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Prefabricated Concrete Technology- Perspectives and Challenges

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ABSTRACT

The technology in construction industry has changed rapidly over the past few years. In order to cope up with the challenges in speed and quality in construction industry to offset the shortage of houses for growing population in any country, the need of the day is prefabricated concrete construction. Pre fabricated concrete systems also provides the benefits of improved durability at a relatively lower cost.The different categories of pre fabrication concrete systems - component systems, panelised systems, volumetric systems and modular systems are adapted depending upon the functional needs and site conditions.Though, precast concrete technology provides an opportunity to construction industry in terms of rapid constructional speed and equally matched with better quality, it also accompanies with challenges in its structural design, stability and reliability. The prime aspect of precast concrete structures is that it requires special connection detailing for the continuity and monolithic action of different precast components under both normal and lateral loading conditions. The behaviour of joints under action of loading should be analyzed and it paves a potential direction for providing innovative connection detailing of future use. This paper emphasizes problems confronted in precast concrete technology, especially the research challenges on joints and connections. Likewise it also highlights the research made in the area of pre-fabricated concrete structures.

Keywords: Prefabricated Construction, Structural Challenges, Structural Joints, Structural Connections.

1. INTRODUCTION

There is a boom in construction industry with the use of pre-cast structural members for the construction in a fast pace and to meet the desired quality. The main difference between cast-in-situ constructions (built from one mould) to that of precast construction lies in the structural continuity. The connections (bridging links between components) in a prefabricated structure requires special conscious effort to confirm the structural continuity. The connection handling, joint types, ductility and durability of the materials chosen, properties of fire resistance, behaviour impact on design forces, and the methods followed during the construction/production dictates the behaviour of precast structure.

Engström [1] documented the factors affects the design of connections and joints in precast strcuures. The factors includes behvaiour at normal loading and dynamic loading, performance of structure during the working condition, structural behaviour during the hazards and etc. Celik [2] identified the list of probable causes of damages to prefabricated structures during the earthquakes at Turkey are as short column, short beam, poor material quality, soft/weak storey, poor joint detailing, irregular structural systems, inadequate element dimensions or lateral stiffness, pounding between adjacent building and damage of construal elements. However, the most important aspect was the poor detailing of joints, especially beam-to-column joints. Sesigiir et.al [3] also observed that the weak performance of prefabricated structural building and concluded that it was due to poor joint detailing and inadequate lateral stiffness.

The study of joints and novel approaches on joints/connection is a major research area of prefabricated concrete structures. This paper emphasizes the impact of joints/connections on prefabricated structural stability and reliability. Organization of remaining sections of the paper is as follows: Section 2 describes types of precast systems, its behaviour and the design challenges. Section 3 explains the types of joints and challenges involved on precast concrete structures. Section 4 brings the briefly the design challenges in precast concrete systems. Section 5 concludes and reconfirms the potential need of further studies in this domain.

2. PRECAST SYSTEMS

As per IS15916:2011, precast system classified as open fabrication system (partial and full fabrication), large panel prefabrication systems (staircase systems, balconies, precast floors and precast wall) and box type construction. The precast systems can be categorized as large panel prefabrication systems, frame systems, shear walls and mixed systems, depends on the loading capacity of the structures [4].

Large Panel Systems

Large Panel Systems are precast systems based on large prefabrication components such as large panels for walls, floors, roofs, balconies, staircase etc. The large panel systems are load-bearing members and that can carry the vertical and lateral loads, resists gravity load. Usually wall panels are of one storey height and floors/roof panels are as one-way or two-way slabs. Having durable large panel systems with adequate strength for panel connections – vertical or horizontal joints – is one of the important requirements in prefabricated large panel systems. The primary function of vertical joints is to resist vertical forces, whereas horizontal joints is to resist both gravity and seismic loads.

