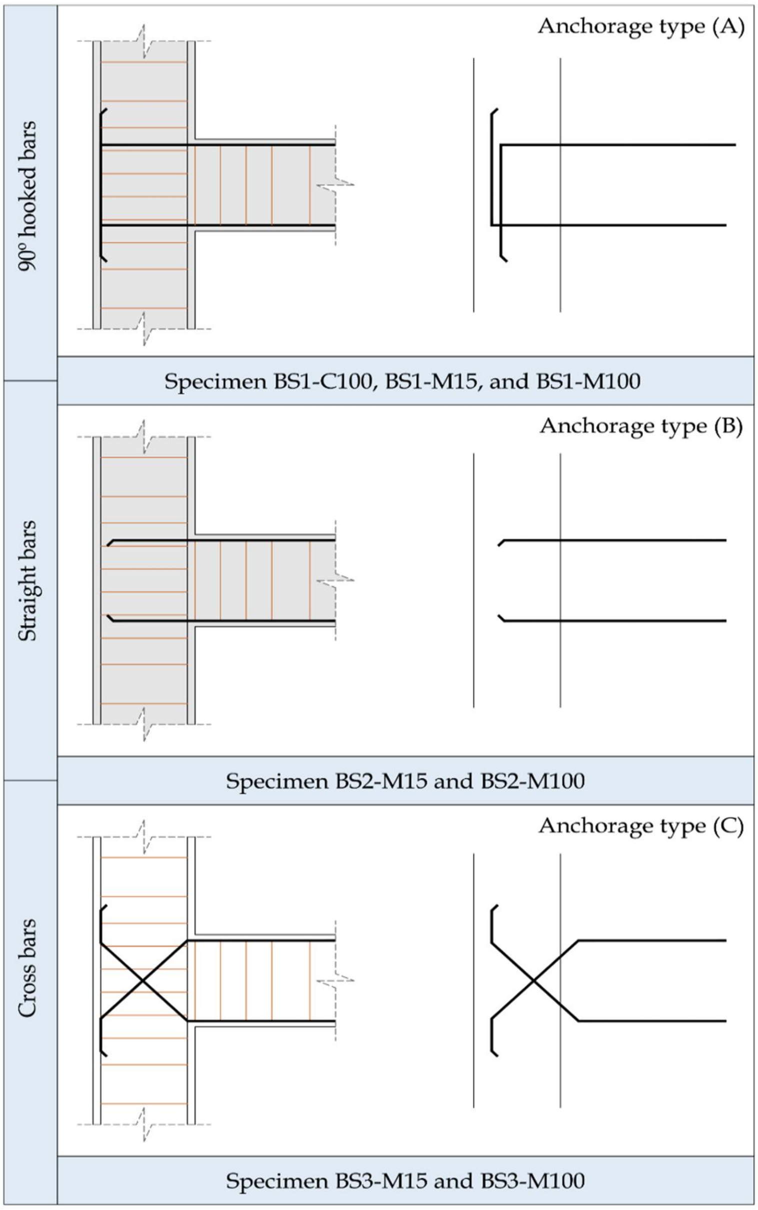


Fig. 1: Schematic view of employed anchorage systems

Curr. Sci. Int., 14(1): 25-39, 2026
EISSN: 2706-7920 ISSN: 2077-4435 **DOI: 10.36632/csi/2026.15.1.3**

3.2. Materials and Mixture Proportions

Two concrete systems were investigated. The conventional RC specimens were produced using ordinary Portland cement (OPC) following standard mix-design procedures to achieve the target strength. In contrast, the GPC specimens were produced using a metakaolin-based binder activated by a sodium silicate–sodium hydroxide solution. Two replacement regimes were considered: one with 15% metakaolin replacement and another with 100% metakaolin as the sole precursor; activator dosages were adjusted appropriately to ensure comparable workability and early-age strength. Locally sourced aggregates were used for both systems, in conformity with applicable standards. Detailed mix design proportions for both systems are presented in Table 1 and Table 2. Compressive strength tests on cube specimens after 28 days of curing revealed that the conventional RC mix achieved an average strength of 33.06 MPa, while the GPC mixes exhibited 34.14 MPa for the 15% metakaolin replacement and 43.04 MPa for the 100% metakaolin mix. These results indicate that full replacement with metakaolin leads to a significant strength enhancement relative to both the conventional and partially replaced systems.

Table 1: Mix design proportions for NC and GPC (kg/m³)

Component	**Normal concrete**	**GPC (15% Metakaolin Replacement)**	**GPC (100% Metakaolin)**
Binder	350 (OPC)	~297.5 (15% of OPC replaced by MK)	350 (100% MK)
Water	168	168	168
Fine Aggregate	746	746	530
Coarse Aggregate	1123	1123	1240
Superplasticizer	6.16	6.16	6.16

Table 2: Mix design proportions for metakaolin-based geopolymer concrete (kg/m³)

Metakaolin	**Fine aggregate**	**Coarse aggregate**	**NaOH (solution) (kg/m^3)**	**Na_2SiO_3 (kg/m^3)**	**Water**	**AS/MK**	**W/S**
350	530	746	68	170	20	0.74	0.36

AS: Alkaline solution, W/S: water to solid ratio

3.3. Casting, Curing, and Specimen Fabrication

Specimens were cast in reusable molds under controlled laboratory conditions. Conventional RC samples were subjected to standard moist-curing protocols, while GPC specimens were cured under ambient conditions with measures implemented to prevent moisture loss. Thorough mixing and consolidation were ensured through the use of mechanical vibrators, thereby minimizing entrapped air and promoting a uniform microstructure across all joints.

