Seismic Performance and Failure Analysis of Precast Concrete Building

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Abstract. This study investigates the seismic performance of precast concrete buildings, analyzing key failure modes observed in past earthquakes. The research highlights the primary factors contributing to the failure of these structures, such as poor joint and connection details, inadequate diaphragm action, improper design of ductile elements, poor quality control, and insufficient separation between structural and non-structural elements. Specific earthquake events, including the 1964 Alaska, 1976 Tangshan, and 1994 Northridge earthquakes, serve as case studies for identifying these issues. Remedies for improving the seismic resilience of precast concrete buildings are also proposed, focusing on design improvements, quality control, and ensuring structural integrity. The findings of this study offer valuable insights for enhancing the earthquake resistance of precast concrete buildings, with a particular focus on developing region-specific guidelines for India.

KeywordsPrecast Concrete, Seismic Performance, Earthquake Resilience, Structural Failure, Diaphragm Action, Ductile Elements, Quality Control, Seismic Design, India, Building Safety.

INTRODUCTION

Precast concrete structures consist of elements cast in controlled environments and assembled on-site, offering significant benefits in quality, durability, and efficiency. These components include beams, columns, slabs, stairs, and walls, designed to meet specific structural needs. Precast concrete is increasingly employed in earthquake-resistant designs, where robust connections are essential to ensure safety and performance. Connections play a vital role in transferring loads and maintaining structural integrity during seismic events. Improperly designed connections can lead to catastrophic failures, making their design a critical aspect of precast construction.

Precast beams are central to the structural framework and are designed to handle moments and shear forces effectively. The connection between beams and columns, especially at the column face, is often a vulnerable point that requires careful consideration. Moment transfer and shear transfer mechanisms must be designed to accommodate deformations and prevent cracking. Shear friction across interfaces, influenced by surface texture and reinforcement, is crucial in maintaining the integrity of these connections. Composite systems, combining precast and cast-in-place elements, further enhance performance by providing flexibility in design and better post-yield behavior.

Bolted assemblies offer additional flexibility and improve post-yield ductility in precast structures. These assemblies use steel connectors like bolts, plates, and angles, designed to handle seismic forces efficiently. Properly designed bolted connections ensure minimal rotation at joints and provide a reliable load path during earthquakes. Beam-column joints are another critical area where ductility and strength must be carefully balanced. The design of these joints focuses on ensuring the beam mechanism governs the post-yield behavior, minimizing the risk of brittle failure in the joint region. Research has demonstrated the effectiveness of innovative joint designs, emphasizing the importance of tailored solutions for different structural configurations.

Precast shear walls, designed to resist lateral forces, play a significant role in seismic load management. These walls can be flexure- or shear-dominated, depending on the structural requirements. Stability concerns, such as the behavior of thin wall sections under high axial loads, are addressed through design provisions that focus on strength and ductility. Openings in shear walls introduce additional complexities, requiring careful consideration of load paths to prevent excessive deformations. Coupling beams connecting stiff wall elements often experience high post-yield deformations and must be designed to handle these stresses effectively.

In flooring systems, hollow-core units are commonly used for their lightweight and strength. However, issues like web splitting, where longitudinal separation occurs under stress, must be mitigated through improved seating connections and perimeter details. Delamination, caused by concentrated reinforcement in topping layers, is another challenge that can lead to failure if not addressed. Proper design and adherence to standards significantly improve the performance of precast floors under seismic loads.

Precast construction offers numerous advantages, such as high-quality finishes, durability, fire resistance, and acoustic efficiency. Factory-controlled production ensures consistent quality and reduces the impact of adverse weather conditions on-site. The speed of construction is another significant benefit, as precast elements can be manufactured and erected simultaneously, reducing overall project timelines. Additionally, precast structures exhibit superior durability against environmental and mechanical stresses, making them suitable for challenging environments.

Despite these advantages, precast construction has some limitations. High initial capital costs for setting up production facilities and the need for skilled labor are significant barriers to widespread adoption. The rigidity of precast systems also limits flexibility for future modifications, making them less adaptable to changing requirements. In developing countries like India, the cost of precast systems is often higher than traditional methods due to the availability of cheap labor and limited manufacturing facilities.

