Precast High-Rise Residential Projects in India: Design Implementation

Sudheer Bommi, Krishna Somaraju, Krishnamurthy Senou, Amit D. Barde

Abstract: A real time case study with a focus on design implementation for Pragati Towers – Stilt+23 floors complete pre-fabricated high rise residential project, designed & built by Larsen & Toubro construction for the first time in India for a seismic zone III location is presented in this paper. Innovative connections are implemented and their feasibility in regards to the India construction industry is explained with reference to other globally available systems. Two computational models were investigated to find the effect of modelling the vertical joints between the wall panels are also presented in this paper. Challenges faced while implementing the adopted precast techniques such as technology acceptance, design of connections, ensuring water tightness suitable to Indian building requirements are also discussed. Design concepts to prevent progressive collapse are also highlighted. A standard bench mark setup for precast housing solutions as a fast track technology achieved.

The demand for housing has increased significantly during last decade all over the world. It is felt particularly in countries where population growth rate is high and the economy is developing fast. For instance, India is urbanizing at a pace that is higher than the world average. Its cities today are unable to cope with burgeoning population. In India that has a housing shortfall of nearly 18.7 million homes (Refer Table 1), and project execution challenges including shortages in skilled manpower & time constraints. Inflationary trends of Indian economy have increased the cost of building materials to the extent that many developers/contractors find it difficult to offer an affordable housing to the citizens due to low productivity of labours and wastage of materials. Considering the above scenario, Larsen & Toubro felt it is important to treat housing construction as a manufacturing industry.

Precast can be better and workable technology which supports our aspiration. Prefabrication with mechanized building systems, with its adaptability and quality consciousness, provides speedy, cost efficient and sustainable solution.

Project Details

Pragati towers project in Mumbai, India consists of eleven residential high-rise, total precast buildings using precast concrete system. All towers rise about 70 m above ground. Each tower consists of over 300 apartments with a total construction area of around 2.6 million square feet. The project was developed by Larsen & Toubro Realty Limited and Omkar Realtors & Developers Private Limited Joint Venture.

The project was designed and constructed by Larsen & Toubro Construction.

<table>
<thead>
<tr>
<th>Monthly per capita expenditure</th>
<th>Housing shortage in million (2012)</th>
<th>In Percentage</th>
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</thead>
<tbody>
<tr>
<td>EWS 0-5000</td>
<td>10.55</td>
<td>56.18%</td>
</tr>
<tr>
<td>LIG 5001 - 10000</td>
<td>7.41</td>
<td>39.44%</td>
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<tr>
<td>MIG &amp; above &gt;10001</td>
<td>0.82</td>
<td>4.38%</td>
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<tr>
<td>Total shortage</td>
<td>18.78</td>
<td>100.00%</td>
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Source: Report of the Technical group (12th Five year plan:2012 - 17) on estimation of urban housing shortage

Table 1: Housing shortage in urban India

![Fig. 1 Pragati Towers (Part 1 of Phase 1)](image-url)
part of this year. All apartments of Phase 1 are identical that made precast technology a viable option. Figure 2 shows the overall layout of Phase 1 of the project. Table 1 shows the overall scope of precast construction for Phase 1 Buildings along with other building details.

<table>
<thead>
<tr>
<th>Pragati Towers - Phase 1 – Six High-rise Buildings</th>
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<tbody>
<tr>
<td>Overall Built Up Area</td>
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<tr>
<td>Structural Frame</td>
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<tr>
<td>Total Apartments</td>
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<tr>
<td>Structural System – Superstructure</td>
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<tr>
<td>Structural System - Substructure</td>
</tr>
<tr>
<td>Ground and Terrace Work</td>
</tr>
<tr>
<td>1st to 23rd Floor Work</td>
</tr>
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<td>Total Precast Member Count</td>
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Table 2- Pragati Towers – Phase 1 Project Details

A typical apartment floor plan is shown in Figure 3. Each apartment comprising of 269 square feet of carpet area, consists of a living room, a study room, and a kitchen along with toilet and bath units, planned for a typical EWS family of four. Figure 4 shows the precast panel layout used for the project.

Design Implementation

Foundation system of the project consists of piles with pile caps connected with tie beams. Ground floors were constructed by conventional method i.e In-situ construction. Superstructure i.e 1st to 23rd floor consists of precast construction of RC walls & solid floor slabs, columns, and beams. Floor slab is considered to act as a rigid diaphragm to transfer the lateral forces to walls/columns. Precast concrete RC/shear walled structures, also called large panel systems, are load bearing members and are capable of carrying the vertical and lateral loads. The wall panels can be connected to each other and to the floor diaphragm to form an emulative monolithic structure.