3.4. Test Setup and Instrumentation

Cyclic loading tests were performed using a steel loading frame with sufficient capacity to replicate seismic forces (shown in Fig. 3 for an overview of the test setup and instrumentation). Each specimen was instrumented with high-precision load cells, Linear Variable Differential Transformers (LVDTs), and strain gauges to capture real-time load–deflection behavior, reinforcement strains, and local joint deformations. A constant axial load was applied to the column to simulate service conditions, while the beam tip was subjected to a controlled reverse cyclic load.

Throughout testing, load, deflection, and strain data were recorded at high resolution. Visual inspections were conducted to document crack initiation and propagation. The collected data were processed using advanced analytical software to derive key performance parameters, such as initial cracking load, ultimate load capacity, ductility factor, and cumulative energy absorption. Comparative analysis between conventional RC and GPC specimens was performed to elucidate the effects of metakaolin replacement levels and reinforcement anchorage details on joint performance.

3.5. Loading Protocol

A standardized reverse cyclic loading protocol was implemented, wherein the applied load was incrementally increased until specimen failure. Both forward and reverse cycles were executed, enabling the generation of hysteresis curves that provided critical insights into stiffness degradation, energy dissipation capacity, and ductility. The loading history is depicted in Fig. 4, and the collected high-resolution data were processed using advanced analytical software to derive key performance parameters, including initial cracking load, ultimate load capacity, ductility factor, and cumulative energy absorption.

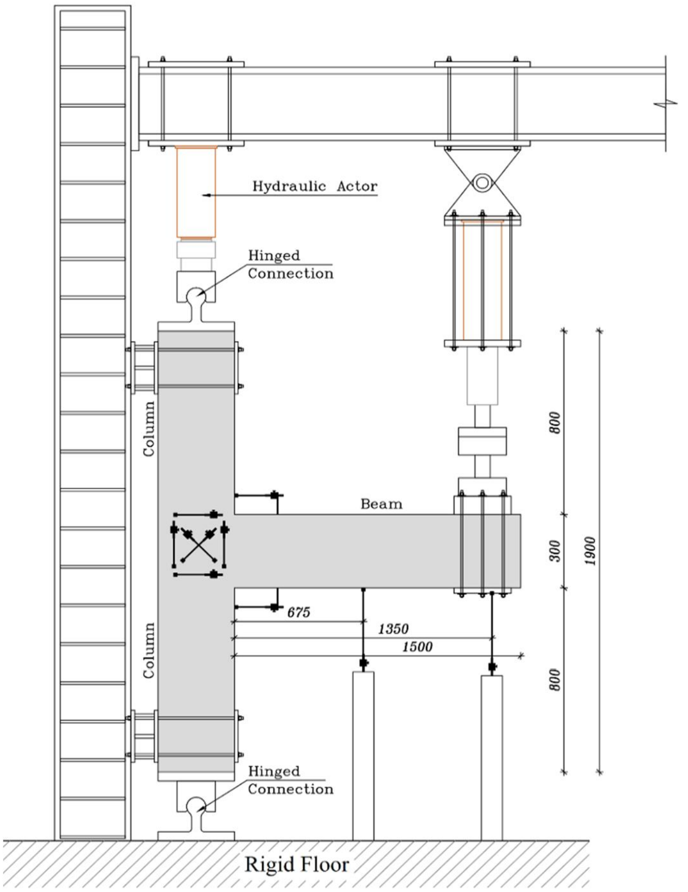


Fig. 3: Overview of test setup and instrumentation (dimensions in mm)

3.6. Specimen Details and Reinforcement

The beam–column joints were designed according to a strong-column, weak-beam concept, with reinforcement details as specified in Table 3 for the properties of the reinforcing bars and Table 4 for specimen details and anchorage schemes is provided in. These tables summarize the bar diameters, yield strengths, and the grouping of specimens based on the concrete mix and anchorage configuration. Fig. 1 illustrates the geometry and reinforcement detail of the test specimens.

In summary, the experimental program is structured to systematically evaluate the seismic performance of conventional RC and metakaolin-based GPC beam–column joints. The detailed investigation into mix proportions, specimen fabrication, test setup, and loading protocol provides a robust framework for comparing the effects of metakaolin replacement levels and reinforcement anchorage details on joint behavior under cyclic loading conditions.

