



Hysteretic Performance of Precast Beam-Column Joint with Improved Energy Dissipation Capacity

Hitesh Gaur¹, Vijay Tarun Kumar Moka², Siva Chidambaram Rajendran³(✉), and Naveen Kwatra¹

¹ Department of Civil Engineering, Thapar Institute of Engineering and Technology, Patiala 147004, India

nkwatra@thapar.edu

² Academy of Scientific and Innovative Research (AcSIR), Ghaziabad 201002, India

³ CSIR-Central Building Research Institute, Roorkee 247667, India

krsinelastic@gmail.com, schidambaram@cbri.res.in

Abstract. The structural elements are factory-made and transported to the site and connected using different mechanisms in precast concrete framed structure construction. The improved quality control reduced the construction period and the use of alternative construction materials made the precast construction more effective than the cast-in-situ construction. The connection between the structural elements such as beam to column, column to column, column to the foundation, beam to beam, slab to the beam plays a crucial role in deciding the performance of precast construction. The reconnaissance survey of many earthquakes shows the susceptibility of these structures under seismic force and shows the importance of connections in seismic resistance. Also, the various structural failures due to man-made mistakes exhibit the importance of proper design, execution with better workmanship. The connections can be categorized into three types such as dry, wet, and hybrid connections and the performances are distinct and vary concerning the materials used and methodology adopted. This article presents an overview of various precast structural connection systems and their hysteresis behavior. Also, an experimental program is conducted to study the cyclic behavior of indigenous precast beam-column connections with better seismic resistance. Precast column and beams were cast separately and connected using the proposed mechanism and tested under quasi-static loading. The hysteresis behavior and energy dissipation capacity are the parameters used to quantify the performance of the connections. The experimental behavior is compared with the performance of various connections proposed and observed that the proposed connection effectively works in resisting the seismic force with better damping capacity. Also, the failure pattern shows that the formation of plastic hinges away from the joint leads to ductile failure.

Keywords: Precast structures · Failures · Beam-column connections · Hysteresis behavior

1 Introduction

The requirement of housing and commercial structures in urban areas within the limited construction resources and time led the way to precast concrete construction. The pre-cast construction method is one of the prime techniques to construct multi-storied buildings in urban locations without disturbing the nearby locations in a limited time span. The various advantages of precast construction such as reduced construction time span, high standard workmanship, better quality finish, easy installation and can be dismantled when required. Structural elements were made at the factory level and transported to the site and then elements will be assembled using the connection mechanisms. The type of connection used between the different structural members significantly decides the behavior of precast concrete structures. In general, three types of connection mechanisms are adopted in precast construction such as wet connections, dry connections, and hybrid techniques. The connections are one of the most crucial parts of a precast structural system. Shear failure at the connection region may cause catastrophic failure. The plastic hinge formation in precast structures is not easy as that of monolithic construction due to the connection mechanisms. The seismic codes also suggest eliminating failure in beam-to-column joints by constructing high ductility and high strength connections. The collapse of various precast structures during seismic activity shows different behavior such as (i) Major structural failure of buildings under construction (ii) Major structural failure of a completed structure (iii) Minor/No damage in the completed structure. The collapsed structure shows many deficiencies such as (i) lesser ductility capacity, (ii) inadequate shear resistance capacity, (iii) improper detailing, (iv) improper design, (v) slenderness ratio of columns, (vi) absence of integral action of the connections (vii) improper connection mechanism. Among many reasons, connection failure plays a crucial role. Joints may be recognized as the delicate and therefore most critical components of a precast concrete framework. In recent years, a range of experimental research works has greatly enhanced our understanding of the action of interactions between precast concrete components Siva et al. (9). Many connection methodologies have been proposed with better hysteresis behavior compared to the existing connection mechanisms. Similarly few improvements for the existing connections have also been proposed and experimentally validated. This article presents an overview of the improved connections and cyclic behavior of indigenous precast connections developed.

2 Literature Review

The seismic behavior of precast connections is varying with respect to the connection type. Several studies have been carried out to understand the cyclic behavior of different connections over the years to obtain a deeper understanding of the shear resistance and hysteresis behavior of precast connections.

2.1 Precast Corbel-Based Connections

Corbel-based connections are highly susceptible to lateral loading due to the absence of integral action. Yuksel et al. (10) had proposed an industrial type corbel-based connection

using a steel plate with welding. The connection consists of a steel plate welded with beam reinforcement which will be mounted on the top of the corbel and additional reinforcements are installed in the joint for a negative moment. The steel plate is built-in on the bottom face of the girder and welded to the steel plate on the top of the corbel and tested under reversed cyclic loading. The test results indicate that the study varied from 0.25% to 1.0% story level drifts in elastic range and showed nonlinear behavior at 2.0% drift. The sample continues to retain up to 4.0% story drift of the load-carrying capacity, but it was noticed that strength and stiffness begin to decrease after 3.0% story. The improvements produced consist of the configuration of the stirrups, i.e. its size is increased and the connection strength is limited to $0.3d$ in addition to the welding size.

