Hysteresis Behaviour of Precast Shear Wall – Slab Connection under Reverse Cyclic Loading

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Abstract. An experimental study focused on precast shear wall-slab joint failure is presented in this paper. For the precast specimen, the shear wall and slab are precast members and were connected with cast-in situ concrete using dowel bars. The specimen was tested under reverse cyclic loading and the structural behaviour of the connection was evaluated. The parameters considered are cracking pattern, hysteresis behaviour, energy dissipation and ductility. This study also aimed to develop 3-D finite element (FE) model of precast shear wall – slab dowel connection using ABAQUS software in order to investigate the joint failure of the specimen such as damage and hysteresis behaviour. The non-linear behaviour of concrete was defined using concrete damaged plasticity (CDP) model and the interactions between the precast members were modelled using cohesive element. FE model was then validated against the experimental results of precast dowel connection which are vulnerable to wall-slab joint shear failure. The failure pattern of the tested specimen showed the “Strong joint–Weak member” concept. The comparison between experimental and numerical results showed that the FE model developed was capable of simulating the seismic performance and the joint failure of precast shear wall-slab connection using dowel bars.

1. Introduction
Precast construction technology has gained consistent growth in recent years. The prefabrication comprises of different members cast in a factory and erected in the site to create a structural system. The crucial region in precast structures was the connection between the members. This was due to the important role they play in controlling the behaviour of the building subjected to seismic loading. The connection between shear wall and slab was a critical region in structures to resist lateral load. The intense stress occurred at the joint between the shear wall and slab when earthquakes occurred [1]. Zenunovic and Folic [2] have studied the connections between the cast-in situ wall with the precast slab. The energy dissipation of the connection was observed to be similar to the cast-in-situ connection. Arthi S and Jaya KP [3] studied the seismic response of shear wall and diaphragm connection using dowel bars. The precast connection showed superior behaviour with respect to ultimate load and ductility compared with monolithic connection. Therefore, it was imperative to analyse the behaviour of the precast wall and diaphragm connection under seismic loading. The investigation of such performance needs computation of structures, materials and the loading effects. The FE method will be the best solution to include the variation in these parameters. Due to the advancements in the computation, the efficiency of FE programs to predict the performance of RC structures has already been established [4], [5], [6]. Generally, the different types of connections in precast structures are emulative, dry, welded and bolted connection. In case of wet connection, the horizontal forces between precast members are transferred by dowel bars, shear keys and interface friction. The performance of connection between
beam and column using dowels was investigated [7]. Yuksel et al. [8] have discussed different types of connection between beam and column. The authors have proposed one of the connection detailing with the presence of corbel. In the proposed connection, half depth of the beam was precast and the longitudinal reinforcement was tied with the stirrups protruding from the precast beam. Finally second concreting was done. Finite element analysis of precast connection using dowels was done using the ABAQUS software to reproduce the cyclic performance of the connection. The dowel bar from the column are connected to the beam, and then the gap was filled with mortar [9], [10]. It was found that defining the material properties and the contact surface between the precast members was important for FE analysis. [11]. Soudki et al. [12] have studied the precast connections between walls. The precast connection was proposed by using reinforcement, shear keys, and tendons between walls. Feng et al. [13] investigated the shear performance of precast column using grouted sleeve connected rebar subjected to seismic loading and developed the non-linear FE model using ABAQUS software. The specimens were tested under cyclic loading. The authors observed that the grouted sleeve connection ensured the transfer of shear force and showed similar behaviour as compared to the cast-in-situ connection. The connection between the precast walls using dowel bars and bolted steel channels was studied by Taheri et al. [5]. The interface shear strength at the contact surfaces was significant for the modelling of precast structures. [14], [15]. Some research work explained the capability of the Concrete Damaged Plasticity model which exactly simulates the behaviour of the structures [16], [6]. From the literature survey, it was understood that, the connection between precast members was important and only minimum works was carried out related to wall and slab connection. Therefore, the objective of this work is to assess the structural performance of exterior precast shear wall and slab connection by conducting an experimental testing and finite element modelling subjected to seismic loading.

