Flexural Behavior of Precast Concrete Column-Column Joint with Bolt-Plate Connection

Tanayut Kaewjua[1,*], Withit Pansuk[2]

[1,2] Center of Excellence in Innovative Construction Materials, Department of Civil Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, THAILAND

**Corresponding author; E-mail address: 6670111221@student.chula.ac.th*

Abstract

This research investigated the flexural behavior of precast concrete column-to-column joints utilizing a bolt-plate connection system to enhance both structural performance and construction efficiency. Experimental flexural tests were conducted on Three different joint configurations, including strong and weak-axis orientations with bolt-plate connections and a conventional joint for comparison. The study aimed to evaluate key performance parameters such as ultimate flexural strength, stiffness characteristics, and failure mechanisms under controlled loading conditions using four-point bending tests. The findings indicated that the bolt-plate connection system resulted in approximately a 65% reduction in moment capacity and a 95% decrease in stiffness compared to conventional joints. Despite these reductions, the bolt-plate connections exhibited sufficient structural performance for practical applications. The results provided valuable insights into the structural behavior of bolt-plate connections and highlighted their limitations in terms of flexural strength and stiffness. The study's findings contribute to the development of practical design guidelines for optimizing the implementation of bolt-plate connections in modern precast concrete structures, supporting efforts to enhance sustainability and streamline construction processes.

Keywords: Precast concrete column-column joint, Flexural behavior, Flexural performance, Experimental testing

1. Introduction

Precast concrete construction has gained significant momentum as a preferred solution in modern structural engineering due to its ability to optimize project timelines, enhance quality control, and support sustainable development goals. By shifting the fabrication of structural components to factory-controlled environments, precast systems offer superior material quality, precise dimensional tolerances, and consistent performance compared to traditional cast-in-place methods. These benefits collectively reduce construction errors, accelerate site operations, and minimize environmental impacts by lowering concrete waste and emissions.

In addition to improved construction efficiency and quality, precast systems provide significant advantages in safety, cost predictability, and logistics management, particularly in urban and high-rise developments where space and time are constrained. The modular nature of precast components also supports faster installation, flexibility in design, and long-term maintainability.

However, one of the most critical aspects of precast systems is the behavior of the connections between structural elements, especially column-to-column joints, which govern the integrity and continuity of the structure. Each connection type—whether grouted, bolted, or hybrid—exhibits its own mechanical behavior, such as varying levels of moment resistance, stiffness, ductility, and deformation capacity. These behavioral characteristics are influenced by geometry, reinforcement detailing, and construction methods. Therefore, it is essential to experimentally determine and classify the performance of each joint type under realistic loading conditions, so that their roles in global structural performance can be accurately modeled and properly designed for safety and efficiency.

While many traditional joint methods such as in-situ grouting and welding have been widely used, they are labor-intensive, time-consuming, and prone to construction inconsistencies Zhang et al. [1] and Baji, H.[2] In response, dry mechanical connections—such as bolt-plate joints or column shoe systems—have emerged as viable alternatives. These systems are designed to simplify site assembly, reduce reliance on temporary support, and allow for higher accuracy and repeatability.

Bolted column shoe connections have gained attention for their modular, demountable, and sustainable nature. Yrjölä and Kinnunen [3] presented a new generation of bolted column shoes that are more compact, easier to install, and optimized for smaller column sections without compromising structural performance. Their research emphasized the environmental benefits of these systems, highlighting reduced carbon footprint, improved logistics, and enhanced safety on site. The ability to dismantle and reuse precast components also aligns with circular construction principles and international sustainability standards such as ISO 20887.

Building on these developments, Kinnunen [3] reported a comprehensive experimental study on HPKM® column shoes, verifying their structural performance under various loading conditions. Tests confirmed that these connections achieved equivalent or superior performance to cast-in-place joints in terms of rotational stiffness, bending strength, fire resistance, and shear capacity. These findings solidify the practical viability of bolt-based connections even for high-performance structural systems, especially where site speed and flexibility are critical.