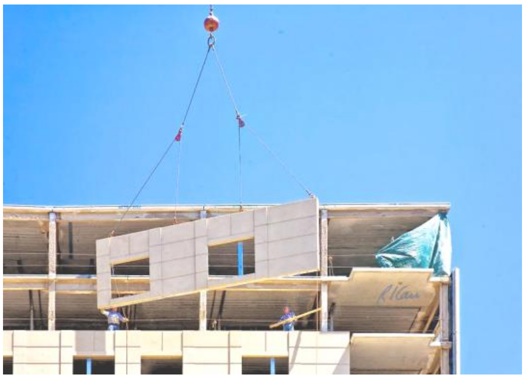

FIG 1: Large panel systems [5]

Depending on the construction process, i.e. the connection happened at the construction site or not, the panel connections are of two types - wet joints and dry joints. Wet joints fabricated at construction site by filling concrete between the precast panels. Large Panels welded, looped, or connected with reinforcing bars at the joints, to have the structural continuity. The structural continuity of wet joints is almost same as that of prefabricated structure. Dry joints made by bolting or welding steel plates or other steel inserts cast into the ends of the precast panels. In this case, the force transfer is at few discrete points, where the bolt or weld happened. The stability of large panel systems is achieved by tying the columns or by using boundary elements (bulbs) as stiffening elements to the wall panels.

A comparative study of the behaviour of large panels according to the types, construction process and stability techniques and joint detailing is the need in construction industry. The different types of large wall panel systems are transverse walls, longitudinal walls or by load-bearing walls in both directions and the study of structural behaviour and reliability analysis of these types of large wall panels are mandatory to be carried out. In similar direction, the comparative behaviour study and reliability analysis of solid cross-section, hollow-core and grouted hollow core types of slabs is another research challenge. The economic and faster methods of connection detailing, manufacture or manner of storage, transportation and erection of large panel systems are perennial concerns within precast concrete structures industry. The behaviour analysis of connections and joint handling is another research challenge. The solutions of these challenges are tightly coupled with economic considerations and codal provisions.

Frame Systems

Frame structures are the structures having beams, columns and slabs to resist both lateral loading and gravity loads and it is commonly considered for overcoming the large moments developed by applied loading. Frame systems are of rigid or braced types as using either linear components or beam column components as part of assembly. Even though the precast beam-column have the merit of placing the connecting faces away from the critical frame regions; but have the difficulties with respect to handling, transportation, form work of these components. Thus, the linear elements are the preferred in construction industry. In case of linear elements, the placing of the connecting faces happens at the beam-column junctions. The beam-column joint detailing is of following types -using corbel at the columns, hinged beam-column or rigid beam-column connections. The behaviour and analysis of these joints and appropriate design of beam-column detailing are of great importance in precast frame systems.

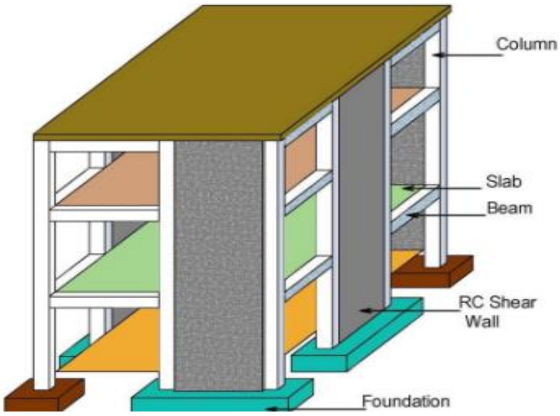

FIG 2: Precast Frame Systems [5] **FIG 3: Slab-Column Systems with Shear Walls [8]**

SHEAR WALLS

These precast systems use the shear wall mechanism to resist lateral loading and slab and column structure to sustain gravity load effects. Lift-slab system with walls and prestressed slab-column systems are types in these systems, where in lift slab system, has the load bearing structure with precast reinforced concrete columns and slabs (Fig 3). All precast structural elements are assembled by means of special joints. Thus, the joint detailing requires special attention at slab-column systems. Wang et. al [7] indicated the typical challenges precast shear wall structures and proposed new ideas. They indicated the challenge of overall stiffness of precast shear wall structure and proposed an effective usage of post-tensioned un-bonded pre-stressed fabricated of short limb shear wall for strong wall-weak beam connection. The preferred notion in the indutsry is that the large panel construction performs better than frame system, espcially during the sesimic and other dynamic loads. There is a need of innovative connection detailing mechanisms in frame systems, to overcome the limiation with respect to the seismic and other dynamic loads.

3. JOINTS BETWEEN PRECAST CONCRETE ELEMENTS

The most important research problem faced by the precast industry is to have reliable and economical mechanism to join prefabricated members. The locations of high stresses are the weak points in a prefabricated structural system. The connection handling should be achieved with a minimum number of joint members, and have the transmissibility of the existing forces under the best possible conditions and minimized secondary forces.

