Comparative Performance of Precast Column-To-Foundation Connections

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Comparative Performance of Precast Column-To-Foundation Connections: A Review

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Abstract. Since the introduction of precast concrete as a structural element in the early 20th century, precast concrete has evolved significantly into an essential construction technology in various modern construction projects. This is due to several advantages of precast concrete, such as time efficiency, relatively lower costs, good quality control, and environmental friendliness. However, precast concrete also has disadvantages when applied as part of a seismic-resistant building framework, primarily in the connection between elements, which does not perform as well as monolithic joints in terms of structural performance. The precast column-to-foundation connection is one of the most critical connections, as it experiences the largest axial-moment combination forces in a structure. Commonly used types of precast connections include pocket connections, baseplates, anchor connections, and grouting sleeves. The results of previous research reviews suggest that pocket connections demonstrate reliable structural performance, provided the column's embedment length into the foundation exceeds 1.0 Diameter. Meanwhile, the structural performance of baseplate and anchor connections is significantly influenced by the thickness of the baseplate, the number of anchors, and their configuration. For grouting sleeve connections, the key factors are the diameter and spacing of the sleeves, as well as the length of the reinforcement bars. On average, test results for precast column-to-foundation connections indicate that all the connections above can achieve the strength of monolithic joints. However, structural performance characteristics such as ductility, energy dissipation, and stiffness degradation require further modifications to match the performance of cast-in-place monolithic joints.

Keywords: Precast Concrete · Column-Foundation Connection · Combined Bolt-Pocket Connection · Cyclic Loading

1 Introduction

The application of a precast system in construction must consider the seismic region where the building is constructed. This is due to the inherent weakness of the precast system, namely the flexibility of the connections [1, 2]. In seismic-resistant building design, structural connections in high-seismic-risk areas are required to accommodate inelastic deformations without losing stiffness and structural strength [3].

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The column-to-foundation connection is one of the most critical connections in precast reinforced concrete structures. This connection bears the largest combination of lateral, axial, and moment forces from the building. Currently, the common types of column-to-foundation precast connections used in construction are pocket connections, mechanical anchor connections, baseplate connections, and grouting sleeve connections.

In general, connections in precast concrete structures are divided into two categories: wet and dry connections. Wet connections are precast connections that utilize fresh concrete or grout material poured to encase dowel bars or parts of the precast elements being connected. Pocket connections and grouting sleeve connections fall into this category. On the other hand, dry connections refer to connections between precast elements that employ mechanical connectors, such as anchor bolts and welded steel profiles, as joining media anchored to the precast components.

Wet connections offer advantages in terms of structural strength and stiffness, but they are less practical in terms of construction methods, execution precision, and the time required. On the other hand, dry connections are advantageous in terms of practicality and construction speed, though several studies have indicated that dry connections rarely achieve the same strength as the connected elements or as cast-in-place monolithic joints.

In the concept of seismic-resistant structural connections, whether for steel connections or precast concrete connections, several fundamental principles of strength and structural performance must be designed to meet standards, including strength, stiffness, and ductility. This study will thoroughly examine several common precast column-to-foundation connection concepts, focusing on combined axial-lateral cyclic loading models as a representation of structural and seismic loads. The study will focus on methods, strength, and structural performance, as well as a comparison of the results obtained. It is expected that this review will contribute positively and provide valuable insights for designers and construction practitioners in selecting the appropriate connection type for modern constructions.

2 General Review and Method

2.1 Pocket Connections

A pocket connection is a column-to-foundation connection where the end of the column is inserted into a 'pocket' within the foundation at a specific depth and then connected using grouting material or non-shrink mortar. Pocket connections are divided into three types: fully embedded pocket connections, partial pocket connections, and external pockets [4]. Meanwhile, *Eurocode 2 EN 1992–1-1:2004* provides more detailed explanations regarding pocket connections with rough and smooth surface walls [5].

General specifications regarding the design and infill materials are outlined in *FIB 43(Federation Internationale du Beton).* According to these requirements, the infill material must have a minimum compressive strength of 40 MPa, the space between the wall and column should not be less than 75 mm, and the embedment depth must be greater than 12 times the diameter of the largest reinforcement bar (12db) [6]. *PCI 1st 2008* specifies that the minimum embedment depth of the column into the foundation is 1.5 times the column diameter *(1.5D),* with a space between the wall and column of

50–70 mm [7]. In contrast, *EN 1992–1-1:2004* requires a minimum column embedment depth into the foundation of *1.2D.* [5].