Recent innovations further reinforce this approach. For instance, Zhan et al. [4] introduced a detachable precast joint system utilizing embedded steel plates and high-strength bolts. Their study showed that these joints not only improved construction speed but also enhanced structural integrity, with more than 11% greater initial stiffness and a 74% reduction in maximum strain compared to monolithic joints. These mechanical systems, though promising, require thorough investigation into their flexural behavior to confirm long-term reliability and structural resilience.

A key parameter in understanding the behavior of such joints is the moment–rotation relationship, which captures the interaction between applied bending moments and the rotational deformation of the connection. Studies by Mohd. Radzi et al. [5] and Lacerda et al. [6] emphasized that bolted connections generally exhibit semi-rigid characteristics, which significantly affect global structural response. Proper classification of joint stiffness and ductility is necessary for accurate modeling in design software, particularly in performance-based and seismic design frameworks.

To evaluate these characteristics, full-scale experimental testing is commonly employed. Standards such as EOTA TR 067 [7] provides established guidelines for testing column shoe systems under controlled flexural loading. These procedures enable engineers to determine rotational stiffness, bending resistance, and failure mechanisms in realistic conditions. Such data is crucial for developing design models that can replicate actual joint behavior under service and ultimate loads.

This study investigates the flexural behavior of precast concrete column-to-column joints using bolt-plate connections through large-scale experimental testing. The research focuses on evaluating key performance indicators such as ultimate moment capacity, rotational stiffness, deformation patterns, and failure modes. Three joint configurations were tested under four-point bending and compared against a monolithic control specimen. By integrating insights from previous research and applying standardized evaluation methods, this study aims to support the advancement of practical, efficient, and sustainable precast connection systems suitable for a wide range of modern construction applications.

2. Joint Configuration

The bolted column-to-column joint used in this study adopts a dry mechanical connection system designed to facilitate rapid assembly and ensure structural continuity without the need for in-situ concrete casting. As illustrated in Fig. 1, the joint comprises key components including anchor bolts, a base plate, anchor rebars, non-shrink grout bedding, and standard reinforcement details.

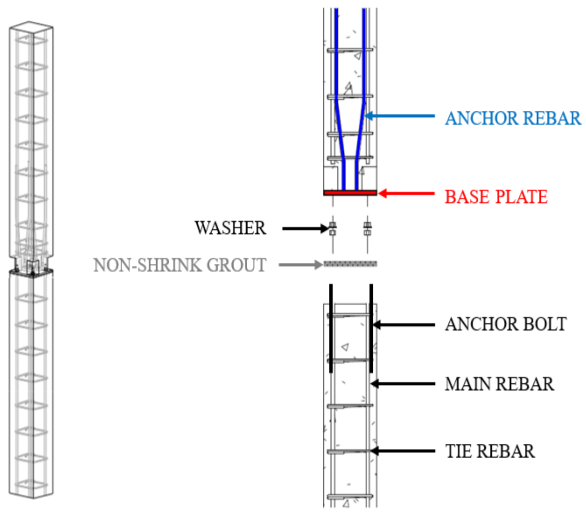

Fig. 1. Joint configuration

The lower precast column segment is pre-installed with vertically embedded anchor bolts, which protrude from the top surface and align with the base plate of the upper column. The upper column includes pre-positioned anchor rebars, which are welded or mechanically anchored to the base plate. These rebars are designed to transfer axial and bending forces from the upper to the lower segment.

During installation, a thin layer of non-shrink grout is applied between the columns to ensure uniform load transfer and eliminate gaps. The base plate rests on top of this grout layer and is secured using washers and nuts threaded onto the exposed anchor bolts. This configuration provides a high degree of mechanical interlock and allows the joint to resist axial compression, flexural tension, and shear forces.

Reinforcement details within both column segments consist of main longitudinal rebars and transverse tie rebars, maintaining structural integrity and confinement. The use of anchor rebars and bolts creates a semi-rigid connection capable of transferring moments across the joint interface, while still allowing controlled deformation underloading.

