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RESEARCH PAPER

Seismic Performance of Precast Shear Wall–Diaphragm Connection: A Comparative Study with Monolithic Connection

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Abstract

The primary objective of the present study is to understand the behaviour of innovative precast shear wall–slab connection subjected to reverse cyclic loading. The response of the precast connection is then compared with that of the similar monolithic connection. One-third scaled-down models were used for the investigation. In the monolithic connection, typically used U-shaped bars were employed for the connectivity between shear wall and slab. In the precast connection, the connectivity was established in two steps. In the first step, the precast slab and a lower half portion of the shear wall were connected through dowel bars and tied with the screed reinforcement. In the second step, the bottom and top panel of the shear walls were connected through the dowel bars. The specimens were subjected to reverse cyclic loading at the slab ends on both sides. The seismic performance regarding strength, load–displacement relationship, crack pattern, energy dissipation, moment–rotation curve, stiffness and ductility were obtained and compared with the monolithic connection. The average ultimate load and moment-carrying capacity of the precast specimen are found to be 28.66% and 21.74% greater than the monolithic specimen. The cumulative energy dissipation and ductility factor of the precast specimen are found to be 128.95% and 74.34% higher than the monolithic specimen. It is concluded that the precast specimen showed better performance concerning the ultimate load, moment, energy dissipation and ductility with reference to the monolithic specimen.

Keywords Reinforced concrete · Precast shear wall · Diaphragm · Dowel · Reverse cyclic loading · Load–displacement relationship · Ductility

1 Introduction

In recent years, the construction industry in India is progressively growing. To build a structure within a short period, the industry is increasingly focusing on precast technology. The prefabricated structures are those buildings where the members are systematised and manufactured in a factory, transported to the site and then erected to form the structural system. It is considered cost-effective, and at the same time, it offers a better quality of construction due to its industrialised mass production and time-consuming process. The structural behaviour of precast systems is different from that of the monolithic system, because in the case of the cast-in situ building, they have intrinsic structural continuity, whereas it is not so in precast structures. The main challenge in designing the precast concrete structures is the connection between various components of the structures [1]. The connection is one of the crucial elements to limit the structural damage. The main purpose of the structural connection is to transfer the forces between the precast components to establish the integrity of the structure.

Shear walls play a significant role in resisting lateral force which may arise from earthquake and wind loading. The connections between the floor slab and shear walls are a critical section in structures to resist both the gravity and lateral loading. The most critical areas in the design and detailing of seismic resistant structures are the shear wall–floor slab joint. Failures in the joint region are caused by the poor detailing of the connection between the shear wall and the diaphragm.

Even though the importance of the joints in experiencing forces and deformations during lateral loading caused by earthquakes is enormous, particular guidelines about the

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precast joint detailing are not incorporated in Indian codes for precast construction. Therefore, studying the structural behaviour of precast shear wall and slab connection is required to exhibit adequate design and detailing of precast connections. Many research works have been carried out on monolithic shear wall–slab connections under lateral loading. From the works in literature, it is clear that the precast connections behave similarly to the cast-in situ connections. The existing databases of tested specimen particularly for precast shear wall–diaphragm connection detailing are very limited. So, it is very important to carry out detailed investigations on the performance of precast shear wall–diaphragm connection. Hence, this work focuses on studying the seismic behaviour of the proposed precast dowel connection and monolithic connection in order to compare the structural performance of monolithic and precast structural systems.

The objective of the present work is to investigate the performance of a precast shear wall–diaphragm connection using dowel bars subjected to reverse cyclic loading and to compare with the monolithic connection. This investigation was carried out to study the joint behaviour between precast shear wall–diaphragm connection regarding ultimate strength, displacement, hysteresis behaviour, moment-carrying capacity, energy dissipation, stiffness and ductility under reversed cyclic loading.