Similar to the Yuksel et al. (10) concept Guerrero et al. (2) used a steel plate at the bottom of the precast U-shaped beam shell and another plate over the corbel. Once the beam shell is placed over the corbel, both plates have been welded together. The topmost beams will be cast with fresh concrete to increase the monolithic action. The hysteresis behavior of the precast joint and failure pattern results show that at 2.5% inter-story drift the sample failed and exhibits brittle failure. A maximum crack width of 7 mm was observed on the corbel. The failure was considered as the loss of lateral resistance was 20% of peak strength and also the loss of stability. In between 2–2.5% drift, this connection started to dissipate more energy until failure which leads to large propagation of damage after 2% drift. The increased damping leads to more propagation of damage and yielding of the bars. The hysteresis curve shows a similar trend in load and stiffness behavior. But the failure pattern was distinct due to the presence of corbel. In precast connection, the failure was concentrated at the corbel connection region. This proves that the corbel-based connection can be utilized with proposed connection details to enhance the energy dissipation and ductility capacity.

Nimes et al. (4) experimentally investigated the behavior of wet precast beam-column corbel-based connections under the progressive collapse state and compared them with the monolithic specimen. Progressive collapse is defined as the local failure that occurs in a primary structural component and spread to adjacent elements and ultimately leads to the collapse of the entire structure. The connection consists of a two-span beam and three columns with the removal of the middle column indicate the column removal scenario.

In the first connection, the beam was rested on the corbel having the top reinforcement bars of the beam are protruded into the column face projecting bars from the column (100 mm) and are connected by welding. In the second connection, the beam was cast with normal cast-in-situ concrete to 90 mm from the bottom of the beam, and the remaining 45 mm from the top was left free. Two bars were provided from the column into the beam open area through stirrups to provide continuity and the beam was rested on the corbel in both connections. After placing reinforcement, the gap was filled with micro concrete. In both connections, two bars were inserted from the corbel into the connection zone. In the third connection, the steel billet was used in place of the corbel.

The test result shows that initially, the beam-column connection behaved as a fixed beam with less deflection at the center. As the load goes on increasing, the extreme ends lose their fixity. In monolithic connection, it is visible that the crack occurred at the top face of the left beam near the removed column and the top surface near the extreme ends of the beam-column junction. In the first specimen, the crack was observed at the junctions

having filled with micro concrete. In the second connection, the cracks were obtained at the side face of the beam filled with micro concrete at the beam-column junction, and column ends. In the third specimen, the cracks were developed at the junction of the steel billet and the beam. The load-carrying capacity of precast specimens is more compared to monolithic specimens i.e., precast specimens are capable of resisting more loads. Among the precast specimens, the second specimen has more load-carrying capacity and the third specimen has the least load-carrying capacity. The failure was developed at the interface between the region filled with cast-in-situ micro concrete and the normal concrete.

2.2 Precast Connection Using Steel Plates and Steel Connectors

Ertas et al. (5) investigated the cyclic behavior of two types of precast connections. The first connection is similar to that of Yuksel et al. (10) and the second one has bolted connection. In the bolted connection, the steel boxes were used instead of steel pipes through the holes to allow more dimensional tolerance and to minimize the fieldwork. This will reduce production errors. The steel box is directly welded to the beam shear reinforcement. During the test, the sliding of the steel box concerning the beam concrete was observed. To avoid the sliding of the steel box in the bolted connection, the modified bolted connection was proposed to have a channel at the top and bottom of the cross-section to place the bolts.

The test results show that the monolithic specimen experienced cracks and spalling of concrete at the beam end region. There was no pinching and significant strength degradation observed during reversed cyclic loading up to a 4% drift ratio. There were no diagonal cracks in the joint region due to the presence of steel fiber reinforced concrete. At a higher drift level, the crack widening was accelerated and eventually leading to the failure at the beam hinge region. The modified bolted specimen showed better performance compared to monolithic and corbel-based precast connections. The hysteresis behavior of the modified bolted connection, which shows free from pinching and enlarged loop. This shows higher energy dissipation compared to monolithic and corbel-based connections. It has greater initial stiffness than other specimens due to pre-tensioning was applied to the bolts and yielding of bolts took place at smaller drift levels.