One of the distinguishing features of this joint system is its dry assembly method, which eliminates the curing time associated with wet joints and significantly accelerates construction. Additionally, the bolted configuration enhances modularity and demount ability, aligning with sustainable construction principles and enabling future reuse or replacement of components.

3. Experimental Program

3.1 Material Properties

The material properties used in this experiment reflect commonly used materials in Thai construction. These standard materials help ensure that the results of this study are relevant and applicable to typical local building practices. The details of the materials used are summarized below

Concrete: Compressive strength of 35 MPa (cylinder test result)

Main Reinforcement: SD-40 steel rebars with a yield strength of 390 MPa and tensile strength of 560 MPa.

Stirrup Reinforcement: SR-24 steel rebars with a yield strength of 235 MPa and tensile strength of 385 MPa.

Steel Plate: SS400 grade steel with a yield strength of 235 MPa and tensile strength of 400 MPa.

Bolt: 8.8 grade with a yield strength of 660 MPa and tensile strength of 830 MPa.

3.2 Specimen Details

Three specimens were prepared to assess the performance of bolt-plate connection systems in comparison to conventional joints. All samples measured **200 mm x 200 mm** in cross-section and were reinforced with **4-DB12** main bars and **RB6@75** tie bars. Identical materials and reinforcement configurations ensured consistency across specimens to isolate the effects of connection types. The test samples are represented in Fig. 2.

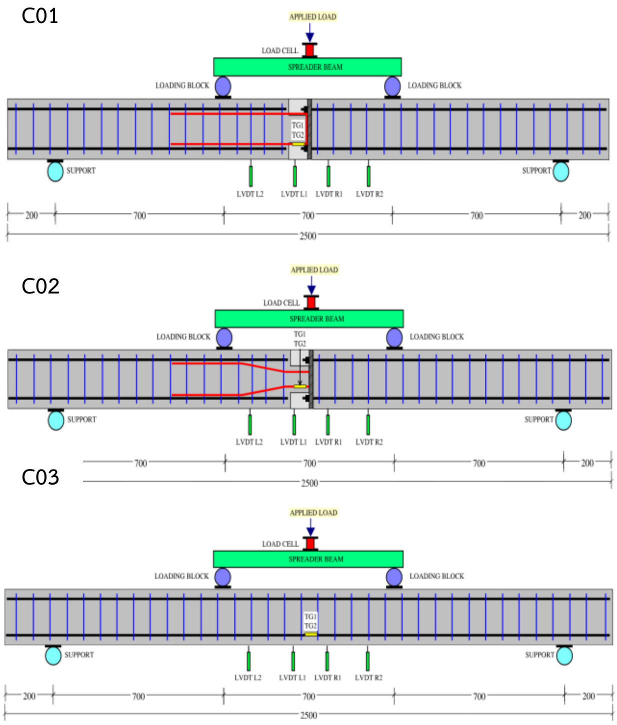

Fig. 2. 4-point flexural test setups—C01: Precast joint with bolt-plate connection (strong axis), C02: Precast joint with bolt-plate connection (weak axis), and C03: Conventional joint (comparison).

3.3 Flexural Testing Configuration

To evaluate the flexural behavior of precast column-to-column joints, two types of flexural testing methods were adopted: the 3-point and 4-point bending tests. These were selected to simulate realistic service loading conditions and to comprehensively assess each joint's performance in terms of strength, stiffness, and deformation capacity.

The 4-point flexural test followed ASTM C78/C78M-21 [8] and was used for C01, C02, and C03, as illustrated in Fig. 3. In this method, two equal loads are applied symmetrically at one-third of the span, creating a constant moment region between the loading points. This setup allows a more detailed investigation of flexural stiffness, cracking behavior, and joint response across a wider span.