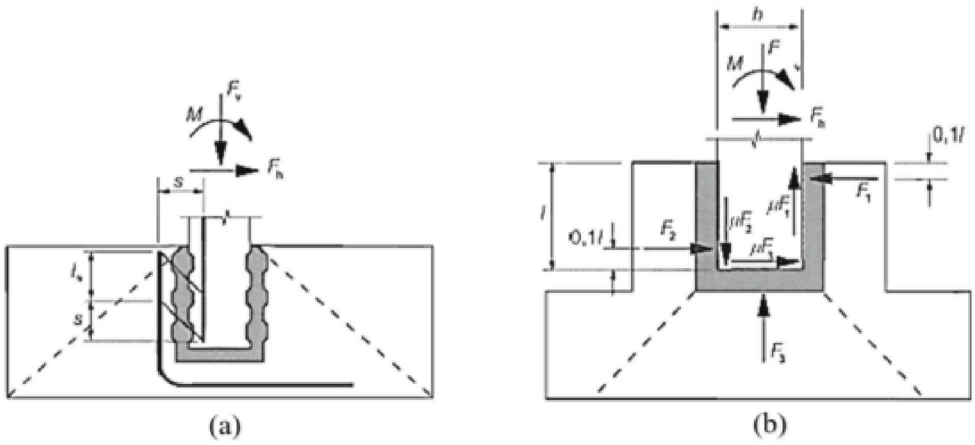


Fig. 1. Column-to-Foundation Pocket Connection Types: (a) Fully Embedded Pocket with Rough Walls; (b) External Pocket with Smooth Walls.

Figure 1 Illustrates the types of pocket connections: (a) Fully Embedded Pocket with Rough Walls and Column Surface; (b) External Pocket with Smooth Wall Surface. Research on the capacity and performance of these connection types has been extensively conducted by Canha (2009), Aboukifa (2017), Haraldsson (2013), Khaleghi (2012), and Hemmamathi (2021).

Canha *et al.* (2009) conducted research using full-scale precast column-to-foundation connection specimens with smooth external wall surfaces. The study involved experimental testing, numerical modeling using *ANSYS* software, and calculations with a strut-and-tie model to predict the strength and stresses at the base of the embedded column. Two column specimens were embedded into foundations at depths of *2.0D* and *1.6D* with eccentric axial loading, as shown in Fig. 2 [8].

The research results indicate that column embedment depths of *2.0D* and *1.6D* exhibit good safety levels, with failure occurring in the column area. The strut-and-tie method analysis with a μ value of 0.6 provides results that are closer to the experimental outcomes compared to the μ value of 0.6 required by *Eurocode 2* [5].

Aboukifa *et al.* (2017) also conducted experiments and strut-and-tie analysis on 6 pocket connection specimens with embedment depths of *1.33D* and *2.0D*, and variations of external, partial, and fully embedded pockets. The study concluded that the strut-and-tie analysis provides predictions that closely match the experimental results. The *1.33D* embedment depth still offers a greater lateral load capacity compared to the lateral capacity of the column element, and the fully embedded pocket type is the strongest among the pocket types, outperforming the partial and external pockets [4].

Haraldsson (2013) conducted experimental testing on three pocket joint specimens with variations in embedment depth, shear reinforcement, and foundation plate thickness. The embedment depth variations were *1.1D* and *0.5D.* The study utilized a combination of axial and cyclic lateral loads greater than 10%. The hysteretic curves from the tests are shown in Fig. 3 [9].

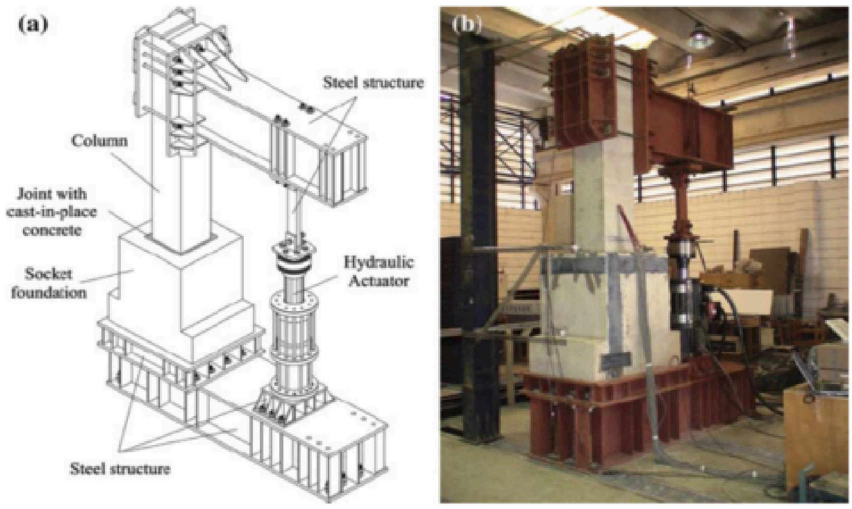


Fig. 2. Setting of eccentric axial loading on external pocket connection specimens [8].

