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Effect of Connection Detailing on Reverse Cyclic Behaviour of Precast Beam to Column Grouted Cementitious Billet Connections

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In reinforced concrete framed structures exposed to high lateral loads, the performance of the beam to column joints has been acknowledged to have a significant impact on the overall behaviour of the structures. The present study conducted an experimental investigation on four 1/3rd scale Precast Concrete (PC) beam-to-column grouted cementitious billet connections subjected to reverse cyclic loading. Their performance was compared with a reference monolithic connection. The various precast connections studied are Billet with Dowel (BD) connection, Billet with Dowel-cleat Angle (BD-CL) connection, and Extended Billet with Dowel-cleat Angle (EBD-CL) connection. The ultimate load-carrying capacity, ductility factor, hysteretic behaviour, load ratio, energy dissipation, and stiffness degradation of the monolithic (MO) and precast (PC) specimens were studied, and a comparison of their performances was made. The results show that the EBD-CL connection has comparable ductility and strength.

Keywords: precast concrete, beam to column connection, reverse cyclic loading, grouted cementitious billet, cleat angle.

1. INTRODUCTION

In a Reinforced Concrete (RC) framed construction a beam-column connection plays a crucial role in maintaining a structure's continuity and transferring the forces. It has a significant impact on the structure's stability, flexibility, robustness and constructability. During the loading of the structure, connections play a predominant role in energy dissipation, load redistribution and determining the seismic resistance efficiency of the framed structure.

During the last few decades, precast construction has attracted a lot of attention and it is now being used in many structural applications. A precast system is made up of several structural components that are cast in a controlled environment or factory before being transported and put together on-site to create a structural system. Expansion in recent years in the international arena was because of its several advantages over conventional building techniques, including improved quality control, structurally efficient, aesthetics, energy saving, lower manufacturing costs, and faster production. When compared to cast-in-situ concrete construction, PC structures take 20 % less time to construct. [1 – 6].

Though it boasts many advantages, there was hesitancy in using it in seismic risk regions during past earthquakes. Toniolo and Colombo (2012) [7] observed that Precast Shed industrial buildings failed in the L'Aquila earthquake due to insufficient anchorage of dowel bars and some spalling occurred on the beam to column bearing. Savoia et.al (2017) [8] observed that in the Emilia earthquake, the RC precast industrial buildings collapsed because the connections were not built as per the seismic specifications. The major factor for the collapse was attributed to a lack of mechanical connection between the precast components as well as poor connection behaviour. The performance of Precast Concrete (PC) constructions in the previous earthquakes demonstrates the importance of connection, design and detailing in the seismic performance of PC constructions, as their behaviour is crucial.

Failure in recent earthquakes occurred due to inadequate design and a discontinuity between the precast components. Precast connections can be categorised as a limited ductile connection and ductile connections. Wet connections (with lap splice, grout, or in-situ concrete) and Dry connections (with welding and bolting reinforcing bars, plate, or steel insertion) are limited ductile connections. Numerous studies have been conducted on wet connections between beam to column connections, Cheok and Lew (1991) [9], Nimse et al. (2014) [10], Elsanadedy et al. (2017) [11], beam to slab connections, Vinutha et al (2021) [12], Sarkis et al. (2022) [13], Vinutha et al. (2024) [14], wall to slab connections, Han et al. (2019) [15], Arthi and Jaya (2020) [16], wall to wall connections Hemamalini and Vidjeapriya (2020) [17], Hemamalini et al (2021) [18], Parisutham et al. (2023) [19], column to foundation connections, Metelli et al. (2008) [20], Hemamathi and Jaya (2021) [21], Breccolotti et al (2016) [2] investigated PC-reinforced beam to column connection to increase the ductility of the concrete struts in the wet joint, loop splices and cast-in-place concrete wet joints containing steel fibres are utilised. The addition of the steel fibres improved the strength and ductility.

For dry connections, cast-in-place is not required, dramatically increasing construction efficiency and

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minimising environmental impact. Dry connections are typically categorised as bolted and welded connections. E.Aguiar et al. (2012) [22] studied the dowel behaviour in the connection between the PC beam and column by Varying the diameter and inclination, studying the load-transmission and shear mechanism. According to the findings, the inclined dowel has a much better ultimate load-carrying capacity and shear stiffness than the perpendicular dowel. Vidjeapriya and Jaya (2013) [5] investigated the monolithic and PC beam to column connections under reverse cyclic loading, using a single and double stiffener at a cleat angle, and a corbel connects the PC column to the PC beam. It was observed that both the precast specimens exhibited satisfactory behaviour in terms of energy dissipation and ductility when compared with the monolithic specimen. Vidjeapriya et al (2014) [4] studied the behaviour of two PC connections, where a corbel connects a beam to a column using a dowel bar and a dowel bar-cleat angle. It was observed that the monolithic specimen outperformed the PC specimen regarding energy dissipation and strength. PC specimens using a cleat angle and a dowel bar showed better behaviour in terms of ductility. Vidjeapriya et al (2014) [23] and (2015) [24] studied the behaviour of a long dowel with a single stiffener and a short dowel with single and double stiffener connections in precast beam-column connections. It was observed that a long dowel with a single stiffener performed well in terms of ductility and a short dowel with a double stiffener performed well in terms of ductility and energy dissipation.

Bahrami et al. (2016) [1] tested two new PC beams to columns of moment-resisting connections under lateral load. In type 1, a bolted inverted E connection was used to join PC beams to the continuous PC column with a corbel, and in type 2, the connecting element was a welded box section connection. The proposed connection achieved lateral resistance of 98 %, lateral stiffness of 80 % and ductility of 80 % to the equivalent MO connection, respectively.

Nzabonimpa et al. (2016) [25] studied a dry mechanical beam to column junction for connections between concrete components with fully restrained forces and concluded that mechanical dry connection of extended steel plate with the bolted connection can be used for reinforced concrete PC frames and steel-concrete composite PC frames. Yang et al. (2016) [26] developed a hybrid H steel-precast concrete (HSPC) to overcome the limitations of the conventional hybrid beam system where the H-steel beams embedded in the concrete beams and the H-steel beams supported by columns are bolted together. The three different parts of the designed HSPC beam system are reinforced concrete, joint and H steel. When compared to conventional beams regarding ductility, the newly created HSPC beam performed extremely well.

Nowadays, using the precast technique in construction has increased. However, moment-resisting frames can be built utilizing cast-in-situ techniques, which naturally enable this behaviour that is typically challenging to accomplish with precast elements [1]. An attempt has been made to develop a jointed precast connection and compare the seismic behaviour with a reference monolithic specimen.

When joining precast beams and columns using wet connections, the advantage of speedy construction is influenced by the sufficient time required for curing the wet concrete in the connection, when a dry connection is adopted, then its leads to faster construction. Therefore, the current study’s focus is on the functionality of mechanical devices used in dry connections.

2. SIGNIFICANCE OF THE RESEARCH STUDY

From the literature, it is inferred that numerous studies have been conducted on wet connections, but these connections cannot be repaired and also affect the speedy erection of the structural components. Wet connections are more rigid than dry connections, and hence its design is difficult and time-consuming [1]. Moreover, large volumes of in-situ concrete are required for wet connections, which negates the essential benefits of prefabrication. The precast concrete construction industry needs connections with easy and quick installation, leading to faster construction using mechanical elements. Compared with wet connections, dry connections have advantages in terms of speedy erection, easy maintenance, re-use and being easily reparable when damage occurs in the joints. An area of concern for dry connections is its performance in past earthquakes. During the L'Aquila earthquake (2009) precast industrial buildings failed due to inadequate dowel bar anchorage and the Emilia earthquake (2012) resulted in the collapse of RC precast industrial buildings due to inadequate seismic connections and poor connection behaviour.

Despite extensive research on precast structures over the past four decades, the PC beam-to-column connections behaviour under various possible structural loadings has not been fully understood and research on PC Beam-to-column connection using dry connections was minimal. Precast concrete structures with pinned connections are widely used globally, but corbel is not preferred by architects due to its limited appearance. Architectural demands necessitate the design of invisible or hidden connections, making the Billet connection a viable option for meeting both architectural and moment connection requirements [27]. Hence it is very important to carry out detailed investigations on the seismic performance of precast beam to column dry connections. The current study is focused on the functionality of mechanical devices (dry connection) in precast beam to column connections under cyclic loading.