These configurations were selected to reveal the performance differences between bolt-plate connections and conventional joints under different bending scenarios. The use of both testing methods ensured a comprehensive evaluation of joint behavior in realistic structural conditions.

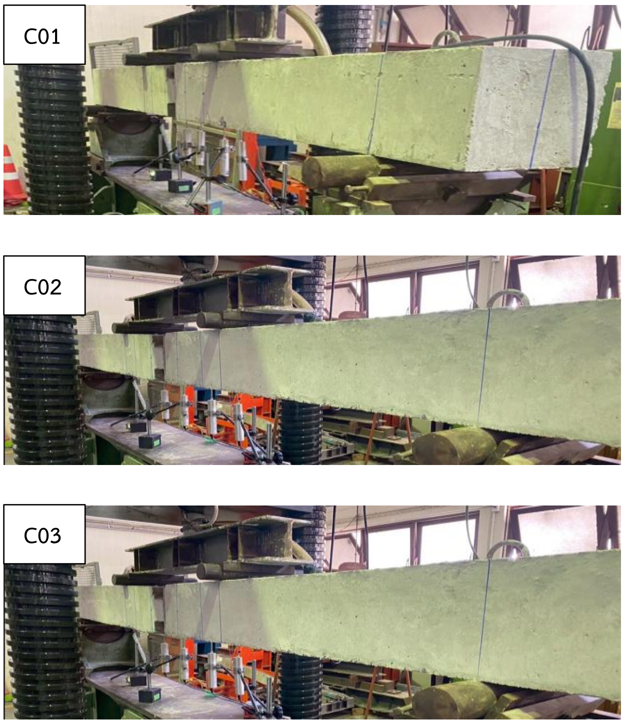

Fig. 3. Actual test setups for 4-point flexural test

3.4 Measurement Techniques

To ensure accurate and reliable results, the flexural tests were supported by a carefully arranged instrumentation system. A load cell was positioned above the actuator to capture real-time applied forces with high precision. LVDTs (Linear Variable Differential Transformers) were installed at mid-span zones to measure vertical deflection and calculate joint rotation from different position of them.

Strain gauges were affixed to the bottom longitudinal reinforcement near the joint area to record tensile strain during loading, as shown in Fig.4. and for Conventional column, it was installed at the middle of bottom beam. These instruments provided insights into stress development and potential yielding behavior.

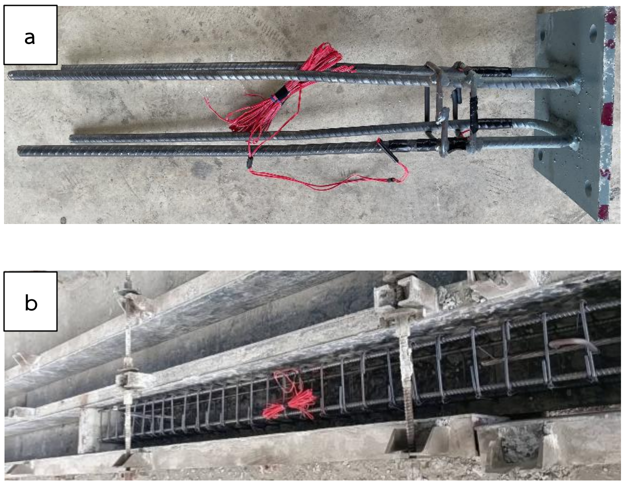

Fig. 4. Positions of strain gauges on (a) precast joint with bolt-plate connection and (b) conventional joint.

All sensors were connected to a digital data logger system as shown in Fig. 5., enabling continuous monitoring throughout the test. Inspections were conducted alongside instrumentation to joint separation and failure progression. Photographs were taken during key stages to support the measured data.

Fig. 5. Data logger applied during testing

4. Result and Discussion

4.1 Failure mechanisms

The failure of specimen C01 was characterized by localized concrete crushing and edge spalling around the bolt anchorage zones. Cracking initiated at the lower region near the embedded bolt and propagated toward the top surface. The separation at the joint interface suggests partial bolt slippage and loss of bearing area. This indicates that the connection transferred load primarily through bearing at the bolt-concrete interface until local crushing initiated joint opening. The absence of significant concrete breakout implies that the failure was more governed by bearing stress and sliding rather than full flexural cracking.