1.1 Literature Review

A lot of research has been done in the shear wall–slab monolithic connection detailing with cross bars, additional bars, hook bars, shear reinforcement and stirrups connecting additional U-hook [2–6]. Kaushik and Kaustubh [7] studied the damage in the shear wall–slab joint of a building under three levels of ground motions. Three models were created, namely frame along one bay, wall–slab model, wall sub-assembly model. The beams, columns, shear wall and slab are modelled and analysed using ABAQUS software. They have generated three ground motions with PGA of 0.14 g, 0.56 g and 1.12 g. The authors concluded that the maximum stress concentration develops initially at the lower end of the shear wall and then propagates to the junction and also the level of damage depends on the magnitude of acceleration with the maximum damage incurred for PGA of 1.12 g. Hutchinson et al. [8] investigated the behaviour of horizontal connections between the precast shear wall with hollow-core floor slabs using post-tensioned bars subjected to monotonic shear loading. The authors investigated the study on nine prototype specimens with two levels of load perpendicular to the connection to simulate the effects of dead loads. The authors concluded that the capacity of the connection under shear increases with the increase of load and the failure of the connection supporting hollow-core slab are controlled by friction resistance and the shear-resisting capacity of the hollow-core slab. The shear strength of the connection also depends on the bond between the concrete fill and the hollow-core slab. Zhao et al. [9] studied the mechanical behaviour of the precast shear wall with the different detailing of hollow-core slabs under cyclic loading. In slab 1, the bi-directional holes of the slab are all circular, while the diameter of transverse holes is less than that of longitudinal holes. In slab 2, the transverse holes remain square, and longitudinal holes remain circular, and the side-length of the transverse holes is larger than the diameter of the longitudinal holes. The authors concluded that the compressive capacity of walls could be affected due to the dimension of transverse holes is larger than that of longitudinal holes. Zenunovic and Folic [10] have done the experimental work on connections between the monolithic wall with the monolithic and precast slab. In this study, three specimens were tested under static loading. The authors concluded that the precast slab connection shows opening of joints outside of the wall and energy dissipation capacity similar to that of monolithic connection. Manoj et al. [11] compared the behaviour of precast beam–column connection with the monolithic connection subjected to cyclic loading. In this study, the precast connection at the joint region was made by welding the reinforcement bars and continuous U-shaped bars as beam reinforcement. The authors concluded that the joint detailing with the beam bars welded to the column was recommended for earthquake-resistant precast structures in high seismic zones. Rahman et al. [12] investigated the performance of precast beam–column wet connection and compared with the monolithic connection. In precast connection, half-depth of beam was installed on both sides of the corbel followed by placing two top reinforcement bars and the second stage of concreting was done. The authors concluded that the moment resistance of precast specimen was higher than the monolithic specimen and this type of precast connection can be considered for the moment resisting connections. Vidjeapriya et al. [13] developed the two types of precast beam–column connection using dowel bar and dowel bar with cleat angle subjected to cyclic loading. It was concluded that the connection with dowel bar and cleat angle performed better than the monolithic connection. Some other works were also carried out on precast connection [14, 15] using dowel bars. The codes such as PCI [16], ACI also provide very little information regarding precast shear wall–slab connections. Experiences from the researcher [6] are used to carry out the experimental work for the study presented in this paper.

2 Experimental Testing

2.1 Specimen Details and Design Criteria

The shear wall–slab connection in an eight-story RC precast building located in Chennai was taken for this study. STAAD PRO software was used for the modelling and analysis of

Table 1 Properties of concrete

S. no.	Mechanical properties at 28th day	Average strength of concrete N/mm^2	Size of specimens	Number of specimens
1.	Compressive strength (f_{ck})	39.4	150 mm × 150 mm × 150 mm	3
2.	Tensile strength (f_{ct})	3.21	150 mm diameter 300 mm height	3

this structure. The resultant forces around the exterior shear wall–slab joint due to different load combinations according to IS 1893 part (1):2016 [17] were computed. The critical design forces such as axial load, bending moment and shear force are 1757.11 kN, 2520.48 kN m and 963.04 kN, respectively. The design and detailing of shear wall and the slab was done as per IS 456-2000 [18] and IS 13920-1993 [19], respectively. The monolithic and precast specimen was cast with one-third scaled-down model. The dimension of the shear wall and slab were 800 mm × 80 mm × 1000 mm and 800 mm × 430 mm × 60 mm, respectively. The precast slab thickness is about 30 mm and the thickness of screed concrete on top of the precast portion is 30 mm. The specimens were cast with M-30 grade of concrete and HYSD bars of Fe-500 grade of steel. The 28th day compressive and tensile strength was tested with control cubes and cylinders, respectively. The average compressive and tensile strength of the concrete is shown in Table 1.

2.2 Monolithic Specimen (MS)

The RC monolithic specimen was designed as per IS 456:2000 and detailed as per IS 13920-1993. The reinforcement detailing and the cage are shown in Fig. 1a, b, respectively. U-Shaped bar in the joint region to connect the shear wall and slab was provided as per British standard [20], and is shown in Fig. 1b. The U-shaped bar was extended into the slab by the development length (L_d) of 270 mm which was calculated as per IS 456-2000.