Table 2: Properties of Reinforcing Bars

	$d_b(mm)$	$A_s(mm^2)$	$f_y(MPa)$	$f_u(MPa)$	$E_s(GPa)$	$\varepsilon_y(\%)$
Steel Stirrups	10	78.5	585.69	734.66	230	0.2
Steel bars	12	113	557.04	707.36		

Table 3: Specimen details

Specimen	Concrete Mix	Anchorage scheme
BS1-C100	Only Cement 350kg/m^3	Type (A)
BS1-M15	GPC (15% Metakaolin Replacement)	Type (A)
BS1-M100	GPC (100% Metakaolin)	Type (A)
BS2-M15	GPC (15% Metakaolin Replacement)	Type (B)
BS2-M100	GPC (100% Metakaolin)	Type (B)
BS3-M15	GPC (15% Metakaolin Replacement)	Type (C)
BS3-M100	GPC (100% Metakaolin)	Type (C)

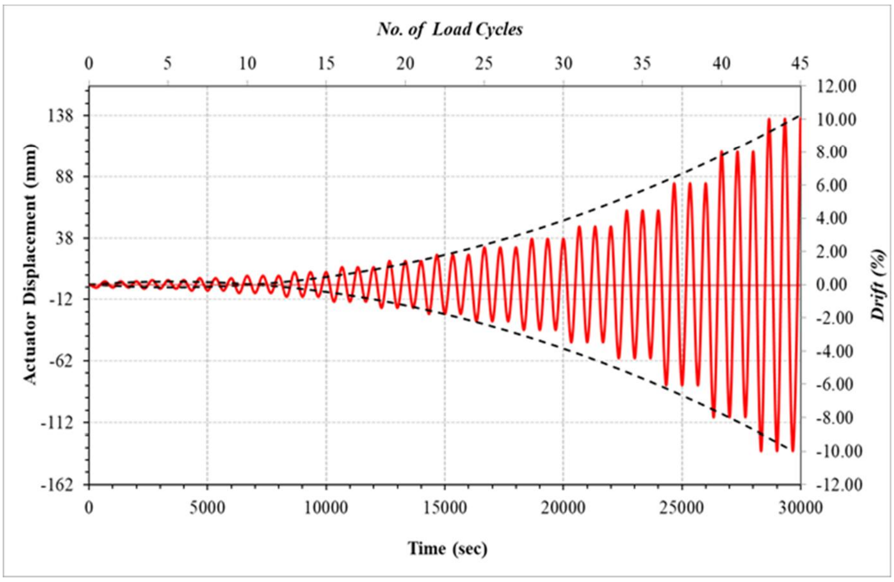


Fig. 2: Cyclic loading history

4. Test results

The following section presents the experimental findings from cyclic testing of beam–column joints fabricated with conventional reinforced concrete (RC) and metakaolin-based geopolymer concrete (GPC). Data were systematically recorded to capture the load–deflection response, hysteretic behavior, crack evolution, energy dissipation, stiffness degradation, and the influence of various reinforcement anchorage configurations. The results, detailed in Tables 1–4 and Fig. 3–9, provide an in-depth understanding of how metakaolin replacement levels (15% and 100%) and anchorage details affect joint performance under simulated seismic excitation.

4.1. Hysteretic behaviour

The cyclic loading tests yielded detailed load–deflection hysteresis loops that illuminate critical aspects of the joints' structural response under simulated seismic excitation. Conventional RC specimens displayed a predominantly linear elastic response up to the initial cracking point, followed by a rapid transition into a nonlinear regime marked by a pronounced reduction in stiffness and relatively narrow hysteresis loops. This behavior suggests that RC joints, while initially robust, are prone to brittle failure as cyclic loading progresses, with a limited capacity for energy dissipation and rapid stiffness degradation.

In stark contrast, the geopolymer concrete (GPC) specimens—particularly those fabricated with 100% metakaolin replacement exhibited significantly broader hysteresis loops with higher peak load values and larger deflections before failure (shown in Fig. 5). The expanded hysteresis envelopes indicate a superior ability to undergo inelastic deformations while sustaining load, thereby demonstrating enhanced ductility and energy absorption characteristics. Notably, the GPC mix with 15% metakaolin replacement achieved a balanced hysteretic performance; it maintained an initial.