Design Codes

Mumbai region is categorized as Seismic Zone 3 (Moderate Seismic Zone - typical Seismic Zones are defined from Zone 2 (Least Active) to Zone 5 (Highest)). Mumbai is also a coastal city with design wind speed of 44m/s (~ 98.5 mph) which was considered for this project. Seismic forces governed the design. The Bureau of Indian Standards (BIS) specifies building codes in India. IS 456 - 2006 is regarded as the primary building code for reinforced concrete structures. IS 1893 – 2002 provides guidelines for earthquake resistant design and IS 13920-1993 provides detailing requirements for ductility in concrete structures subjected to seismic forces. IS 11447 - 1995 provides design guidelines for large panel prefabricated construction. IS 15916-2010 is the most recent addition that provides guidelines for Design and Erection of Prefabricated Concrete.

Design Philosophy

As precast technology was adopted for a high-rise residential structure in India, the emulative design philosophy was selected based on mutual agreement between the Client, Consultant, and Contractor. Onsite, wet grouted joints for horizontal and vertical connections between walls and in-
situ concrete joints for slab-to-wall and slab-to-slab joints, termed as "stitched" joints were selected. ETABS software was used to build the structural model for analysis. Various modeling approaches were considered and compared to come up with the design forces at all joints in the structure.

**Emulative System**

Emulative detailing is defined as designing connection system in a precast concrete structure so that its structural performance is equivalent to that of a conventionally designed cast in place, monolithic concrete structure. Emulative design creates construction that either is monolithic at the critical joint locations or provides connections that act as if they are monolithic at those locations. In general, emulative connections involve connecting reinforcing bars across a joint by lap splicing, welding or couplers. Concrete is made continuous by filling the joint with high quality non-shrink non-metallic high strength grout in horizontal & vertical joints or cast in place concrete in vertical joints. The provisions for reinforced construction given in Indian standards [5, 6] apply specifically to monolithic reinforced concrete construction. Precast concrete members may be used only if they can provide same level of ductility as that of a monolithic reinforced concrete construction during or after earthquake. Specialist literature [7] must be referred to for such structures.

**Modeling Strategies**

The analysis of the structure was carried out using the ETABS software package. The entire superstructure was modelled primarily using shell elements. The walls were of shell elements and theslabs of membrane elements. A floor was considered as a rigid diaphragm at the respective level, to transfer the lateral forces to walls. The horizontal joints of the wall panels were idealized to simulate an equivalent monolithic behavior, in presence of the continuous vertical dowel bars. Therefore, the shell elements representing the panels were made continuous at the floor levels. A few beams and columns present in the structure were modelled using frame elements. Appropriate loads and its combinations, as per relevant clauses in IS codes, for most unfavorable effects were chosen for design. In absence of a model for shear transfer the vertical joints between the panels were modelled as the following two extreme conditions.

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**Integrated Model**

In this case, perfect shear transfer was assumed through monolithic behavior of two adjacent panels connected by the grouted loops. The vertical joint strip was modelled as a 100mm widestrip of shell element. Its thickness was considered same as that of the adjacent wall panels. In a grouted keyed connection, Clause 5.3.1 of IS11447: 1985 permits the joints to be modelled monolithic. Clause 8.1 of IS15916: 2010 permits the precast structure to be analyzed as monolithic, provided the joints are designed to take the respective forces. Figure 5 (a) shows the ETABS view of the integrated model.

**Discrete Gap Model**

In this model, no shear force was assumed to transfer between the wall panels. To idealize this condition, a 20mm gap was provided at the vertical joint locations. This uncoupled the adjacent walls. The walls were connected only at the floor levels by the diaphragm constraints. Figure 5(b) shows the gaps at the location of two joints in the discrete gap model.

It was observed from the results that, when a vertical joint was modelled as a gap i.e discrete gap model, the resulting structure was more flexible and the top displacement was higher in the gap model, the drift in both the models were within the allowable limit of 0.4%. From the results it was observed that the integrated model behaves as a perfect vertical cantilever while the other model behaves differently. Also, the bending moments and shear forces were more in the discrete gap model. Similarly the tensile forces were also higher, which resulted more number of dowel bars. Since this project was the first of its kind in India, we also checked w.r.t to conservative discrete gap model and provided high amount of reinforcement. The dowel bars were provided with a uniform lap length of 1.3m from foundation till roof through the precast walls. From the shear and tension force demand, this constant length of dowel bars was sufficient at all locations.

**Connections**

Connections are needed not only to transfer loads but also to provide continuity and overall monolithic behavior of the entire structure. A complete system of precast units can
be integrated to form a structure that behaves monolithically with sufficient strength, stiffness & durability to resist seismic & other dynamic loadings. To have a good interaction of wall elements, the elements have to be connected to the foundation, to each other and to the adjacent floor diaphragms. The connections act as bridging links between the components. The wall panel connections can be classified into horizontal joints & vertical joints.