Compression Joints

Compression joints used for column-to-column connections; the vertical load is transmitted between two columns, one above the other. Compressive bearing stress acts either directly between precast concrete components, or through the intermediate medium (mortar or concrete). The selection of the type of joint depends on factors such as tolerances and the location of load transfer. To avoid the eccentricity between the component axes, an intermediate medium between the components can be used. For example, the direct contact without intermediate medium can considered only if the conditions such as accurate manufacture dimensions, high quality installation procedure and the bearing stress is less than $0.2f_{ck}$ of the weaker concrete possible [11].

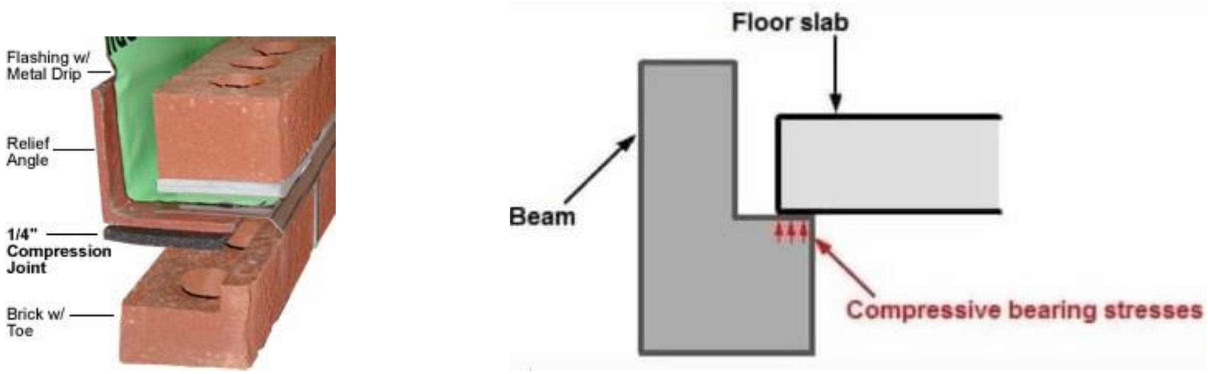

FIG 4: Compression Joint [9, 10]

Barboza and et. al. [12] carried out an experimental investigation on the load-bearing capacity of mortar joints used in precast concrete structures and concluded that the most suitable mortar layer thickness should be 13% of the joint width and recommended to use high compressive mortar. Barboza and et. al. [12] also suggested for provision of additional reinforcement at the ends to precast components to have high ductility and reduced rupture area.

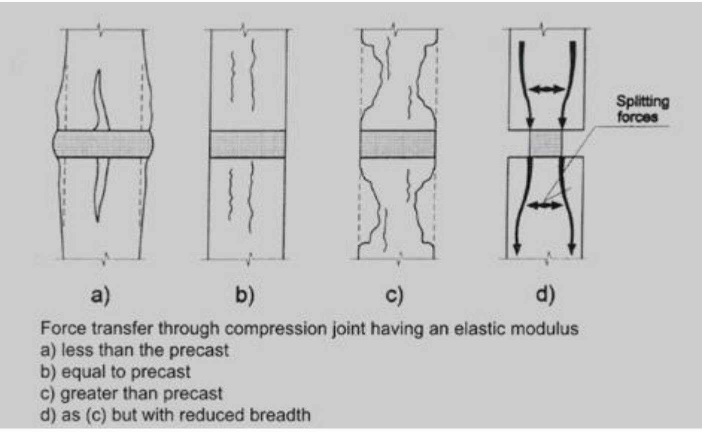

FIG 5: Compression Joint – Force Transfer [6]

Elliot [11] indicated the challenges with the compressive joints are spalling, crushing and splitting of the joined members due to chance eccentricities and spurious shear forces and moments. Elliot [11] also indicated the challenge of localized contraction and split of joined members due to the uneven elastic responses between the bearing medium and the precast concrete [11].

Tensile Joints

Horizontal reinforcement bars and vertical projecting bars of precast members are to be filled with concrete after construction, but even after the complete anchorage, the possibility of quick breakdown near the interface and eventual separation of two halves of joints. This is due to the elastic deformation in the bar, and it develops *tensile* cracks and produces the slippage at the interface. This is to make sure that the filled concrete at construction site have the positive bonds with the joints of vertical lapping. Bljuger [13] reused the compression deformability equation for determining the crack width of tensile joints and published values of deformability that used for measuring the crack width.

