



SEISMIC PERFORMANCE OF PRECAST CONCRETE STRUCTURES: A CRITICAL REVIEW WITH REFERENCE TO INDIAN DESIGN STANDARDS

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Abstract

Precast concrete construction is increasingly used to improve construction speed, manufacturing quality, and productivity. In earthquake-prone regions, however, its performance depends on the ability of individual precast components and their connections to act together as a stable, continuous structural system. This paper critically reviews the seismic performance of precast concrete structures, emphasizing connection behaviour, lateral-load-resisting systems, diaphragm action, ductility, structural integrity, and the implications of Indian seismic design standards. A narrative literature review was conducted using peer-reviewed review articles and research publications concerning seismic-resistant precast concrete buildings. The reviewed evidence was organized around structural systems, connection mechanisms, seismic response, construction-stage stability, and code-related design considerations. Relevant Indian Standards were identified using the Bureau of Indian Standards catalogue. No new experimental tests, numerical simulations, or quantitative performance measurements were undertaken.

1. Introduction

1.1 Background

Earthquakes impose rapidly changing inertia forces on buildings, potentially causing damage to structural members, connections, non-structural components, and foundations. The severity of structural damage depends on the characteristics of the ground motion, soil conditions, building configuration, mass and stiffness distribution, strength, ductility, and the continuity of the structural load path.

Conventional cast-in-situ reinforced concrete construction develops structural continuity through reinforcement and concrete placed at the construction site. Precast concrete construction follows a different process: beams, columns, slabs, walls, and other components are manufactured separately and subsequently assembled. This approach can improve production control, reduce on-site formwork, and enable parallel manufacturing and site preparation. However, the interfaces between precast elements introduce additional structural considerations. Forces must pass through mechanical connectors, reinforcement splices, grouted sleeves, bearing interfaces, welded plates, post-tensioning systems, or cast-in-situ joint regions. The seismic performance of a precast structure therefore depends not only on the capacity of its individual members but also on the strength, stiffness, deformation capacity, and reliability of its connections. Kurama et al. (2018) reviewed the development of seismic-resistant precast concrete systems, including moment frames, structural walls, floor diaphragms, and bridges. Their review established that appropriately engineered precast systems can be used in seismic regions, while emphasizing the importance of connection design and system-specific detailing.

More recently, Guaygua et al. (2023) conducted a systematic review of seismic-resistant precast concrete buildings based on literature published between 2012 and May 2023. Their work highlights the continuing importance of investigating connections, structural performance, and research gaps. These publications provide a foundation for evaluating precast construction as a seismic engineering system rather than merely a prefabrication

technique. India has significant regional variation in seismic hazard, building typology, construction practice, and industrialized-construction capacity. The design requirements for a precast building consequently depend on its location, occupancy, structural configuration, importance, and intended performance. Indian Standards provide provisions for earthquake-resistant design, ductile detailing, reinforced concrete design, and prefabricated concrete construction. In particular, IS 15916 addresses the design and erection of buildings using prefabricated concrete, while IS 1893 establishes earthquake-design requirements and IS 13920 addresses ductile design and detailing of reinforced concrete structures subjected to seismic forces. These documents must be applied in a coordinated manner. Compliance with a general prefabricated-construction standard should not be interpreted as proof that every proposed precast connection is suitable for every seismic demand. Similarly, conventional reinforced concrete detailing requirements do not automatically validate a proprietary precast joint without checking its force-transfer mechanism and deformation capacity.

A major challenge in precast seismic design is achieving structural integrity across discrete components while maintaining the benefits of off-site manufacture. Inadequate joint detailing may cause local failure before the intended ductile mechanism develops. Problems may include reinforcement pullout, anchorage failure, brittle shear failure, inadequate confinement, connection sliding, excessive residual drift, or loss of bearing. Additional challenges arise from floor diaphragm behaviour, wall-to-foundation connections, torsional response, structural irregularities, and the temporary instability of partially erected buildings. The central research problem is therefore to understand which structural mechanisms govern the seismic performance of precast concrete buildings, how those mechanisms should be evaluated, and how Indian design practice can address the associated risks. The objectives of this review are:

1. To classify the principal precast structural systems and their seismic load-resisting mechanisms.

2. To critically examine the behaviour of emulative, mechanical, and hybrid connections under cyclic loading.
3. To evaluate the roles of ductility, energy dissipation, diaphragm action, anchorage, and structural robustness.
4. To identify the relevance and limitations of Indian Standards for precast seismic design.
5. To establish research gaps and recommend directions for improved seismic resilience in Indian precast construction.