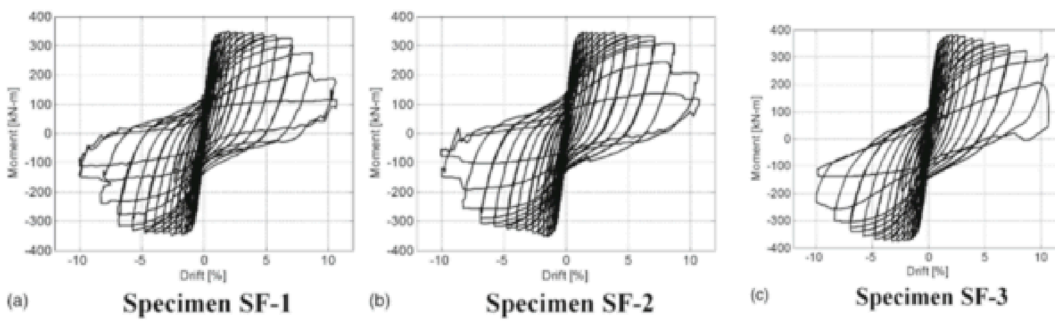


Fig. 3. Hysteretic curves of cyclic lateral testing for pocket joints. [9]

Based on the graph in Fig. 3, the experimental results indicate that the pocket joints exhibit good lateral resistance, even for an embedment depth of *0.5D*. The resulting hysteretic curves also demonstrate that the ductility, strength degradation, and energy dissipation of the pocket joints have satisfactory performance, making them suitable for earthquake-resistant precast structural applications.

Other studies related to the influence of column embedment depth in foundations specify different ratio values. For instance, Matsumoto (2001) requires a minimum embedment depth ratio of *1.0D*, Motaref (2011) and Khaleghi (2012) use a ratio of *1.2D*, Saiidi (2013) recommends *1.5D*, and Larosche (2014) suggests 1.*3D* [10].

2.2 Anchore Connections

The use of anchor bolts for precast concrete connections has been extensively developed for various joint models, such as beam-column connections, column-column connections, and column-foundation connections. This type of joint leverages the tensile and shear strength of the bolts as the connecting strength elements. Additionally, the thickness of the base plate and the bond between the base plate and the concrete in the column and foundation are key factors determining the strength of this type of connection.

Anchor connections offer advantages in terms of construction speed. Previous research on this type of connection has been conducted by LaFraugh *et al.* (1966), Jourma Kinnuen (2017), Ettore Faga *et al.* (2010), Metelli *et al.* (2014), Brunno dell Lago (2016), Camnasio & Kiriakopoulos (2018), and Wang *et al.* (2020) [1, 2, 11–15].

Kinunnen *et al.* (2017) conducted experimental testing and theoretical analysis on 24 precast column-foundation connections of the *HPKM* (*Headed Plate Keyed Mortise*) Peikko model. The tests included bending resistance, stiffness resistance, shear tests, and fire tests. The results of the axial and bending moment tests showed good agreement between the analysis and experimental results, indicating that the connection exhibited bending performance comparable to that of a monolithic reference connection. The stiffness tests revealed significant differences, particularly in the notched areas due to the reduction in column cross-sectional area. Conversely, the shear resistance was higher than the theoretical analysis. [2].

