Development of a new hybrid precast beam-to-column connection

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Abstract. This paper presents conceptual design and development of a new hybrid precast beam-to-column connection. The hybrid precast connection is made of steel connection which is embedded in concrete beam and column. The beam and column are connected to each other by bolts connectors. The performance connection is evaluated through the quasi-static test. To aid the aim, the monolithic connection and hybrid connection of the same beam and column size are modeled in 3-dimensions using ABAQUS commercial software. The results of the finite element analysis indicated that the hybrid connection was slightly stiffer than the monolithic connection while the ductility of both connections was similar. In addition, the failure mode of hybrid precast connection followed the strong-column weak-beam concept.

1. Introduction
Recently, the usage of precast structures extensively increases due to faster construction rate, higher quality products, reduction of formwork and scaffolding during construction [1,2]. Nonetheless, the precast structures have lower ductility as compared with cast in-situ structures, which makes them vulnerable to catastrophic failure under earthquake excitations. Due to unpredictably of the earthquake and also high logistical and economical values of civil structures, the engineers should design civil structures for higher ductility and/or provide seismic control devices to enhance their lateral strength and seismic performances [3–7]. In order to increase the ductility of the connection, the formation of the plastic hinges should fall in the beam far away from the surface of the column, which associates with greater lateral load and energy dissipation [8].

Otani [9] stated that the concept of weak-beam/strong-column in frame buildings was designed to avoid sudden collapse during earthquake excitations. However, this concept in the inelastic analysis should achieve at both the interior as well as exterior connections. To achieve this concept, ACI 318M-05 [10] and ACI-ASCE 352 [11] specified that the summation of flexural strength of lower and upper columns should be 1.2 times greater than both adjacent side beams to prevent the early collapse of columns in the moment resisting frames. Steel connections usually have inherent ductility due to its material properties [12] whereas the concrete connections have higher lateral stiffness. In composite connections, these two properties have compiled together in order to have better ductility and lateral stiffness to eliminate catastrophic failure of the structure during seismic excitations [13,14].

Hawileh et al. [15] investigated 3D nonlinear modeling on the behavior of precast hybrid beam-column connection under cyclic loading. The material non-linearity and pretension effect are considered during the modeling. The load-displacement envelope from the finite element analysis and experimental results correlated fairly well (within 15% difference). Kaya and Arslan [16] compared the analytical and experimental results on post-tensioned precast beam-to-column connections with different stress levels to determine strength, stiffness, and behavior of the connection subjected to cyclic loadings. As the conclusion, the finite element analysis gave excessive beforehand information, significantly reduce the
cost and time consumption to investigate precast beam-to-column connections behavior. Parastesh et al. [17] proposed a ductile precast moment-resisting beam-to-column connection in high seismic zones, which provide good structural integrity. The investigated precast connection specimens had greater ductility (up to 46% with the closed stirrups) and energy dissipation (up to 30%) as compared to similar monolithic connection specimen. Psychairs and Mouzakis [18] inspected a parametric study on precast beam-to-column connection with dowels under monotonic and cyclic loading. From various design parameters, the results showed higher shear ductility in dry pinned joints with sufficient concrete cover of the dowels. Also, the number of dowels had increased the force under monotonic loading significantly whereas during cyclic loading this parameter insignificantly changed forces.

Li et al. [19] deliberated the behavior of flush endplate composite connection under unbalanced moment with different shear-moment ratios. As the conclusion, the endplate yielded first in the absence of shear connectors, also the shear force was high compared to the steel beam shear capacity. In addition to these, the performance of composite connections has been improved due to the major contribution of reinforcement in the connections. There are many more developments in the area of precast connections, which has been carried out by the researcher groups around the world, at where the behavior of the connection studied based on failure mode, displacement ductility, concrete strength, energy dissipation and bending strength [20–24]. As the outcome of the discussed literature, the precast connection should be designed to resist earthquake loadings and also should be ductile enough during seismic excitations. The formation of plastic hinges should be away from the connection face and distributed along beam and column where the beam failure should occur before the column as the concept of weak-beam/strong-column. The 3D modeling can be used to study the connection behavior which causes a significant reduction in the cost and time consumption of the study.

This paper investigates a novel hybrid precast connection under cyclic loadings for Industrialized Building system (IBS). The proposed connection is a semi-rigid ductile connection which is made of the steel and concrete sections. It can be easily assembled by bolt fastener, which significantly reduces the uncertainties of welding and reduces the erection times. The steel connector is consisted of short-segment of I-section, end plate and square hollow sections (SHS). One side of I-section is embedded in concrete beam while the other end is welded to the endplate. The endplate is spaced at 80 mm from the beam surface, which provides adequate space for assembly purposes. Two hollow sections with same height and thickness are embedded into the columns. This configuration provides feasibility of adding more numbers of stories in the IBS. The cross-section area of the bottom SHS is slightly bigger than top SHS so that they can fit into each other. The composite beams and columns are assembled together by bolts. The detail of proposed connection is shown in Figure 1. The proposed connection is modeled precisely in finite element software and tested through the quasi-static test.
2. Methodology