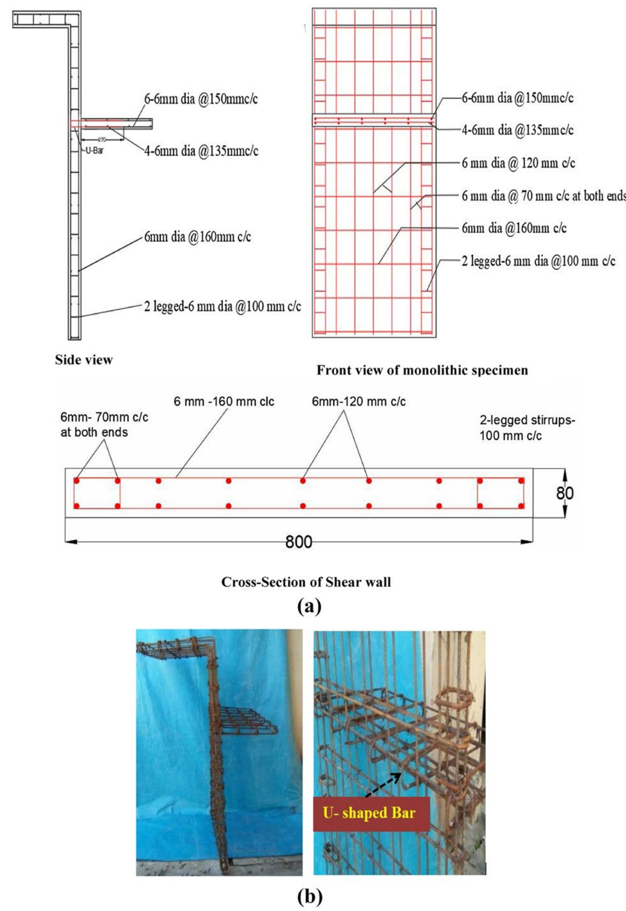

Fig. 1 **a** Reinforcement details of monolithic connection. **b** Bar bending

2.3 Precast Specimen (PS)

This type of connection consists of three parts such as shear wall–lower panel, upper panel, and precast slab with in situ concrete topping. The reinforcement detailing and the cage are shown in Figs. 2 and 3, respectively. The dowel of 6 mm diameter was used to connect the shear wall and slab. Mesh reinforcement was provided above the precast slab and in situ concrete topping was done to maintain the diaphragm action of the structure. The upper panel was provided with the duct to create housing for inserting the dowel from the lower panel. The gap between the duct and dowel was filled with high-strength, non-shrink M-60 grade grout. The diameter of the duct and dowel was 20 mm and 10 mm, respectively. The dowel design was done based on the guideline given by Elliot [21]. The erecting stages of the precast specimen are shown in Fig. 4.

2.4 Test Setup Program

When an earthquake occurs, the lateral load acts on every joint region of the structure. Due to this lateral loading, the shear wall–slab joint assembly is subjected to in-plane moment. This in-plane moment has been simulated