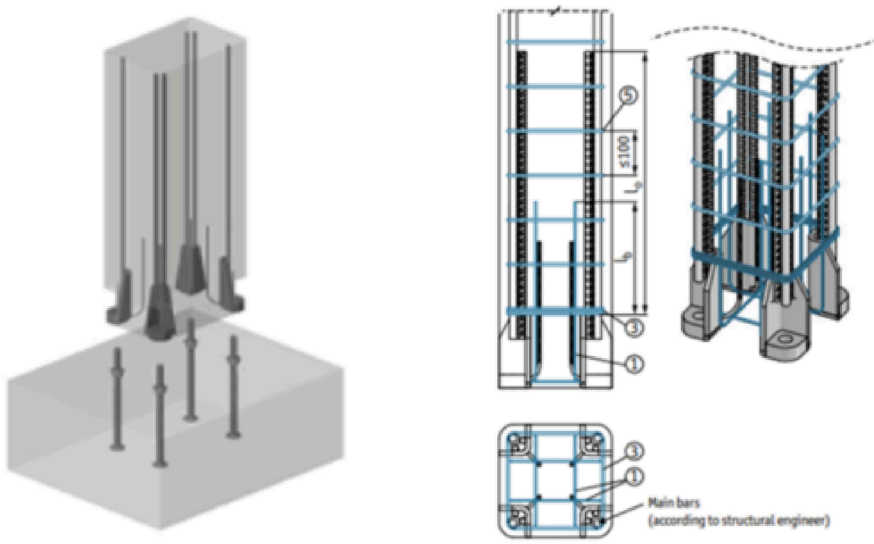
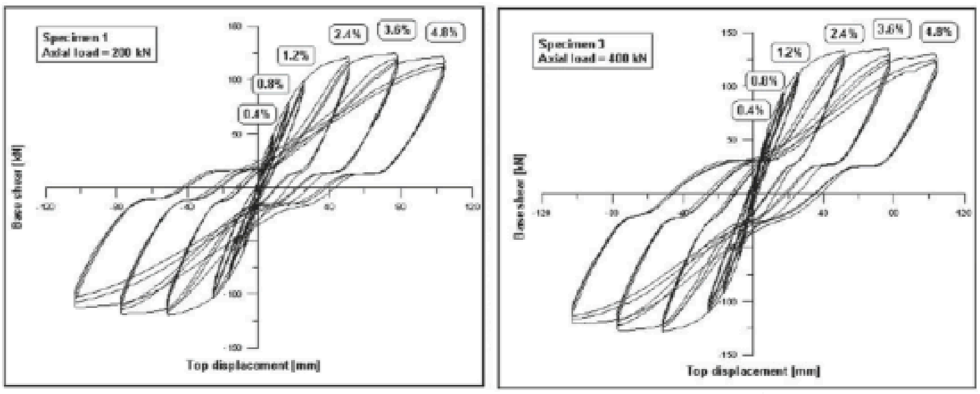


Fig. 4. HPKM Column-to-Foundation Connection Peikko [1].

Faga *et al.* (2010) conducted experimental testing on three precast columns connected with mechanical anchor joints and steel plates embedded in the pile cap and equipped with hybrid connections at the columns. The loads applied included quasi-static cyclic horizontal lateral loads and constant axial loads, varying for each test specimen at 5%, 10%, and 15%. Numerical analysis was performed by modeling the test specimens using *2D* and *3D* nonlinear finite element methods with the aid of Opensees and Midas *FEA* software (Fig. 4).

The results of the testing are shown in Fig. 5. The influence of axial pressure on the columns directly affects the lateral resistance of the specimens. Meanwhile, the hysteretic curves indicate that this connection exhibits good ductility but relatively low energy dissipation. The structural damage pattern observed after loading occurred at the joint area due to anchor yielding, with no significant damage to the column elements. The numerical and experimental analyses yielded almost identical results [12].



(a) (b)

Fig. 5. Hysteresis Curve of Anchor Connection Testing [2].

2.3 Baseplate Connections

Precast column connections with baseplates generally consist of a steel baseplate, column anchor reinforcement, and anchor bolts. As a connection, the baseplate must be designed to withstand internal forces from the column structure and transfer them to the underlying concrete foundation structure (Fig. 6).

Generally, there are two types of baseplates based on the internal forces they transfer: pin baseplates and fixed baseplates. Pin baseplates are designed to withstand axial forces (compression (N) and tension (T)) and shear forces (V). In contrast, fixed baseplates are designed not only to resist axial and shear forces but also to accommodate moments (M).

Several studies on baseplate connections have been conducted, including those by French et al. (1989), Li *et al.* (2009), Englekirk (1996), Choi *et al.* (2013), Vidjeapriya and Jaya (2013), Pul and Senturk (2017), Negro *et al.* (2013), Smith *et al.* (2013), Chen *et al.* (2019), Fan *et al.* (2020), Aninthaneni and Dhakal (2017), Nzabonimpa and Hong (2018), and Dal Lago (2016). These studies indicate that baseplate connections do not perform as well as monolithic cast-in-place connections (*CIP*), highlighting the need for modifications to the connection system, as demonstrated by Pul (2021) and Zhou (2022) [1, 16].

According to *Fib 43*, the following are some installation requirements for baseplates:

a. The anchor bolt length should range between 375 mm and 450 mm for bolts with diameters from 20 mm to 32 mm.
b. The bearing area of the bolt head should be increased by using a steel plate with dimensions 100 x 100 x 8 mm.
c. The bottom of the bolt must be at least 100 mm above the reinforcement at the bottom of the foundation.
d. Shear reinforcement (in the form of links) around the bolts is usually required, especially when there are beams or walls with edge distances less than 200 mm.