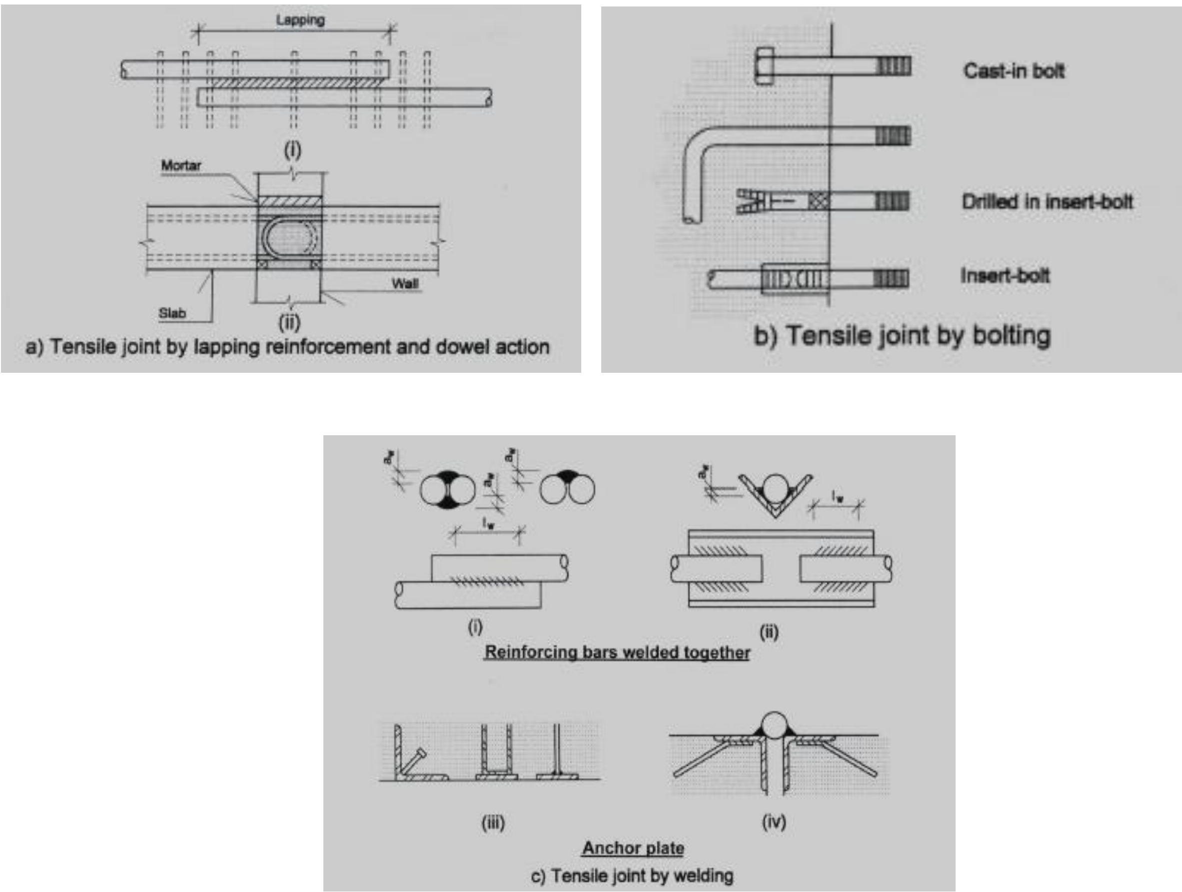

FIG 6: Tensile Joints – (a) Dowel (b) Bolting (c) Welding [6]

The common techniques used are bolting, welding and post tensioning as tensile joints in the construction industry. The *bolting* technique with bolts, threaded sockets, rails and captive nuts is used to handover tensile and shear forces. The *welding* technique used to connect the components through the projecting bars. *Post-tensioning* with the application of clamping forces across the joints used to curtail the tension and shear forces.

Shear Joints

At shear joints, shear forces transferred between components through bond, bolts, welds, friction, shear keys and reinforcement. The shear force arises due to roughened surfaces, permanent gravity loads, by pre-stressing reinforcement bars or steel bars or rods placed across the joint or application of grout in the joints.

