Hybrid Beam-Column Connection of Precast Concrete Structures: A Review

Yanisfa Septiarsilia[1*], *Data* Iranata[1], and *Budi* Suswanto[1]

[1]Sepuluh Nopember Institute of Technology, 60111 Surabaya, Indonesia

Abstract. The use of precast concrete materials as structural elements has become common practice. Precast concrete material offers various advantages over cast in place concrete, including energy-saving, pollution reduction, increased labor productivity, high material durability, reduced formwork and scaffolding usage, faster construction, and the ability to carry out construction in any weather conditions. However, there are some disadvantages in assembling precast elements, particularly in connection areas, which serve as the main structure of a building. Several studies have been conducted to develop connection types for precast concrete. Some of these include dry connections and wet connections, each with their own advantages and disadvantages. To mitigate the weakness of both connection types, many studies are currently focusing on developing a combination of dry and wet connections known as Hybrid Connections. Various developments have been made in the Hybrid connection system.

1. Introduction

Precast concrete structure is known as the assembly of monolithic elements manufactured with fabrication standards and then transported to the construction site for assembly [1]. Precast concrete offers several advantages over conventional concrete, including energy efficiency, pollution reduction, increased labor productivity, high material durability, reduced formwork and scaffolding usage, faster construction, and the ability to carry out construction in any weather conditions, as well as ease in Quality Control [2][3][4]. Precast concrete technology offers numerous advantages compared to cast-in-place concrete structures. However, the application of precast concrete has weaknesses, particularly in terms of connections, especially in beam-column connection elements. Weaknesses in beam-column connections significantly impact the structural performance under seismic loads. The beam-column connection region must ensure sufficient strength and ductility to meet load-bearing requirements during seismic events. This is crucial for moment frame structural systems subjected to lateral loads, as the beam-to-column connections must be capable of withstanding substantial forces and displacements [5]. The beam-column connection is a crucial element in transferring forces between connected beams and columns. If not well-planned in terms of connection placement and strength, it can lead to alterations in force flow within the structure. This could potentially disrupt the intended hierarchy of failure modes that the structure is designed to achieve [6]. Weaknesses in beam-column connections significantly impact the structural performance under seismic loads. In structures subjected to lateral loads, such as moment frame systems, the beam-column connections must be capable of withstanding substantial forces and displacements. The beam-column connection region must ensure sufficient strength and ductility to meet load-bearing requirements during seismic events. This is crucial because the beam-column connections play a vital role in maintaining the overall stability and integrity of the structure, especially when it comes to resisting the dynamic forces generated by earthquakes [5]. Therefore, the behavior of connection elements must ensure strength and stiffness during seismic events, allowing the structure to achieve the required ductility as stipulated by moment frame systems [3][7][8]. Several similar studies have been conducted on buildings subjected to significant earthquakes. The findings from these investigations have led to the conclusion that inadequate shear capacity is often attributed to improper detailing in beam-to-beam and beam-to-column connections, which can result in structural failure [9]. The results of these investigations have led to the conclusion that inadequate shear capacity is often due to improper detailing in beam-to-beam and beam-to-column connections. Therefore, the development of new beam-column connections that are reliable and exhibit favorable behavior under seismic forces is necessary

*Corresponding author: yanisfa.septi@gmail.com

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

[10]. This improper detailing can lead to structural failures, primarily as a result of insufficient shear resistance within these connections [4], This is illustrated in Figure 1.

Fig. 1. Structural failures of precast elements in beam-column connections in building structures due to seismic loads [4]

Currently, various connection systems have been developed to enhance performance, particularly under seismic loads. One of these advancements pertains to the Hybrid beam-column connection, which offers several advantages. The Hybrid Connection is a combination of both Dry Connection and Wet Connection methods. Hybrid Connections come with numerous benefits, such as reducing formwork and scaffolding usage during construction, eliminating the need for corbels, improving the reinforcement continuity between beams and columns, and enhancing the overall connection integrity to prevent premature failures [11]. Connections using steel in beams and columns can enhance ductility at joints and ensure that concrete in the joint area remains undamaged. Connections rely on the transfer of forces between beam and column elements and the continuity between them. Precast Hybrid Connections have the same capacity as monolithic connections, including strength, energy dissipation, and drift [12][13].

2. General Review and Method

Precast concrete connections in seismic-resistant structures are classified into two types: emulative and jointed. Emulative connections are designed and detailed so that the behavior, including strength, stiffness, and energy dissipation, of precast concrete can be compared with conventional concrete (monolithic systems). Emulative connections are further divided into two types: ductile and strong. Structures with ductile connection elements are designed to allow flexural yielding and plastic hinge formation at the joint between elements. On the other hand, structures with strong connections are designed with predetermined flexural yielding in the precast elements. In jointed construction, the concept of precast connections is utilized with a nonlinear approach, focusing on the end of the precast elements in the connection region. The emulative connection is shown in Figure 2 [14].