Choi et al. (1) had characterized five connections using steel sections. In which column constructed with embedded steel I-section with extruded portion to establish the connection between the beams. Precast beams are also cast with encased steel sections with extruded portions to establish the connection. Both the extruded steel plates have to be connected using bolts and will act as yielding portions during cyclic loading. The bolted portion will be cast with ECC (engineered cementitious composite). The developed connection was of two types i.e. outside (connection at 0.3d from an interface) and inside type of connection. The failure pattern of the joint shows that initial cracks were formed at the interface of the beam-column joint and followed by flexural cracks in the beams. The flexural cracks extended longitudinally and propagated transversely with very similar crack spacing, away from the column face. In beams, most of the flexural cracks were perpendicular to the member axis.

All sample's nominal strength under alternate positive and negative loading conditions was measured at a 1.5–2% drift. Until 3.5% drift, there was no strength degradation but approximately at 4.25% drift ratio, the strength was decreased. In the RC sample, the Ultimate strength of 119 kN was observed at a 3.5% drift ratio, and until at 4.25%, hysteretic behavior was stable in load carrying capacity without displaying rapid deterioration. The precast outside type joint has an in-situ area of 500 mm, shows an ultimate strength of 155 kN at a 3.5% drift ratio followed by a drop in load rapidly.

In PC-OH-25, the ultimate strength was 133 kN at a 2.2% drift ratio. PC-IH-50 represented a stable hysteresis loop behavior until 4.25% drift. In PC-I-25, with a small area of ECC, the ultimate strength of 138 kN was noticed at a 2.2% drift and stable hysteresis behavior until a 3.5% drift. At 3.5% drift, in precast samples, cumulative energy was higher in outside type specimen compared to conventional sample by approximately 42% and difference of 6% between monolithic RC Sample and precast inside specimen. PC-IH-50 samples having lateral bars in joints with larger ECC areas have dissipated lower energy due to the effect of pinching. The maximum strength was improved by 15% in both the inside and outside specimens compared to the RC sample. In which the outer connection shows greater energy dissipation and strength than the inside connection.

Similar to Choi et al. (1), the concept of using I-shaped steel tube into the column and beam connected by web plates with bolts Zhang et al. (12) developed five hybrid precast concrete beam-column joints using encased steel section with extruded portions in which web connection plate and energy dissipation plate at the connection region. SFRC has been used at the bolted region to cover the connection portion.

The test results show that the monolithic sample experienced initial cracks occurring perpendicular to the beam axis and extended transversely followed by joint shear crack. The joint was damaged severely and the joint reinforcements were exposed due to the spalling of cover concrete. In type 1 and type 2 precast connections, the presence of embedded I-section in column significantly plays a role in deciding the failure pattern and hysteresis behavior. Similarly, the presence of steel fiber reinforced concrete also plays a vital role in controlling the crack growth and restricting the spalling of joint cover concrete. The type 2 joint with SFRC successfully shifted the failure away from the joint as expected in seismic design. But fails to provide better hysteresis behavior compared to the type 1 system with a flange cover plate. The type 1 joint experienced joint shear failure but shows tremendous enhancement in energy dissipation and displacement ductility.

Similar to concepts of Choi et al. (1) and Zhang et al. (12) of using embedded steel section at the center of the column which is connected to the beam web plates via bolts Rong et al. (8) conducted an experimental study on the cyclic behavior of precast column to beam connections using encased steel I-section with different configurations. The different configurations such as embedded length of the section in the column, stiffening rib and headed stud. All the joint specimens were tested under cyclic loading till complete failure occurs.

The hysteresis behavior shows that the absence of a web plate significantly reduces the lateral loading capacity and the addition of a web plate enhances the shear resistance capacity by 25% with an enlarged loop. Thus the specimens with a web shear plate possess more than 150% higher energy dissipation than a joint without a web shear

plate. The absence of steel fiber reinforced concrete shows severe distress at the joint region and spalling of joint concrete was observed.

2.3 Precast Connection Using Grout Sleeves

Yan et al. (11) proposed a precast beam-column joint using grout sleeves tested under low cyclic loading. The reinforced bars are placed on the precast beam through the holes reserved in the beam, then to connect the column and beam using high-performance grout is poured in the hole. Two types of grout sleeves rebar were connected i.e. beam rebar was attached using full grout sleeve and column rebar is attached using half grout sleeve. At the beam surface, initial flexural cracks were developed aside from the column and a plastic hinge was slowly formed near the joint region. In the middle of the connection core, initial diagonal cracks were observed and further the cracks were headed to the core edge.

The hysteresis behavior shows that the presence of grout sleeves significantly increases the lateral load-carrying capacity and enhances the shear resistance capacity by 10% with a little enlarged loop. The specimen with grout sleeves shows more energy dissipation by 130% than the cast-in-situ joint. The precast sample shows shear failure and also concrete palling appeared in the joint. Grout sleeves for precast specimens and cast-in-place parts are two important factors that affect the plastic hinge performance in the beam. They can improve the strength and stiffness of the beam part near the joint, which shows that the ultimate and yield displacement of precast samples is higher than the cast-in-situ sample.