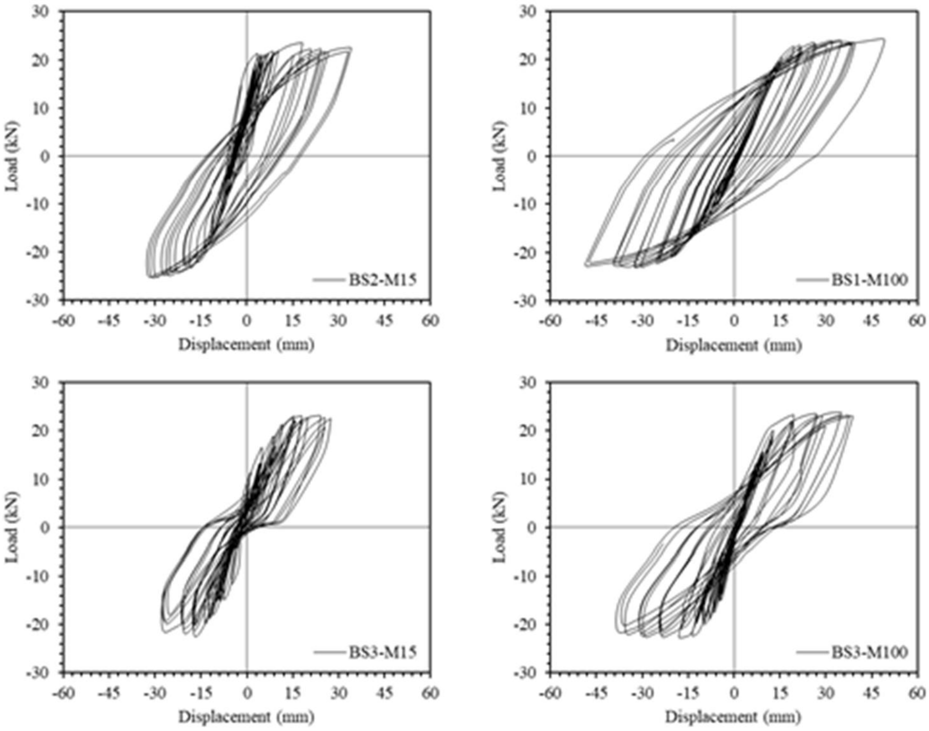
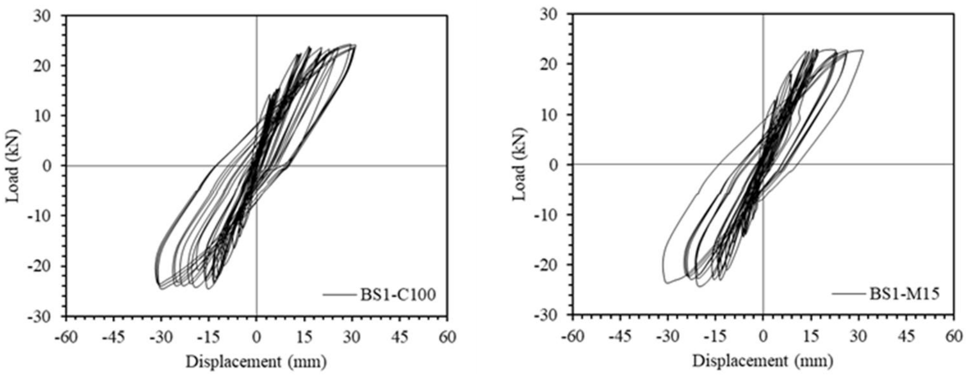


Fig. 3: Load-displacement hysteretic response of all test specimens

Stiffness comparable to that of the RC specimens while simultaneously exhibiting improved cumulative energy dissipation over successive cycles (refer to Fig. 6). This behavior is attributable to the denser and more homogeneous microstructure of the geopolymer matrix, which fosters enhanced bond strength and delays crack coalescence.

Overall, the comparative analysis reveals that whereas conventional RC joints tend to suffer from abrupt stiffness loss and brittle failure under repeated loading, the GPC joints—especially those with full metakaolin replacement—demonstrate a more gradual degradation of stiffness and a sustained energy dissipation capacity. These findings suggest that GPC joints can better accommodate the cyclic deformations typical of seismic events, thereby offering a more resilient alternative for structural applications in earthquake-prone regions.



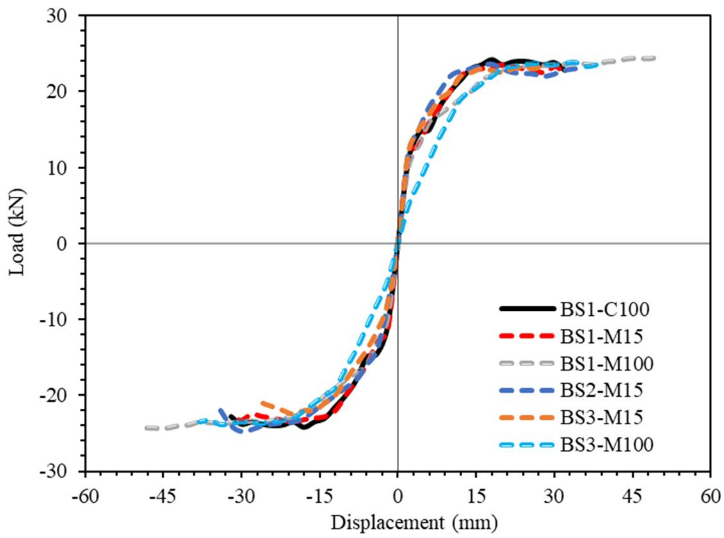


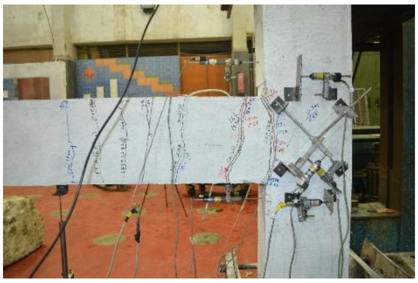
Fig. 4: Comparison of envelopes of hysteretic curves

4.2. Crack Patterns and Failure Modes

Detailed visual examinations and post-test assessments revealed marked differences in crack development and failure mechanisms between the conventional RC joints and the geopolymer concrete (GPC) joints. In both material systems, the inception of cracking was consistently observed at the beam–column interface, which represents a critical stress concentration zone. However, the RC specimens exhibited wider, more pronounced cracks that rapidly coalesced into localized regions of damage, indicative of a brittle fracture mechanism. This behavior, characterized by concentrated crack propagation and abrupt loss of load-bearing capacity, suggests that the conventional RC joints are more susceptible to sudden stiffness degradation under cyclic loading (shown in Fig.7).