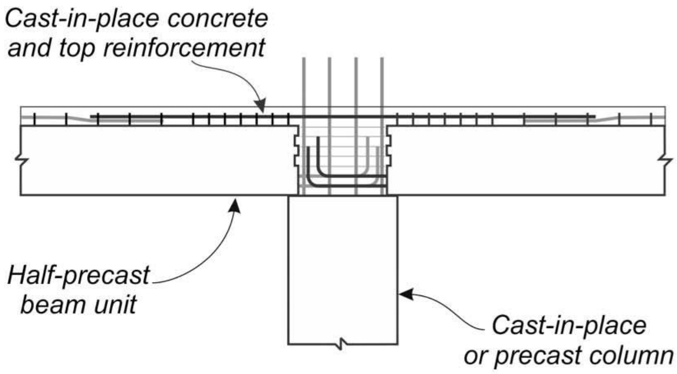

Fig. 2. Sambungan Emulative pada Beton Precast [14]

Moment frame systems incorporating precast elements, there are challenges in finding an economical and practical approach for assembling and integrating precast and conventional elements. This must be done while ensuring the stiffness, strength, ductility, and stability of the structure. Considerations extend to the construction phase as well as the load capacity during service and ultimate conditions, both at the serviceability limit state and the ultimate limit state [2].

According to [11], precast connections are classified into two types in construction methods: dry connections and wet connections. However, for the purpose of enhancing capacity and structural continuity while facilitating implementation, a combination of dry and wet connections is developed into a hybrid connection. The concept of the beam-column connection must possess stiffness and strength with clear force transfer, allowing shear forces and moments to be transmitted safely. Plastic hinges should be limited to ensure stability and safety in the connection region. Innovative beam-column connections have been studied to achieve the criteria of strong connections with weak members. The type of connection used significantly influences the behavior of the structure. Shear failure in the connection region can lead to collapse. The ratio of column flexural strength (ΣMc) to beam flexural strength (ΣMb) is one parameter that affects connection performance. According to the requirements of [15], the flexural strength ratio should be ≥ 1, as indicated in Fs= ΣMc/ΣMb.

2.1. Experimental Program

In the study of beam-column connection elements, experimental testing is conducted. This involves testing specimens of beam-column elements under axial loading and cyclic loading. The testing process follows relevant reference standards associated with each type of test.

Test Set Up and Loading Procedure

The boundary conditions and test setup for the interior beam-column connection specimen is illustrated in Figure 3 [16]. The geometry and dimensions of the specimens are determined based on the span of the beam and column in the prototype structure. Several LVDTs (Linear Variable Differential Transformers) are positioned on the column and beam sections to monitor lateral movements throughout the testing. The hydraulic actuator functions as the source of cyclic loading, following the pre-planned load cycle. An example of how the load cycle is determined is illustrated in Figure 4 [16].

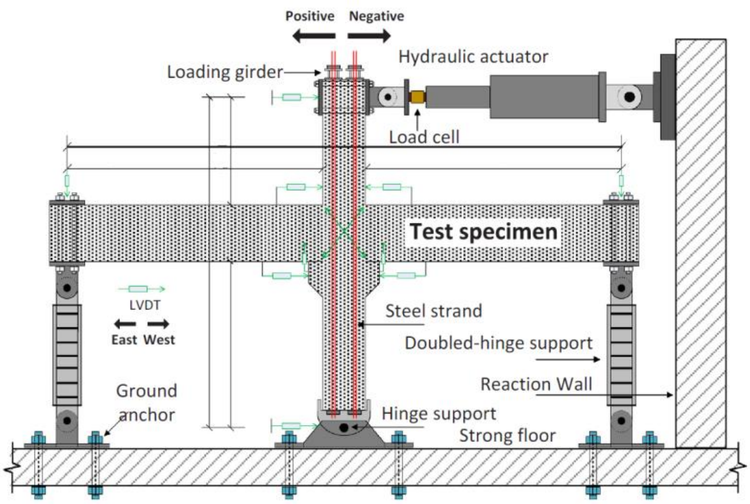

Fig. 3. Test Set Up [16]

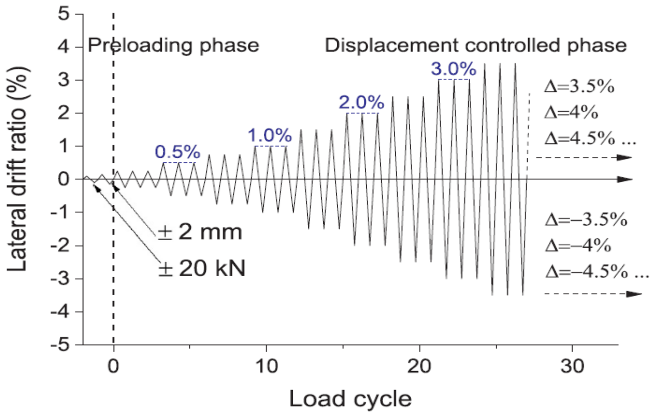

Fig. 4. Loading Cyclic Procedure [16]

In this study, the load cycle used is based on the standard guidelines [17]. The testing under cyclic loading follows the provisions in Section 5.2 of [17], as shown in Figure 5. The loading procedure is related to controlling the deformation parameter (displacement) with respect to the yielding condition (fy). There are two crucial parameters that determine the capacity:

1. Increasing the deformation control parameter to determine each deformation level.
2. Cycles at each deformation level.