**Horizontal Joint**

The horizontal joint between the wall panels was adopted via projecting dowel bars from lower walls, inserted into the dowel tubes of upper wall and grouted using non-shrink, non-metallic grout. The projecting length of dowel bar was kept at anchorage length. The dowels were entered on the thickness of the wall. Continuity is achieved through non-contact lap splices of dowel bars in grouted steel corrugated ducts. Traditional method i.e. non-contact lap splices (refer figure 6.a), a construction friendly option with good erection tolerances, was adopted as a replacement to the expensive proprietary products such as splice sleeve system (refer figure 7) which is a global practice. An alternate method i.e. connection with mechanical splice (couplers, refer figure 6.b) can also be proposed.

Horizontal joint design adopted is based on shear friction concept recommended in PCI standards [8]. Shear friction to be applied where it is appropriate to consider shear transfer across given plane, such as an existing or potential crack, an interface between dissimilar materials or an interface between two concrete cast at different times. The basic assumption in shear friction concept is that concrete within direct shear area being considered will crack. Ductility is achieved by placing reinforcement across this anticipated crack so that tension developed by reinforcement will provide a force normal to the crack plane. This normal force in combination with friction at the crack interface provides shear resistance. The normal compressive reaction across the crack will result in shear transfer by friction along the crack. Reinforcing bars placed across the joints will transfer additional shear force by dowel action of the bars, while the force induced by pullout resistance will increase the shear transferred by friction.

An alternate method also adopted & connections are checked as there may exist quality issues & uncertainties in the preparation of interface sleeve system (courtesy: ACI 550.1R-01) [9].

**Vertical Joint**

Vertical joints are the structural joints which have to transfer shear forces. Vertical joints are designed based on shear friction concept as a global practice. Dowel bars are provided in the form of projected rebar’s. Overlapping hoops & drop in hoops are tied as confinement reinforcement and the section is poured with cast in place concrete at joint locations (Refer figure 9). However, an alternate method was adopted for Pragati towers i.e. Vertical joints were provided with specially formed shear keys to increase shear stiffness and the shear capacity. Direct diagonal compression transfer between keys, friction and dowel action are mobilized due to shear displacements at the interface between the prefabricated concrete panel and the insitu joint concrete. The shear key works as mechanical locks preventing any significant slip along joint. The horizontal component of the inclined compressive force must be balanced by transverse tensile stresses. For this purpose transverse reinforcement must be provided connected by means of loops, anchored in the body of panel [10]. Transverse reinforcement was provided in the form of wire loops (proprietary products) for ease of erection where there is no site formwork required (refer figure 8). Vertical joint was designed based on Indian standards IS: 11447 – 1985[11] & fundamental principles. The resistance calculated is only static resistance. As the project falls in seismic zone 3 there is a possibility of vertical joint to resist cyclic actions induced by earthquake loading. Shear keys behave a significantly stiff component until the shear key effect is destroyed by cracking or local crushing at the heaviest loaded contact surfaces. When the shear key effect is decreases due to this degradation of the shear keys, the behavior changes to frictional phase associated with significant shear slip along the cracked section. As there is insufficient literature & testing available regarding cyclic actions on shear keys, on the conservative front for the project specified two models were generated & worst of the same results are adopted in the design [14].
Floor to Floor diaphragm

The stability of precast concrete buildings is provided in two ways. First the horizontal loads due to wind or earthquake are transmitted to shear walls by the floor acting as a horizontal deep beam. Floor systems play a key role in the lateral resistance of building structures by providing diaphragm action. Diaphragm action serves to transfer lateral load at each level to the lateral load resisting elements and unite individual lateral load resisting elements into single lateral load resisting system. Floor to floor connection was designed against diaphragm action & ties are provided to achieve structural integrity. Progressive collapse effects are also taken into account. Refer to figure 10 for floor to floor diaphragm connection details adopted for Pragati towers.

Progressive Collapse

In prefabricated construction, the possibility of gas or other explosions which can remove primary structural elements leading to progressive collapse of the structure shall be taken into account. It is therefore necessary to consider the possibility of progressive collapse in which the failure or displacement of one element of a structure causes the failure or displacement of another element and results in the partial or total collapse of building. The building is designed to prevent progressive collapse as per the Codal provisions [12].