India's infrastructure needs are growing rapidly, with urbanization and population growth driving demand for efficient and resilient construction methods. Traditional RCC buildings have shown vulnerabilities during past earthquakes, highlighting the need for improved construction practices. Precast concrete offers a solution that addresses these challenges by providing standardized, high-quality components that enhance seismic performance. The introduction of precast construction in India requires a concerted effort to develop expertise, update engineering curricula, and create awareness of its benefits. By promoting research and aligning with international standards, precast concrete can become a cornerstone of sustainable and earthquake-resistant infrastructure development in the country.

Analyze the failure modes of precast concrete buildings during past earthquakes. Identify key issues responsible for the poor performance of precast structures in seismic conditions. Propose remedies and improvements for enhancing the seismic performance of precast concrete buildings. Evaluate the role of quality control, connection details, and diaphragm action in preventing structural failures. Provide recommendations for the development of seismic design guidelines for precast concrete buildings in India

CASE STUDIES

Alaska Earthquake 1964 Failures occurred in buildings with precast elements, such as J.C. Penny and Alaska Sales and Service, where weak connections between precast panels and steel frames led to collapse or misalignment during the earthquake.

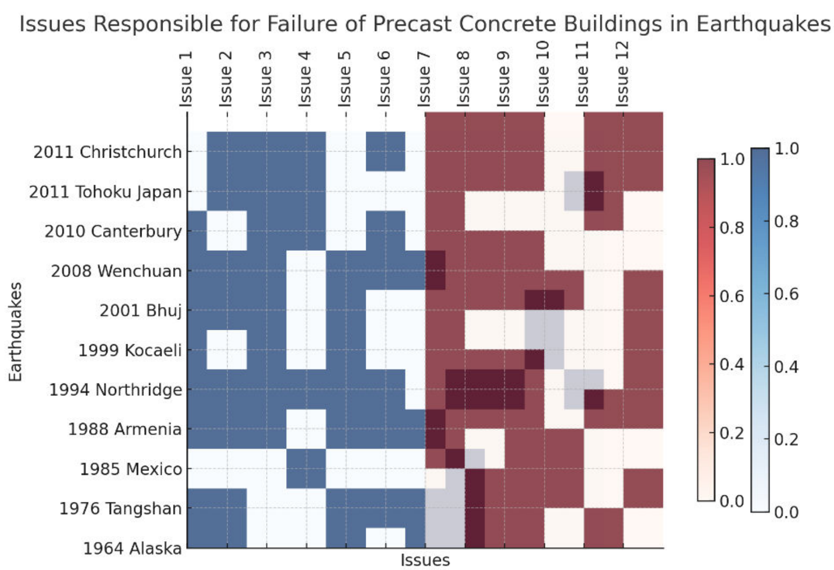
Tangshan China 1976: In Tangshan, the failure of precast concrete buildings was attributed to weak connections, stress concentrations, and poor design, resulting in extensive damage or collapse, especially in brick and frame buildings.

Mexico Earthquake 1985: In Mexico City, a precast parking structure collapsed due to pounding and inadequate precast joint connections. However, many other precast buildings withstood the quake without significant damage.

Armenian Earthquake 1988: Precast buildings in Armenia experienced failures due to weak connections between floor planks and beams, with hollow-core planks lacking proper interconnection and reinforcing elements.
Northridge Earthquake 1994: Precast elements, especially in parking garages, suffered damage from insufficient ties and connections. Floor elements became unseated, causing collapse, while other components performed well in regions with strong ground motions.
Kobe Earthquake 1995: Precast apartment buildings in Japan showed good performance, with only minor cracking observed in some splice areas. No significant damage was seen in tall precast structures.
Kocaeli Earthquake 1999: Precast warehouse buildings in Turkey failed due to poor seismic detailing at beam-column connections, column damage, and masonry infill interaction, which led to excessive lateral drift and column failures.
Chi-Chi, Taiwan Earthquake 1999: In Taiwan, precast concrete elements, used for non-load-bearing panels and slabs, did not experience failures. Most damage was in cast-in-place buildings.
Bhuj Earthquake 2001: Precast elements in school buildings in India failed due to poor connections, inadequate anchorage, and lack of diaphragm action. Roof panels dislodged due to insufficient seating.
Wenchuan, China Earthquake 2008: Precast floor systems failed due to inadequate connections to vertical supports, resulting in slab unseating. Unreinforced masonry buildings also collapsed due to weak connections and lack of proper reinforcement.
Canterbury, Christchurch, New Zealand Earthquake 2010 & 2011: The Canterbury Television building showed failure due to poor connections between frame and masonry walls, weak concrete, and inadequate reinforcement, which reduced structural stability under lateral loads.

