

Structural Connections for Precast Concrete Buildings - Review of Seismic and Other Design Provisions in Various International Codes - An Overview



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Precast concrete is significantly being used in earthquake resisting structures in many parts of the world.

Due to the lack of understanding of the basic nature of seismic behavior, the precast concrete structures were viewed with scepticism in seismic regions. Some countries considered the use of precast concrete in earthquake resisting structures with suspicion because of their bad performance in major earthquakes. Examples of poor behavior of precast concrete building structures are during 1976 Tangshan (China), 1985 Michoacan (Mexico), 1988 Armenian, 1994 Northridge and 1999 Kocalli earthquakes due to improper design and detailing of ductile element, inadequate diaphragm action, poor joint and connection details, inadequate separation of non-structural elements and inadequate separation between structures. These are presented in the state-of-the-art report by Park and co-workers (fib, 2003).

Countries like Japan, Canada, Italy, Chile, Mexico, New Zealand and USA, which are well known for high seismicity, adopt precast concrete construction practices. In these countries, the design and construction practices are usually supported by the results from experimental investigations.

Recent experimental investigations have mainly focussed on developing techniques to reduce damage in structures using precast elements. For example, with reference to New Zealand, University of Canterbury conducted tests to design connection details between hollow-core floors with beams and walls that could sustain up to 6% of inter-storey-drift.

Perspective of the past:

The evolution of the precast industry in seismically active regions of the United States and other parts of the world, with an emphasis on the need to develop technology compatible with precast concrete construction, are discussed and presented by Englekirk²¹. It was reported that precast concrete construction is extensively used and is being promoted in Japan on high rise buildings even though Japan is not having a specific national design standard on precast concrete structures. The technical justification for precast systems in Japan is provided by experimental studies. Further research

on the behavior of precast concrete elements and structures under seismic loading is reported in references ¹⁵⁻¹⁹.

To limit the possibility of progressive collapse and to obtain a monolithic action, structural integrity is taken care of in precast concrete structures by means of longitudinal and transverse ties connecting members to a lateral load resisting system. Forces shall be permitted to be transferred between members by grouted joints, shear keys, mechanical connectors, reinforcing steel connections, reinforcing topping, or a combination of these means. The adequacy of connections to transfer forces between members is determined by analysis or by test. In designing a connection using materials with different structural properties, their relative stiffnesses, strengths, and ductilities are considered.

Provisions related to seismic design considerations are continuously being improved and incorporated in different international standards. Development in the codal provisions and guidelines of American and New Zealand construction practice is discussed.

A brief history of building code provisions for precast / prestressed concrete in the United States was presented by D'Arcy, et al.²², in which it was reported that the first set of specific design provisions ever developed in the United States for precast concrete structures in regions of high seismicity appeared in NEHRP¹⁷ Recommended Provisions. The NEHRP provisions presented two alternatives for the design of precast lateral-force-resisting systems: one, emulation (same as) of monolithic reinforced concrete connection and the other, use of the unique properties of precast concrete elements interconnected predominantly by dry connections (jointed precast). For emulation of the behavior of monolithic reinforced construction, two alternatives were provided: structural systems with "wet" (ductile) connections and those with "strong" (elastic) connections. The design provisions for precast structures in high seismic regions were expanded in NEHRP (FEMA, 2001) Provisions¹⁹. The seismic-force resisting system for high seismic regions suggested in NEHRP (FEMA, 2001) provisions¹⁹ are special moment resisting frames and special structural walls with superior type dry

connections. The ACI 318-02, introduced design provisions for precast concrete structures located in regions of moderate to high seismic risk or assigned to intermediate or high seismic design categories. Provisions for non-emulative (jointed precast) design of precast wall systems were not included in ACI318-02.

A perspective on the seismic design of precast concrete structures in New Zealand is presented by Park¹⁴. Trends and developments in the use of precast reinforced concrete in New Zealand for floors, moment resisting frames and structural walls of buildings with aspects of design and construction, particularly the means of forming connections between precast concrete elements were discussed and presented by Park¹⁴.

Seismic performance of precast concrete systems-Codal provisions

Failure of precast concrete buildings in 1964 Alaska, 1976 Tangshan (China), 1988 Armenia, 1994 Northridge, 2001 Bhuj and 2008 Wenchuan (China) earthquake was mainly due to collapse of floors for some or other reasons.

One of the main reasons of collapse of floors were loss of seat due to failure of support system, poor connections, excessive deformation of support system (beam elongation) and deformation incompatibility between the support and the floor. A possible solution to avoid these failures can be by providing the sufficient seating incorporating the effect of all possible movements into account.

Fig. 1 shows such detail of required bearing length at the support suggested by NZS 3101: 2006.