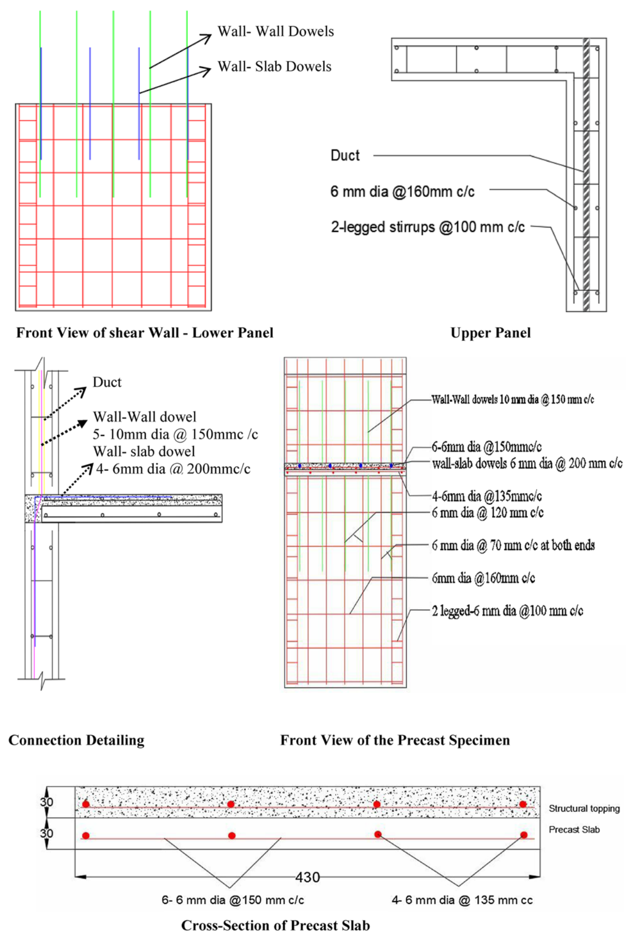

Fig. 2 Reinforcement details of precast connection using dowel bars

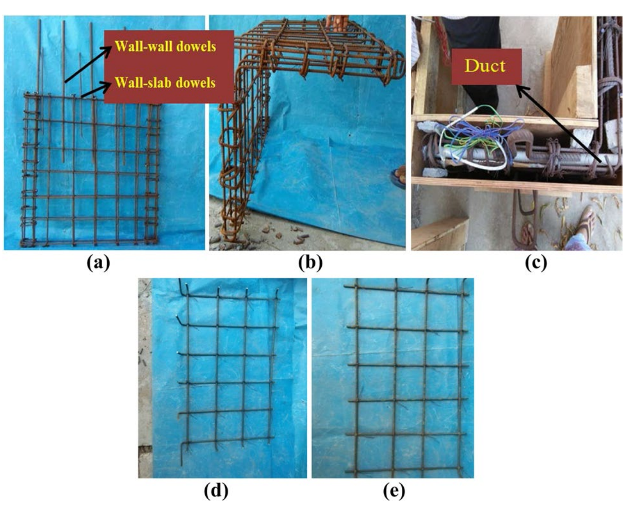

Fig. 3 Bar bending. **a** Reinforcement cage of shear wall–lower panel. **b** Reinforcement cage of shear wall–upper panel. **c** Provision of duct in upper panel for the dowel bars. **d** Reinforcement cage of precast slab. **e** Reinforcement cage of structural topping

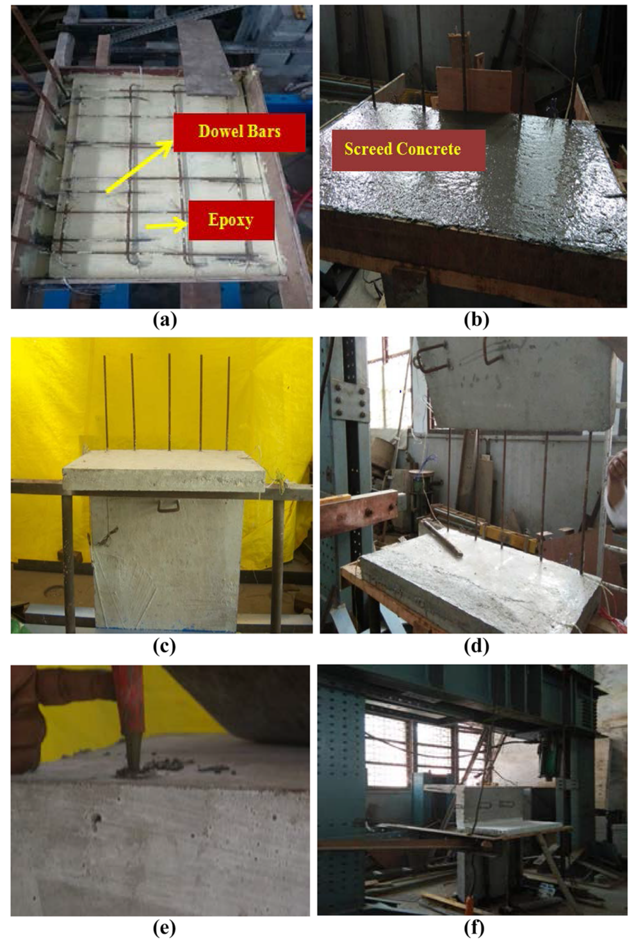

Fig. 4 Construction sequence of precast specimen. **a** Erection of lower panel and connecting dowels with topping reinforcement and application of epoxy coating; **b** cast-in-concreting; **c** erection of precast shear wall–lower panel and slab; **d** erection of upper panel; **e** grouting; **f** final stage of specimen

experimentally through a couple of forces acting at the slab ends on both sides, as shown in Fig. 5a. The experimental test setup is shown in Fig. 5b. To simulate the effects of dead load, concrete cubes were arranged at the top of the projecting slab and maintained throughout the test. The bottom of the shear wall was fixed with the frame which is mounted on the strong floor in the laboratory. Two numbers of double acting hydraulic jacks with a capacity of 40 t in tension and 20 t in compression were mounted on the loading frame for the application of reverse cyclic loading. Hydraulic jacks and linear variable differential transformer (LVDT) with a maximum displacement of 50 mm were used for the application of load and displacement, respectively. Load and LVDT indicator were used for measuring load and displacement, respectively.