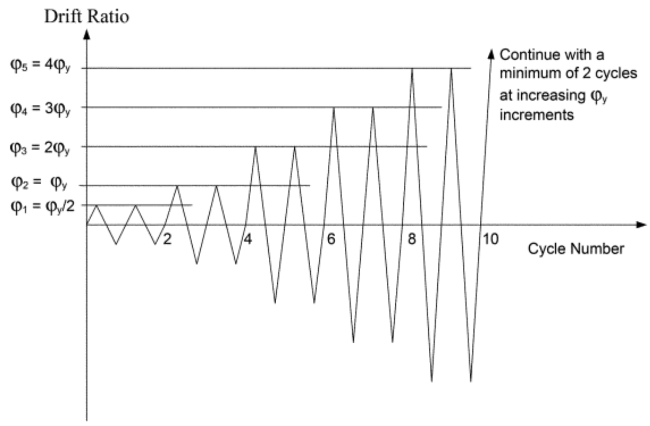

Fig. 5. Cyclic Loading Protocol [17]

The minimum cycle requirement at each drift ratio level is two cycles to observe the damage pattern occurring at that specific drift level, but three cycles are commonly used in testing. The selection of the number of cycles at each deformation level is adjusted according to the system being tested.

Structural testing is conducted to determine whether the structural performance aligns with the planned criteria. There are four structural performance levels based on ASCE/SEI:

1. Operational: No significant damage to structural and non-structural components.
2. Immediate Occupancy: No significant damage to structural components; non-structural components remain safe and functional if utilities are available.
3. Life Safety: Significant structural damage with stiffness reduction. Non-structural elements remain safe but may not function.
4. Collapse Prevention: Damage to both structural and non-structural components. Structural strength and stiffness are degraded.

These performance levels are chosen based on the potential damage that a structure might experience during an earthquake. Figure 6 illustrates the structural performance levels based on lateral drift ratio observed in frame buildings.

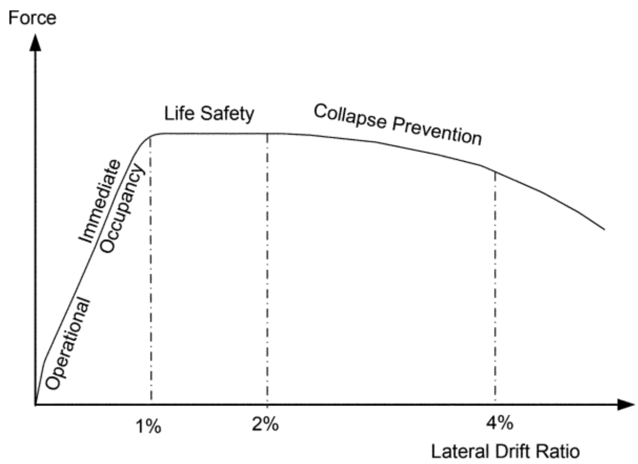

Fig. 6. Performance Level [17]

2.2. Computer Modelling using ABAQUS

Numerical modeling was carried out using the ABAQUS software with the finite element method. In the numerical modeling, dimensions of beam and column elements, as well as specific material parameters, were taken as measured values from actual testing. Numerical modeling was conducted as an effort to validate and verify experimental results. An example of the modeling process and its outcomes on the beam-column joint is illustrated in Figures 7

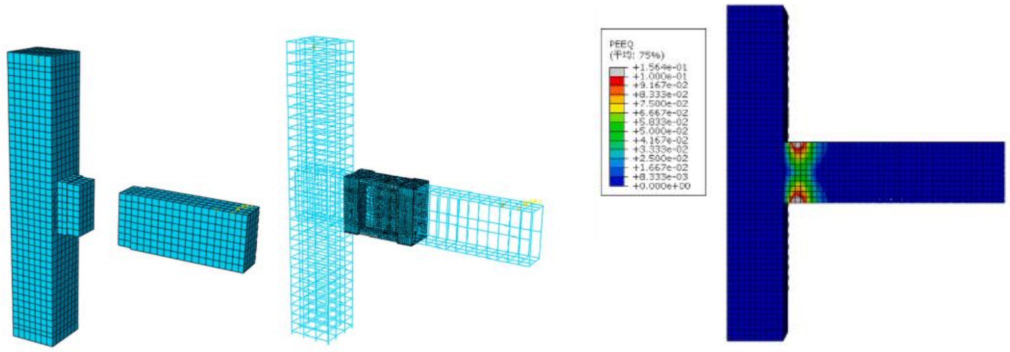

Fig. 7. Beam-column connection modeling using ABAQUS [18]

The processes within the ABAQUS modeling are divided into several stages or modules. Each module has specific functions in defining the model, and each module contains tools relevant to its specific function. Some of these modules include:

1. Parts Module: In this module, individual parts of elements are created by sketching their geometries or by importing geometries from other geometry programs.
2. Property Module: Sections and mechanical properties are created and applied to each part in this module.
3. Assembly Module: In this module, individual parts with their respective coordinate systems are combined into a global coordinate system. The relative positions between parts are adjusted to create a unified model. Parts placed in the assembly module are called part instances. An ABAQUS model can only have one assembly.
4. Step Module: In this module, analysis steps are created and configured. Output requests can also be configured based on requirements.
5. Interaction Module: Mechanical and thermal interactions between regions of the model or between the model and its environment are defined in this module. For instance, contact interactions between surfaces. ABAQUS/CAE cannot recognize mechanical contact between part instance surfaces of an assembly unless that contact is specifically defined in the interaction module. Interactions are step-dependent objects, meaning each interaction must be defined in the analysis step in which it operates.
6. Load Module: Loads, boundary conditions, and predefined fields are defined in this module. Loads and boundary conditions are step-dependent, meaning they must be defined in the analysis step they operate in. Some predefined fields are step-dependent, while others are applied only at the start of analysis.
7. Mesh Module: This module provides tools to create element meshes on the assembly that has been constructed.
8. Job Module: Analysis of the model is performed and monitored in this module. Multiple models and runs can be executed and monitored simultaneously.
9. Visualization Module: This module offers graphical representation of the element model and analysis results. Output information corresponds to requested output information, specifically output requests made in the step module.