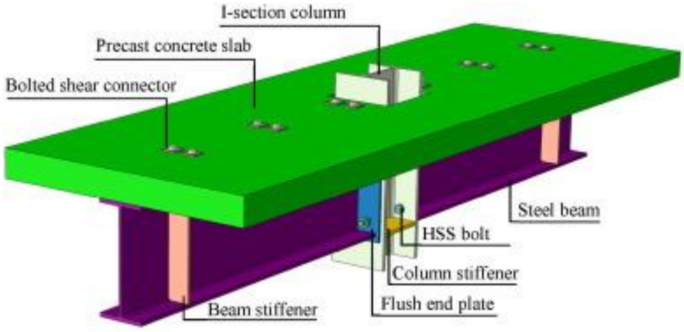

FIG 7: Shear Joints [14]

When the dowel is placed across the joints, there is a possibility of bending deformation due the shear force, and it eventually leads to the crushing of concrete at joints. Shear capacity depends on the bar diameter and the strength of the concrete.

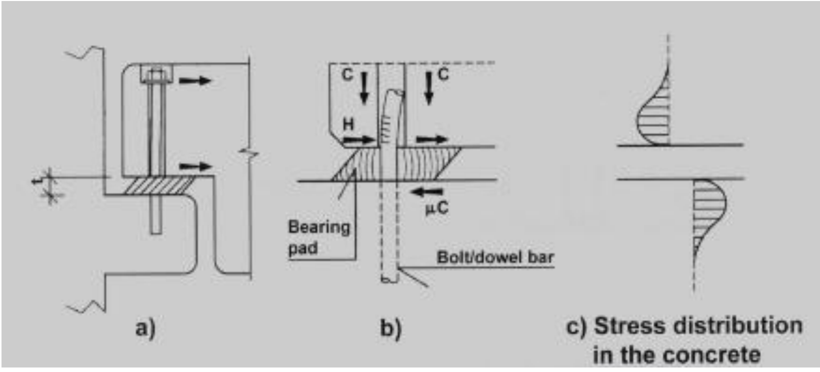

FIG 8: Shear Joints –Behaviour of Dowel [6]

Shear deformation are due to the localized damage at the shear interface. Bljuger [15] and Walraven et. al. [16] mathematically formulated shear deformation in cracked concrete interfaces. They infer that the sliding movement is due to the matrix damage, stiffness of cement pastes and modulus of elasticity of concrete.

FLEXURE AND TORSIONAL JOINTS

Flexural and torsional forces converts as a couple of tension and compression/shear. An exmaple of flexural and torsional joint is a cold joint, where the concrete poured to a precast surface without applying bonding agents and is a possible flexural and torsional joint.

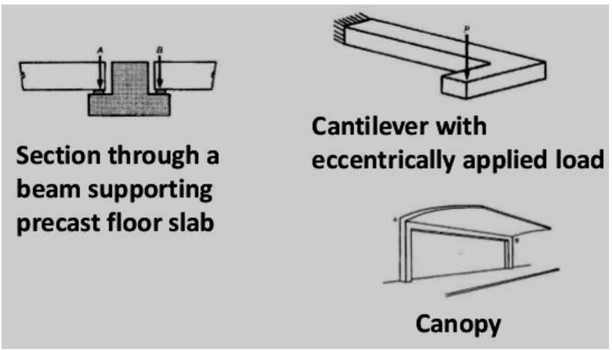

Fig 9. Torsion Joints [17]

The most important precaution is to reduce the possibility of cold joints and by placing extra mid-depth reinforcement.

Fig 10. Precast Coupling Beam – Cold Joints [18]

Connections in Precast Concrete

A connection is the total construction that includes the union between two or more components. Where as a joint is the individual boundaries between two elements, that is part of connection. For example, in case of precast beam to column, the interface between the beam and column is termed as *joint* but the entire assembly inlcuding beam, column, grout used at construction site etc. together is termed as *connection*. Connections are vital elements of the precast concrete design and construction. The structural behaviour of the frame can be controlled by the appropriate design of connections. The general categories of connections are pinned connections and moment resisting connections (full strength/rigid and partial strength/semi rigid). The specific connections in sketletal frames includes floor slab to beam, at supports and at longitudinal joints.