3 Experimental Work and Test Results

In this study an experimental work is presented which evaluates the differences between the monolithic joint and the hybrid wet precast beam-column joint under focused seismic parameters as hysteresis loop, energy dissipation, and failure pattern also how the performance varies under the quasi-static loading.

3.1 Material Used and Detail of Specimen

The ordinary Portland cement (OPC) of grade 43 was used as the cementitious compound for the production of M30 grade concrete to cast the precast structural column and beam elements. In the proposed connection HPFRCC was used. OPC of grade 43 as a cementitious compound, sand, steel fibers according to the volume of cement, and polypropylene fiber according to the weight of the cement was used in HPFRCC preparation. Fe500 reinforcement bars were used in joint specimens. Two beam-column joints were cast using 4 nos. of 12 mm diameter bars as the main reinforcement and 6 mm diameter bars as the transverse reinforcement in the beam and the column. The monolithic joint was cast as per IS 456:2000 detailing with a development length of 400 mm. In precast beam-column connections, the members were cast separately with a shear key and protruding bars of length 100 mm in the beam and the column which were connected by using a hybrid rebar coupler of 120 mm length. The spacing of transverse reinforcement

was kept 100 mm *c/c* in the columns and 120 mm *c/c* in the beams but closely spaced at the end near the precast connection region and HPFRCC was used at the proposed connection region. The figure depicts the typical reinforcement and connection details of type 1 and types 2 joints.

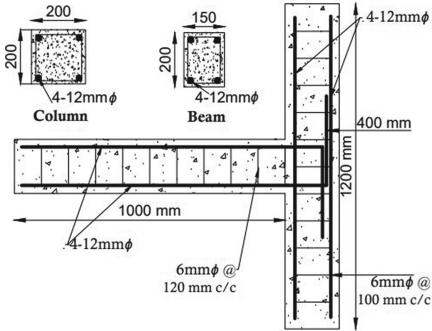


Fig. 1. Reinforcement detail of MJ1.

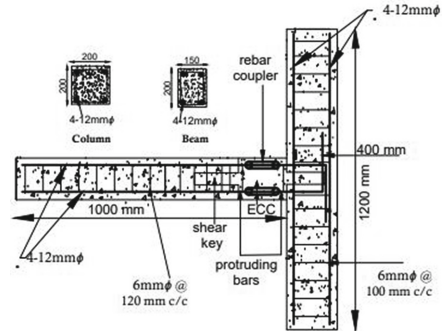


Fig. 2. Typical reinforcement detail of PJ1.

3.2 Connection Methodology and Test Setup

The structural elements i.e. beam and column were cast separately and connected using a hybrid rebar coupler to connect the reinforcement protruding out from the beam and the column. After joining the reinforcement using a hybrid coupler, geo-grid was used as confining reinforcement at the connection followed by HPFRCC was used in the casting the connection region and shear key region. Two beam-column connections were tested under reversed cyclic loading using FEMA 461 loading protocol in which the first specimen was the conventional joint and the second specimen was the hybrid precast joint with approximately similar reinforcement detailing as shown in Fig. 1 and Fig. 2. Both the beam-column joints were tested under displacement-controlled reversed cyclic loading to determine the hysteresis behavior of the specimens and to evaluate the performance of the precast beam-column joint with respect to the conventional joint. The column was subjected to a 25 kN axial load whereas the beam was attached with the hydraulic jack to undergo displacement as shown in Fig. 3.

3.3 Results and Discussions

3.3.1 Hysteresis Curve

The observed peak load-carrying capacity of the monolithic joint and the precast joint was 20 kN and 22 kN respectively. The load-displacement curve shows that the maximum load-carrying of PJ1 was slightly higher than MJ1 but the ultimate displacement of PJ1 is 50% higher than MJ1. The connection between the cast in situ concrete and precast element was the weakest part of the connection and hence the failure focused on the joint interface. Also, it is noteworthy to mention that the inclined crack at the beam hinge

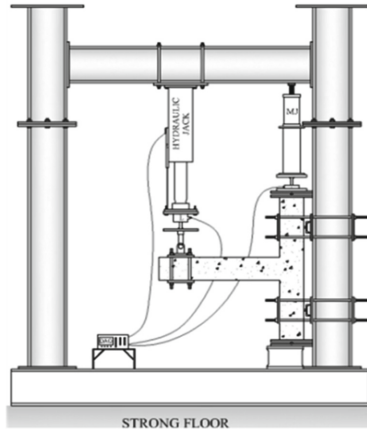


Fig. 3. Test setup.

region between the coupler significantly reduced the load-carrying capacity in negative pull compared to positive push. Thus the negative portion of the hysteresis curve shows sudden degradation in load after the peak. The rocking action between the old and new composite fails to dissipate energy like the MJ1 and thus the hysteresis curve of PJ1 is pinched and failed to show energy dissipation at the initial stage of loading. But the degradation in the load-carrying capacity of MJ1 was observed after 35 mm displacement and the joint only carried displacement till 60 mm whereas the PJ1 suffers very little degradation in the load-carrying capacity and continues till 80 mm displacement. The precast beam-column joint provides more geometrical stability to the specimen due to the presence of HPFRCC in the connection region (Fig.4 and 5).