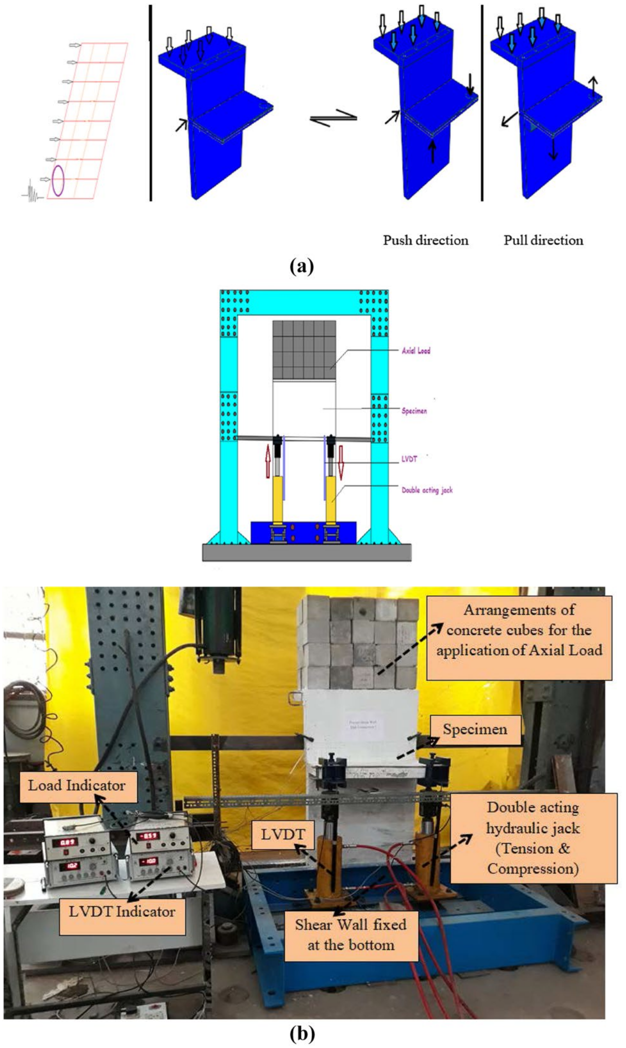

Fig. 5 **a** Experimental simulation of lateral load. **b** Experimental setup

2.5 Loading Protocol

To include the gravity load from the above stories, an axial load was chosen as 10% of its load-bearing capacity of the wall. In the loading scenario, the effect of seismic forces was simulated by applying reverse cyclic loading (Fig. 5a). Each reversed cycle of loading consisted of push (positive) and pull (negative). In this study, the push and pull loading generates clockwise and anti-clockwise in-plane moment at the joint region, respectively. The test was carried out under a displacement controlled loading concept. Three cycles at the same displacement level were applied. The reverse cyclic loading protocol as per ACI T1.1-01 [22] was used (Fig. 6).

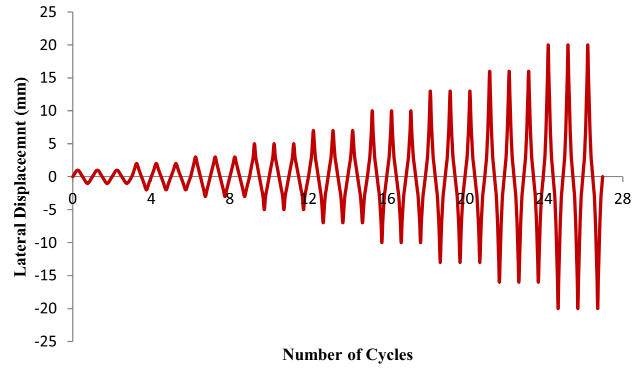

Fig. 6 Loading sequence

Table 2 Comparison of the ultimate load of both the specimens

S. no.	Specimen	Ultimate load (kN)		Displacement at ultimate loads (mm)
		Positive direction	Negative direction	
1.	Monolithic	10.9	9.27	10
2.	Precast	13.35	12.60	20

3 Results and Discussion

3.1 Strength

The capacity of the structure to resist the designed loads defines the strength parameter. The ultimate load for the MS in the push was about 10.9 kN and in the pull was found to be 9.27 kN. For PS, the ultimate load was found to be 13.35 kN and 12.60 kN in the push and pull direction, respectively. The ultimate load-carrying capacity of both the specimens is shown in Table 2, and represented graphically in Fig. 7. The ultimate load of the PS with the dowel connection was 22.48% and 35.92% higher than the MS in the push and pull direction, respectively. The performance of precast specimen with dowel bars proves to be superior to the monolithic specimen.

3.2 Crack Pattern

According to observation, in both the monolithic and precast specimen, there are no visible cracks seen in the shear wall indicating that the wall does not achieve its plastic condition. They exhibited damage in the slab region under reverse cyclic loading. Cracks were seen on both the top and bottom faces of the slab and the failure pattern of both the specimens is shown in Fig. 8. In monolithic specimen, initial cracks were developed in the slab diagonally and extended towards the joint region. The first crack was formed in the slab at 2 mm

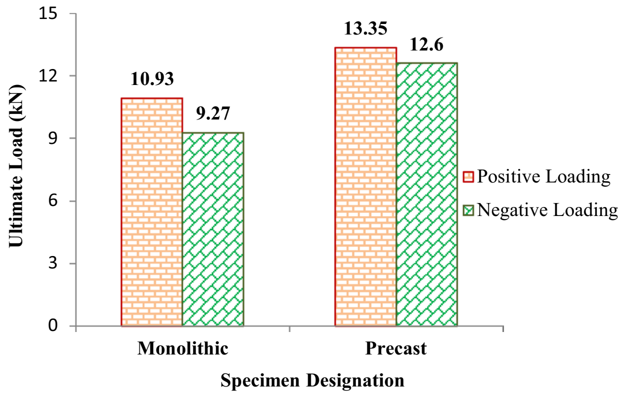

Fig. 7 Graph showing the comparison of ultimate loads for both the specimens

(8.7 kN) displacement cycle, and the cracks were propagated in the slab region as the displacement increases. At 5 mm (10.2 kN) positive displacement cycle, visible shear cracks were observed in the joint area and get widened in the joint region at 10 mm (10.9 kN) positive displacement cycle. The crack width of about 0.3 mm formed at the joint region. The ultimate load-carrying capacity was achieved at 10 mm displacement. The maximum displacement reached by the monolithic specimen is 20 mm. At the ultimate displacement, the crushing of concrete occurs at the loading point in the slab. The crack in the MS is narrower and more number of cracks was formed when compared to PS, as shown in Fig. 8c.