3. Preview Research Work

In this chapter, several studies with various variations of hybrid beam-column connection development are discussed. Hybrid Connection studies have been widely conducted recently, due to the need for advancements in precast assembly methods that can accelerate the construction process. In the details of the proposed beam-column connection in the study [19], the beam-column joint elements, which are detailed in nature, use a steel connector and ECC material (engineered cementitious composite) that can enhance the constructability of the connection and transfer forces between precast elements. Modifications to the connection involve using a U-shaped form in the joint

https://doi.org/10.1051/e3sconf/202343402019

area, and within this U-shaped form, ECC will be filled with a composition of 1%. The proposed connection model in this study is detailed in Figure 8.

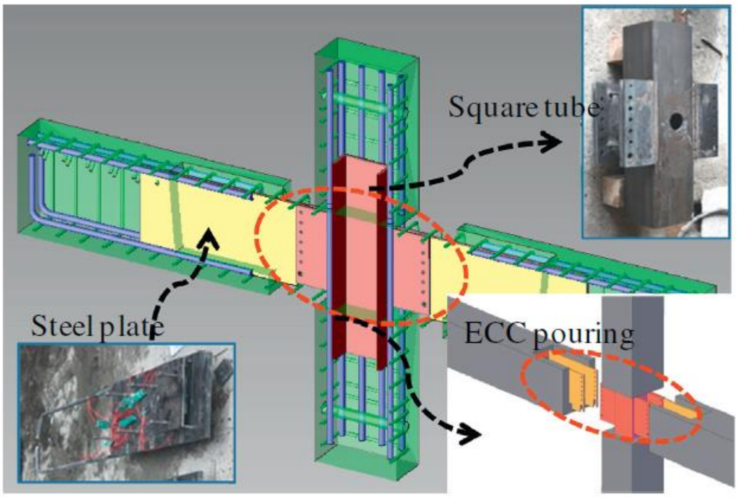

Fig. 8. Proposed model of beam-column connection [19]

The study [19] conducted tests on two types of connections, namely the inside type with a steel connection within the column and the outside type with a steel connection outside the column, as detailed in Figure 9. The construction method involved assembling the precast column, then assembling and bolting the precast beam onto the steel column connector. Experimental testing was performed on one control specimen and four modified specimens in half scale. The results of the study showed that the proposed hybrid beam-column connections exhibited an increase in maximum strength compared to the control specimen. Furthermore, the developed connections met the requirements of the ACI standards and demonstrated excellent seismic performance, including strength, stiffness, ductility, and energy dissipation.

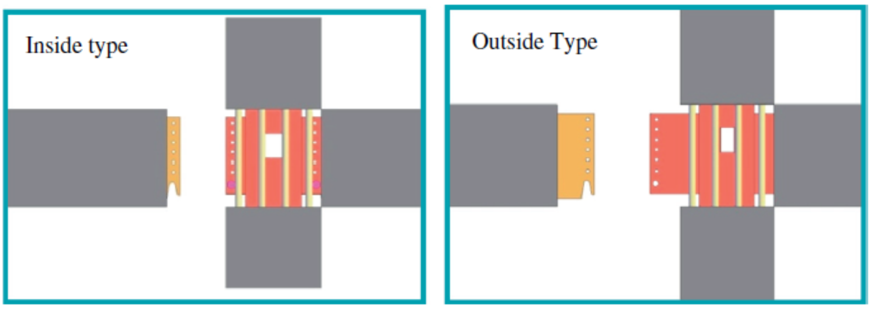

Fig. 9. Inside Type and Outside Type of Steel Connection [19]

Fig. 10. The specimen model of a hybrid beam-column connection using a pipe tube [20]

[20] also conducted hybrid experiments using steel plates and steel tubes as shown in Figure 10. In this study, experiments were performed on two types of hybrid external connections and two types of monolithic connections. The hybrid connection type in this research prevents the melting of steel reinforcement in the beam region. Additionally, the steel plate embedded in the beam enhances the melt capacity of longitudinal reinforcement at the top and bottom of the connection. This is evidenced by the absence of any melted steel at a distance of 1050 mm from the face of the column, as the steel plate influences tensile and compressive forces during seismic loading.

The results of the study [20] indicated that the displacement and drift ratio in the precast specimens were higher compared to the monolithic specimens. The drift ratio for PC1 was 1.3 and for PC2 was 1.9. The strength degradation values for PC1 and PC2 were 6.8% and 4.8% respectively. The research recommended that strength degradation should be less than 20%. Moreover, the maximum drift ratio values for RC1 and RC2 specimens were 5%, while for PC1 and PC2 specimens, they were 6.5% and 9.5% respectively. These findings suggest that the precast specimens exhibited better ductility and energy dissipation compared to the monolithic specimens. Additionally, the energy dissipation capacity of the precast specimens was higher. As a result, the proposed precast connections demonstrated improved seismic performance compared to the monolithic connections in the study, while also meeting ACI requirements.