In this study, an experimental program is conducted to investigate dry precast connections under reverse cyclic loading. There are three types of precast concrete connections used which include the billet with a dowel, billet dowel-cleat angle and billet dowel-cleat angle with increased bearing length.

3. ANALYSIS AND DETAILING

An investigation of a three-story RC structure was conducted using Staad.pro Software. For this study, a critical exterior beam-to-column joint is taken into account. To maintain joint integrity and reduce stiffness degradation, The design and detailing of the monolithic test specimen are according to IS 456:2000 [28] and IS 13920:2016 [29]. This improves the ductile behaviour of the beam-to-column joint [30]. The design of the bolt and cleat angle is designed according to IS 800:2007 [31].

In the beam, flexural reinforcement consists of 4 bars of 10 mm in diameter with one bar on every transverse reinforcement corner. The shear reinforcement consists of two-legged stirrups 3 mm in diameter and spaced at 60 mm. The lateral tie spacing was reduced to 30 mm at 280 mm from the column face. There are four bars with a diameter of 10 mm in the column reinforcement arrangement as well. Along the height of the column (apart from the joint region), there were 50 mm between the lateral ties, each having a diameter of 5 mm. The lateral tie spacing decreased to 25 mm at the joint region. The PC specimens were detailed, similar to the monolithic specimen.

4. MATERIAL PROPERTIES

M30 grade concrete and Fe500D grade reinforcement bars were utilised to prepare each specimen. Three 150×150×150 mm cubes were found to have a mean compressive strength of 39.55 MPa. The precast beam to column joint and billet region was filled with commercially available non-shrinking and flowable grout (NS 2), achieving a mean compressive strength of 82.43 MPa at 28 days. The compressive test results of cementitious grout are shown in Fig. 1. Reinforcement bars were teated to ensure their yield strength.

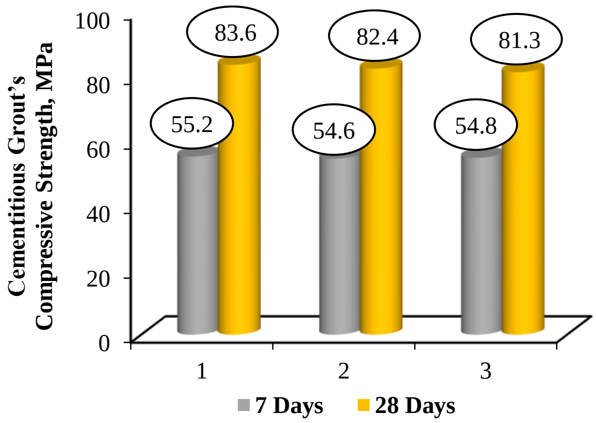


Fig. 1. Cementitious grout's compressive strength

5. CONNECTIONS

Precast concrete structures with wet connections need complex design and lengthy execution. As a result, the precast concrete industry requires connections with a quick, simple installation that leads to the development of using billet and dowel mechanical precast beam to column dry connections.

The monolithic RC beam to column specimen is designed as per IS 456:2000 [28] and detailed as per IS 13920:2016 [29] respectively as shown in Fig. 2 and the isometric view of the monolithic specimen is shown in Fig. 3 a.

To connect the beams, a dowel recess is located inside the beams using PVC sleeves. In this connection, the precast concrete column is cast in with a steel billet and a 10 mm dowel is used to connect the beam and billet.

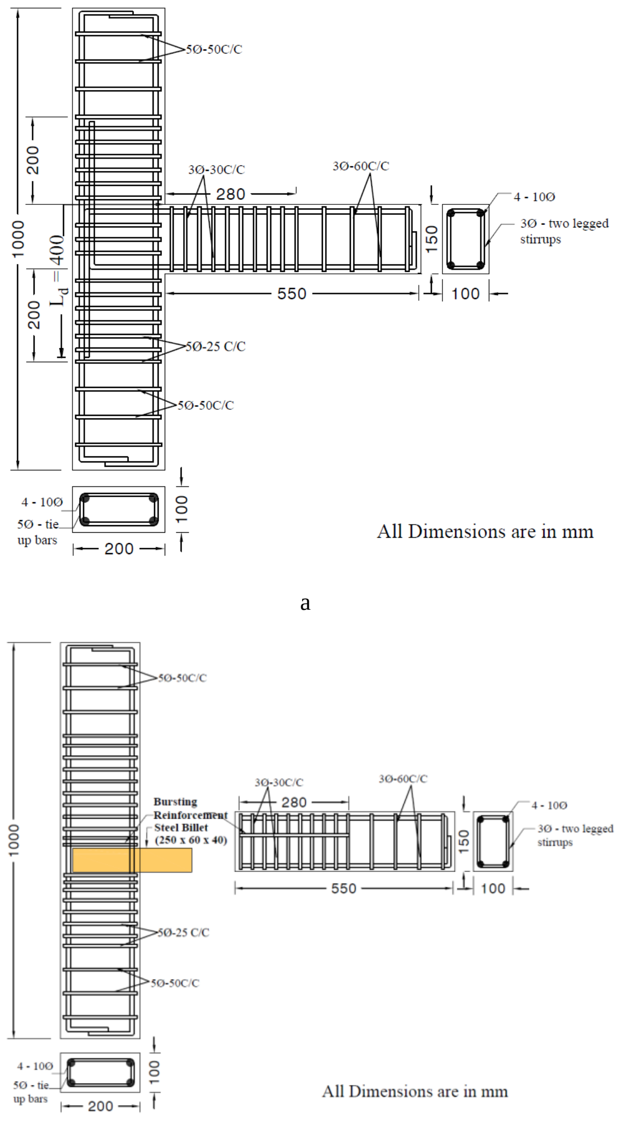


Fig. 2. Detailing of monolithic specimen and precast specimen: a – monolithic connection; b – precast beam-column connection

This connection was designed based on the recommendation of BS 8110:1997 [32]. The schematic illustration of the 3D view of the PC connection using billet and dowel is shown in Fig. 3 b.

In this connection, the precast concrete column is cast in with a steel billet. The cleat angle is connected to the column by one bolt, and the billet is connected to the cleat angle by another bolt through a recess in the beam. The schematic representation of the 3D view of the pre-cast connection using billet and dowel is shown in Fig. 3 c.

This connection looks like the (BD-CL) PC connection except for the extended steel billet which has an increased bearing length and an additional dowels bar. The schematic illustrations of the 3D view of the PC connection made with billet and dowels are shown in Fig. 3 d. The gap between the precast column and the beam was filled with non-shrinking and flowable grout in all the precast connections. For all the precast connections, the beam and column face at the junction were filled with NS 2 grout.

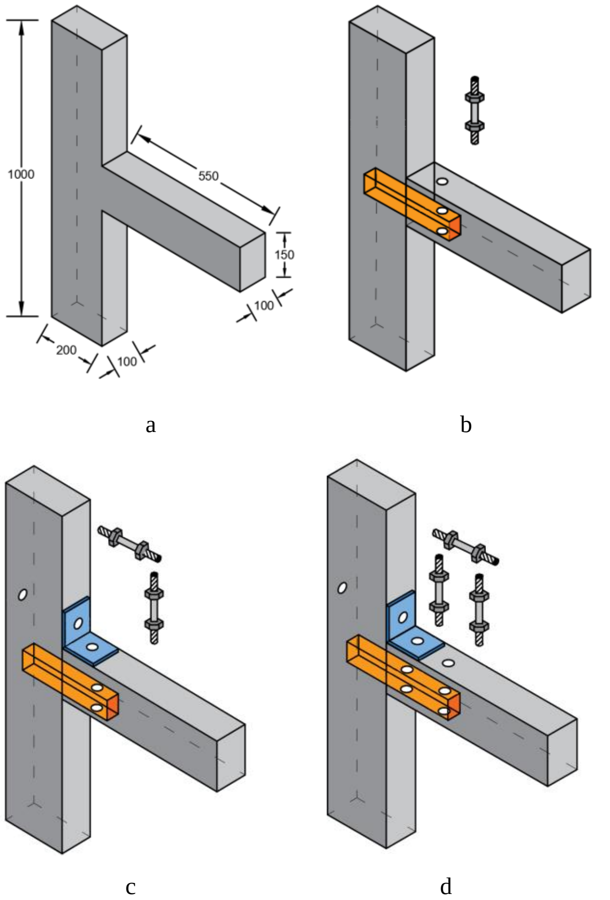


Fig. 3. 3D view of monolithic specimen and precast specimens: a – monolithic specimen; b – billet with dowel; c – billet with dowel-cleat angle; d – extended billet dowel-cleat angle