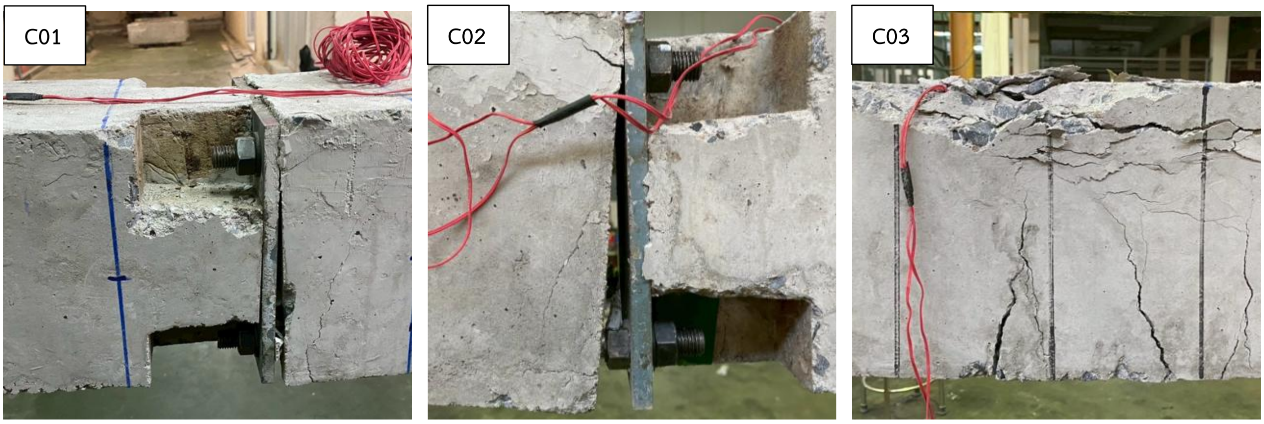

Fig.6. Failure of specimen C01, C02, and C03 after 4-point flexural test

Specimen C02 exhibited joint opening combined with a clear loss of interface integrity between the plate and concrete surface. The concrete cover near the bolts fractured, and clear separation between the precast elements was visible. This suggests that the weak axis configuration allowed for higher rotation and induced prying effects at the bolt ends. The system primarily failed through progressive interface opening, reduced confinement, and bolt tilting, indicating a more flexible but less ductile response compared to the strong-axis connection.

The conventional specimen C03 failed by the formation of wide, diagonal cracks near the center of the beam under flexural load. Severe concrete crushing occurred at the top fiber, accompanied by vertical and inclined flexural-shear cracks spreading downward. This mode of failure is typical for monolithic flexural behavior, governed by reinforcement yielding followed by concrete crushing in the compression zone. Unlike the bolt-plate joints, the failure was gradual and ductile,

4.2 Ultimate moment capacity

The ultimate flexural moment capacities of the tested specimens are summarized through the moment-rotation curves (Figs. 7–9). Specimen C03 (monolithic joint) exhibited the highest ultimate moment capacity of 20.12 kNm, followed by specimen C01 (strong-axis bolt-plate joint) at 7.13 kNm, and specimen C02 (weak-axis bolt-plate joint) at 6.32 kNm. These results reflect the superior load-bearing performance and continuity of the monolithic joint compared to the bolt-plate connections, where stress concentrations and localized concrete crushing reduced moment resistance.

4.3 Moment – Rotation relationship

The moment–rotation curves for specimens C01, C02, and C03 are presented in Fig. 7–9. These plots provide insight into the flexural performance and rotational ductility of each joint configuration under four-point bending.