[7] conducted experiments on an innovative hybrid connection using Steel Fibre Concrete (SFC), and the specimen model can be seen in Figure 11. The proposed connection configuration consists of three parts: a precast beam with embedded steel profile, a precast column with embedded steel, and the beam-column joint area modified with Steel Fibre Concrete. Several test results demonstrated that connections utilizing SFC and steel plates exhibited smaller shear deformations, relatively controlled crack patterns in the core region, and overall integrity of the connection parts. The research findings indicated that connections with SFC exhibited improved shear capacity and better energy dissipation compared to the control specimens.

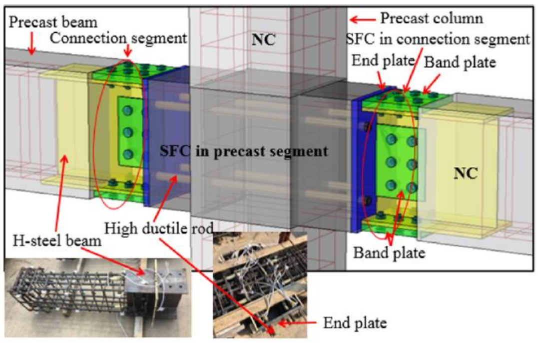

Fig. 11. The specimen model of a hybrid beam-column connection using Steel Fibre Concrete (SFC) [7]

According to [18], precast beam-column connections are required to possess good stiffness and strength with clear force transfer, ensuring effective distribution of bending moments. The plastic hinge regions must be confined to ensure the safety of the connection area. To achieve a seismic-resilient hierarchical structure, adhering to the principle of "strong connection, weak members," the proposed model boasts advantages in terms of installation and potential disassembly. This is achieved using I-connectors and bolts, as depicted in Figure 12.

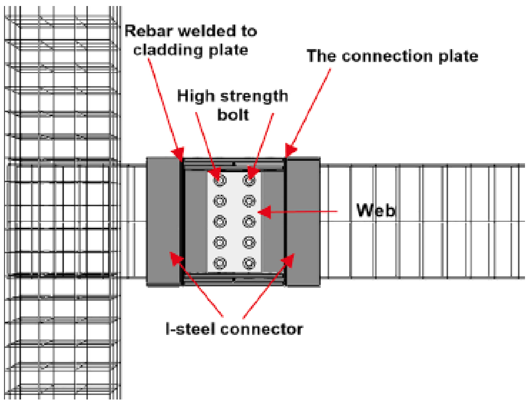

Fig. 12. Hybrid Connection with I-Steel Connector [18]

In this study, experimental testing was conducted on one cast-in-situ specimen as a control (CIS) and one proposed hybrid precast connection (HBC). The testing procedure utilized 14 strain gauges and 3 LVDTs to measure displacements at the beam end, column end, and midpoint of the column. The axial loading was applied to 0.4 times the column capacity along with cyclic loading. The results from the experimental testing revealed similar failure modes. The load-carrying capacity of the CIS connection element was 224.3 kN, while the HBC was 233.7 kN. This indicates that the load-carrying capacity of the proposed precast connection is 4.1% greater. Moreover, the energy dissipation capacity and ductility of the HBC were also higher compared to the control specimen. Based on the hysteresis curve in Figure 13, it is evident that the seismic performance of the HBC connection is slightly better than that of the CIS connection

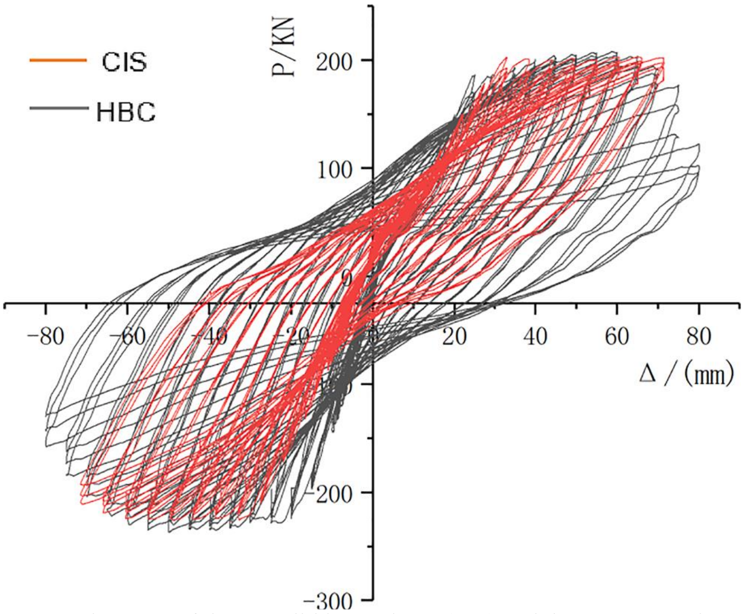

Fig. 13. The Hysteresis Curve of the monolithic specimen (CIS) and the precast specimen (HBC) [18]

Several summaries from previous research related to precast hybrid beam-column connections are presented in Table 1 [19][20][21][22][1][23][7][11][24][25][26][13][18][12][27][28] [29][30][31][32][33][34][28].