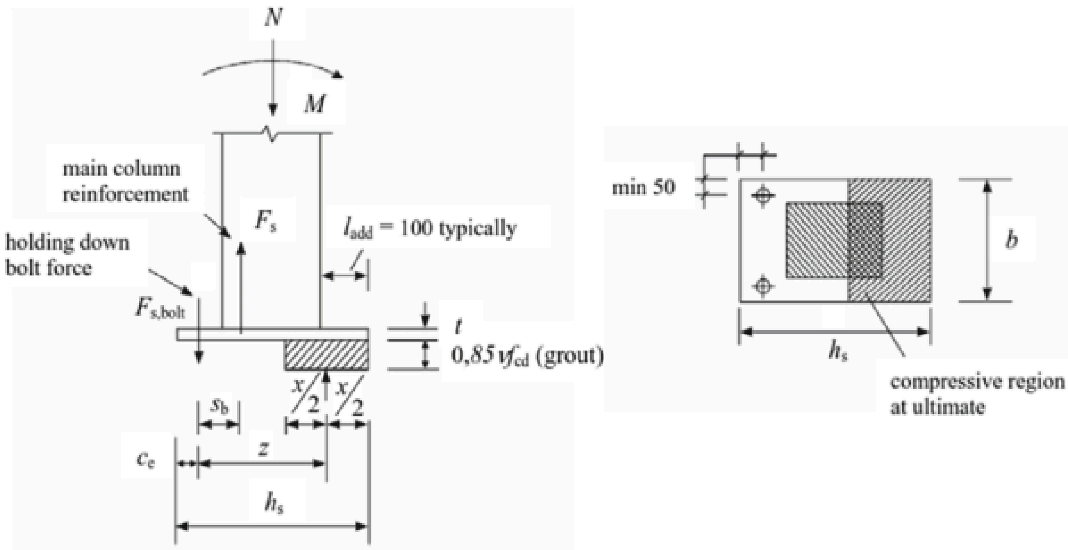


Fig. 6. Design principles for precast connections with baseplates. [6]

Pul *et al.* (2021) conducted a comparative experimental study on two full-scale precast column-foundation connections and two monolithic cast-in-place column-foundation connections. The tests were performed in both strong and weak axis directions. The loads applied were a combination of quasi-static cyclic axial and lateral loads. The precast connection model utilized rivet head anchor bars as shown in Fig. 7