The moment–rotation curve of specimen C01, representing a bolt-plate connection under strong-axis bending, shows a moderately stiff and gradual response. In the early stage, the moment increases steadily with slight curvature before reaching yield point. The yield point occurs at a moment of 5.83 kNm and a corresponding rotation of 0.05246 radians. Beyond yielding, the moment continues to increase smoothly, reaching the ultimate value of 7.13 kNm at a rotation of 0.09991 radians. The overall curve progression is stable without abrupt changes, indicating controlled deformation behavior. The calculated ductility factor is 1.91, suggesting that specimen C01 behaves as a semi-rigid connection with moderate rotational capacity.

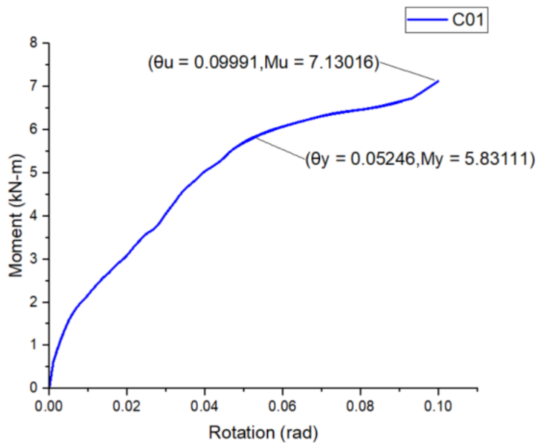

Fig. 7. Moment-Rotation curve of C01

The moment–rotation curve of Specimen C02, which represents a bolt-plate connection under weak-axis bending, shows a more gradual and flexible response compared to C01. The curve begins with a linear slope and reaches the yield point at a moment of 5.46 kN·m with a corresponding rotation of 0.05132 radians. It continues to rise steadily and reaches its ultimate moment of 6.32 kN·m at 0.15288 radians. The curve indicates a longer rotation range beyond yielding, and the calculated ductility factor is 2.98, suggesting that C02 also behaves as a semi-rigid connection with greater rotational capacity than C01. The relatively flat curve beyond the yield point implies that the joint can redistribute stress effectively without experiencing sudden failure, which is beneficial in seismic or dynamic load scenarios.

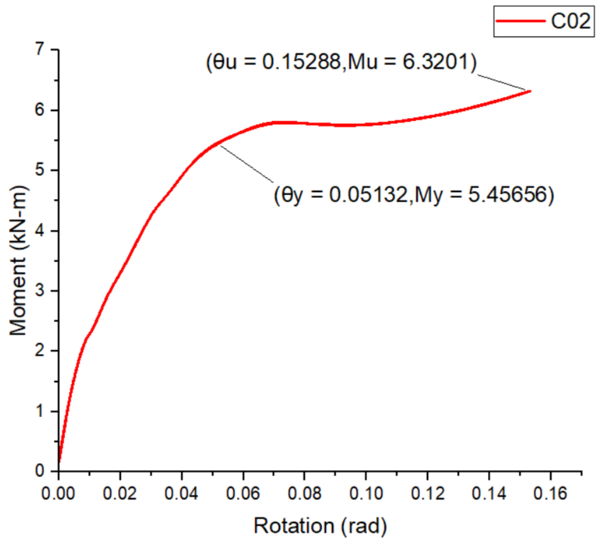

Fig. 8. Moment-Rotation curve of C02

The moment–rotation curve of Specimen C03, representing a monolithic cast-in-place joint, shows a sharply rising and steep behavior. The curve reaches the yield point at a moment of 18.74 kN·m with a rotation of 0.0079 radians, followed by the ultimate moment of 20.12 kN·m at 0.01675 radians. The curve remains nearly linear until the peak and then flattens quickly, indicating limited deformation after yielding. The calculated ductility factor is 2.12, and the joint behaves as a rigid connection with high stiffness and limited rotational capacity.