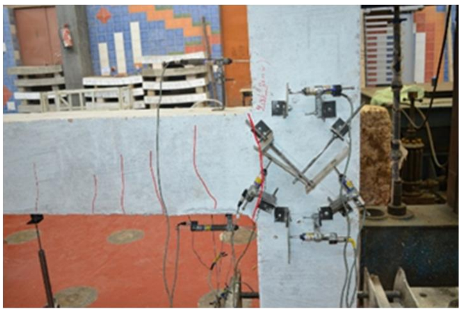
In contrast, the GPC specimens demonstrated a more refined and distributed pattern of cracking. Specifically, the joints fabricated with 15% metakaolin replacement presented numerous fine, evenly distributed microcracks rather than a few dominant cracks. This more uniform crack dispersion suggests an improved stress distribution within the geopolymer matrix, delaying the coalescence of cracks into a critical failure plane. Moreover, the 100% metakaolin specimens, while exhibiting higher ultimate strengths, tended to develop cracks in a more controlled manner with gradual propagation, culminating in a ductile failure mode that involved progressive yielding of the reinforcement and crushing of the concrete in the beam's plastic hinge zone.

The comparative analysis underscores that the conventional RC joints, due to their more heterogeneous and less ductile failure behavior, suffer from rapid degradation of structural integrity once cracking initiates. Conversely, the GPC joints, benefiting from a denser microstructure and enhanced bond characteristics, maintain a more gradual evolution of damage, thereby providing a more resilient response under cyclic loading conditions. These observations are corroborated by the measured deflection patterns and stiffness degradation data (refer to Table 4), which indicate that the controlled crack propagation in GPC joints contributes significantly to their superior energy dissipation and ductility under seismic-like loading.

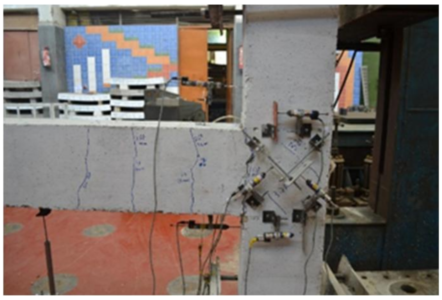


BS1-C100

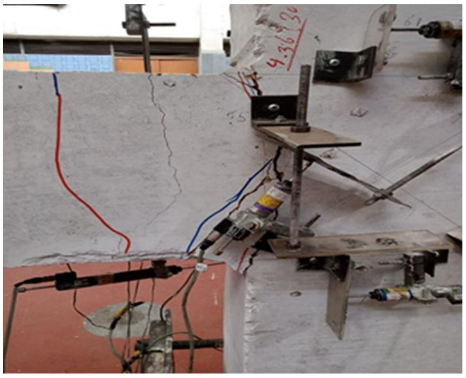
BS1-M15



BS1-M100

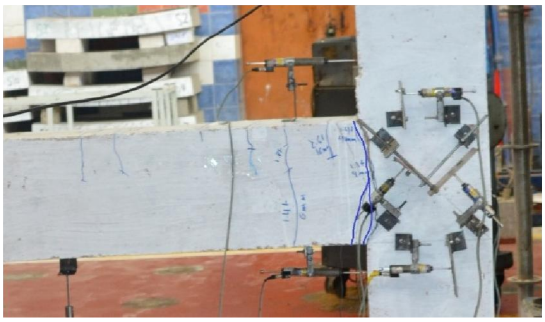


BS2-M15



BS2-M100

BS3-M15



BS3-M100

Fig. 5: Final failure modes of all test specimens

4.3. Energy Dissipations

The energy dissipation capacity was quantified by calculating the area enclosed by the hysteresis loops for each load–deflection cycle. As shown in Fig. 8, GPC joints—particularly those with full metakaolin replacement—demonstrated significantly greater cumulative energy absorption compared to conventional RC joints. The enhanced energy dissipation in GPC specimens is indicative of their superior ductility and ability to undergo extensive inelastic deformation before failure. This capability

EISSN: 2706-7920 ISSN: 2077-4435 **DOI: 10.36632/csi/2026.15.1.3**

is critical in seismic applications where high energy dissipation is required to mitigate the effects of earthquake-induced loads.