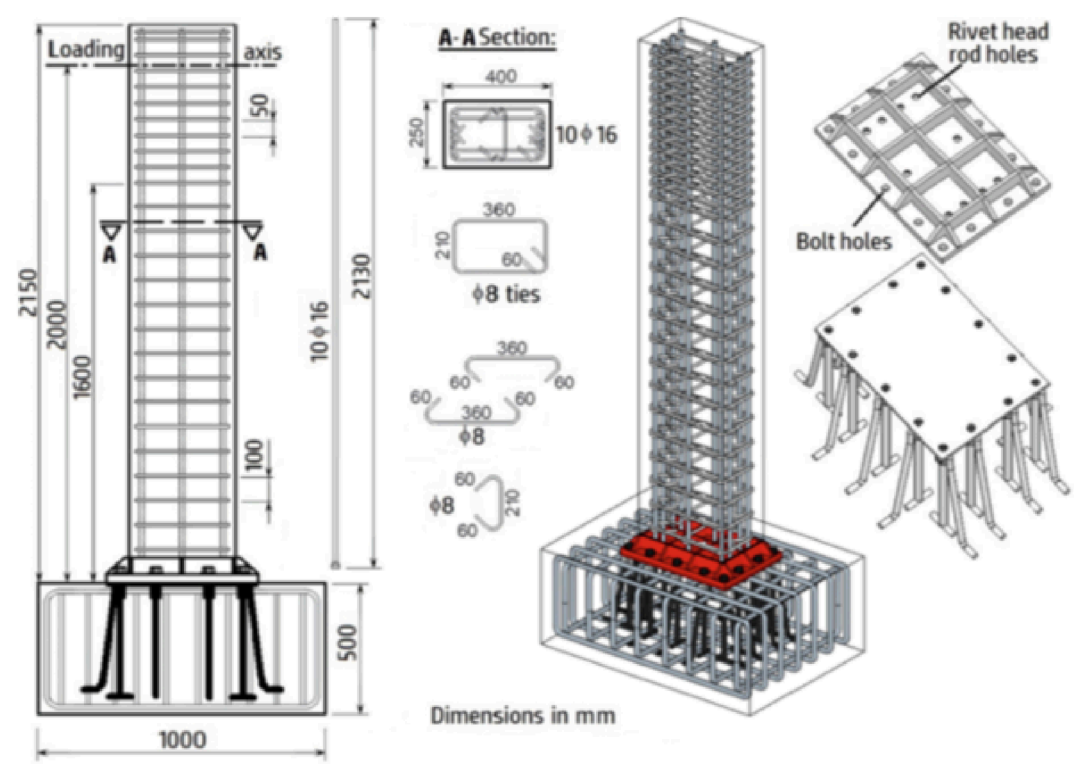


Fig. 7. Modified baseplate connection model with rivet head rebar anchors.[16]

The experimental results indicate that the lateral deformation capacity of the monolithic connection and the modified baseplate connection model are nearly identical. Meanwhile, the energy dissipation capacities of both connections show no significant difference. Therefore, it can be concluded that the modified baseplate column-foundation connection with rivet head rebar anchors performs as well as the monolithic cast-in-place connection. [16].

Zhou (2022) conducted experimental testing on a modified baseplate precast column-foundation connection model using the Notched Perfobond Connections (*NPCs*) method, with *SCCN* (*Steel Concrete Composite Connection*) type details as shown in Fig. 8. The loading applied consisted of cyclic lateral loads with a rate of 30 mm/min and a target drift of 3 cycles.

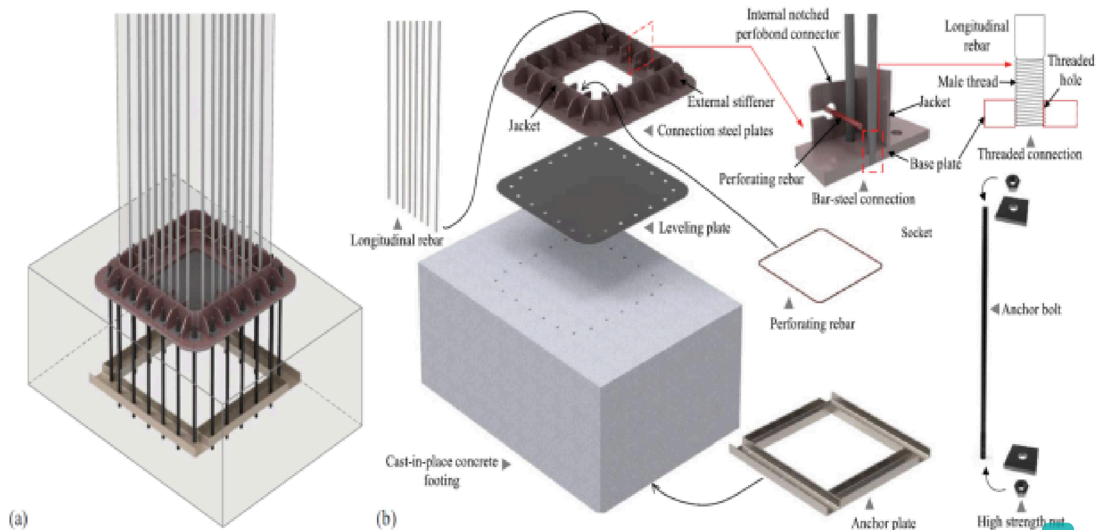


Fig. 8. *SCCN* Connection Model Details: (a) *SCCN* Connection Concept; (b) Components of the *SCCN* Connection [17].

The test results showed that the ductility of the connection specimens ranged from 3.06 to 3.95. The observed strength degradation and energy dissipation indicate that the connection performs better than monolithic cast-in-place connections [17].

2.4 Grouting Sleeve Connections

The grouted sleeve-type precast column-foundation connection uses a coupler device for connecting steel reinforcement. The load transfer mechanism between the two reinforcements is achieved through the bond between the reinforcements, high-quality grout, and the steel coupler sleeve [18]. The grouted sleeve (*GS*) mechanical connection type has been used in bridges located in low-seismic zones in the United States due to its ability to accelerate construction time and its reliability in supporting gravity loads (Fig. 9).

FIB Chapter 43 specifies several limitations related to column connections using the grouted sleeve method. The coupler sleeve must not be too small. The recommended minimum diameter of the sleeve is Ø_bar + 30 mm, with a spacing between sleeves of no less than 75 mm.