6. EXPERIMENTAL TEST SETUP AND LOADING

A loading frame of 2000 kN capacity was used for testing monolithic and Precast specimens. An axial load of 0.1 $f_c'A_g$ (45 kN) to simulate Gravity load was applied to the column using a hydraulic jack [5]. Displacement controlled loading system was adopted [33]. Using 100 kN and 200 kN hydraulic jacks, the reverse cyclic loading was applied by keeping the column vertical and the beam horizontal. At the top, the column was laterally restrained and hinged to the strong reaction floor. Fig. 4 shows the experimental setup. The reverse cyclic loading history used for this testing program is shown in Fig. 5 and Table 1 is as per ACI 374.1-05. This code uses the displacement control method for loading the specimens. It considers specific criteria for displacement-controlled loading patterns. It includes:

1. For every drift ratio, three complete reverse cycles must be used.
2. The initial drift ratio should be within the linear elastic response range for the protocol.
3. Successive drift ratios should be values between one and one-quarter times, and one and one-half times compared to the previous drift ratio.
4. Testing shall continue with gradually increasing drift ratios until the drift ratio equals or exceeds 0.0035.

Table 1. Cyclic loading sequence

S. No	Displacement, mm		Increment, mm
	Start	End	
1	1	6	1
2	6	20	2
3	20	40	3

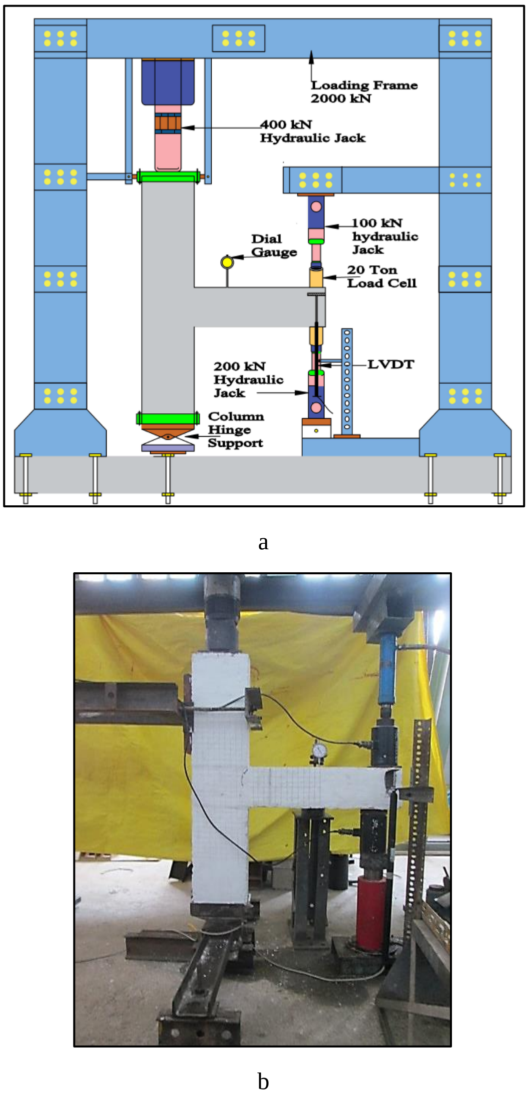


Fig. 4. Experimental test setup: a – schematic view; b – test setup

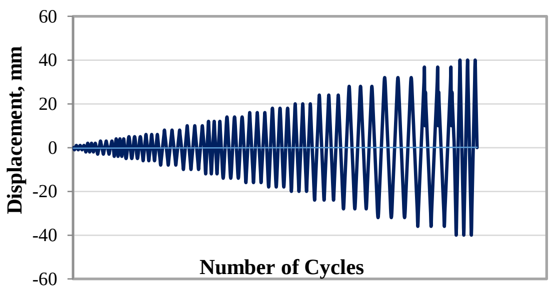


Fig. 5. Cyclic loading sequence

7. RESULTS AND DISCUSSION

The experimental investigation was carried out for the specimen under reverse cyclic loading. Three types of PC beam-to-column connections are compared with the monolithic connection. The experimental comparison considered for PC beam-to-column connections are billet with dowel connection, billet with dowel-cleat angle connection, and extended billet with dowel-cleat angle connection.

7.1. Strength

The ultimate load-carrying-capacity of the billet with dowel-cleat angle in the positive and negative directions are 21.3 % and 26.9 % greater than the Billet with Dowel due to the enhanced stiffening provided to the connection by the cleat angle. The ultimate load-carrying-capacity of the extended billet with dowel-cleat angle is 53.6 % in the positive and 51.3 % in the negative directions greater than the billet with dowel-cleat angle. The extended billet with dowel-cleat angle has load-carrying capacity 5 % greater than the monolithic in the negative direction due to the increased development length of the billet. Pre-cast and monolithic both showed the same post-elastic behaviour under ultimate load. The extended billet with dowel-cleat angle was found to have a larger ultimate strength than the monolithic during negative loading (downward direction). This is because of the higher resistance provided by the cleat angle connected with two dowel bars in the negative loading when compared to the MO specimen in the negative loading. The results are comparable to those obtained by Vidjeapriya and Jaya [5]. At the joint, the dowel bars increased the shear resistance at the connection zone. Fig. 5 shows the ultimate load of the specimens in the positive and negative directions. The yield loads of the specimens are shown in Table 2.

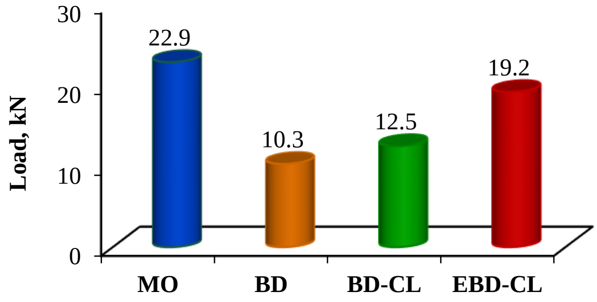
Table 2. Yield loading

S. No	Specimens	Yield load, kN	
		Positive	Negative
1	Monolithic specimen	17.18	17.1
2	Billet with dowel	8.63	9.95
3	Billet with dowel-cleat angle	10.27	11.87
4	Extended billet with dowel-cleat angle	17.07	18.37

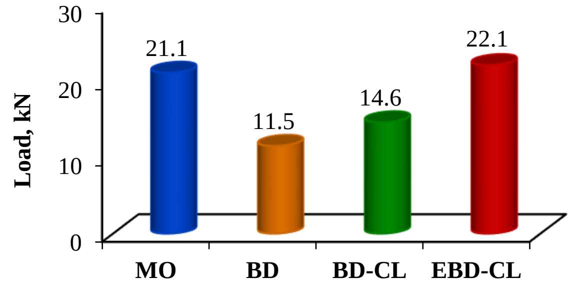
Fig. 6 a and b show the positive loading (ultimate) and negative loading (ultimate) respectively. Table 2 represents the yield load of all the connections.