For the stability of structure, three dimensional interactions between structural members are necessary to produce a robust design. The connections are normally designed for shear and compression. But in the case of accidental loading such as explosion, high tensile stresses along with large deformations will occur. To take up such forces, the connections should have sufficient strength, continuity and ductility. Strength is to take up the extra forces acting, continuity to redistribute the loading in case of accidental collapse and ductility to accommodate large deformations as well as for energy dissipation. To take care of these demands, tie reinforcements in all the three dimensions are an absolute necessity. Figure 11 schematically shows the provision of tie reinforcement in the structure. The internal ties are to take up the lateral forces from shear wall action. Peripheral ties ensure the diaphragm action of the slabs. Floor to wall ties take up the horizontal forces from anchorage of floors to their support and vertical ties ensure the cantilever action of walls.

To avoid progressive collapse, the structure should be sufficiently robust and redundant. Identification and proper design of the key elements in the structure is necessary to avoid progressive collapse. Recommendations in the codes were adopted to find the design load and the required amount of tie reinforcements. Here, tie reinforcements were provided horizontally, both internally and peripherally. The reinforce-
ment at the shear key locations provide the horizontal tying and that at the joint regions gives the necessary vertical tying effect. The horizontal ties provide a cantilever action to hold the damaged parts. The vertical ties help to suspend the lower damaged elements to the intact upper portions. The horizontal and peripheral tie systems provide a catenary action to bridge the damaged portion. The wall-to-slab ties help to suspend the debris, and prevent the damaged floor from falling down on to the intact lower portions.

Water Tightness

The joint design was looked at, taking into consideration the local tropical climate with heavy monsoons. The grouted joints helped achieve water tightness. Backer rods were placed at the exterior face of exposed to weather joints to prevent water entry. In addition, waterproofing sealant was applied at these joints as an additional line of defense. The gable end faces of the buildings were looked at in great detail due to the direct exposure to heavy rains. As shown in Figure 12, the horizontal joints on these elevations were detailed with an additional overlapping nib covering the joint across the length to avoid direct exposure of rain water. The nibs also provided a horizontal band as an architectural feature on the elevation.

Challenges Experienced

The task of taking up a high-rise residential building using precast technology was a daunting task. There was a steep learning curve for all involved to understand the technology and global standard practices and apply the learnings to the project in a workable fashion within the available resource constraints. Several aspects and standard practices used overseas were modified to fit the Indian construction practices. Some of the major aspects discussed in the paper are summarized below along with the respective solutions followed, in contrast with standard global practices, to adopt this technology. The knowledge and understanding acquired during this process will be carried forward to the new projects underway.

Technology Acceptance by the Client & Consultant

The client and consultant graciously accepted the technology based on the examples of precast buildings from around the world. Most examples were selected such that they matched a majority of project parameters on Pra-gati Towers with respect to customer needs, architecture, seismic design and site logistics. Without the client’s cooperation, patience and willingness to experiment with a new technology, this project could not have been conceived and materialized.

Design Philosophy

Jointed construction has been a widely accepted design philosophy globally for precast concrete construction. It offers the added advantage of speed and ease of construction. However, in-situ reinforced concrete system has been the most accepted system for residential construction over the last few decades in India. Thus, emulative design approach was followed instead of jointed design approach. Several methodologies were proposed and mock-up samples and load tests of critical connections were completed to come up with the final feasible options that would satisfy the design intent.

Design of Connections

Overseas standard emulative connection details such as sleeve connectors and loop connectors were weighed against the local design constraints such as cost and production/erection feasibility instead of blind adoption of methods used overseas. The approaches that worked well such as loop connectors were used with minor modifications. On the other hand, some approaches such as sleeve dowel connectors were avoided for high import costs and strict tolerances required for erection and production. Notched half slab concept was used which provided the comfort of jointed construction to a certain extent along with viable detailing to achieve emulative behavior.

Executive Summary & Conclusions:

1. To meet the demands of large volumes of construction in affordable housing sector in shorter duration there is a need for a fast track technology in mass housing.
2. The emulative monolithic wall system seems to be adequate in moderate seismic zones. The provisions of tie reinforcements, reinforced shear keys and dowel bars provide the required structural integrity for the precast system. The modelling of vertical joints without considering the shear transfer through the shear keys, reinforced with shear links, lead to a conservative design.
3. Vertical joints are designed based on shear friction concept as a global practice & dowel bars are provided in the form of projected rebar’s, overlapping hoops & drop in hoops etc filled with cast in place concrete at joint locations.
4. For this project vertical joints are provided with specially formed shear keys to increase shear stiffness and the shear capacity. The shear key works as mechanical locks preventing any significant slip along joint. Transverse reinforcement provided in the form of wire loops (proprietary products) for ease of erection where there is no site formwork required.
5. As there is insufficient literature & testing available regarding cyclic actions on shear keys, on the conservative front for this project specified two models are generated.
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Acknowledgement

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