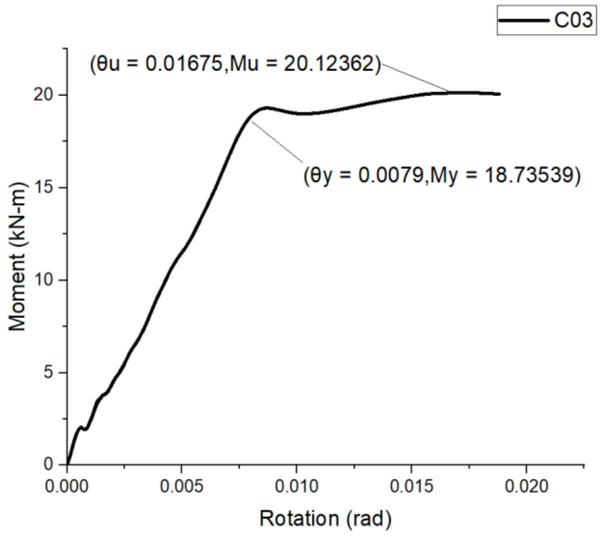

Fig. 9. Moment-Rotation curve of C03

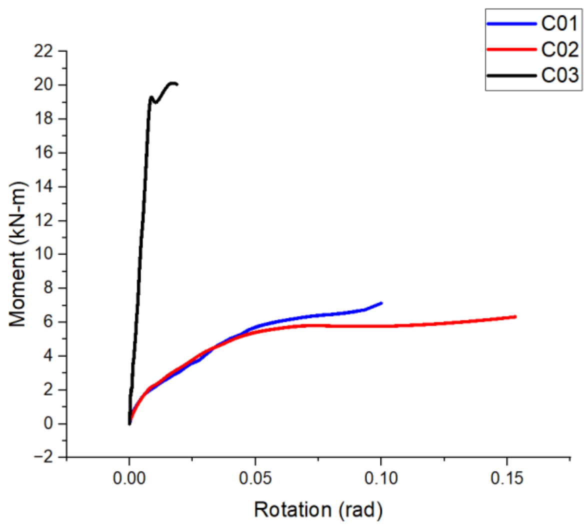

Fig. 10. Comparison of Moment–Rotation Relationships for All Specimens

The combined moment–rotation curves for specimens C01, C02, and C03 as shown in Fig. 10 illustrate clear differences in structural behavior due to their joint configurations. C03, the monolithic cast-in-place specimen, exhibits the steepest initial slope, reflecting high stiffness and strength, with a nearly linear response up to its ultimate moment. However, its rotation capacity is limited, as indicated by the short horizontal range, confirming that C03 behaves as a rigid connection. In contrast, C01 and C02, which are bolt-plate joints, show significantly lower stiffness and strength but much broader rotation capacity, characteristic of semi-rigid behavior. Between the two, C02 demonstrates the highest ductility factor, allowing more deformation after yielding despite having the lowest moment capacity. C01 maintains a more stable and gradual curve than C02, suggesting more balanced behavior between stiffness and flexibility. These comparisons highlight a trade-off between strength and rotational capacity: while C03 is best suited for applications requiring high moment resistance, C01 and C02 offer advantages where controlled flexibility or post-yield rotation is desirable.

4.4 Rotational stiffness

The slope of the moment–rotation curve represents the rotational stiffness of the joint, indicating its resistance to angular deformation under flexural loading. As the joint undergoes nonlinear behavior, the stiffness typically degrades due to cracking, interface separation, and local damage. To evaluate this stiffness consistently, secant stiffness is used—defined as the slope of the line connecting the origin to a key point on the curve, usually the yield point or the point where the slope begins to change before the peak moment. This provides a practical and meaningful representation of joint rigidity before major inelastic deformation occurs.

In this study, the calculated secant stiffness values revealed distinct differences among the specimens. The conventional monolithic joint (C03) exhibited the highest stiffness at 2371.57 kN·m/rad, reflecting its rigid, continuous load path and full reinforcement continuity. The bolt-plate connection specimens showed significantly lower stiffness, with C01 at 111.12 kN·m/rad and C02 at 106.29 kN·m/rad, corresponding to their reduced moment capacity and localized deformation behavior. These results confirm that while bolt-plate systems may offer construction advantages, they exhibit considerably lower initial rotational stiffness compared to monolithic designs.