7.2. Load-displacement relationship

The load-displacement hysteresis curve for the monolithic specimen shows the same pattern in both positive and negative directions. In this study, it is observed that the billet with dowel connection performs well in the positive direction due to the stiffness offered by the billet. In billet with dowel-cleat angle connection, strength degradation was observed at 18 mm displacement cycle in a positive direction whereas 16 mm displacement cycle in a negative direction. Load-displacement hysteresis of extended billet with dowel-cleat angle was wider than billet with dowel due to the stiffened behaviour of cleat angle in the downward direction and extended billet in the upward direction. The hysteresis loop for monolithic was stable and wider when compared with pre-cast connections. A similar trend was observed by Nimse et al. [10]. The test was carried out up to 40 mm displacement, where the strength was reduced to 50 % of its ultimate strength.



a



b

Fig. 6. a – positive loading (ultimate); b – negative loading (ultimate)

Because of the predetermined gap at the joint region, there was more pinching seen in the precast specimen. Fig. 7 depicts the load-displacement hysteresis curves. Fig. 8 shows the load-envelope curve for the monolithic and precast specimens.

7.3. Crack pattern

The observed crack pattern in every specimen during loading reverse cycles is shown in Fig. 9. In the monolithic specimen, the initial flexural crack at the beam to column joint was initiated at a 3 mm (10.5 kN) displacement cycle and it has continued to spread at 12 mm and 16 mm cycles of displacement. The shear crack occurred at a 5 mm (12.5 kN) displacement cycle and the further crack developed at 12 mm (17.8 kN) and 16 mm (19.8 kN). Concrete spalling occurred in beam to column junction at 32 mm. Reinforcement was visible at 36 mm. The test was terminated at 40 mm displacement cycles (15.4 kN) due to the joint region's concrete crushing and spalling. Fig. 9 a demonstrates the test specimen's crack pattern. In the BD connection, the first flexural crack at the junction of the beam and column was initiated at a 1 mm (6.5 kN) cycle of displacement and it propagated further at 14 mm and 18 mm displacement cycles. All the cracks were concentrated at the beam column face due to the predefined gap provided between the beam and column. Bidin discovered a similar crack pattern during his studies [25]. In the BD-CL connection, the initial flexural crack at the beam to column joint was initiated at a 2 mm (8.5 kN) displacement cycle and it has been further propagated at an 8 mm displacement cycle. The shear crack occurred at 8 mm (11.95 kN) displacement cycle and the crack further developed at 12 mm (12.95 kN).

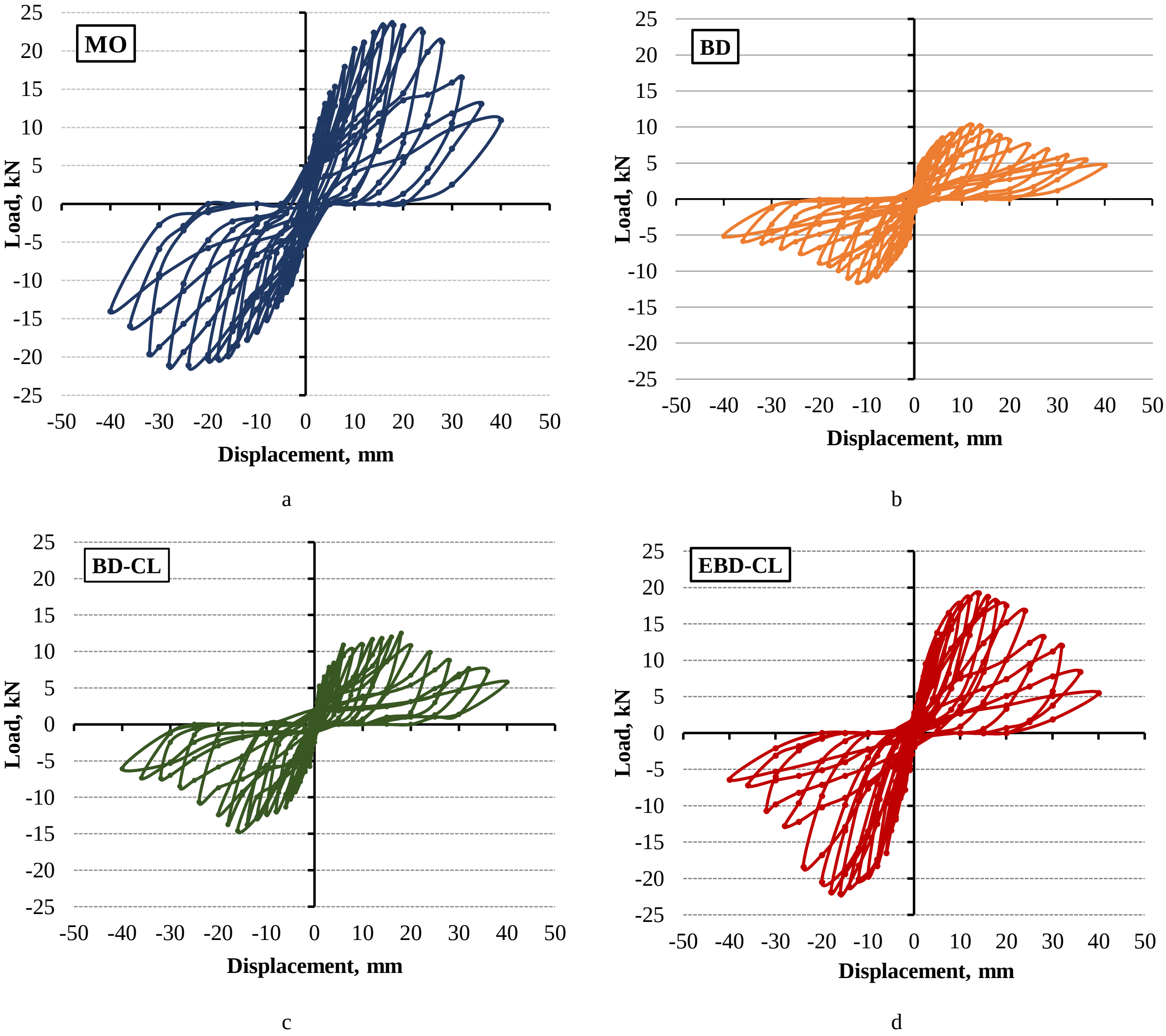


Fig. 7. Load-displacement curves: a – monolithic specimen; b – billet with dowel; c – billet with dowel-cleat angle; d – EBD-CL

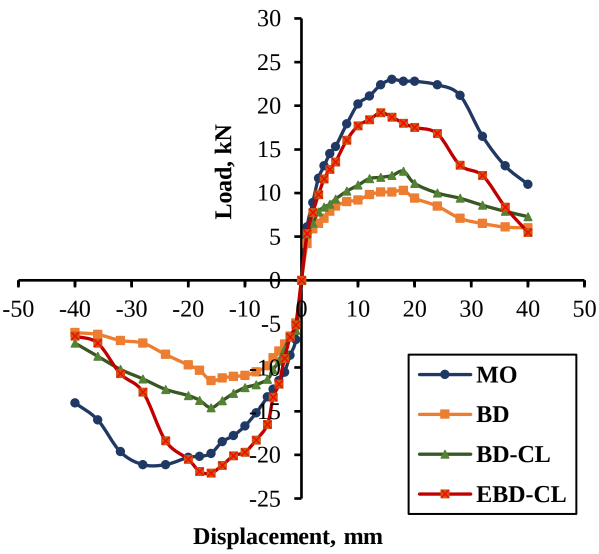


Fig. 8. Load-envelope curve

Initially, cracks were formed at the predefined gap and due to the stiffening behaviour of the cleat angle, further cracks were formed near the recesses of the dowel bar and propagated at higher loading. Beyond the ultimate load, the cracks that had previously opened did not close. Concrete crushing was visible at the corners where the beam and column interfaced.

In the EBD-CL connection, at the beam to column joint, the initial flexural crack was started at 4 mm (11.9 kN) displacement cycle and it has been further propagated at 6 mm (16.5 kN) and 10 mm (19.7 kN) cycle of displacement. The shear crack occurred at a 5 mm (14.4 kN) displacement cycle and the further crack developed at 12 mm (20.1 kN) and 16 mm (22.1 kN). The spalling of concrete took place in the beam to column junction at 28 mm. Cracks were formed near the recesses of the dowel bars (Vidjeapriya et al. [4]). Compared with other Precast connections, EBD-CL has less opening of a crack in the joint between beam and column and has a wider hysteresis curve. The use of extended billet, two dowels and cleat angle in joints promotes better stress distribution and uniform cracking, akin to monolithic joints. The ductility and energy dissipation were higher when compared with other precast connections. In monolithic specimens, the shear cracks originated from the beam-column critical region and extended in the joint region diagonally at both sides. As the displacement increased, the diagonal cracks moved closer to the beam-column joint region. Cracks were found surrounding the recess for bolt accommodation in the precast beam and cleat angle, but no visible crack was observed in the precast column. The grouted cementitious layer between the beam and column junction plays a vital role in providing the initial resistance, as indicated by the observation and crack pattern [19]. The crack pattern of the precast and monolithic specimen is shown in Fig. 9 and Table 3.