In order to study the behavior of the proposed connection, its performance is compared with a monolithic connection. The dimensions of the beam and column for the precast connection is the same with the monolithic connection as shown in Figure 2 (a). The bottom of the column is pinned to prevent horizontal and vertical movement. The beam ends are roller supported, which only allowed to move horizontally. An axial load equal to 10% of the product of concrete compressive strength into gross section area of the column is applied at the top of the column as a preload. The boundary condition of the connections is shown in Figure 3 (a). The cyclic loading is applied at top of the column. The load control used up to 10% of yield load then continued by displacement control. The test procedure is according to ACI T1.1-01 which evaluate the performance of the beam-to-column connection for seismic activities [25]. Figure 2 (b) shows the displacement loading protocol employed for the quasi-static test. The compressive strength of concrete is set as 27.5 MPa with poison ratio of 0.2. The yield strength of steel sections is set as 437 MPa with a young modulus of 200 GPa and poison ratio of 0.3.
The eight-node linear brick element with a reduced integration and hourglass is used for modeling concrete and steel sections, whereas the two-node linear 3-D truss element is adopted for the reinforcements and links, which are embedded in concrete. The hexahedral mesh is used for concrete beam and columns. The mesh detailing of the model is depicted in Figure 3 (b). Concrete damaged plasticity (CDP) model is used to simulate the nonlinear behavior of concrete. The concrete model is a combination of multi-hardening plasticity and scalar damage elasticity to characterize the irreversible damage which occurs through the fracturing progress. The stress-strain data of steel with the classical isotropic material law which fulfills the Von-Mises plasticity model are adopted for steel sections.

![Model Mesh Detailing](image)

**Figure 3.** a) Boundary condition and b) mesh detailing of the model.

### 3. Results and discussion

The performance of connections is generally investigated through hysteresis curves. The displacement is measured at the top of the upper column while the force is measured at the base of the column. Figure 4 shows the force-displacement curves of the monolithic and hybrid connections. The hybrid connection showed higher stiffness as the slope transition from the yield to ultimate load is steeper than the monolithic connection. The ultimate strength of the precast connection at both positive and negative cycles are increased by 5.6% and 7.2% compared with the monolithic connection. The displacement ductility is defined as the ratio of the displacement at ultimate load ($\Delta_u$) to displacement at the yield load ($\Delta_y$) which is one of the seismic criteria of connection behavior under cyclic loadings. The displacement ductility is:

$$\mu = \frac{\Delta_u}{\Delta_y}$$  \hfill (1)$$

The displacement at yield load is obtained from the straight line passes through 75% of ultimate load and origin which intersect with the parallel line of the X-axis that passes through the ultimate load.

Furthermore, as Table 1 illustrates, displacement ductility of the precast connection is slightly improved by 7% in positive cycle whereas, in the negative cycle it is the same as the monolithic connection.

Figure 5 shows the stress distribution among the proposed hybrid precast connection. As this figure demonstrated, the stresses are relatively small at steel section of the connection while the stresses at the reinforcements and links in the concrete section are larger. The maximum Von-Mises stress is 378 MPa which is located at main reinforcement of the left beam. The maximum principal stress in concrete is also located at the left beam. It can be concluded that the failure occurred at left beam which is far from
the connection and follows the strong-column weak-beam theory. The precast connection has a good seismic behavior due to the compiled behavior of the steel and concrete.

![Figure 4. Load-displacement hysteresis curves of monolithic and hybrid precast connections.](image)

**Table 1.** Key results of monolithic and the hybrid precast connections.

| Specimen  | Positive cycle | Negative cycle |
|-----------|----------------|----------------|
|           | $P_u$ (kN)     | $\Delta_u$ (mm) | $\Delta_y$ (mm) | $\mu$ | $P_u$ (kN) | $\Delta_u$ (mm) | $\Delta_y$ (mm) | $\mu$ |
| Monolithic| 125.7          | 56.3           | 40.3            | 1.4   | 117.6       | 55.8           | 40.6            | 1.4   |
| Hybrid    | 132.7          | 34.5           | 23.3            | 1.5   | 123.1       | 33.9           | 24.3            | 1.4   |

$\Delta_y$: Yield displacement, $P_u$: Ultimate load, $\Delta_u$: Ultimate displacement, $\mu$: Displacement ductility.

![Figure 5. Stresses distribution in hybrid precast connections.](image)

4 Conclusion

This paper proposed and developed a new hybrid precast beam-to-column connection. The proposed hybrid connection can easily be erected and assembled at the site. The connection is made of steel sections embedded in concrete beam and column. The performance of the proposed connection studied
by the quasi-static test. A comparative study between monolithic and hybrid connection leads to the following conclusion:

- The ultimate strength of the hybrid precast connection was higher than the monolithic connection and both connections had similar ductility demands.
- The steel reinforcement yielded in the beam and also the maximum stress of the concrete located in the beam which led to the failure of the beam before the column. This is favorable according to the weak-beam/strong-column theory. Further, the beam can be easily disassembled and replaced after the earthquake events.
- It can be stated that even though there is a discontinuity in the connection reinforcements but the precast joint behave monolithically, with a good seismic performance.

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