2. Seismic Behaviour of Precast Concrete Structural Systems

2.1 Precast moment-resisting frames

Precast moment-resisting frames generally consist of columns, beams, and joints designed to resist gravity and lateral loads. Under earthquake excitation, lateral forces generate bending moments, shear forces, axial forces, and interstorey deformation. The seismic behaviour of a precast frame depends on whether its joints behave as moment-resisting connections, nominally pinned connections, or partially restrained connections. A moment-resisting frame must transfer the required bending moments and shears while maintaining adequate rotation capacity. A frame with predominantly pinned beam-column joints generally requires another reliable lateral-load-resisting system. A critical design objective is to establish a favourable hierarchy of strength. Where the intended mechanism involves ductile member yielding, brittle joint shear failure, anchorage failure, or premature connection separation must be prevented to the extent required by the governing design approach. In precast frames, this objective requires coordination among reinforcement development, mechanical connectors, joint confinement, column strength, beam reinforcement, and the detailing of beam and column interfaces.

2.2 Precast structural-wall systems

Precast structural walls can provide substantial lateral stiffness and strength. They are commonly assembled from individual panels connected vertically, horizontally, and to the foundation. Under earthquake loading, wall panels may experience in-plane bending, shear, axial compression, uplift, and sliding. Depending on the connection configuration,

deformation may be concentrated within the wall panel, at the base connection, or along joints between panels. A wall system must have a continuous force path from the floor diaphragms through the wall connections to the foundation. Vertical joints must transfer the forces required by the structural model, while horizontal joints must provide the intended combination of shear transfer, compression bearing, tension resistance, and deformation capacity. Particular attention is required at wall ends, openings, coupling regions, and foundation interfaces. Local damage at these locations may influence the global response of the building.

2.3 Precast floor diaphragms

Floor diaphragms transfer horizontal inertia forces from floor masses to the vertical lateral-load-resisting system. In precast construction, floor units may be hollow-core slabs, solid panels, double-tee units, or other precast elements. Diaphragm behaviour depends on the floor units, topping where present, reinforcement continuity, joint shear transfer, perimeter ties, collectors, chords, and connections to walls or frames. A diaphragm may be sufficiently strong under gravity loading yet inadequate for seismic force transfer. Openings, discontinuities, offsets, and irregular

layouts can cause force concentrations that are not represented adequately by a simplistic rigid-diaphragm assumption. The analytical model should therefore represent the diaphragm behaviour in a manner appropriate to its geometry, connection details, and stiffness. The designer must also verify the load path between the diaphragm and the vertical elements.

2.4 Hybrid and post-tensioned systems

Hybrid systems combine precast elements with cast-in-situ concrete, reinforcing steel, post-tensioning, or mechanical connectors. Some systems are intended to emulate the behaviour of monolithic reinforced concrete, whereas others deliberately use joint opening and specialized deformation mechanisms.

Post-tensioned precast connections may develop restoring forces that help reduce residual deformation. Supplemental reinforcement or replaceable energy-dissipating components may be incorporated to dissipate seismic energy.

However, the presence of post-tensioning does not automatically guarantee low damage or satisfactory seismic performance. The design must consider tendon force, anchorage, joint opening, friction, energy dissipation, deformation capacity, and the behaviour of the surrounding concrete.

Table 1. Principal precast structural systems and seismic considerations

Structural system	Principal lateral-load mechanism	Important seismic checks
Precast moment frame	Flexural and shear resistance of members and joints	Joint strength, anchorage, rotation capacity, column stability
Precast structural walls	Wall bending and shear, with joint force transfer	Wall-base connection, vertical joints, sliding, overturning
Precast floor diaphragm	In-plane transfer of floor inertia forces	Joint shear, collectors, chords, perimeter ties, openings
Hybrid frame	Combined behaviour of precast elements and wet or mechanical connections	Interface continuity, deformation compatibility, failure hierarchy
Post-tensioned precast system	Prestress, bearing, friction, and designed deformation mechanisms	Tendon anchorage, joint opening, recentering, energy dissipation

9. Critical Discussion and Research Gaps

9.1 System-level behaviour

A recurring limitation in connection-focused research is the difficulty of transferring the results of a local test to an entire building. Connection tests provide valuable information about strength, deformation, and failure modes, but they do not independently establish the response of a multistorey structure. System-

level studies should examine the interaction of connections, diaphragms, vertical elements, and foundations. The resulting models should be validated against appropriate experimental evidence and used within the limitations of the selected analysis method.