7.4. Energy dissipation

The specimen's energy dissipation capacity can be determined by the "area beneath the load-displacement curve" [34]. Fig. 10 shows the energy dissipation comparison of pre-cast and monolithic specimens. The results indicate that the monolithic specimen dissipated more energy than the precast specimens., measuring 3871 kN mm. When compared to the monolithic specimen, the energy dissipation capacity of the extended billet with dowel-cleat angle beam to column connection was found to be 80.11 % of the monolithic specimen due to the presence of two dowel bars and stiffening resistance offered by the cleat angle, the damage in the concrete was more and it dissipates more energy.

Fig. 9. Crack pattern of the monolithic and precast specimens: a – monolithic Specimen; b – billet with dowel; c – billet with dowel-cleat angle; d – extended billet dowel-cleat angle

Table 3. Crack differences between the monolithic and precast specimens

Monolithic	BD	BDCL	EBDCL
Cracks usually begin at the interface between beam and column, where stress concentrations are highest.	Cracks frequently occur at the embedded dowel connections due to stress concentrations at these points.	Cracks usually begin at the beam-column interface and around the cleat angle connections.	Cracks usually begin at the beam-column interface and around the dowels and cleat angle.
Monolithic joints typically exhibit a ductile failure mode.	The failure modes exhibit a combination of ductile and brittle.	The configuration with cleat angle improves ductile failure characteristics and plastic deformation ability compared to a joint with only a billet dowel.	The configuration of precast joints with extended billet, dowels and cleat angle is the most ductile, enhancing its ability to undergo plastic deformation.
The widespread cracks help to dissipate energy.	Energy dissipation occurs due to the plastic deformation of the dowel and the surrounding concrete.	The failure process involves a more evenly distributed crack pattern, characterized by improved energy dissipation and less brittle failure.	The crack pattern is uniformly distributed, similar to monolithic joints, enabling effective energy dissipation and larger deformations before failure.

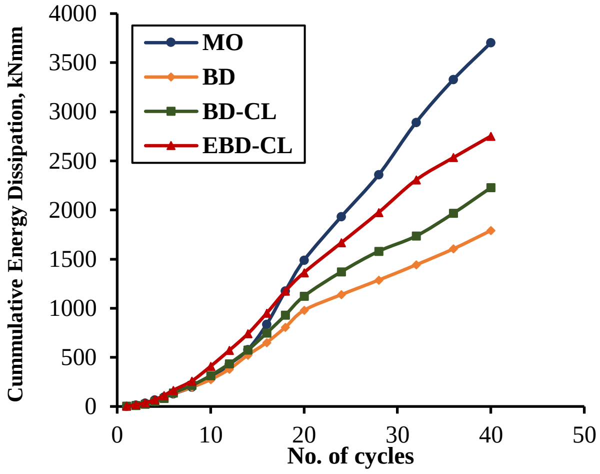


Fig. 10. Energy dissipation capacity

Billet with dowel-cleat angle was 60.15 % of the monolithic specimen. Billet with Dowel dissipated 49 % of energy compared to the monolithic connection. As displacement increases, with every displacement cycle, the hysteresis loop's area increases [1]. The specimen's final displacement was 40 mm.

7.5. Ductility

Ductility is defined as the "ability of the structures to undergo deformation without any loss of stiffness". To prevent inelastic failure, ductility is a critical component of seismic behaviour. The "ductility is the ratio of ultimate by yield displacement". The ductility was calculated based on Park's (1989) [35] methodology. Table 4 (Fig. 11) compares the ductility factors in precast specimens under positive and negative loading with the specimen MO.

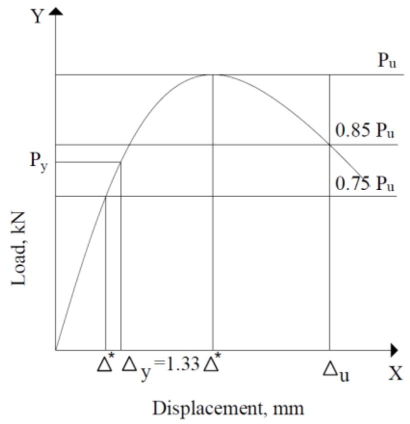


Fig. 11. Ductility curve

Table 4. Ductility factor

Specimen	Yield displacement Δ_y, mm	Ultimate displacement Δ_u, mm	Ductility factor μ
MO	9.5	33	3.47
BD	6	18.75	3.13
BD-CL	7.75	24.6	3.17
EBD-CL	7.3	23.25	3.22

Monolithic specimens are known for their high ductility due to their continuous construction and uniform material properties, allowing for significant plastic deformation before failure. It is observed that displacement ductility of the extended billet with dowel-cleat angle was found to be 98 % of the monolithic specimen due to the deformability of the extended billet, dowels and cleat angle and it shows comparable ductility [5]. All the precast specimens show similar ductility and the variation of ductility when compared with the monolithic specimen was insignificant. The ductility factor for the PC Specimens is an indication of the connection's acceptable performance in the plastic stage.

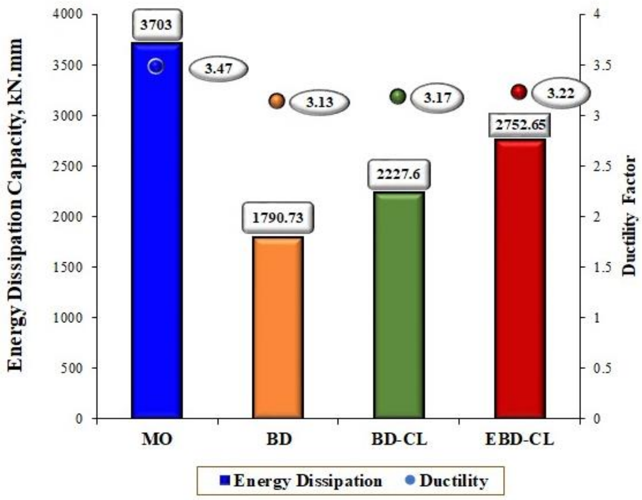


Fig. 12. Correlation between energy dissipation and ductility

Ductility is significant in determining the design seismic forces since it is connected with the energy dissipation structural capacity created by nonlinear behaviour. The graph in Fig. 12 compares the energy dissipation and ductility factor [36].

7.6. Stiffness degradation

Using the hysteresis load-displacement curves, the stiffness of the specimens was determined. The behaviour of a structure under an earthquake is impacted by variations in the stiffness of its components. The term stiffness refers to the rigidity of the structure like the beam to column joint. The specimen's stiffness degradation was computed using "secant stiffness". It is defined as the "slope of the line that connects the peak negative and positive response during a load cycle" [37]. All the structural components will exhibit a certain level of decrease in stiffness as shown in Fig. 13 a. Because of the growing accumulation of damage in the beam and column for the MO specimen and the precast beam, stiffness gradually reduced with rising displacement levels [4]. Due to the dowel bar's bond failure and cleat angle at the beam column joint as well as the opening and closing of the gap at the beam and column, the severe stiffness degradation in the PC specimen was more prominent. The MO specimen had an initial stiffness of 11.36 kN/mm, while the EBD-CL specimen demonstrated higher initial stiffness compared to other precast specimens. The initial stiffness loss for all precast specimens was found to be 96.7 % [5].

In RCC structure, the cracking of components is under cracking, and loss of bond will reduce the stiffness [4, 5]. Stiffness was higher before the 5 mm cycle because of minor cracking. To compare the test specimens, each secant stiffness measurement was normalised (k_{norm}) about the secant stiffness at a displacement level of 5 mm.