In the precast specimen, hairline cracks were developed along the upper surface of the slab in the initial stage. The cracks developed diagonally from the loading point and these cracks widened and expanded in the slab and the joint region. The first crack was formed in the slab at 2 mm (10.37 kN) displacement cycle and as the displacement increases the cracks gets widened. The ultimate load-carrying capacity was achieved at 20 mm displacement cycle. The maximum displacement reached by this precast specimen is 28 mm. The shear cracks at the joint region initially developed at the interface between the precast slab and screed concrete which gives clear evidence that the inelastic behaviour occurred at this location. However, in the precast

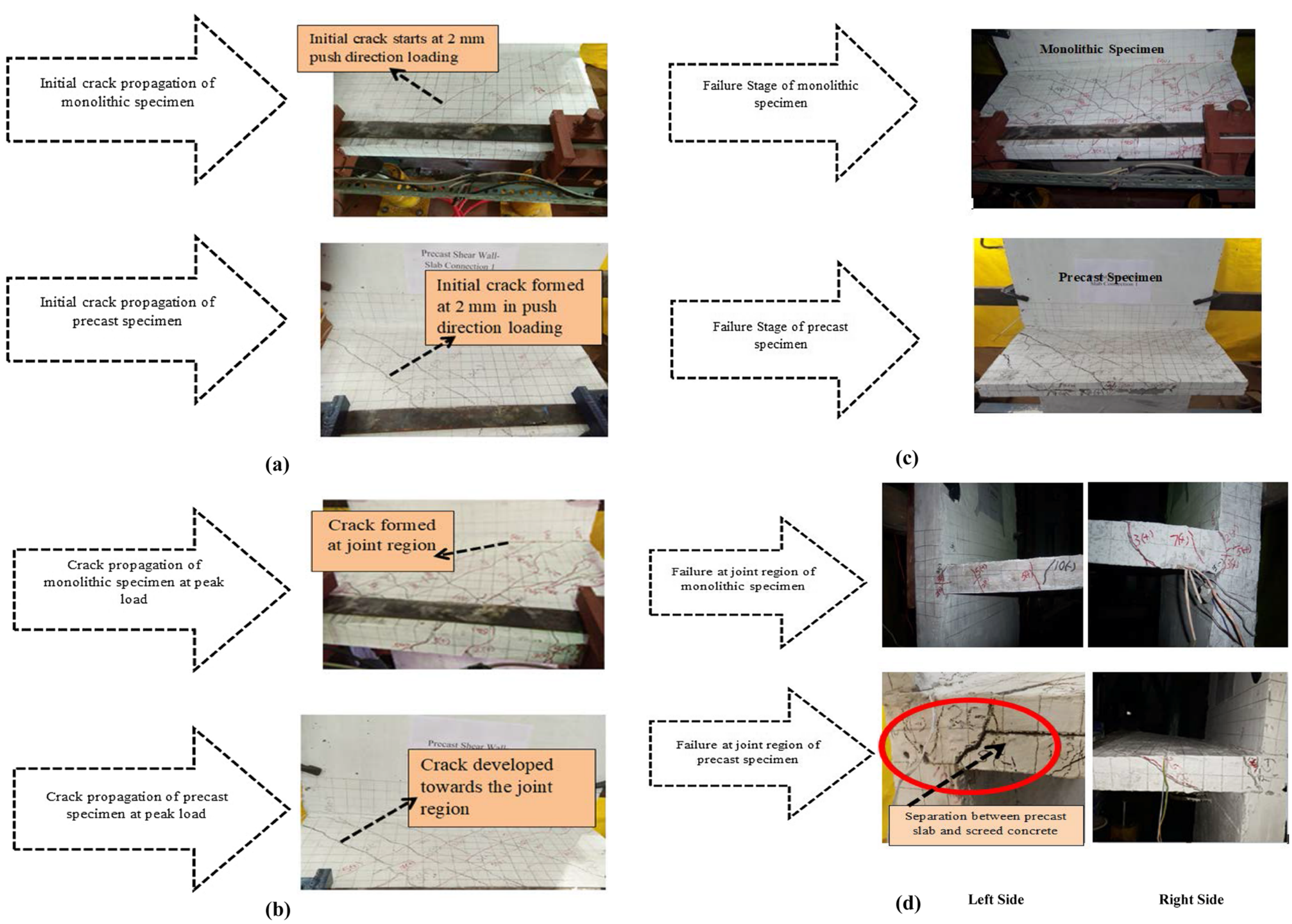

Fig. 8 Crack pattern of monolithic and precast specimen. **a** Initial crack. **b** Crack propagation at peak load. **c** Failure stage. **d** Failure of connection region