9.2 Need for Indian experimental evidence

Indian construction conditions vary in terms of materials, workmanship, manufacturing

facilities, and erection practices. Further experimental research can help establish the performance of connections suited to locally available materials and practical construction tolerances. Relevant research topics include grouted sleeve connections, mechanical splices, wall-to-foundation connections, diaphragm joints, and hybrid systems. Testing should document material properties, connection geometry, axial load where applicable, cyclic loading procedures, and failure mechanisms. The objective should not be to assume that locally developed systems are deficient, but to establish a transparent evidence base for their reliable application.

9.3 Nonlinear modelling and validation

Nonlinear analysis can support the investigation of cyclic degradation, joint opening, reinforcement slip, concrete damage, and residual deformation. However, the reliability of the results depends on the material models, interface formulations, boundary conditions, and validation data. A sophisticated numerical model is not a substitute for experimental validation. Model calibration and validation

should be distinguished, and uncertainty in the predicted response should be acknowledged.

9.4 Repairability and functional recovery

Collapse prevention is an essential safety objective, but it does not guarantee that a building can be repaired economically after a severe earthquake. Future work should examine residual drift, replaceable energy-dissipating components, inspection access, and the practical replacement of damaged connectors. These topics are particularly relevant to buildings where rapid restoration of function is important.

9.5 Digital construction and monitoring

Building information modelling, digital component identification, automated dimensional inspection, and sensor-based monitoring can improve coordination between design, manufacture, and erection. Further investigation is needed to quantify whether these technologies reduce connection defects, erection errors, or construction delays. Their value should be evaluated through measurable outcomes rather than assumed from the use of digital tools alone.

Table 4. Research gaps and proposed directions

Research gap	Recommended research approach	Expected contribution
Limited transferability of individual connection tests to complete buildings	Full-scale subassemblies and system-level analytical studies	Better understanding of global seismic response
Uncertainty in connection behaviour under cyclic loading	Reversed-cyclic testing and validated nonlinear modelling	Improved estimates of strength, stiffness, and deformation capacity
Sensitivity to erection tolerances and workmanship	Controlled tests and field-quality studies	More reliable construction and inspection procedures
Residual deformation and post-earthquake repair	Repeated loading, residual-drift evaluation, and replaceability studies	Improved repairability and functional recovery
Code application to novel precast systems	Comparative code review and performance-based verification	Clearer design pathways for innovative connections
Construction-stage instability	Erection-sequence analysis and temporary-works assessment	Improved safety during assembly

10. Conclusions

This paper critically reviewed the seismic performance of precast concrete structures, with emphasis on structural systems, connection behaviour, ductility, diaphragm action, robustness, construction-stage stability, and Indian design standards.

The principal conclusions are as follows:

1. **Precast construction can be compatible with earthquake-resistant design.** Its seismic suitability depends on the design of the complete structural system and should not be inferred solely from the quality or strength of individual precast components.

2. **Connections are fundamental to seismic performance.** Their strength, stiffness, anchorage, deformation capacity, and cyclic degradation govern the transfer of forces between members and influence the global response of the building.
3. **Emulative, mechanical, and hybrid connections offer different advantages.** Their suitability depends on the intended structural mechanism, construction conditions, and evidence supporting their performance. No connection category is universally superior.
4. **Ductility and energy dissipation require a controlled failure hierarchy.** Premature joint shear, anchorage failure, concrete breakout, connector fracture, and loss of bearing can prevent the intended ductile response and must be addressed through appropriate design and verification.
5. **Diaphragm action and structural integrity are essential.** Reliable load transfer between floor systems, walls or frames, and foundations is necessary for the assembled building to resist earthquake actions as intended.
6. **Construction-stage stability must be designed explicitly.** Lifting, temporary bracing, erection sequence, and dimensional tolerances influence structural safety before the permanent system becomes effective.
7. **Indian standards must be applied together and verified for current applicability.** IS 15916, IS 1893, IS 13920, and IS 456 address complementary aspects of design and construction. The relevant edition, amendments, and project-specific requirements should be checked before implementation.
8. **Further research should emphasize system-level validation and repairability.** Experimental studies, nonlinear models, construction-quality investigations, and performance-based evaluation can improve confidence in precast systems under Indian seismic conditions.

In conclusion, the seismic performance of precast concrete structures is governed by the integration of structural configuration, connection design, load-path continuity, quality assurance, and appropriate code application. A coordinated approach to design, manufacture, erection, and verification is essential to

realizing the potential of precast construction while maintaining the required level of earthquake safety.

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