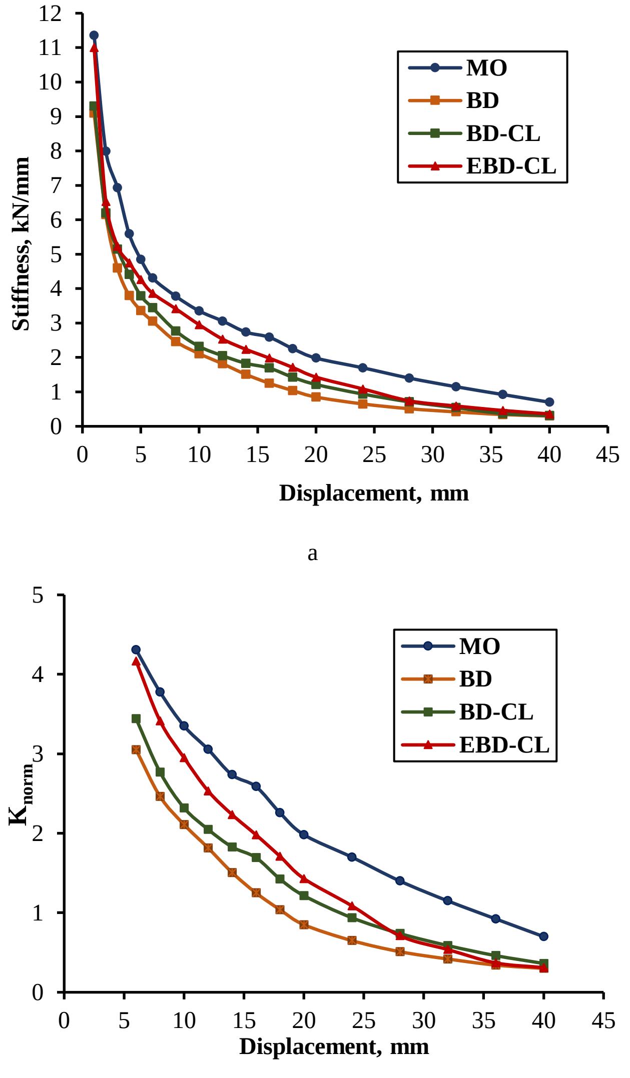


Fig. 13. a – stiffness degradation; b – normalized stiffness degradation

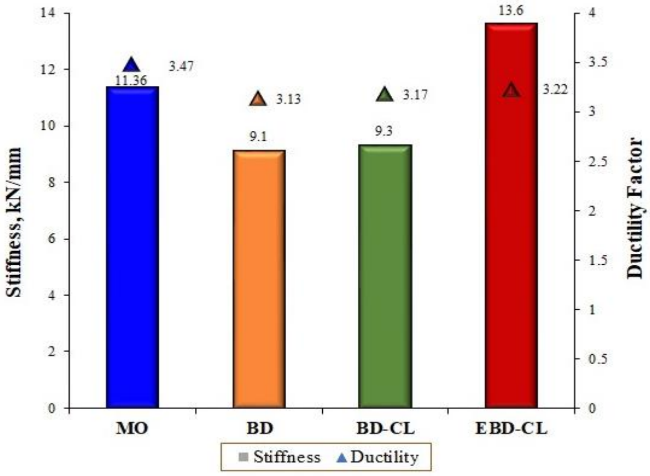


Fig. 14. Relationship between the ductility factor and stiffness

Fig. 13 b shows the normalized stiffness degradation. The graph in Fig. 14 shows the relationship between the ductility factor and stiffness. The EBD-CL specimen exhibits enhanced stiffness and ductility, attributed to the inclusion of extended billet, dowels, and cleat angle, and ductile detailing.

7.7. Load ratio

In the post-elastic stage, "the ratio between the maximal load in each cycle to the specimen's yield load is known as the load ratio". The joint's lateral load resistance is determined from the "ability to deform well in the inelastic range and by dissipating more energy through the hysteric behaviour". The load ratio has been evaluated to assess each specimen to maintain post-yield performance [38, 39]. The high post-elastic strength enhancement factor suggests that monolithic joints can maintain and potentially enhance their load-carrying capacity post-yielding.

The monolithic specimen maintained the yield loads up to 32 mm displacement cycles, while BD-CL and EBD-CL demonstrated a decreasing trend after the displacement cycle of 28 mm. The greatest resistance is displayed by specimens MO, BD-CL, and EBD-CL, where load ratios are 1.21, 1.11, and 1.25, respectively. The EBD-CL specimen exhibits the highest post-elastic strength enhancement factor, indicating its robust capacity to carry loads beyond its initial yield strength. This high load ratio indicates the EBD-CL joint's robust performance and resilience to seismic loads. Fig. 15 shows the load ratio of various specimens.

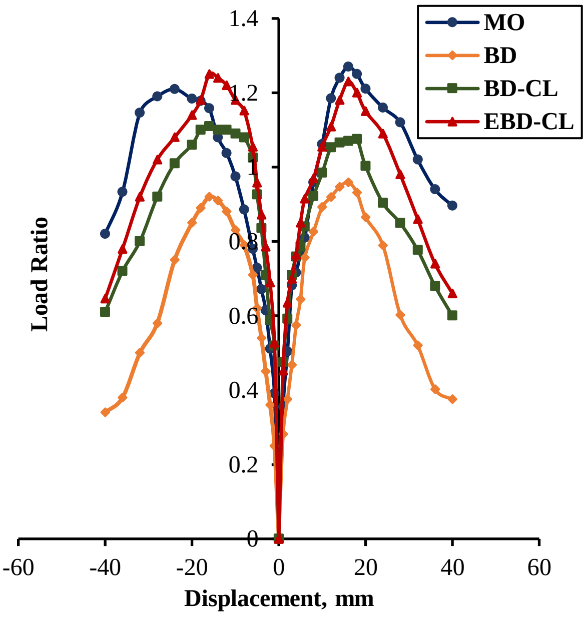


Fig. 15. Load ratio

7.8. Fixity factor

The connection classification using Monforton's fixity factor (γ) is determined using Eq. 1. Table 5 shows Monforton's fixity factor value for the precast specimens.

$$\gamma = \frac{1}{1 + (\frac{3EI_{cr}}{S_E L})}, \quad (1)$$

where E is the Young's modulus of concrete; I_{cr} is the second moment of area; S_E is the connection stiffness; L is the length of the beam.

Table 5. Monforton's fixity factor (γ)

Connection	Fixity factor	Classification
BD	0.53	Semi-rigid with medium strength
BDCL	0.58	Semi-rigid with medium strength
EBDCL	0.685	Semi-rigid with high strength

Ferreira et al. (2005) [40] provided the beam to column connection classification system calculation. The contributions of two dowel bars, extended billet, and cleat angle increased the fixity factor value in EDB-CL.

8. THEORETICAL STUDY

ACI 352 R-9 states that the design shear force V_u should be calculated on a horizontal plane at the joint's mid-height by taking into account the normal compression and tension forces in the members that frame the joint in addition to the shear forces acting on the joint's free body boundaries. The Eq. 2 should be satisfied:

$$\Phi V_n \geq V_u, \tag{2}$$

where V_n is the nominal shear strength of the joint, calculated using Eq. 3 and Φ = 0.85.

$$V_n = 0.083\, \gamma \sqrt{f_c'}\, b_j\, h_c \text{ (MPa)}, \tag{3}$$

where γ is the strength coefficient; h_c is the depth of the column in the direction of the joint shear; b_j is the effective joint width.

Based on the loading conditions of the connection and the expected deformations of the associated frame elements when resisting lateral loads, two types of structural connections are distinguished: Type 1 and Type 2. Members intended to meet ACI 318-08 strength criteria (ACI 318-08) for members without negligible inelastic deformation make up a Type 1 connection. In Type 2 frame members, connections are made to withstand deformation reversals into the inelastic range with continuous strength.

The NZS 3101-2006 and ACI 318-08 stipulate that the joint shear stresses in the core within a maximum allowable value to prevent diagonal cracking. Table 5 displays the formula used to limit joint shear stress according to different codes.