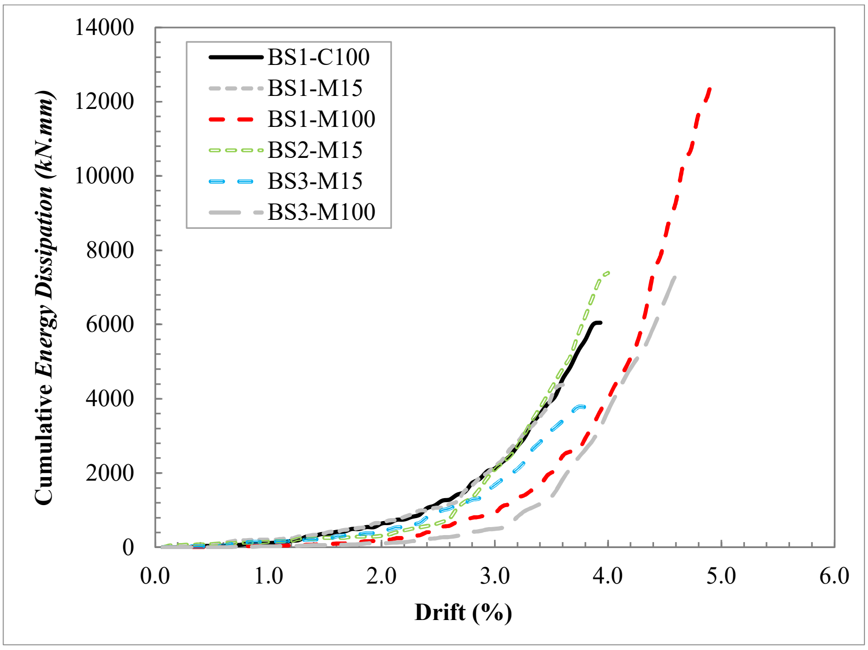


Fig. 8: Energy dissipation ratio of beam-column joint specimens

4.4. Stiffness Degradation

Secant stiffness was evaluated for each loading cycle to assess stiffness degradation under cyclic loading. The data, plotted in Fig. 9, show that all specimens experienced a reduction in stiffness with increasing load cycles; however, the rate of degradation was notably lower in the GPC joints relative to the RC joints. In particular, GPC specimens maintained a more consistent stiffness over higher load levels, suggesting a more effective load transfer between the geopolymer matrix and the reinforcement. This delayed stiffness degradation is attributed to the improved bond quality and denser microstructure of the GPC.

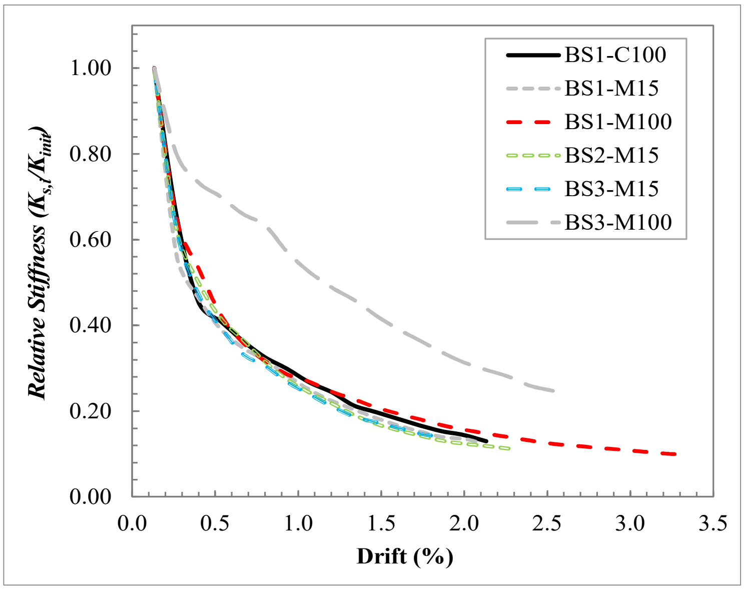


Fig. 6: Degradation of peak-to-peak secant stiffness for all test specimens

4.5. Effect of Anchorage Configurations

The influence of reinforcement anchorage configurations on the cyclic performance of beam–column joints was rigorously examined by comparing specimens employing three distinct detailing strategies: Type A (90° hooked bars), Type B (straight bars relying solely on bond over an extended development length), and Type C (bars arranged in a cross configuration to form a mechanical interlock). The experimental results reveal substantial variations in joint behavior attributable to these differing anchorage schemes.

Specimens with Type A detailing, incorporating 90° hooked bars, exhibited a higher initial cracking load, attributable to the enhanced end-bearing effect provided by the hook geometry. This configuration facilitated early crack resistance by effectively transferring tensile forces into compressive stresses within the confined joint core. However, despite the advantageous initial performance, these joints demonstrated a gradual reduction in stiffness following crack initiation, suggesting that the hooked system, while beneficial in delaying crack propagation, may be susceptible to bond degradation under repeated cyclic loading.

In contrast, Type B specimens, which utilized straight bars, showed comparatively lower performance in terms of ultimate load capacity and energy dissipation. The reliance on bond over an extended development length in these specimens resulted in a more pronounced bond-slip phenomenon, which, in turn, precipitated earlier stiffness degradation and reduced overall ductility. The lack of a geometric anchorage mechanism inherent to the straight bar configuration rendered these joints less effective in mitigating the adverse effects of cyclic loading.