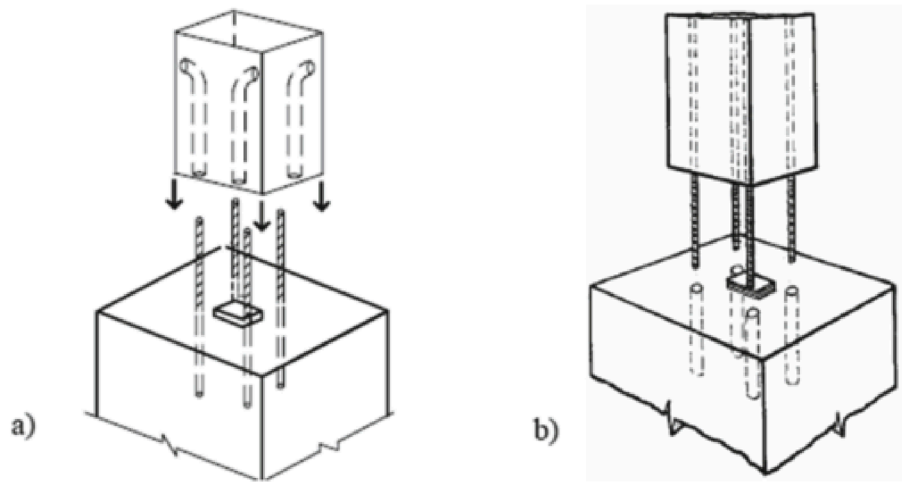


Fig. 9. Grouting Sleeve connection model: (a) Upper sleeve grouting sleeve; (b) Lower sleeve grouting sleeve.

Numerous experimental and analytical studies have been conducted on the application of this type of connection in high-seismic zones, including research by Haber *et al.* (2017), Al Jelawy *et al.* (2018), and Tullini *et al.* (2019). The average findings of these studies indicate that damage progression and plastic hinge mechanisms occur when grouted sleeve connections are used in precast concrete elements. The strength and stiffness of the precast concrete specimens were found to be similar to or only slightly different from those of monolithic specimens without grouted sleeves. [19, 20].

Buratti *et al.* (2014) conducted a comparison between grouted sleeve connections and monolithic cast-in-place connections. The grouted sleeve connection was modified by placing the sleeve in the foundation using hollow square pipes and stressing. The loads applied were cyclic lateral loads with a drift of 11%. The study concluded that the grouted sleeve and stressing connections exhibited better hysteretic behavior compared to monolithic cast-in-place connections. This was observed from the values of energy dissipation, ductility, stiffness degradation, and lateral resistance capacity.[21].

Tullini et al. (2019) investigated the effects of configuration, sleeve placement position, and axial load on grouted sleeve connections to determine their impact on structural performance. The findings indicated that as axial load increases, the damage to the column also increases, but the likelihood of buckling decreases. The optimal sleeve position was found to be within the confined core area of the concrete but as far as possible from the neutral axis of the column cross-section [20].

Hemamathi et al. (2021) conducted a performance comparison of five types of column-foundation connections: monolithic cast-in-place (*CIP*) connections, baseplate connections, two types of external pocket connections with 1.625D embedment depth and varying pocket wall reinforcement, and grouted sleeve connections (Fig. 10). The loading applied consisted of axial-lateral cyclic loads. The study results are as follows: [22].

a. The order of ultimate lateral load capacity and strength degradation from highest to lowest is as follows: Monolithic connection, Pocket Connection, Baseplate Connection, and Grouted Sleeve Connection.

b. The order of total energy dissipation from highest to lowest is Pocket Connection, Monolithic Connection, Baseplate Connection, and Grouted Sleeve Connection.
c. The order of ductility from highest to lowest is Pocket Connection, Grouted Sleeve Connection, Baseplate Connection, and Monolithic Connection.