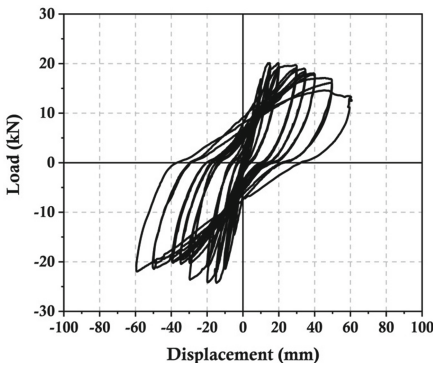


Fig. 4. Hysteresis curve of monolithic joint.

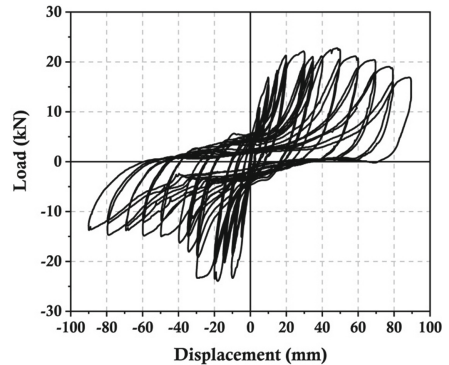


Fig. 5. Hysteresis curve of precast joint.

3.3.2 Energy Dissipation

The sum of the area under the hysteresis curves is used to determine the energy dissipated in the joint. Figure 6 shows that from the initial stage of loading the precast specimen started exhibiting higher energy dissipation till 45 mm displacement. At 60 mm displacement, the energy dissipated by the MJ1 is 5300 kN-mm and it is 4600 kN-mm for PJ1. At 90 mm displacement, the PJ1 dissipated 7300 kN-mm energy which is 37% higher than MJ1 due to its higher displacement ductility capacity than MJ1.

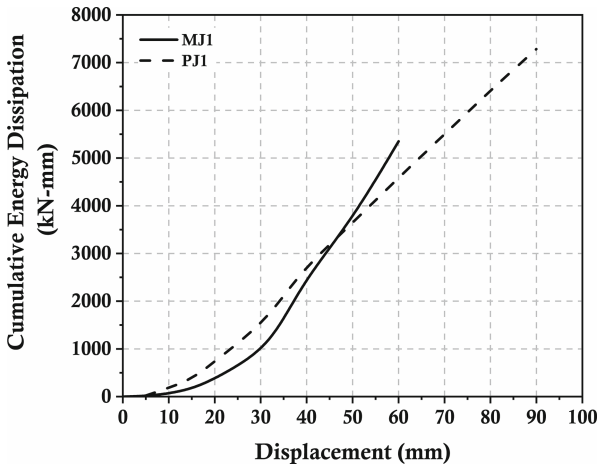


Fig. 6. Cumulative energy dissipation.

3.3.3 Failure and Crack Pattern

During the testing, cracks were marked on the surface of the joint specimens. Figure 7 and 8 show the typical crack and failure pattern of monolithic and precast joint specimens.

MJ1- Due to the brittle nature of concrete, it was unable to resist the early crack formation which leads to slipping of longitudinal reinforcement and formation of diagonal cracks as shown in Fig. 7. Initially, the flexural cracks were formed at 15 mm displacement away from the joint region in the beam. At 30 mm displacement, the joint started distortion and separation of the interface between the beam and column, also shear crack was observed on the column. At 40 mm displacement, shear cracks near the joint region were observed. The lack of confinement at the hinge region led the reinforcement top buckle and cover concrete to spall as shown in Fig. 7. At 50 mm huge spalling of concrete occurred and the longitudinal reinforcement was visible in the bottom area of the joint and at 60 mm displacement the spalling of concrete was more and the joint was distorted with a diagonal crack at the center of the joint.