FACTORS CONTRIBUTING TO POOR PERFORMANCE

The following table summarizes the key issues responsible for the failure of precast concrete buildings during past earthquakes, along with the corresponding earthquakes where these issues were observed. The graph has been compressed, and the issues are grouped for better clarity.



GRAPH.1*Issues responsible for the failure of precast concrete building in Earthquakes*

Issues Responsible for Failure:

Poor Joint and Connection Details: Lack of proper detailing, positive anchorage, and welded lap splices.
Inadequate Bearing Area: Loss of seat, falling of floors due to insufficient bearing.
Inadequate Diaphragm Action: Floors not transferring seismic forces effectively.

Deformation Incompatibility: Misalignment between floors and beams, affecting cast-in-place topping.
Improper Design of Ductile Elements: Failure in the proper design and detailing of beam-column connections.
Lack of Structural Integrity: Absence of proper seismic load path and structural integrity.
Poor Quality Control: Deficiencies in fieldwork, including poor reinforcement placement and concrete quality.
Improper Distribution of Lateral Load-Resisting Elements: Shear failures and poor distribution of vertical load-resisting elements.
Inadequate Ductile Behavior of Gravity Systems: Incompatibility of gravity frames with lateral load-resisting systems.
Inadequate Separation of Structures: Issues with building separation leading to pounding during seismic events.
Inadequate Separation of Non-Structural Elements: Poor interaction between structural and non-structural elements.
Failure of Bracings and Tie Connections: Failure in bracings and connections that transfer lateral loads.

Poor Joint and Connection Details

Poor joint and connection details in beam-column joints of precast concrete elements have led to failures during earthquakes, primarily due to brittle failure of reinforcing bars near welds. Examples of such failures include unseating of precast beams during the 1976 Tangshan earthquake and brittle beam-column connections in the 1994 Northridge earthquake. These failures occurred because connections were designed only for gravity loads, ignoring seismic behavior, and lacked capacity design principles. To address these issues, solutions include improving connection details to emulate monolithic behavior, avoiding welding of reinforcing bars near joints, properly designing connections with capacity design principles, and ensuring adequate development length and confinement of pins or bolts used in connections.

Inadequate Diaphragm Action

Floors in precast concrete buildings must transfer seismic forces to the supporting structure via diaphragm action, requiring proper connections between floors and structural elements. Inadequate connections lead to a lack of diaphragm action, resulting in unseating and collapse of floor/roof panels during earthquakes. Examples include the 1964 Alaska, 1976 Tangshan, and 1994 Northridge earthquakes, where floor panels dislodged due to poor connections. To ensure adequate diaphragm action, improvements include proper floor-to-support connections, sufficient seating width, collector elements between diaphragms and vertical elements, and appropriate seismic load paths.

Improper Design and Detailing of Ductile Elements

Ductile elements in precast concrete buildings, such as wall panels and beam-columns, often fail due to poor design and detailing, leading to catastrophic collapses in past earthquakes. Examples include the 1964 Alaska, 1976 Tangshan, and 1988 Armenia earthquakes. The failures were primarily due to brittle behavior caused by poor connections, inadequate confinement, and improper design. The capacity design concept should be applied to ensure proper plastic hinge locations and ductile detailing, particularly for interior gravity columns, as evidenced by the 1994 Northridge and 1999 Kocaeli earthquakes.

Poor Quality Control of Field Work

Poor fieldwork quality control, such as eccentric splices and minimal hoop reinforcement, was reported in the 1988 Armenia and 1976 Tangshan earthquakes. These issues led to progressive failure in building frames due to inadequate confinement and poor construction practices, highlighting the need for strict quality control and adherence to codes.

Inadequate Separation of Non-Structural Elements

During the 1999 Kocaeli earthquake, the interaction of stiff masonry infill with columns caused column failure, leading to structural damage. Similarly, out-of-plane failures of masonry infilled walls were observed, emphasizing the importance of adequate separation between structural and non-structural elements to prevent failures during seismic events.

Inadequate Separation Between Structures

Inadequate separation between structures can cause pounding during earthquakes, resulting in damage or collapse. The 1985 Mexico and 1994 Northridge earthquakes demonstrated this issue, with precast concrete structures collapsing due to pounding between adjacent buildings. Proper separation is essential to prevent such failures.

Bracings and Rigid Connections

Failures due to improper design of bracings and rigid connections were observed during the 1964 Alaska and 2001 Bhuj earthquakes. Inadequate connections failed to transfer lateral forces, compromising the stability of structures. Proper design of bracings and connections is crucial to ensure the lateral stability of buildings during earthquakes.