The joint shear strength (V_u) of all the specimens is shown in Fig. 16. The nominal shear strength (Φ V_n) is calculated based on Eq. 3 is 190.65 kN. Because precast specimens have billets, their predicted joint shear strength is larger than that of monolithic specimens. The joint shear strength of the BDCL and EBDCL specimens was 10 % more than the monolithic specimen.

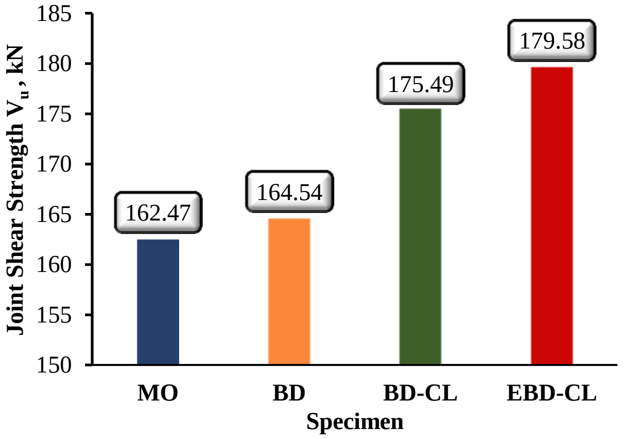


Fig. 16. Joint shear strength of all specimens

All the specimens satisfied the condition mentioned in Eq. 2. The joint region's shear stress was calculated and tabulated in Table 6. To prevent diagonal crushing, the amount of horizontal joint shear stress must be kept to a minimum. The shear stress was found within the permissible limits provided by the various codes as shown in Table 7.

Table 6. Shear stresses in joints based on different codal provisions

Code	Maximum joint shear stress formula, N/mm^2	Ultimate joint shear stress, N/mm^2
NZS310-2006	$\tau_{NZS} = 0.2$ fc′	6.33
ACI318-08	$\tau_{ACI} = 0.083\ \gamma \sqrt{fc'}$	5.63
IS:13920-2016	$\tau_{IS} = 1.0 \sqrt{fck}$	6.28

9. CONCLUSIONS

In this research experimental investigation has been carried out for three types of pre-cast beam to column connections. Subsequently, the outcomes have been compared with a monolithic beam to column connection under reverse cyclic loading. The connections are PC beam-to-column billet with dowel, billet with dowel-cleat angle, and extended billet with dowel-cleat angle. The following conclusions were drawn from the experimental study:

1. Of the three precast specimens, the extended billet with dowel-cleat angle connection exhibited an ultimate load carrying capacity 5 % greater in the negative direction than the monolithic due to the greater stiffening effect provided by the cleat angle, extended billet and the two dowel bars.

Table 7. Ultimate shear stress in joints comparison with ACI, NZS and IS code

Specimen	Ultimate load			Ultimate joint shear stress comparison with various codal provisions			
				Calculated	ACI	NZS	IS
	P_u, kN	P_u, Cal, kN	$\frac{P_u}{P_{u,cal}}$	τ_{jh}, MPa	$\frac{\tau_{jh}}{\tau_{ACI}}$	$\frac{\tau_{jh}}{\tau_{NZS}}$	$\frac{\tau_{jh}}{\tau_{IS}}$
MO	22.9	19.87	1.15	5.08	0.90	0.80	0.81
BD	11.5	19.87	0.58	2.55	0.45	0.40	0.41
BD-CL	14.6	19.87	0.73	3.24	0.58	0.51	0.52
EBD-CL	22.1	19.87	1.11	4.90	0.87	0.77	0.78

2. Load-displacement hysteresis of extended billet with dowel-cleat angle was wider than billet with dowel connection. The hysteresis loop for monolithic was stable and wider when compared with all precast connections.
3. It was observed that the energy dissipation of the extended billet with dowel-cleat angle exhibited 80.11 %, while the PC billet-cleat angle exhibited 60.15 % and the billet with dowel was 49 % of energy dissipation of the monolithic specimen.
4. It was noted that the displacement ductility of the extended billet with dowel-cleat angle was found to be 98 % of the monolithic specimen. The EBD-CL has higher ductility compared with other precast specimens indicating a robust ability to absorb and dissipate seismic energy. The cleat angle distributes stresses evenly, reducing the risk of localized failures and improving the joint's ductility.
5. Regarding energy dissipation capacity and ductility, the extended billet with dowel-cleat angle beam to column connection exhibits comparable behaviour to the monolithic specimen. The EBD-CL specimen exhibits comparable performance because of the stiffening effect of the cleat angle and extended billet, more damage occurred in the connection region and improved stress distribution was attained through the extended billet, dowels and cleat angle.
6. The MO specimen had an initial stiffness of 11.36 kN/mm, while the EBD-CL specimen demonstrated higher initial stiffness compared to other precast specimens. The initial stiffness loss for all the precast specimens was found to be 96.7 %.
7. Pre-cast and monolithic connections showed similar behaviour in the post-elastic stage under ultimate load. The EBD-CL specimen exhibits the highest post-elastic strength enhancement factor, indicating its robust capacity to carry loads beyond its initial yield strength. This high load ratio indicates the EBD-CL joint's robust performance and resilience to seismic loads.
8. The contributions of two dowel bars, extended billet, and cleat angle resulted in an increase in the fixity factor value in EDB-CL.
9. Hence the extended billet with dowel-cleat angle showed comparable behaviour with the monolithic specimen in terms of ultimate loading carrying capacity, ductility, initial stiffness, and load ratio.
10. The study emphasises the significance of design details like cleat angle and extended billet with dowels in enhancing the performance of precast joints, which can help engineers optimise joint designs.
11. The study shows that suitable design enhancements in precast joints can achieve comparable behaviour to monolithic construction, making it a viable option for seismic risk regions.
12. The study's findings can guide future building codes and standards, offering evidence-based guidelines for the use of precast dry connections in seismic applications.

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REFERENCES

1. **Bahrami, S., Madhkhan, M., Shirmohammadi, F., Nazemi, N.** Behaviour of Two New Moment Resisting Precast Beam to Column Connections Subjected to Lateral Loading *Engineering Structures* 132 2017: pp. 808 – 821. https://doi.org/10.1016/j.engstruct.2016.11.060
2. **Breccolotti, M., Gentile, S., Tommasini, M., Materazzi, A.L., Bonfigli, M.F., Pasqualini, B., Gianesini, M.** Beam to Column Joints in Continuous RC Frames: Comparison Between Cast-In-Situ and Precast Solutions *Engineering Structures* 127 2016: pp.129 – 144. https://doi.org/10.1016/j.engstruct.2016.08.018
3. **Yuksel, E., Karadogan, H.F., Bal, I.E., Ilki, A., Bal, A., Inci, P.** Seismic Behavior of Two Exterior Beam to Column Connections Made of Normal-Strength Concrete Developed for Precast Construction *Engineering Structures* 99 2015: pp. 157 – 172. https://doi.org/10.1016/j.engstruct.2015.04.044
4. **Vidjeapriya, R., Vasanthalakshmi, V., Jaya, K.P.** Performance of Exterior Precast Concrete Beam to Column Dowel Connections Under Cyclic Loading *International Journal of Civil Engineering* 12 (1 A) 2014: pp. 82 – 94.
5. **Vidjeapriya, R., Jaya, K.P.** Experimental Study on Two Simple Mechanical Precast Beam to Column Connections Under Reverse Cyclic Loading *Journal of Performance of Constructed Facilities* 27 (4) 2013: pp. 402 – 414.
6. **Elliott, K.S.** Precast Concrete Structures, Second Edition, CRC Press, Taylor & Francis Group, New York, 2017.
7. **Toniolo, G., Colombo, A.** Precast Concrete Structures: The Lessons Learned from the L'Aquila Earthquake *Structural Concrete* 13 (2) 2012: pp. 73 – 83. https://doi.org/10.1002/suco.201100052
8. **Savoia, M., Buratti, N., Vincenzi, L.** Damage and Collapses in Industrial Precast Buildings after the 2012 Emilia Earthquake *Engineering Structures* 137 2017: pp. 162 – 180. http://dx.doi.org/10.1016/j.engstruct.2017.01.059
9. **Cheok, G.S., Lew, H.S.** Model Precast Concrete Beam-to-Column Connections Subjected to Cyclic Loading *PCI Journal* 38 (4) 1993: pp. 80 – 92.
10. **Nimse, R.B., Joshi, D.D., Patel, P.V.** Behavior of Wet Precast Beam Column Connections Under Progressive Collapse Scenario: An Experimental Study International *Journal of Advanced Structural Engineering* 6 (4) 2014: pp. 149 – 159. https://doi.org/10.1007/s40091-014-0072-3
11. **Elsanadedy, H.M., Almusallam, T.H., Al-Salloum, Y.A., Abbas, H.** Investigation of Precast RC Beam to Column Assemblies Under Column-Loss Scenario *Construction and Building Materials* 142 2017: pp. 552 – 571. https://doi.org/10.1016/j.conbuildmat.2017.03.120
12. **Vinutha, D., Vidjeapriya, R., Jaya, K.P.** Seismic Performance of Precast Slab to Beamconnection: An Overview *Current Science* 121 (1) 2021: pp. 61 – 76.