5. Conclusion

This study investigated the flexural behavior of precast column-to-column joints with bolt-plate connections in comparison to a conventional monolithic joint. All specimens were tested under four-point bending to evaluate moment capacity, rotational stiffness, and failure characteristics.

Table 1 summarizes the ultimate moment capacity and rotational stiffness of all specimens. Specimen C03, serving as the control specimen with a conventional monolithic joint, achieved the highest values in both categories and was used as the benchmark for comparison. The bolt-plate specimens, C01 and C02, exhibited significantly lower moment and stiffness values—approximately 32–35% in strength and only 4–5% in stiffness relative to the control. This quantitative comparison highlights the substantial structural difference between traditional monolithic and bolt-connected joints under flexural loading.

Table 1 Summary of Flexural Performance of All Specimens

Specimen	Ultimate moment (kN·m)	Moment Percentage of C03 (%)	Rotational Stiffness (kN·m/rad)	Stiffness Percentage of C03 (%)	Ductility Factor
C01	7.13	35.43	111.12	4.69	1.91
C02	6.32	31.42	106.29	4.48	2.98
C03	20.12	100.00	2371.57	100.00	2.12

In terms of failure, bolt-plate joints were governed by localized concrete crushing and joint separation, while the monolithic joint failed through flexural cracking and concrete crushing at the top fiber. Notably, insufficient concrete cover around the embedded bolts led to premature spalling and stress concentration in the bolt-plate specimens. The lack of confinement in these regions reduced the effective bearing area and contributed to early failure.

These findings emphasize the need for improved anchorage detailing and sufficient concrete cover in bolt-plate designs to ensure better performance. While bolt-plate systems can accelerate construction and offer flexibility, their structural limitations must be addressed to make them viable alternatives to conventional joints.

Acknowledgement

Thanks Center of Excellence in Innovative Construction Materials, Department of Civil Engineering, Chulalongkorn University for cooperation

References

[1] Zhang, R., Zhang, Y., Li, A., & Yang, T.Y. (2022). Experimental study on a new type of precast beam-column joint. Journal of Building Engineering, 51, 104252. https://doi.org/10.1016/j.jobe.2022.104252

[2] Baji, H. & Ronagh, H., *INVESTIGATION OF DUCTILITY OF RC BEAMS DESIGNED BASED ON AS*3600. 2011.

[3] Yrjölä, J. & Kinnunen, J. *Bolted Column Shoe Connections – Sustainable and Smart Solution for Precast Structures*. in *Building for the Future: Durable, Sustainable, Resilient*. 2023. Cham: Springer Nature Switzerland.

[4] Zhan, H., Ye, M., Jiang, J., Gao, Y., Zheng, C.W., & Duan, S.C. (2024). Structural performance of detachable precast concrete column-column joint. Heliyon, 10(5), e27308. https://doi.org/10.1016/j.heliyon.2024.e27308

[5] Mohd. Radzi, N.A., Hamid, R., A. Mutalib, A., & Kaish, A.B.M. (2020). A Review of Precast Concrete Beam-to-Column Connections Subjected to Severe Fire Conditions. Advances in Civil Engineering, 2020, 1-23. 10.1155/2020/8831120

[6] Lacerda, M.M.S., da Silva, T.J., Alva, G.M.S., & de Lima, M.C.V. (2018). Influence of the vertical grouting in the interface between corbel and beam in beam-to-column connections of precast concrete structures – An experimental analysis. Engineering Structures, 172, 201-213. https://doi.org/10.1016/j.engstruct.2018.05.113

[7] EOTA, *Bending of Column Shoe Connections - Tests and Results*. 2018.

[8] ASTM, *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading)*. 2016.