Inadequate System Behavior (Structural Integrity, Seismic Load Path)

The 1964 Alaska earthquake emphasized the importance of system behavior in seismic performance. Similarly, the 1995 Kobe earthquake demonstrated that buildings designed to emulate monolithic construction performed well. Improving structural integrity, defining clear seismic load paths, and applying seismic design principles are essential for enhancing the earthquake resilience of precast concrete structures.

REMEDIES FOR THE FAILURE OF PRECAST CONCRETE BUILDINGS DURING PAST EARTHQUKES

Poor Joint and Connection Details: To address poor joint and connection issues, it is critical to improve connection designs to mimic monolithic behavior, avoiding welding reinforcing bars near joints. The use of capacity design concepts for connection design is essential, ensuring that connections can withstand seismic forces. Sufficient development length and proper confinement of pins or bolts are necessary to prevent failure in beam-column connections.

Inadequate Diaphragm Action: To ensure adequate diaphragm action, strong connections between floors and supporting elements must be established to transfer diaphragm forces effectively. Sufficient seating width should be provided to accommodate tolerances, and collector elements should be incorporated between the diaphragm and lateral-force-resisting vertical elements. Additionally, proper placement of plastic hinges and seismic load paths should be established to ensure compatibility between lateral-load-resisting elements and gravity frames.

Improper Design and Detailing of Ductile Elements: For ductile elements, capacity design principles must be applied, ensuring that floor and roof elements are designed to be stronger than energy-dissipating elements like columns and walls. It is crucial to focus on detailing ductile behavior in columns and frames, paying attention to lateral deformation and ensuring proper plastic hinge locations. Ensuring proper detailing and confinement for energy-dissipating elements is key to preventing brittle failures during seismic events.

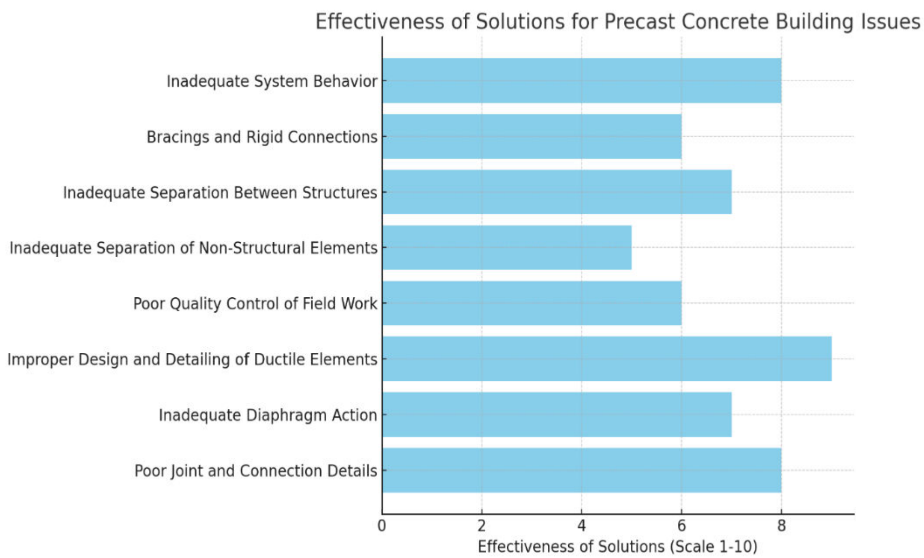
Poor Quality Control of Field Work: Improved quality control during fieldwork is essential, ensuring strict adherence to design specifications, proper splicing of reinforcement, and sufficient confinement reinforcement in columns. Regular inspections should be conducted to prevent deviations from design standards, ensuring the structural integrity of the building during seismic events.

Inadequate Separation of Non-Structural Elements: Proper separation between structural and non-structural elements must be ensured to prevent adverse interactions, especially during earthquakes. This will minimize the risk of failure from interactions such as masonry infill failing or shifting during seismic events.

Inadequate Separation Between Structures: Adequate separation between adjacent structures is necessary to prevent pounding, which can lead to structural failure. This can be achieved by incorporating expansion joints and ensuring that there is sufficient space to accommodate movement during seismic events.

Bracings and Rigid Connections: To enhance the performance of bracings and rigid connections, it is essential to design these elements to efficiently transfer lateral forces. Proper detailing of bracing connections and ensuring that they are appropriately stiffened can prevent failures in these critical areas.