PJ1-The first flexural crack was noticed at 35 mm near the column face in the plastic hinge region as shown in Fig. 8. The coupler-enabled rebar stiffness is higher than the actual rebar. Also, the space provided between the coupled region and the concrete interface was small which led the cracks to initiate from the compression to

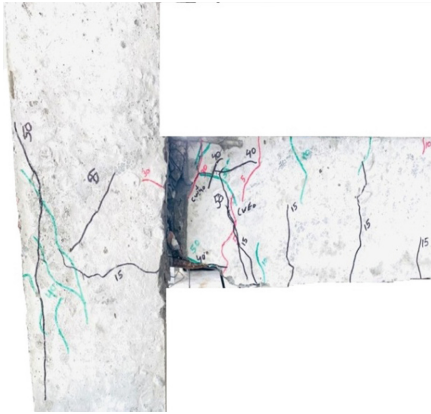


Fig. 7. Crack pattern for MJ1.

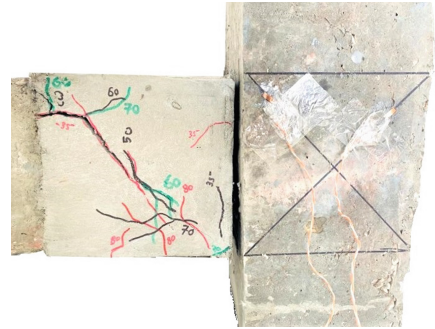


Fig. 8. Crack pattern for PJ1.

tension phase in alternate cycles. This led the cracks to grow inclined as shown in Fig. 8. This phenomenon along with the interface crack widening between the column and the connection led the hinge to experience focused failure, which is away from the joint region. The joint has no evidence of shear failure such as horizontal and inclined cracks as experienced in monolithic connections.

3.3.4 Stiffness Degradation

Figure 9 shows the load-deflection envelope curve of both the joint specimens. In which the initial tangent is used to estimate the initial stiffness and tangent to the post-yield used to estimate the post-yield stiffness behavior of the joints. The initial and yield stiffness for both the specimens are almost similar. This shows that the precast joint specimen has stiffness property as that of the conventional monolithic joint. Figure 10 shows the post-yield stiffness behavior. It can be understood that the trend of stiffness degradation is almost the same for both but the occurrence of early failure of MJ1 led the specimen to fail at 6% drift but the hinge formation away from the joint led the PJ1 to reach 9% drift with 9% of yield stiffness.

3.3.5 Damage Index

The damage tolerance of the beam-column joint is measured using the modified park and damage index as per Eq. 1 (Park et al. 6 and Park et al. 7).

$$D = \frac{\delta_m}{\delta_u} + \frac{\beta}{F_y \delta_u} \int dE \tag{1}$$

where “ δ_M ” is the demand of maximum displacement under cyclic loading; “ δ_U ” is the capacity of ultimate displacement. The integral part is the amount of energy dissipation under cyclic loading and “ F_y ” is the yield strength and “ β ” is the strength degradation, and its value is “0.1” for RC structure.

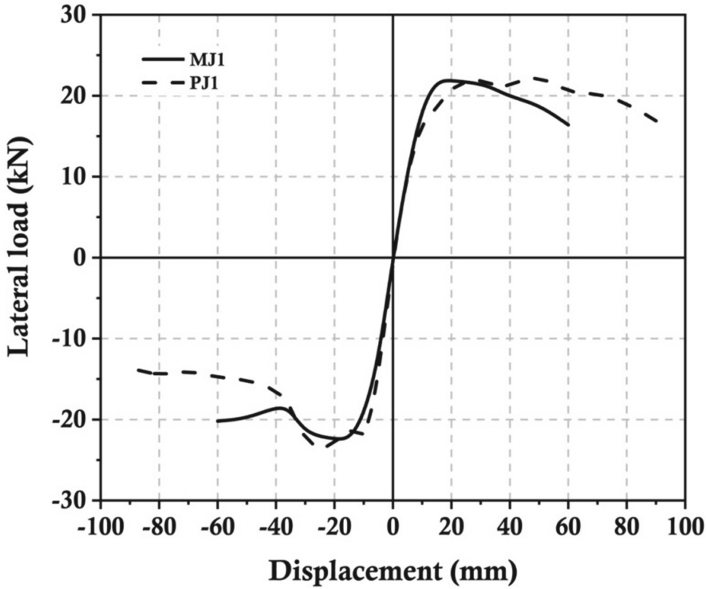


Fig. 9. Load-deflection envelope curve.

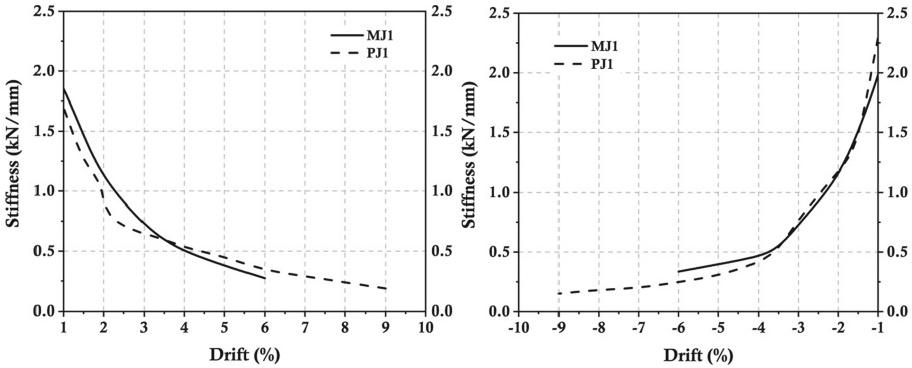


Fig. 10. Stiffness degradation over drift (a) positive (b) negative.