connection, there is a separation of about 0.2 mm of in situ topping from the precast slab at 13 mm (12.17 kN) positive displacement cycle (Fig. 8d). Since the separation in the slab occurs at 13 mm displacement cycle which is higher than the displacement (10 mm) of ultimate load achieved by the monolithic connection. The debonding between the precast slab and screed concrete widened as displacement increases and the crack width at the joint region reached 12 mm at the failure stage. The crack widths are generally high on the precast specimen and at higher displacement lead to crushing of concrete when the reverse cyclic load was applied.

3.3 Load–Displacement Relationships

The hysteretic behaviour of the joint is observed from the relationship between load and displacement. The load–displacement relationship and envelope curve for the monolithic and precast specimen are shown in Fig. 9. The reverse cyclic load is applied at the slab regarding displacement control at a distance 410 mm away from the joint. It has been observed from the hysteresis graph that both the specimens exhibit stable hysteresis loop at the initial stage of loading. The precast specimen shows a wide area of the hysteresis loop as displacement increases, which indicates good energy dissipation capacity when compared with the monolithic specimen.

3.4 Energy Dissipation

The better performance of the structure in the plastic stage entirely depends upon the energy absorption capacity. The specimens under reverse cyclic loading prove to be ductile if it has an adequate amount of energy dissipated without the decrease in strength and stiffness. The area under the load–displacement curve in a given cycle defines the energy dissipated by the specimen during that cycle. The cumulative energy dissipated by the specimen was obtained by summation of energy dissipated in the consecutive cycles. Figure 10 shows an energy dissipation curve for each displacement cycle and the cumulative energy dissipated by both the specimens. It was seen that in comparison with the monolithic specimen, precast specimen exhibits higher energy dissipation of 722.55 kN mm. The cumulative energy dissipated by the PS is 128.95% higher than the MS.

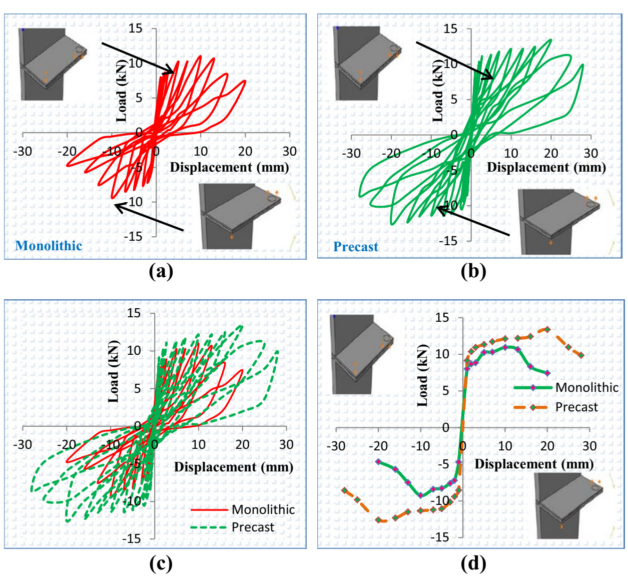

Fig. 9 Load–displacement graph. **a** Monolithic connection. **b** Precast connection. **c** Comparison of both the specimens. **d** Envelope curve

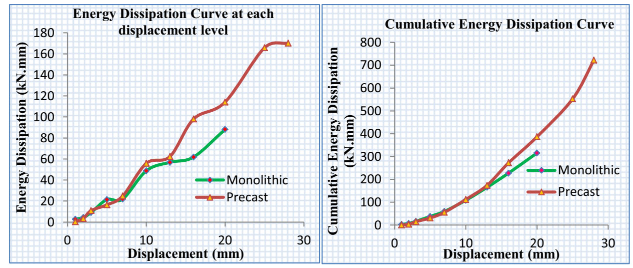

Fig. 10 Energy dissipation curve

3.5 Ductility Ratio

Ductility factor is represented as the ratio of ultimate displacement to the yielding displacement of reinforcing bars. The yield displacement is taken as displacement at 80% of peak load at the increasing branch of the curve, and the ultimate displacement is obtained at 80% of peak load at the decreasing branch of the load–envelope curve [23]. The average ductility ratio for MS and PS was evaluated and given in Table 3. The average ductility ratio of the PS was 74.34% greater than the MS. The ductility factor indicates that both the specimens behave in a ductile manner.