Notably, the Type C configuration—where reinforcement from opposing members was arranged to cross and interlock mechanically within the joint—demonstrated superior performance overall. These joints not only achieved higher ultimate load capacities but also maintained a more consistent stiffness and exhibited enhanced energy dissipation throughout the loading cycles. The mechanical interlock provided by the cross bars ensured a robust transfer of forces and effectively curtailed the propagation of cracks, thereby enhancing the ductile behavior of the joint. The cumulative effect was a marked improvement in both load-bearing capacity and deformation capacity, underscoring the efficacy of the Type C anchorage system in providing resilient performance under seismic-like cyclic loading conditions.

In summary, while the Type A configuration offered improved initial crack resistance, its performance diminished under sustained cyclic loading. The Type B configuration, relying solely on bond, proved suboptimal in terms of load capacity and ductility. Conversely, the Type C configuration emerged as the most effective solution, delivering superior ultimate strength, energy absorption, and sustained stiffness retention. These findings illustrate that the choice of anchorage detail plays a pivotal role in determining the seismic performance of beam–column joints, with cross-bar configurations offering significant advantages in terms of structural resilience and ductility.

4.6 Effect of using CFRP sheets (Post-damage Strengthening Scheme)

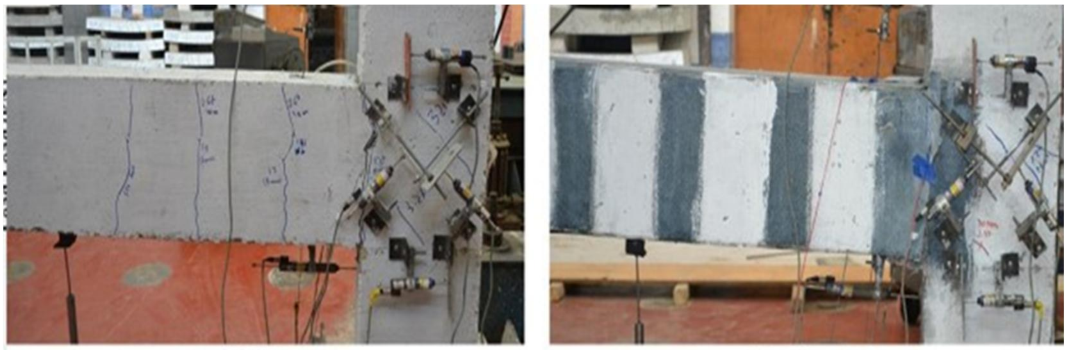
Following cyclic testing, the damaged beam–column joint specimens were repaired and subsequently strengthened using two distinct techniques—externally bonded CFRP (EB-CFRP) sheets. The original design of the beam–column joints, based on a strong-column, weak-beam concept, intentionally concentrated plastic hinge formation in the beam. The objective of the strengthening interventions was to preserve this beneficial failure mechanism by enhancing the flexural capacity of the beam while avoiding severe joint damage, thereby improving overall seismic resilience.

The process began by replacing spalled concrete with high-strength, non-shrink grout and sealing residual cracks with epoxy resin to ensure a uniform substrate. Strengthening was primarily achieved through externally bonded CFRP (EB-CFRP) sheets, featuring two flexural layers on the beam faces and supplementary transverse wraps spaced at 150 mm to enhance shear resistance and prevent debonding. To optimize performance, concrete corners were rounded to a 30 mm radius to reduce stress concentrations, and "CFRP 90° spike anchors" were installed at the corners to further reinforce the bond and mitigate edge debonding (as shown in fig. (10&11).

A comparative analysis of the lateral load-displacement (figure 12) curves reveals a significant enhancement in the seismic performance of the wrapped joints compared to the unwrapped control beams. The unwrapped specimens exhibit narrower hysteresis loops with a more pronounced pinching

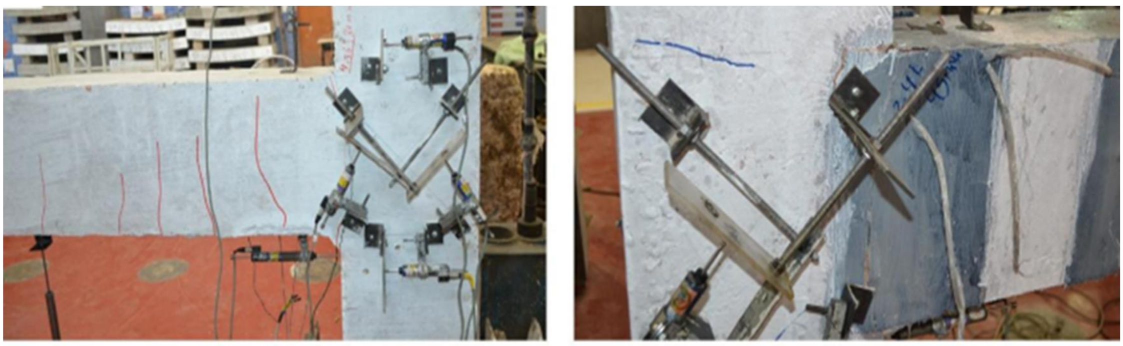
EISSN: 2706-7920 ISSN: 2077-4435 **DOI: 10.36632/csi/2026.15.1.3**

effect, indicating lower energy dissipation and a higher rate of stiffness degradation as the drift ratio increases. In contrast, the CFRP-wrapped joints demonstrate significantly broader and more stable hysteretic loops, signifying superior energy absorption capacity. Specifically, the peak lateral load for the strengthened specimens reached approximately 24.81 kN, representing a notable increase over the control specimens. This improvement is attributed to the external confinement provided by the CFRP sheets, which effectively constrained the joint core, delayed the onset of macro-cracking, and maintained the integrity of the bond between the geopolymer concrete and the internal reinforcement even at high displacement levels. Furthermore, the wrapped specimens maintained a higher percentage of their peak load at late-stage cycles, proving that CFRP wrapping is an essential intervention for achieving high-ductility performance in geopolymer concrete structures.