Figure 11 shows the damage index of monolithic and precast joints. It portrays that the PJ1 possesses on level better damage tolerance from the beginning stage of testing. Initially, flexural cracks occurred in the beam portion followed by diagonal cracks at the joint region. As the load increased the concrete at the interface region experienced concrete crushing and led the concrete cover to spall. In precast specimen PJ1, initial cracks followed by major cracks were focused on the potential hinge connection region proposed in the study. There is no sign of diagonal cracks in the joint region. Thus the better inelastic behavior in terms of displacement ductility and relative energy dissipation led the PJ1 to have two-level better damage tolerances than conventional.

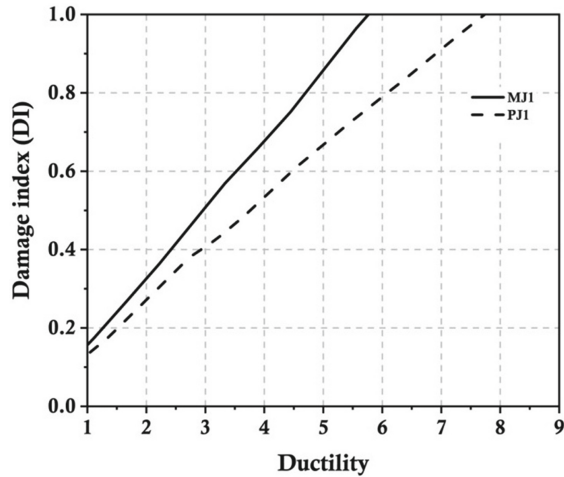


Fig. 11. Damage index versus ductility.

4 Critical Discussion on Precast Joint Performance

It is understood from the literature and experimental study that connections play a crucial role and acts as the deciding parameter in precast structure. The use of corbel connection in precast structure with additional improvement such as welded bearing plate beneath the beam and over corbel, dowel rods to establish the connection between the beam and corbel are certainly increases the performance of precast corbel connections but fails to provide better inelastic rotational capacity and energy dissipation. The failure focused on the interface between the corbel end and the beam bearing surface. This led the beam to slide off from the support. Thus the hysteresis behavior of precast connection with corbel-based connecting mechanism fails to offer better ductile performance. The use of bolted connection shows two distinguished behavior. In the first case the encased rectangular boxes, which were used for bolting work, were slide due to the absence of integrity between the beam and the encased steel box. In the latter case, the boxes were welded with the beam reinforcement which shows significant improvement in the hysteresis behavior. But the failure pattern shows that the joint experienced huge distress during inelastic rotations. The uses of encased steel box section, I-section, and H-sections with steel plate yielding techniques considerably work in resisting the lateral forces and improve the energy dissipation more effectively than the former cases. In these connections, the web stiffeners, flange plates, and the composites used at the connection regions are acting as the performance deciding parameters. The connection between the beam and joint steel plates transfers the forces effectively but the lack of confinement at the joint region shows significant damage at the joint region. In the proposed connection, the extruded rebars have been connected using hybrid rebar couplers and the use of HPFRCC at the connection region made the connection as the hinge and allows higher rotation with better resistance to the applied load. The proposed connection has old and new concrete surface issues and thus the shear area is reduced to the key area. This phenomenon shrunk the hysteresis curve which in terms of reducing the initial stage

energy dissipation compared to monolithic. But the joint has no evidence of diagonal cracks and also shows better damage tolerance than the monolithic.

5 Conclusion

Based on the literature study and the experimental pilots study the following conclusions are drawn.