Table 1. Various Research of hybrid beam column connection

Author (year)	Hybrid Beam Column Connection Detail	Parameter Study	Loading	Experimental/ Numerical Analysis	Conclusion
Choi, et al (2013)	Steel Box & Steel Plate, with U-Shaped and ECC	Inside & Outside Joint	Axial Load (0,1 f'c Ag) and Cyclic Load	Experimental Investigation	The developed hybrid connection has good seismic performance and complies with ACI regulations.
Ghayeb, et al (2017)	Steel Tube &Steel Plate	Stirrups spacing arrangement	Axial Load (0,1 f'c Ag) and Cyclic Load	Experimental Investigation	The proposed hybrid connection's performance exhibits a higher drift ratio compared to the control specimen. The density of stirrup placement significantly influences the seismic performance of the connection.
Pan, et al (2017)	WF&Steel Plate	Bolt System	Axial Load (0,15 f'c Ag) and Cyclic Load	Experimental Investigation	The application of steel connections in joints provides stiffness and shear strength, enabling the structure to achieve the principle of connecting strong members to weak elements.

Javanmardi, et al (2018)	Steel Box & WF	Connection System	Axial Load (0,1 f'c Ag) and Cyclic Load	Experimental Investigation	The strength of the hybrid connection is higher than that of the monolithic connection, allowing the structure to adhere to the principle of connecting strong members to weak elements.
Wang, et al (2018)	Pre-stressed joint using steel jacket, mild steel bars, etc	Geometry steel bars	Axial Load (0,1 f'c Ag) and Cyclic Load	Experimental Investigation	The proposed connection offers the advantages of being replaceable, easy to install, and exhibiting a satisfactory performance under seismic loads.
Lu, et al (2019)	Double grouted sleeves	Long grouted sleeve and transition bar diameter	Axial Load (0,23 f'c Ag) and Cyclic Load	Experimental Investigation	The precast specimen experienced failure due to plastic joint deformations at the beam's end.
Zhang, et al (2020)	H-beam & Steel plate	Steel Connector Configuration and SFC	Axial Load (0,15 f'c Ag) and Cyclic Load	Experimental Investigation	The use of Fiber-Reinforced Concrete (FRC) in the connection reduces the occurrence of cracks in the connection area.
Ghayeb, et al (2020)	Steel coupler, gusset plates and inclined steel bar	Steel Connector Configuration	Axial Load (0,1 f'c Ag) and Cyclic Load	Experimental Investigation	The proposed connection demonstrates superior performance compared to the control specimen.
Senturk, et al (2020)	Anchorage rods, stiffer plates, and high strength bolt	Longitudinal reinforcement ratio	Axial Load (0,1 f'c Ag) and Cyclic Load	Experimental Investigation and Numerical Analysis	The connection offers the advantages of reusability and replaceability. The performance of the proposed connection is superior to the monolithic connection, including ductility and energy dissipation.
Khrisnan and Purushothaman (2020)	Cleat angle	Stiffener of the cleat angle	Axial Load (0,1 f'c Ag) and Cyclic Load	Experimental Investigation	One type of connection meets the design criteria of ACI 374.1-05 requirements.
Esmaili and Ahooghalandary (2020)	Steel plate, heades stut, and steel box	Connection System	Axial Load (0,7 f'c Ag) and Cyclic Load	Experimental Investigation and Numerical Analysis	The proposed hybrid connection meets the criteria of ACI 374.1-05.
Zhang, et al (2021)	SFC and Steel Plate	Steel Connector Configuration and SFC	Axial Load (0,15 f'c Ag) and Cyclic Load	Experimental Investigation	The use of Steel Fiber-Reinforced Concrete (SFC) in the connection reduces the occurrence of cracks in the connection area.
Ye, et al (2021)	Connection Plate	Connection System	Axial Load (0,4 f'c Ag) and Cyclic Load	Experimental Investigation and Numerical Analysis	The innovation of the hybrid connection fulfills the hierarchy of connecting strong members to weak structural elements, and the performance of the hybrid connection is slightly superior compared to conventional connections.
Baran, et al (2021)	Anchorage bars and connection plate	Additional stirrup and anchor hooks	Axial Load and Cyclic Load	Experimental Investigation and Numerical Analysis	The detailing of reinforcement significantly influences the performance of the structure.
Rong, et al (2021)	SFRC and Steel Plate	Steel Connector Configuration	Axial Load (0,15 f'c Ag) and Cyclic Load	Experimental Investigation	The application of Steel Fiber-Reinforced Concrete (SFRC) in the connection area can control cracking and reduce

					shear deformation, thereby enhancing shear capacity.
Feng, et al (2021)	H-Steel connection with HSPC beams and CFST column	Steel Connector Configuration	Axial Load (0,2 f'c Ag) and Cyclic Load	Experimental Investigation	The proposed connection occurs at plastic joints in the beam, thus the design meets the criteria for earthquake-resistant structural design.
Xie, et al (2021)	Replaceable energy dissipation connector	Connection System	Axial Load and Cyclic Load	Experimental Investigation	The behavior of the connection exhibits a semi-rigid connection type.
Zhang and Li (2021)	Steel plate, ED bolt, stiffener, and prestressed tendon	Reinforcement	Axial Load and Cyclic Load	Experimental Investigation	The proposed precast connection demonstrates excellent seismic performance.
Li, et al (2021)	Metallic damper, U-shaped rebar, and steel plate	Stiffener in Connection	Axial Load and Cyclic Load	Experimental Investigation	The structural performance of the connection against earthquakes is very good.
Tong, et al (2022)	Steel sleeve and REDC connector	Connection System	Axial Load (0,3 f'c Ag) and Cyclic Load	Experimental Investigation	Ductile failure occurred in the Reinforced Concrete (REDC) connection, and the connection's performance under seismic loads is very good.
Huang, et al (2022)	Replaceable connection, artificial controllable plastic hinge	Steel Connector Configuration	Axial Load (0,18 f'c Ag) and Cyclic Load	Experimental Investigation and Numerical Analysis	The seismic performance of the connection is better than conventional connection.
Bilal, et al (2022)	Stiffener and cleat angle	Steel Connector Configuration	Axial Load and Cyclic Load	Experimental Investigation and Numerical Analysis	Failure occurred at the steel connector.
Feng, et al (2022)	H-Steel connection with CFST column	RBS and OBW	Axial Load (0,2 f'c Ag) and Cyclic Load	Experimental Investigation	The development of the connection accepted to the principles of structure seismic performance.