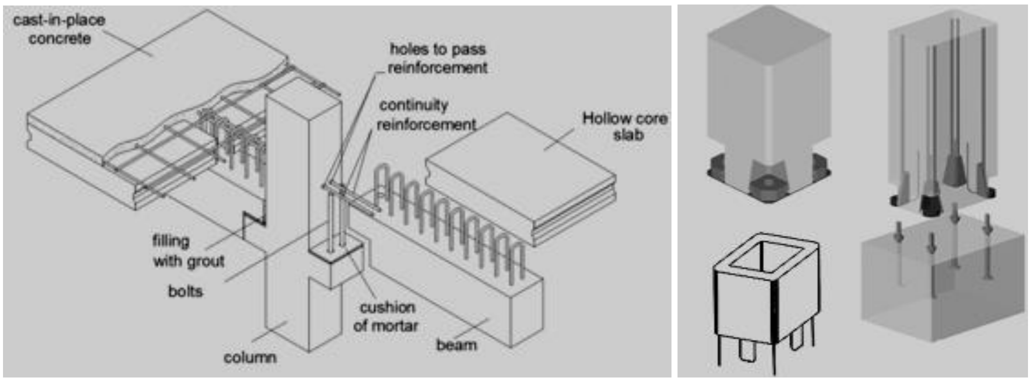

FIG 11. Connections (a) Beam-Column Connection & Slab to beam Connection [19]

(b) Column-to-Column Connection [20]

The most important joints in a multi-storey framed structure are column splices (for getting sufficient compressive strength), floor slabs (in situ concrete is used to infill to transfer horizontal loads) and shear walls. The seismic performance of precast concrete structure very much depended on the ductility capacity of the connectors jointing each precast component, especially at critical joints such as the beam to column connections. According to [21], hybrid post-tensioned beam-column connection and Dywidag Ductile Connector are the best suited connecting mechanisms for moderate and high seismic prone regions. But there is a clear gap of research studies to confirm the appropriate, optimized and practical connection detailing to suit with low seismic regions.

4. RESEARCH CHALLENGES ON PREFABRICATED STRUCTURES

There are abundant research challenges in prefabricated structures due to limited research on different types of precast structural systems. The response reduction factor R (for code based design of earthquake resistance strutures) have different values for different types of precast buidling depending on the performance. The review and unification of codal provisions from different countries are neccasary. The structural challenges of prefabricated structures includes: inadequate diaphragm action,vulnerability in seismic prone areas due to semi rigid joints, issues due to different foundation level and non-adapative to changes in design plans during construction.

Beam-column joint is the most critical part in building system and it is important to have early prediction of the ultimate load and moment- rotation for beam-column joint. Hence, experimental and numerical research for the connections of beam-column joints in precast concrete design and construction is a major research challenge.

The seismic performance of precast construction is still huge speculatin as well as cocnern. At high seismic zones, the building and other structures must be designed to respond safely to dynamic loading conditions. An innovative and improved connection system makes precast concrete structures suitable in seismic areas. The design of innovative mechanism for load bearing structures – large panel, shear wall or frame structures – and its connection systems is a mandatory for the wide spread usage of economical and quality precast cocncrete systems.

5. CONCLUSION

This review paper provides an insight on few practices, research challenges and possible recommendations to the precast concrete industry. The following are the important among those points:

- Beam-column joint is the most critical part in building system and it is important to have early prediction of the ultimate load and moment- rotation for beam-column joint.
- The deeper understanding of the role of connections and the behaviour of joints are mandatory for the proper design of structural connection of precast concrete structures.
- The study is required on the mechanism of force transfer through the connections and joints, stress pattern at assemblage and the fracture patterns at connections during the excessive loading conditions.
- Study on joints of structural members as well as connection as a whole should be performed by the Structural Engineers during planning stage of construction.
- Hybrid post-tensioned beam-column connection and Dywidag Ductile Connectors are the best suited connecting mechanisms for moderate and high seismic prone regions. There is no optimized solution predicted for low seismic zones.
- Rigid Footing System allows for rapid replacement of individual sections. Repairs only require lifting out the damaged section and inserting a new section
- Reliability analysis and optimized design with engineering tradeoff is a mandatory requirement of having safer and quality construction.
- Lack of clear and uniform codal provision for design across developing countries.

Thus, eventhough there are major inventions and design consideration in precast construction industry. But, there is no dearth of challenging problems in precast concrete construction and hence it is continued to be a potential area for research.

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