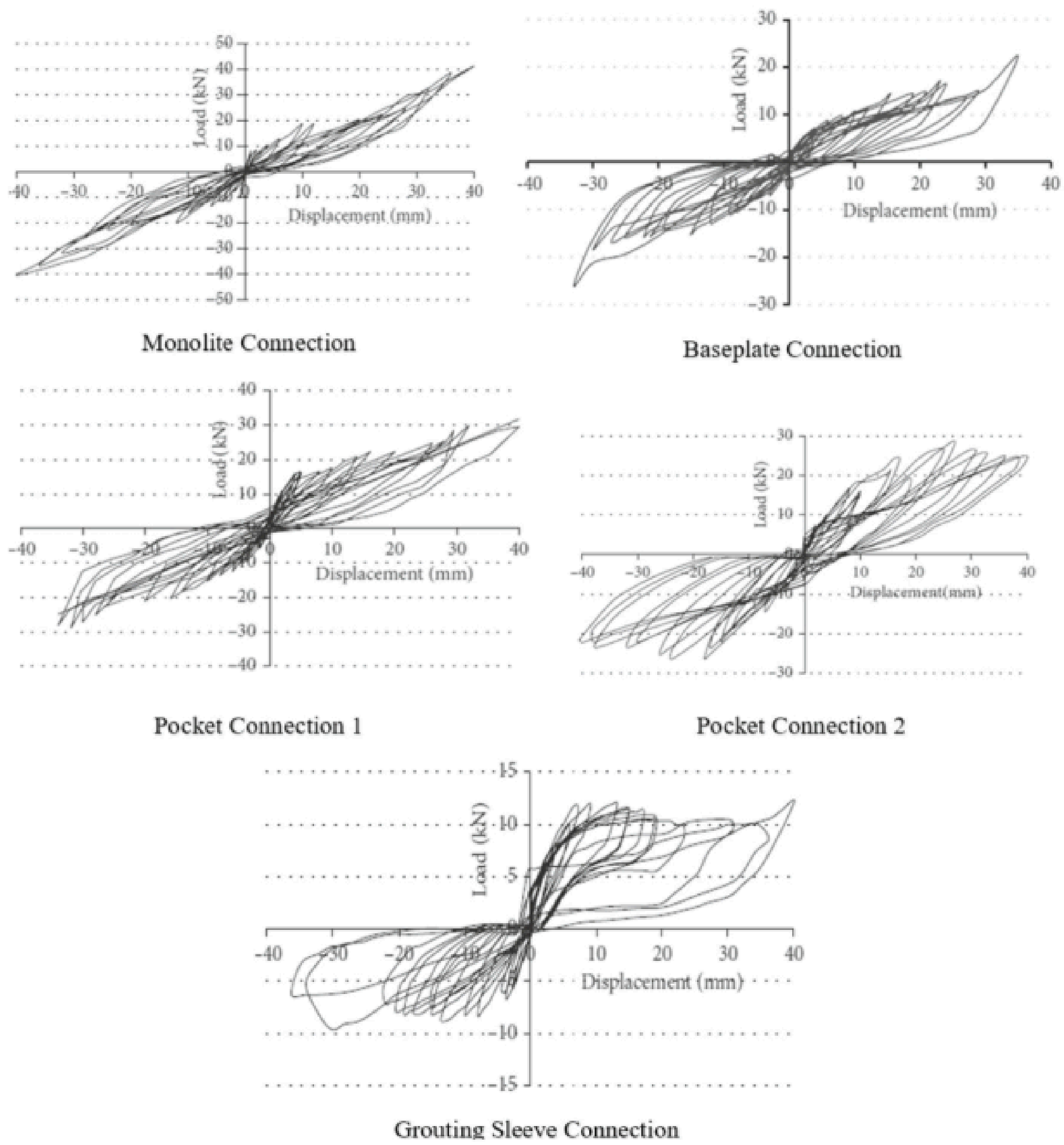


Fig. 10. Hysteresis curve results from cyclic lateral testing of the precast column-to-foundation connection [22].

3 Conclusion

Based on a review of several studies conducted on precast column-foundation connections using various methods, the following conclusions can be drawn:

1. Pocket connections demonstrate excellent structural performance, comparable to cast-in-place monolithic connections, in terms of ductility, lateral resistance capacity, energy dissipation, and strength degradation, as long as the embedded length of the column exceeds 1.0 times the column cross-sectional dimension *(1.0D).*
2. The best type of pocket connection is a fully embedded pocket in the foundation with a roughened surface.
3. The strut-and-tie numerical analysis method provides results that closely align with the experimental conditions for pocket connection types
4. Anchor and baseplate connections offer advantages in terms of speed and ease of construction; however, their structural performance is inferior to cast-in-place connections in terms of energy dissipation and structural stiffness.
5. Modifications to baseplate connections, particularly in the anchor and fin plate sections at the column ends, can enhance the structural performance of the connection to resemble monolithic connections, especially in terms of stiffness and lateral resistance strength.
6. Grouting sleeve connections exhibit the lowest energy dissipation and lateral resistance compared to other types of precast connections. Additionally, this type of connection requires specialized expertise during installation.
7. The strength of grouting sleeve connections is highly influenced by the sleeve dimensions, sleeve configuration, as well as the length and diameter of the spliced reinforcement.
8. The higher the axial force applied to the column, the greater the moment capacity the column can achieve.

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