B-G15 B-G15-F

Fig. 10: Strengthing type B, 15% mitakaoline replacement



A-G100 A-G100-F

Fig. 11: Strengthing type A, 100% mitakaoline replacement

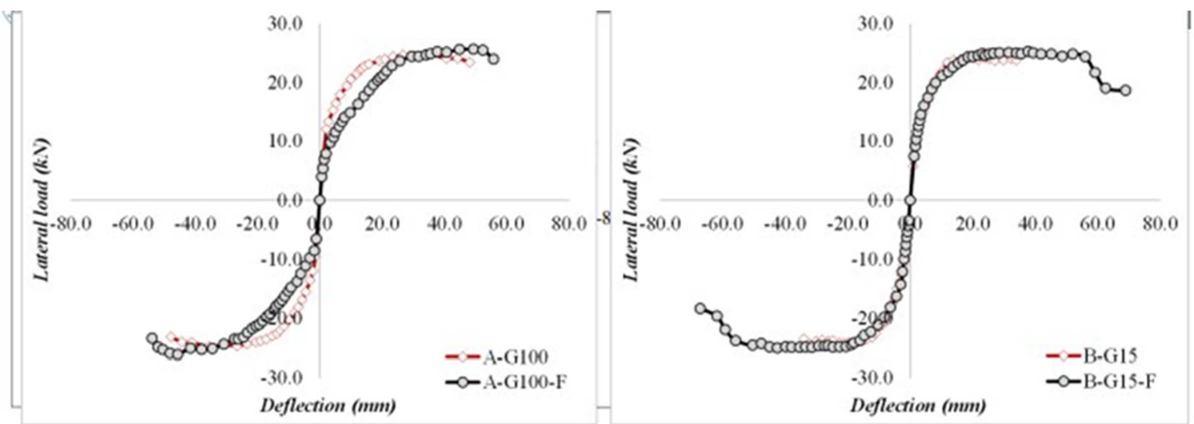


Fig. 12: Effect of strengthening Techniques using CFRP sheets

5. Conclusions

This study has provided a comprehensive experimental evaluation of the cyclic performance of beam–column joints fabricated with conventional reinforced concrete (RC) and metakaolin-based geopolymer concrete (GPC). Through a systematic investigation of two metakaolin replacement levels (15% and 100%) and three distinct reinforcement anchorage configurations (Types A, B, and C), the research has elucidated the significant influence of both binder composition and anchorage detailing on the seismic performance of critical structural connections.

The experimental results indicate that geopolymer concrete joints, particularly those fabricated with full metakaolin replacement, exhibit enhanced compressive strength, improved ductility, and greater energy absorption capacity compared to conventional RC joints. The broader hysteresis loops observed in GPC specimens under reverse cyclic loading underscore their superior ability to sustain inelastic deformations and dissipate seismic energy. Furthermore, the controlled crack propagation and delayed stiffness degradation in GPC joints suggest that the denser microstructure inherent to the geopolymer matrix contributes to a more resilient structural behavior under cyclic loading.

In addition, the comparative analysis of anchorage configurations reveals that while the Type A (90° hooked bars) detail offers higher initial crack resistance, and the Type B (straight bars) detail relies predominantly on bond strength, the Type C configuration—featuring cross bars designed to create a mechanical interlock—demonstrates the most favourable performance. Specimens employing Type C detailing exhibited higher ultimate load capacities, sustained stiffness, and improved energy dissipation, thereby validating the efficacy of mechanical interlocking in enhancing joint performance under seismic conditions.

The application of CFRP sheets (e.g., B-G15-F) reduced the rate of slip accumulation compared to the as-built state but did not fundamentally alter the pinched hysteresis shape of the Type B anchorage. The CFRP provided external confinement that delayed cover spalling, allowing the bond to sustain partial integrity up to higher drifts.

Collectively, these findings substantiate the potential of metakaolin-based geopolymer concrete as a viable and sustainable alternative to conventional OPC concrete, particularly in seismic regions where structural resilience and ductility are paramount. The results not only contribute to a deeper understanding of the material and structural behavior of geopolymer systems under cyclic loading but also provide valuable design insights that can inform future building codes and structural design guidelines.

Future research should focus on scaling these experimental findings to full-scale structural systems, exploring long-term durability under varying environmental conditions, and refining analytical models to better predict the behavior of geopolymer-based joints. Such efforts will further cement the role of geopolymer concrete in sustainable, low-carbon construction and its adoption in earthquake-resistant design.

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