3.6 Moment-Carrying Capacity and Stiffness Degradation

The lateral load at the shear wall–diaphragm connection is simulated by applying force at both ends of the slab. The slab rotation was obtained from the displacement of the slab due to its in-plane moment. The ultimate moment-carrying capacity of the precast dowel connection is 5.47 kN m and 5.17 kN m which is 10.73% and 36.05% higher than the MS in the push and pull loading direction, respectively (Table 4). The moment–rotation graph for both the specimens is shown in Fig. 11.

Table 3 Comparison of ductility ratio of precast and monolithic specimen

S. no.	Specimen type	Yield displacement (mm) Δy		Ultimate displacement (mm) Δu		Ductility factor μ		Average ductility factor μ
		Positive	Negative	Positive	Negative	Positive	Negative	
1	Monolithic	2.41	2.5	15.46	10.66	6.41	4.26	5.34
2	Precast	2.55	2.88	25.72	24.58	10.09	8.53	9.31

Table 4 Ultimate moment of both the specimens

S. no.	Specimen	Ultimate moment (kN m)	
		Push direction	Pull direction
1.	Monolithic	4.94	3.80
2.	Precast	5.47	5.17

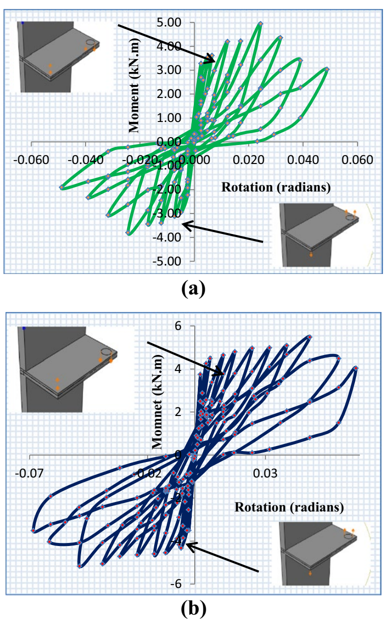

Fig. 11 Moment–rotation graph. **a** Monolithic specimen. **b** Precast specimen

The RC structural components will undergo some level of stiffness degradation due to loss of bond, cracking or high stresses when subjected to reverse cyclic loading. Stiffness degradation of the tested specimens was determined from the slope of the peak-to-peak load for each displacement level. The stiffness is plotted against the number of cycles and shown in Fig. 12. There is degradation of the stiffness as displacement increases due to the accumulating damage in the shear wall–slab joint region. Due to the diaphragm action provided by the screed concrete over the precast slab, the initial stiffness of the PS is higher than the MS.

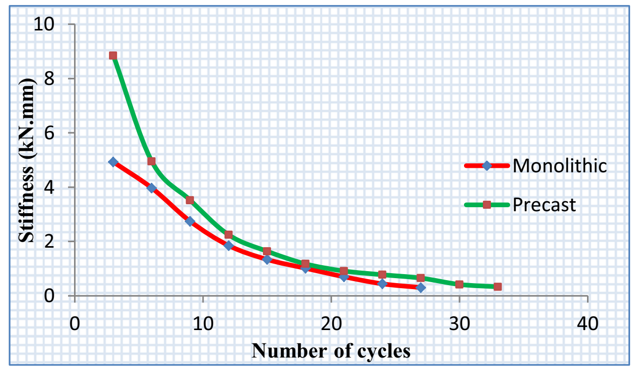

Fig. 12 Stiffness degradation of the specimens

4 Conclusion

In the present work, an experimental study was carried out to investigate the performance of exterior precast shear wall–diaphragm connection using dowel bars subjected to cyclic loading and the results were compared with that of the monolithic connection. One-third scaled models were cast and tested under reverse cycle loading. The seismic performance of precast dowel connection concerning hysteresis behaviour, ultimate strength, moment, stiffness, energy dissipation and ductility factor were compared with the monolithic connection. The following observations are made from the experimental investigations:

- The precast dowel connection shows a wider hysteresis curve compared to the monolithic specimen as the displacement increases due to the predefined gap between the precast shear wall and slab connection.
- The peak load of the PS was 22.48% and 35.92% higher than the MS in the push and pull, respectively, due to the diaphragm action provided by the screed concrete.
- The cumulative energy dissipated by the PS is 128.95% higher than the MS. There is an increase in ductility of about 74.34% in the precast specimen when correlated with the monolithic specimen which proves that PS shows satisfactory performance in the inelastic stage.
- The ultimate moment-carrying capacity of the precast dowel connection is 10.73% and 36.05% higher than the monolithic connection in the push and pull direction,

respectively. The initial stiffness of the PS is also found to be 79.49% greater than the MS.

- It can be concluded that the precast specimen with dowels between the shear wall and slab reveals satisfactory performance in comparison with the monolithic connection using U-shaped bars between shear wall and slab. Dowel action increases the shear capacity of the connection. The screed concrete also provides the diaphragm action which increases the stiffness of the precast slab.

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