13. **Sarkis, A.I., Büker, F., Sullivan, T,J., Elwood, K.J., Brunesi, E., Hogan, L.S.** Aspects Affecting the Nonlinear Behavior of Precast Prestressed Hollow-core Units Failing in Shear *Structural Concrete* 23 2022: pp. 3021 – 3038. https://doi.org/10.1002/suco.202100579
14. **Vinutha, D., Vidjeapriya, R., Jaya, K.P.** An Experimental Assessment on the Seismic Behaviour of Precast Hollowcore Slab to Beam Connection with Different Connection Details *Archives of Civil and Mechanical Engineering* 24 (167) 2024: pp. 1 – 25.
15. **Han, W., Zhao, Z., Qian, J., Zhang, Y., Ma, T.** Experimental Seismic Behavior of Squat Shear Walls with Precast Concrete Hollow Moulds *Earthquake Engineering and Engineering Vibration* 18 (4) 2019: pp. 871 – 886.
16. **Arthi, S., Jaya, K.P.** Seismic Performance of Precast Shear Wall Slab Connection under Cyclic Loading; Experimental Test vs Numerical Analysis *Earthquake Engineering and Engineering Vibration* 19 (3) 2020: pp. 739 – 757.
17. **Hemamalini, S., Vidjeapriya, R.** Influence of Connection Detailing on The Performance of Wall-To-Wall Vertical Connections Under Cyclic Loading *Advances in Concrete Construction.* 9 (5) 2020: pp. 437 – 448.
18. **Hemamalini, S., Vidjeapriya, R., Jaya, K.P.** Performance of Precast Shear Wall Connections Under Monotonic and Cyclic Loading: A State-of-the-Art Review *Iranian Journal of Science and Technology, Transactions of Civil Engineering* 45 (3) 2021: pp. 1307 – 1328. https://doi:10.12989/acc.2020.9.5.437
19. **Joyson Silva, P., Jaya, K.P., Binu, S.** Seismic Performance of Cementitious Grout Filled Coupler and Sleeve Connections in Precast Wall Panels under Cyclic Lateral Loading *Materials Science (MEDŽIAGOTYRA)* 29 (4) 2023: pp. 481 – 489. https://doi.org/10.5755/j02.ms.33883
20. **Metelli, G., Riva, P.** Seismic behaviour of precast column to foundation joint in Tailor Made Concrete Structures, J. C. Walraven and D. Stoelhorst, Eds., Taylor & Francis Group, London, UK, 2008.
21. **Hemamathi, A., Jaya, K.P.** Behaviour of Precast Column Foundation Connection under Reverse Cyclic Loading *Advances in Civil Engineering* 677007 2021: pp. 1 – 17.
22. **Aguiar, E.A.B., Bellucio, E.K., El Debs, M.K.** Behaviour of Grouted Dowels Used in Precast Concrete Connections *Structural Concrete* 13 (2) 2012: pp. 84 – 94. https://doi.org/10.1002/suco.201100048
23. **Vidjeapriya, R., Mahamood Ul Hasan, N., Jaya, K.P.** Experimental Investigations of Precast Beam Column Singley Stiffened Long Dowel Connection, 15th Symposium on Earthquake Engineering, IIT Roorkee. 2014: pp. 505 – 512.
24. **Vidjeapriya, R., Mahamood Ul Hasan, N., Jaya, K.P.** Behaviour of Precast Beam-Column Stiffened Short Dowel Connections Under Cyclic Loading *Advances in Structural Engineering* 2015: pp. 2243 – 2254. https://doi.org/10.1007/978-81-322-2187-6_178
25. **Nzabonimpa, J.D., Hong, W., Park, S.** Experimental Investigation of Dry Mechanical Beam – Column Joints for Precast Concrete Based Frames *The Structural Design of Tall and Special Buildings* 2017: pp. 1 – 19. https://doi.org/10.1002/tal.1302
26. **Yang, K.H., Seo, E.A., Hong, S.H.** Cyclic Flexural Tests of Hybrid Steel-Precast Concrete Beams with Simple Connection Elements *Engineering Structures* 118 2016: pp. 344 – 356. https://doi.org/10.1016/j.engstruct.2016.03.045
27. **Wan Bidin, W.N.** Full Scale Testing of Precast Beam to Column Connection using Billet Connector and Beam Half Joint Subjected to Reversible loading MS Thesis, 2017: University of Malaya, Kuala Lumpur.
28. Bureau of Indian Standards (BIS) **456-2000**. Indian Standard Code of Practice For Plain and Reinforced Concrete, New Delhi, India.
29. Bureau of Indian Standards (BIS) **13920-2016**. Code of Practice For Ductile Design and Detailing of Reinforced Concrete Structures Subjected to Seismic Forces, New Delhi, India.
30. **Alameddine, F., Eshani, M.R.** High Strength RC Connections Subjected to Inelastic Cyclic Loading *Journal of Structural Engineering* 117 (3) 1991: pp. 829 – 850.
31. Bureau of Indian Standards (BIS) **800-2007.** General Construction In Steel - Code of Practice, New Delhi, India.
32. British Standards (BS) **BS 8110-1:1997**. Structural Use of Concrete – Part 1: Code of Practice For Design and Construction, 389 Chiswick High Road London.
33. ACI 374.1-05. Acceptance Criteria For Moment Frames Based on Structural Testing and Commentary, American Concrete Institute.
34. **Balkis Banu, W., Jaya, K.P.** A Study on Exterior Beam to Column Joint with Alternative Ductile Detailing *Journal of Structural Engineering Madras* 49 (3) 2022: pp. 223 – 233.
35. **Park, R.** Evaluation of Ductility of Structures and Structural Sub-Assemblages From Laboratory Testing *Bulletin New Zealand National Society of Earthquake Engineering* 22 (3) 1989: pp. 55 – 166.
36. **Koksal, F., Rao, S.K., Babayev, Z., Kaya, M.** Effect of Steel Fibres on Flexural Toughness of Concrete and RC Beams *Arabian Journal for Science and Engineering* 47 2022: pp. 4375 – 4384.
37. **Saqan, E.** Evaluation of Ductile Beam to Column Connections for Use in Seismic-resistant Precast Frames. PhD Thesis, 2014: University of Texas, Austin.
38. **Chourasia, A., Kajale, Y., Singhal, S., Parashar, J.** Seismic Performance Assessment of Two-Storey Precast Reinforced Concrete Building *Structural Concrete* 2020: pp. 17. https://doi.org/10.1002/suco.201900146
39. **Balkis Banu, W., Jaya, K.P., Vidjeapriya, R.** Seismic Behaviour of Exterior Beam-Column using Steel Fibre-Reinforced Concrete under Reverse Cyclic Loading *Arabian Journal for Science and Engineering* 48 (4) 2023: pp. 4635 – 4655.
40. **Ferreira, M., Elliott, K.S., de Aranjo, D., El Debs, M.K.** Analysis of Multi-Storey Precast Frames Considering Beam-Column Connection with Semirigid Behaviour *Keep Concrete Attractive FIB Symposium*, Budapest, Hungary, 2005: pp. 496 – 501.