Fig. 2 and Fig.3 show the alternative special reinforcing to transfer the shear force and support precast concrete floor units in the event of loss of bearing. Continuous beam reinforcement will transfer shear force to column in case of loss

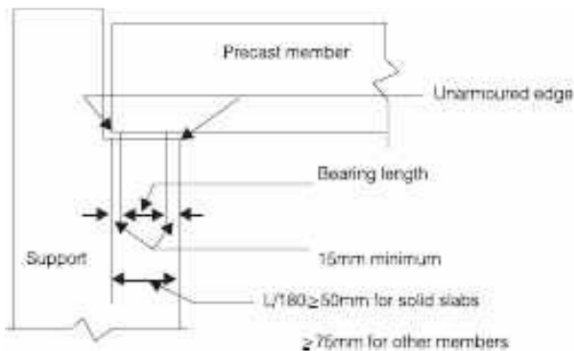


Fig. 1 Required bearing length at the support of a member in relation to its clear span

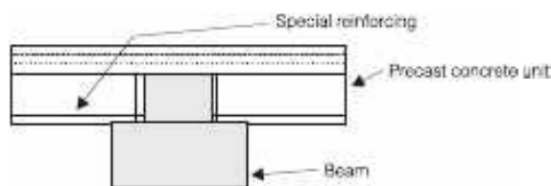


Fig. 2 Alternate continuous reinforcement through the beam at the level of bottom of floor to support precast concrete floor units.

of seating, the other alternative with hanger stirrups in the vicinity of support can also help in the transfer of shear force.

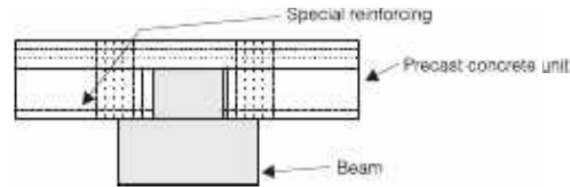


Fig. 3 Alternate continuous reinforcement through the beam at the level of bottom of floor and in the topping of slab floor to support precast concrete floor units.

Connections and Bearing

The codes permit a variety of methods for connecting members in plane and out of plane. These are grouted joints, shear keys, mechanical connectors, reinforcing steel connections, reinforced topping, or a combination of these. Codes suggest a minimum bearing length after considering for tolerances, as the clear span/180 from the edge of the support to the end of the precast member. However it should not be less than 50mm for solid or hollow core slabs and 75mm for beams or stemmed members as per ACI 318-0832. NZS 3101 provides bearing width for hollow core slab as 75mm. Codes have suggested to have a clear distance of 15mm from the unarmored edges and make allowances for concrete cover. Required length of bearing at the support of a member in relation to its clear span is illustrated in Fig. 3. Connections that rely solely on friction caused by gravity forces are not permitted by codes. For hollow-core slabs, the floor should be mounted on low friction bearing strips with a coefficient of friction less than 0.7 and a minimum width of 50mm, as per NZS 3101.

Structural Integrity

Structural integrity is necessary to improve the redundancy and ductility in structures. This also helps to avoid collapse of the structures in the event of damage to major supporting element or an abnormal loading event by maintaining overall stability. Codes suggest provisions for precast concrete structures to achieve structural integrity to the same extent as of monolithic structures. Tension ties are provided in the transverse, longitudinal and vertical directions and around the perimeter of the structure to effectively tie precast concrete elements together. This will also achieve the diaphragm action of the floor and a seismic load path in the structure.

Diaphragm Action

Precast concrete floor could not transmit in plane force induced by earthquakes to lateral load resisting system adequately and failed during past earthquakes. Codes have dealt with the design of precast concrete diaphragms similar to the cast-in-place diaphragms. Design and detailing provisions for both un-topped and composite diaphragms with topping are given in the codes. Codes have suggested the minimum thickness of topping to be 50mm for 20mm cover and 25MPa strength of concrete. It is further needed to be increased depending on the size of reinforcement and clear cover to be used.

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ACI 318-08 recommends minimum thickness of topping to be provided on precast concrete or roof elements, acting as structural elements and not relying on composite action to be 67.5mm.

NZS 3105 relates the minimum thickness of topping with the diameter of bars used. Minimum thickness of topping for 6, 10, 12 and 16 mm stirrups, ties or spirals used is 50, 75, 90 and 105 mm respectively. It is also suggested that if the cover is greater than 20mm then the thickness of topping should be increased by the amount of additional cover.

Deformation compatibility of flooring systems

Elongation of plastic hinge regions in beams result in the deformation incompatibility of floors with the support system. This phenomena is much observed in the collapse of hollow-core floors in 1988 Armenian and 1994 Northridge earthquakes. To overcome this incompatibility issue and avoid the brittle failure, NZS3101 have suggested for the precast floor systems to be designed to have adequate ductility. The code has suggested the connection details that have performed well in analytical and experimental investigations.

Precast Concrete Frame and Wall Systems

Codes have suggested the design and detailing of these systems to be same as cast-in-place system with taking particular care in designing the connection to emulate similar behavior. Precast concrete frame systems composed of concrete elements with ductile connections are expected to experience flexural yielding in connection regions. ACI /318-08 has recommended the reinforcement provisions and type of mechanical splices to achieve the monolithic behavior of connections.