Inadequate System Behavior (Structural Integrity, Seismic Load Path): To improve overall system behavior, structural integrity should be the primary focus. This includes the application of seismic design principles, defining clear seismic load paths, and ensuring that both the factory and on-site work adhere to stringent quality control measures. Ensuring the proper distribution of lateral-load-resisting vertical elements and confirming that the system behaves monolithically will enhance earthquake resilience.



GRAPH.2*Effectiveness of solutions for Precast Building issues.*

CONCLUSIONS

This study draws several key conclusions regarding the seismic performance of precast concrete buildings. It highlights that past earthquakes have shown significant damage to many precast structures, primarily due to factors such as poor construction practices, substandard concrete quality, inadequate floor-diaphragm action, and insufficient seating and anchorage of roof panels on walls. A critical issue identified is the improper connection between structural members, which can lead to structural failure in seismic conditions. The study also points out that the performance of precast buildings in previous earthquakes was hindered by flawed design, leading to skepticism about their reliability in high-seismic regions. However, despite these past challenges, the use of precast concrete in earthquake-resistant structures is on the rise globally. Lastly, the findings of this study can provide a foundation for developing seismic design guidelines tailored to the Indian context.

REFERENCES

1. FINTEL M., "Performance of Precast Concrete Structures during the Romanian Earthquake of March 4, 1977", PCI Journal, Vol. 22, No. 2, Mar.-Apr., 1977, pp. 10-15.
2. FINTEL M., "Performance of Precast and Prestressed Concrete in the Mexico Earthquake", PCI Journal, Vol. 31, No. 1, 1986, pp. 18-42.
3. FINTEL M., "Performance of Buildings with Shear Walls in Earthquakes of the Last Thirty Years", PCI Journal, Vol. 39, No. 3, 1995, pp. 62-71.
4. GHOSH S.K., "Observations on the Performance of Structures in the Kobe Earthquake of January 17, 1999", PCI Journal, Vol. 40, No. 2, 1995, pp. 14-22.

5. IVERSEN J.K., and HAWKINS N.M., "Performance of Precast/Prestressed Concrete Building Structures during the Northridge Earthquake", PCI Journal, Vol. 39, No. 2, 1994, pp. 38-55.
6. HAWKINS N.M., "Seismic Resistance of Prestressed and Precast Concrete Structures Part 2 – Precast Concrete", PCI Journal, Vol. 23, No. 1, January – February, 1978, pp. 40-58.
7. HAWKINS N.M., and GHOSH S.K., "Shear Strength of Hollow-Core Slabs", PCI Journal, Jan.–Feb., 2006, pp. 110-114.
8. HAWKINS N.M., and GOSH S.K., "Proposed Revisions to 1997 NEHRP Recommended Provisions for Seismic Regulations for Precast Concrete Structures Part 3 – Diaphragms", PCI Journal, Vol. 45, No. 6, Nov. - Dec., 2000, pp. 50-59.
9. LEW H.S., and CHEOK G.S., "Simplified Design Provisions for Hybrid Precast Connections", National Institute of Standards and Technology, Gaithersburg, MD, pp. 149-160.
10. MARTIN J.M.R., "A Precast Prestressed Concrete Structural System For Buildings Located In High Seismic Zones", PCI Journal, March-April., 1990, pp. 23-35.
11. GARDINER D.R., BULL D.K., and CARR A.J., "Internal Forces of Concrete Floor Diaphragms in Multi-Storey Buildings", NZSEE, No. 21, 2008.
12. KAM W.Y., PAMPANIN S., DHAKAL R., GAVIN H.P., and ROEDER C., "Seismic Performance of Reinforced Concrete Buildings: Darfield (Canterbury) Earthquake", NZSEE, Vol. 43, No. 4, 2011, pp. 340-350.
13. KAM W.Y., PAMPANIN S., and ELLIOT K., "Seismic Performance of Reinforced Concrete Buildings in the 22 February Christchurch (Lyttelton) Earthquake", NZSEE, Vol. 44, No. 4, 2011, pp. 239-278.
14. LAM D., "Composite Steel Beams with Precast Hollow Core Slabs: Behaviour and Design", Prog. Struct. Engng Mater, No. 3, 2002, pp. 179-185.
15. LIU Y., "Edited Report on the Great Tangshan Earthquake of 1976", Earthquake Engineering Research Laboratory, 2002, California Institute of Technology Pasadena, California.