4. Conclusions

1. The implementation of Hybrid Beam-Column Connections is considered highly practical and exhibits seismic performance that is equivalent, if not better, than monolithic beam-column connections. This includes aspects such as strength, shear capacity, ductility, and energy dissipation.
2. Hybrid Beam-Column Connection demonstrates a structural performance that aligns with the ACI standards by applying the seismic design principle of 'strong joints, weak members.' Therefore, it is highly recommended to implement this connection in areas prone to high seismic activity.
3. Several proposed hybrid connections possess the characteristics of being replaceable and reusable, providing economic benefits for structural repairs.

Acknowledgments

This research was supported by Kementerian Pendidikan, Kebudayaan, Riset, dan Teknologi (Center for Higher Education Funding-BPPT) and Lembaga Pengelola Dana Pendidikan (LPDP) of Indonesian Government.

References

1. H. Wang, E. M. Marino, P. Pan, H. Liu, and X. Nie, Experimental study of a novel precast prestressed reinforced concrete beam- to-column joint, *Eng. Struct.* **156**, 20168–81 (2018)
2. R. Park, Seismic Design and Construction of Precast Concrete Buildings in New Zealand, New Zealand (2002)
3. Vivian W. Y. Tam & Jane J. L. Hao, Prefabrication as a mean of minimizing construction waste on site, *International Journal of Construction Management* **14**, 113-121 (2014)
4. H. Liu, Q. Yan, and X. Du, Seismic performance comparison between precast beam joints and cast-in-place beam joints, Advances in Structural Engineering **20**, 1299-1314 (2017)
5. T. O. Onur Ertas, Sevket Ozden, Ductile Connections in Precast, 66–76 (2006)