2. Experimental work

2.1. Detailing of precast specimen

The critical forces of the structural members were obtained by analysing the -8 storey structure using staad pro software. From the analysis, the shear force at the joint between wall and slab was found to be 963.04 kN. The wall and slab was designed as per IS 456-2000 [17] and detailed as per IS 13920-1993[18]. The dowel reinforcement between precast wall and slab was designed to resist the shear force acting at the connection region [19]. The reinforcement detailing is shown in figure 1. The connection detailing is shown in table 1 and figure 2.

| SL. No | Connection between precast structural member | Reinforcement detailing | Development length |
|-------|---------------------------------------------|-------------------------|--------------------|
| 1     | shear wall-slab                             | 4 nos of 6 mm diameter @ 200 mm c/c | 270 mm             |
| 2     | shear wall - wall                           | 5 nos of 10 mm diameter @ 175 mm c/c | 450 mm             |

2.2. Assembly of precast specimen

One-third scaled-down specimen was cast using M-30 grade of concrete for testing. The cubes were tested on 28th day and the compressive strength ($f_{ck}$) obtained was 39.2 N/mm². The construction sequence of the specimen was as follows:

1. The precast slab was provided with a 20 mm diameter circular duct for connecting the dowel bars protruding from the precast shear wall and the space was filled with high strength grout.
2. Dowel bars from the precast slab was tied with the reinforcement which is placed above the precast slab. Screed concreting was done.
3. The upper wall panel was erected and the space was filled by grouting. The construction stage of the specimen is shown in figure 3.
2.3. Test set-up
The axial load was kept constant throughout the test. During an earthquake, the wall and slab joint would be subjected to an in-plane moment. This was simulated by applying forces at the ends of the slab as shown in figure 4. The displacement and load were monitored using LVDT and load cells which were placed at the slab ends (Figure 5).

2.4. Loading sequence
The sub-assemblage of the specimen was tested under displacement controlled loading protocol. Three cycles for each displacement level was applied at the slab ends. The loading protocol for the tested precast specimen consisted of displacement of ±1 mm, ±2 mm, ±3 mm, ±5 mm, ±7 mm, ±10 mm, ±13 mm, ±16 mm, ±20 mm, and ±27 mm. The loading protocol used for testing is shown in figure 6.
3. Testing results

3.1. Failure mode
The failure of the precast specimen is shown in figure 7. The damage of precast specimen tested under reverse cyclic loading is as follows:

- The initial crack started from the left side of the slab.
- The cracks started diagonally from the loading point at 3mm (5.25kN) positive displacement cycle. At 3mm (5.50kN) negative displacement cycle, the crack extended and developed nearer to the joint region.
- Crack at the joint region started at 10mm (7.95kN) positive displacement cycle and gets widened at 13mm (7.97kN) negative displacement cycle.
- At 16mm (7.50kN) negative displacement cycle, the crack widened at the right side of the precast slab and concrete crushed at the joint region.
- The crack width at the joint region on the left side of the slab was 4mm and at the top face of the slab was 2mm. There was a debonding between the lower panel and slab at 20mm (6.22kN) positive displacement cycle.
- The tested specimen reached a maximum displacement of about 27 mm.

| Precast Specimen | Failure of the structural member | Left side of the joint region | Right side of the joint region |
|------------------|---------------------------------|-------------------------------|--------------------------------|
|                  | Diagonal Cracks                 | Cracks at the joint region     | Debonding between wall and slab |
|                  | Cracking of concrete            |                               |                                |

Figure 7. Failure pattern of the precast specimen.

3.2. Hysteresis behaviour
The hysteresis behaviour of the precast dowel connection regarding the load-displacement relationship has been discussed in this section. The experimentally tested specimen exhibited load-carrying capacity of 8.35 kN at 3.2 % drift (13 mm) and 7.97 kN at 3.2 % drift (13 mm) in the positive (push) and negative (pull) direction loading, respectively. From the load-displacement graph (Figure 8), it was observed that there was linear hysteresis behaviour at the initial loading stage and later pinching effect was observed as displacement increased. After reached the ultimate load, there was a drop in load-carrying capacity of the specimen.

Figure 8. Load-displacement curve.

3.3. Energy dissipation
The total energy dissipated by the specimen was found by the area under the load-displacement (P-Δ) relationship. The cumulative value was found by adding the energy dissipated by the specimen in the
successive cycles of displacement. The area under the P-Δ curve in each displacement became larger as displacement increased as shown in figure 9. The cumulative energy dissipation of the tested specimen was found to be 333.21 kNmm.

3.4. Ductility
Ductility was the crucial index in defining the seismic performance of precast specimen. It was obtained by the dividing the ultimate by yield displacement of the specimen. The calculated ductility factor of the tested specimen is shown in table 2.

Table 2. Ductility of precast specimen.

| S.No | Specimen | Δ_y (mm) | Δ_u (mm) | μ (Average) |
|------|----------|----------|----------|-------------|
| 1    | Precast  | Push: 5.73 | Pull: 5.02 | Push: 23.2 | Pull: 26.5 | Push: 4.05 | Pull: 5.28 | 4.66 |

*Where Δ_y – yield displacement, Δ_u – ultimate displacement, μ - ductility.