1. The precast corbel-based joints are meant for gravity loading but the improvement in the form of dowel rods improves the performance of the corbel-based joint under gravity loading not under cyclic loading. The provision of steel plate welding between the beam and column corbel interconnects the bottom of the beam and the cast in situ concrete at the topmost layers improves the cyclic behavior of the corbel-based joint mechanism. But the failure pattern and hysteresis behavior restrict the application up to a certain extent in the seismic region than the non-seismic region.
2. The precast connections with steel encased sections are effectively work in resisting the lateral load and in improving the seismic behavior of precast joints. The connection between the extruded portions plays a crucial role in deciding the shear resistance capacity of the joint connections. The presence of flange plate and shear plates improves the joint shear resistance and energy dissipation capacity to a higher level compared to the joint without the web shear plates. It is also important to use high strain composites such as SFRC or ECC at the interface region to avoid spalling of concrete at the connection region and to convert the shear failure into ductile failure.
3. In grouting sleeve-based connections the placement of sleeves and performance of sleeves plays a vital role. But in precast connections, these sleeves will be at the region where lap splice is not allowed as per seismic resistance design. But the connection mechanism and the placement of sleeves and the strength of sleeves overcome the limitations. It is well understood that these sleeves-based connections are working very effectively in terms of strength and stiffness but fails to dissipate more energy compared to monolithic. But an improvement in shear stiffness was observed in the precast joint which shows that the connection can be recommended in the seismic region.
4. The experimental outcome of the pilot study shows that the interface between the old and fresh composite plays a significant role in improving the joint shear resistance. This interface issue leads to pinching in the hysteresis behavior of the proposed connections. But the specimen has a higher drift ratio than the monolithic connection. Also, the post-yield hysteresis performance of the proposed scheme effectively works in resisting the applied force and improves the energy dissipation by 25%.
5. The stiffness performance of the precast specimen is almost similar to the monolithic specimen the initial yield, and post-yield level. This demonstrates the connection ability in resistance to the deflection similar to the conventional
6. The placement of the coupler tends the crack to initiate and restrict the rotation of the joint. The hysteresis behavior of the precast joint is not up to the monolithic in terms of initial energy dissipation capacity due to the occurrence of the inclined cracks at

the hinge region. But the use of HPFRCC at the hinge region restricts early-stage crack growth and eliminates the spalling of cover concrete and improves the joint damage tolerance capacity better than monolithic.

References

- Choi, H.K., Choi, Y.C., Choi, C.S.: Development and testing of precast concrete beam-to-column connections. *Eng. Struct.* **56**, 1820–1835 (2013). Article first published online: November 2013. <https://doi.org/10.1016/j.engstruct.2013.07.021>
- Guerrero, H., Rodriguez, V., Escobar, J.A., Alcocer, S.M., Bennetts, F., Suarez, M.: Experimental tests of precast reinforced concrete beam-column connections. *Soil Dyn. Earthq. Eng.* **125**, 105743 (2019). Article first published online: October 2019. <https://doi.org/10.1016/j.soildyn.2019.105743>
- IS 456: Indian standard code of practice for plain and reinforced concrete. Bureau of Indian Standards, New Delhi, India (2000)
- Nimse, R.B., Joshi, D.D., Patel, P.V.: The behavior of wet precast beam-column connections under progressive collapse scenario: an experimental study. *Int. J. Adv. Struct. Eng. (IJASE)* **6**(4), 149–159 (2014). Article first published online: 12 November 2014 <https://doi.org/10.1007/s40091-014-0072-3>
- Ozturan, T., Ozden, S., Ertas, O.: Ductile connections in precast concrete moment-resisting frames. *concr. constr.* **9**, 11 (2006)
- Park, R., Paulay, T.: *Reinforced Concrete Structures*. John Wiley and Sons, Hoboken (1975)
- Park, Y.J., Ang, A.H., Wen, Y.K.: Damage-limiting aseismic design of buildings. *Earthq. Spectra* **3**(1), 1–26 (1987)
- Rong, X., Yang, H., Zhang, J.: Experimental study of precast beam-to-column joints with steel connectors under cyclic loading. *Adv. Struct. Eng.* **23**(13), 2822–2834 (2020). Article first published online: 30 May 2020. <https://doi.org/10.1177/1369433220920448>
- Siva Chidambaram, R., Karade, S.R.: Precast concrete element connections, issues, and innovative solutions. In: *Proceedings International Conference on Advances in Construction Materials and Structures*, A-156, Roorkee, India (2018)
- Yuksel, E., Karadogan, H.F., Bal, I.E., Ilki, A., Bal, A., Inci, P.: Seismic behavior of two exterior beam-column connections made of normal-strength concrete developed for precast construction. *Eng. Struct.* **99**, 157–172 (2015). Article first published online: 15 September 2015. <https://doi.org/10.1016/j.engstruct.2015.04.044>
- Yan, Q., Chen, T., Xie, Z.: Seismic experimental study on a precast concrete beam-column connection with grout sleeves. *Eng. Struct.* **155**, 330–344 (2018). Article first published online: 15 January 2018. <https://doi.org/10.1016/j.engstruct.2017.09.027>
- Zhang, J., Ding, C., Rong, X., Yang, H., Li, Y.: Development and experimental investigation of hybrid precast concrete beam-column joints. *Eng. Struct.* **219**, 110922 (2020). Article first published online: 15 September 2020. <https://doi.org/10.1016/j.engstruct.2020.110922>