6. P. Stylianidis, J. Bellos, Survey on the Role of Beam-Column Connections in the Progressive Collapse Resistance of Steel Frame Buildings, *Buildings* **13**, 1696 (2023)
7. J. Zhang, C. Ding, X. Rong, H. Yang, K. Wang, and B. Zhang, Experimental seismic study of precast hybrid SFC / RC beam – column connections with di ff erent connection details, *Eng. Struct.* 208, 110295 (2020)
8. D. K. Bull and R. Park, “Seismic Resistance of Frames Incorporating Precast Prestressed Concrete Beam Shells,” 1986.
9. A. I. Rather, A. R. Dar, and A. Fayeq, “Materials Today : Proceedings Improved performance of steel fibre reinforced beam-column joint- an experimental study,” *Mater. Today Proc.*, vol. 32, pp. 982–988, 2020, doi: 10.1016/j.matpr.2020.05.674.
10. L. Jaillon and C. S. Poon, “Automation in Construction Life cycle design and prefabrication in buildings : A review and case studies in Hong Kong,” *Autom. Constr.*, 2013, doi: 10.1016/j.autcon.2013.09.006.
11. H. H. Ghayeb, H. A. Razak, and N. H. R. Sulong, “Seismic performance of innovative hybrid precast reinforced concrete beam- to-column connections,” *Eng. Struct.*, vol. 202, no. April 2019, p. 109886, 2020, doi: 10.1016/j.engstruct.2019.109886.
12. E. Baran, M. Mahamid, M. Baran, M. Kurtoglu, and I. Torra-bilal, “Performance of a moment resisting beam-column connection for precast concrete construction,” *Eng. Struct.*, vol. 246, no. May 2020, p. 113005, 2021, doi: 10.1016/j.engstruct.2021.113005.
13. J. Zhang, C. Li, X. Rong, X. Zhang, and Y. Li, “Experimental study on the seismic performance of steel – concrete beam – column connections for prefabricated concrete frames,” *J. Build. Eng.*, vol. 43, no. September, p. 103236, 2021, doi: 10.1016/j.jobe.2021.103236.
14. Y. C. Kurama *et al.*, “Seismic-Resistant Precast Concrete Structures : State of the Art,” vol. 144, no. CAE 1999, pp. 1–18, 2018, doi: 10.1061/(ASCE)ST.1943-541X.0001972.
15. SNI 2847, *PENETAPAN STANDAR NASIONAL INDONESIA 2847 : 2019 PERSYARATAN BETON STRUKTURAL UNTUK BANGUNAN GEDUNG DAN PENJELASAN SEBAGAI REVISI DARI STANDAR NASIONAL INDONESIA 2847 : 2013*, no. 8. 2019.
16. J. Fan, G. Wu, D. Feng, Y. Zeng, and Y. Lu, “Seismic performance of a novel self-sustaining beam-column connection for precast concrete moment-resisting frames,” *Eng. Struct.*, vol. 222, no. June, p. 111096, 2020, doi: 10.1016/j.engstruct.2020.111096.
17. ACI 374.2R-13, *Guide for Testing Reinforced Concrete Structural Elements under Slowly Applied Simulated Seismic Loads*. 2013.
18. M. Ye, J. Jiang, H. M. Chen, H. Y. Zhou, and D. D. Song, “Seismic behavior of an innovative hybrid beam-column connection for precast concrete structures,” vol. 227, no. June 2020, 2021, doi: 10.1016/j.engstruct.2020.111436.
19. H. Choi, Y. Choi, and C. Choi, “Development and testing of precast concrete beam-to-column connections,” *Eng. Struct.*, vol. 56, pp. 1820–1835, 2013, doi: 10.1016/j.engstruct.2013.07.021.
20. H. H. Ghayeb, H. A. Razak, and N. H. R. Sulong, “Development and testing of hybrid precast concrete beam-to-column connections under cyclic loading,” *Constr. Build. Mater.*, vol. 151, pp. 258–278, 2017, doi: 10.1016/j.conbuildmat.2017.06.073.
21. Z. Pan, Q. Si, Z. Zhou, Y. Zhang, Y. Zhu, and X. Chen, “Experimental and numerical investigations of seismic performance of hybrid joints with bolted connections B-B End-plate C-C D-D,” vol. 138, pp. 867–876, 2017, doi: 10.1016/j.jcsr.2017.09.001.
22. Z. He and T. Zhong, “Development of a new hybrid precast beam-to- column connection Development of a new hybrid precast beam-to-column connection,” 2018, doi: 10.1088/1757-899X/431/11/112002.
23. Z. Lu, J. Huang, S. Dai, J. Liu, and M. Zhang, “Experimental study on a precast beam-column joint with double grouted splice sleeves,” *Eng. Struct.*, vol. 199, no. August, p. 109589, 2019, doi: 10.1016/j.engstruct.2019.109589.
24. M. Senturk, S. Pul, A. Ilki, and I. Hajirasouliha, “Development of a monolithic-like precast beam-column moment connection : Experimental and analytical investigation,” *Eng. Struct.*, vol. 205, no. November 2019, p. 110057, 2020, doi: 10.1016/j.engstruct.2019.110057.
25. T. Krishnan and R. Purushothaman, “Effect of stiffeners in cleat angle based precast beam-column connections under reverse cyclic loading,” *Structures*, vol. 25, no. March, pp. 161–172, 2020, doi: 10.1016/j.istruc.2020.03.012.
26. J. Esmaeili and N. Ahooghalandary, “Introducing an easy-install precast concrete beam-to-column connection strengthened by steel box and peripheral plates,” *Eng. Struct.*, vol. 205, no. December 2019, p. 110006, 2020, doi: 10.1016/j.engstruct.2019.110006.
27. X. Rong, X. Zhang, and J. Zhang, “Seismic behavior of innovation steel-embedded precast concrete beam-to-

column joints," *Structures*, vol. 34, no. October, pp. 4952–4964, 2021, doi: 10.1016/j.istruc.2021.10.082.

28. S. Feng, D. Guan, Z. Guo, Z. Liu, G. Li, and C. Gong, "Seismic performance of assembly joints between HSPC beams and concrete-encased CFST columns," *J. Constr. Steel Res.*, vol. 180, p. 106572, 2021, doi: 10.1016/j.jcsr.2021.106572.
29. L. Xie, J. Wu, J. Zhang, and C. Liu, "Experimental study of mechanical properties of beam-column joint of a replaceable energy-dissipation connector-precast concrete frame," *J. Build. Eng.*, vol. 43, no. April, p. 102588, 2021, doi: 10.1016/j.jobe.2021.102588.
30. Y. Zhang and D. Li, "Development and testing of precast concrete-filled square steel tube column-to-RC beam connections under cyclic loading," *Constr. Build. Mater.*, vol. 280, p. 122540, 2021, doi: 10.1016/j.conbuildmat.2021.122540.
31. D. Li, C. Wu, Y. Zhou, W. Luo, and W. Lie, "A precast beam-column connection using metallic damper as connector : Experiment and application," *J. Constr. Steel Res.*, vol. 181, p. 106628, 2021, doi: 10.1016/j.jcsr.2021.106628.
32. C. Tong, J. Wu, M. D. Zakari, and Y. Gao, "Hysteretic behavior of a new precast concrete interior beam-to-column joint with a controllable bending moment," *J. Build. Eng.*, vol. 45, no. October 2021, p. 103557, 2022, doi: 10.1016/j.jobe.2021.103557.
33. W. Huang, G. Hu, and J. Zhang, "Experimental study on the seismic performance of new precast concrete beam-column joints with replaceable connection," *Structures*, vol. 35, no. December 2021, pp. 856–872, 2022, doi: 10.1016/j.istruc.2021.11.050.
34. I. Torra-bilal, M. Mahamid, and E. Baran, "Cyclic behaviour of precast beam-to-column connections : An experimental and numerical investigation," *Structures*, vol. 35, no. June 2021, pp. 939–957, 2022, doi: 10.1016/j.istruc.2021.11.046.