4. Finite Element Modelling
One – third scaled-down specimen was modelled using FE software ABAQUS as similar to the experimental programme. The modelling stages in FE analysis are as follows:

4.1. Modelling
In the present work, the concrete and grout parts are modelled using a three dimensional solid element and the assigned concrete region was meshed using C3D8R element with hourglass control. The reinforcement and the dowel bars were modelled using 3D wire planar elements and meshed by using a 2-noded B31 beam element. The modelled specimen is shown in figure 10.

4.2. Material property
Concrete Damaged Plasticity (CDP) model was used for defining the nonlinear behaviour of concrete. The Young’s modulus of concrete defined in the FE analysis was 32725.49 N/mm² and poisson ratio was 0.2. The value of eccentricity, dilation angle, initial biaxial to uniaxial ratio, viscosity , k, defined in this study was 0.1, 38°, 1.12, 0.666 and 1 and The performance of concrete to dynamic loads in the CDP model is shown in figure 11. The modulus of elasticity of steel was 200000 N/mm² and Poisson ratio was and 0.3.

4.3. Interactions
The contact surface and the interaction between the precast members play an essential role in the finite element modelling for nonlinear analysis. In this analysis, five contact surfaces were defined between the structural members and shown in table 3.
Table 3. Interaction Property.

| S.No | Contact Surface                        | Interaction Property                          |
|------|----------------------------------------|-----------------------------------------------|
| 1    | Precast lower shear wall-precast slab  | Cohesive Element (eight noded, three-         |
|      | contact surface                        | dimensional cohesive elements COH3D8)         |
| 2    | Precast slab-screed concrete contact    | Cohesive Element                              |
|      | surface                                |                                               |
| 3    | Screed concrete- upper shear wall       | Tie Constraint                                |
| 4    | Interaction between dowels-concrete/    | Embedded Constraint                           |
|      | grout                                   |                                               |
| 5    | Reinforcement and concrete              | Embedded Constraint                           |

5. Finite element results

5.1. Hysteresis behaviour
From figure 12, the precast specimen showed spindle-shaped hysteresis behaviour with low pinching due to the bond between the reinforcement and concrete in the joint region. The maximum drift ratio (%) undergone by the precast specimen was 6.8% (27mm). The specimen exhibited load-carrying capacity of 9.35 kN at 3.2% drift (13 mm) and 8.82 kN at 3.2% drift (13 mm) in the push and pull loading, respectively. The failure of the precast specimen from the FE analysis is shown in figure 13.

5.2. Ductility
The ductility factor of the modelled specimen was calculated and shown in table 4. Although ABAQUS can estimate the capacity and behaviour of specimens well, it cannot account for pinching effects on cyclic behaviour of RC structures [4], [20]. The ductility obtained by finite element analysis was 10.9% higher than the experimental result.

Table 4. Ductility of precast specimen.

| S.No | Specimen | \( \Delta_y \) (mm) | \( \Delta_u \) (mm) | \( \mu \) | \( \mu \) (Average) |
|------|----------|---------------------|---------------------|---------|-------------------|
|      |          | Push    | Pull    | Push    | Pull   | Push | Pull |
| 1    | Precast  | 3.52    | 3.84    | 17.99   | 20.05  | 5.11 | 5.2  |
|      |          |         |         |         |        | 2    | 5.17 |

*Where \( \Delta_y \) – yield displacement, \( \Delta_u \) – ultimate displacement, \( \mu \) - ductility.

6. Conclusions
In this study, a one-third scaled-down exterior precast shear wall – slab specimen was subjected to reverse cyclic loading. The tested specimen was also modelled using finite element software as similar to the experimental programme. The conclusions made from this study are as follows:

1. The precast specimen exhibited an ultimate load-carrying capacity of 8.35 kN in the positive direction and 7.97 kN in the negative direction.
2. It was observed that there was linear hysteresis behaviour at the initial stage and the area under the hysteresis loop becomes larger as displacement increases which showed good energy dissipation capacity of the dowel connection.
3. The proposed precast dowel connection showed ductile behaviour and the ductility was found to be 4.66.
4. The crack propagation was more in the precast slab than the joint region which satisfied the “strong joint – weak member” concept.
5. The finite element results were found to be 11% greater than the test results and also exactly predicted similar behaviour as experimental testing.

7. References
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**Acknowledgement**

This research was supported by the Council of Scientific & Industrial Research (CSIR). The authors are grateful to the funding agency for their support.