Design for the structural purpose:

The main purpose of the structural connections is to transfer forces between the precast concrete elements in order to obtain a structural interaction when the system is loaded. By the ability to transfer forces, the connections should secure the intended structural behavior of the superstructure and the precast subsystems that are integrated into it. This could for instance be to establish diaphragm action in precast floors and walls, or cantilever action in precast shafts. For this reason, the structural connections should be regarded as essential and integrated parts of the structural system should be designed accordingly and with the same care as for the precast concrete elements. It is insufficient just to consider the connections as details for site erection. The advantages that normally are obtainable with prefabrication can be lost with an inappropriate design and detailing of the structural connections.

Ductility

Connections should preferably behave in a ductile manner. Ductility can be defined as the ability to have large plastic deformations before failure. In structural materials, ductility is measured as the magnitude of the deformation that occurs between yielding and ultimate failure. Ductility in building frames is usually associated with moment resistance. In concrete members with moment-resisting connections, the

flexural tension is normally resisted by reinforcing bars. Ductile joints can be achieved by giving the brittle parts of the joint an extra capacity, for example by calculating with reduced allowable stress in these components. Typical brittle components are welds, short bolts in tension, bolts subjected to shear, reinforcement anchorage zones, etc.

Tests are conducted at department of civil engineering, University of Manitoba on precast concrete shear wall connections. The observations / conclusions thereon are as follows:

- 1) All connections tested were capable to withstand large nonlinear deformations well beyond first yield with very good energy absorption. Connections with bonded mild reinforcement had ductility around 5. Post-tensioned connections had ductility of 6.
- 2) Debonding of continuity element across the connection significantly enhanced the response of the connection in terms of energy dissipation and ductility.
- 3) Presence of shear keys across joint interface limited the slip mechanism which is desirable in the overall precast wall connection response.
- 4) Seismic response up to a ductility of three could be resisted by all the tested configurations without any apparent damage to the precast wall connection. This level represents typical seismic demand for low to moderate seismicity.

Movements

Connections must not hamper necessary movements in the structure. Necessary movements will in most cases be the deformation of beams and slabs due to loads and/or prestressing forces. Typically this problem arises when a vertical facade panel is connected to a beam or slab somewhere in the span (away from the support). If the connection detail makes the vertical movement of the beam or slab impossible, this may cause damage to the connection detail itself, or to the elements. Even if there is no damage, unwanted forces may be introduced in the elements, causing unwanted deformations. The solution is to construct the connection detail with a sliding arrangement, or it can be made as a hinge.

Types of Joints

The most serious problem facing the precast industry is finding a reliable and economic method to join prefabricated members. Connections or locations of high stress concentrations are weak points in the structural system; and they have to withstand high forces and displacements during strong earthquakes. Thus, to design and properly detail joints is the most important factor in achieving the safe and economical precast structures.

Three types of joints are distinguished viz.

- 1) Embedded steel shapes anchored to the precast members by studs or rods and the connection completed with site welding or bolting. They are known as dry connections.

Drawback is the failure of the connections by shearing of studs, pull out of the anchor rods, splitting of the concrete, brittle failure of the welds and bolt threads during earthquakes indicate that dry or mechanical connections

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are points of high stress concentrations and represent weak points in the system which can jeopardize its structural integrity and safety.

Workmanship in field is an important factor of uncertainty and it appears that site welding is very susceptible to brittle failure.

- 2) Poured in-situ reinforced concrete joints with dowels and reinforcement either spliced or lapped or welded, are known as wet connections. This type of connections show excellent performance during earthquakes. They tend to behave monolithically, provide continuity, higher redundancy and add to the structural integrity of the system.
- 3) Post tensioning the precast elements together with tendons crossing the joints.

Connections in framed structures

Beam column connections are classified as, Rigid, Semi rigid and Hinge.

Rigid connections are incorporated into framed structures as moment resistant joints to provide resistance against the gravity and earthquake loads. They are capable of transmitting the moment, shear and axial forces.

Semi rigid connections are similar to rigid ones, except that they have lower yield moments and do not develop full continuity.

Simple supported and hinged joints are designed to resist gravity loads only and have no moment resistance.

Joint types of cast in place and post tensioned, are currently the most reliable means of connecting precast members and are used in ductile moment resistant frames.

Research work in New Zealand indicates these joints and systems to have good energy dissipation capacity.

Wall panel structures:

Shear connections between floor and wall panels in precast box type structures may be dry, wet or may be connected by post tensioning. Dry joints are points of high stress concentrations, which may lead to progressive joint deterioration. Thus wet poured in-situ strips with over-lapped hooks or dowels are preferred over mechanical devices and they are more reliable and effective. Tests carried out in Japan showed that precast panels connected by wet joints behave monolithically and those with dry joints tend to behave independently.

S.no	Aspect	Indian (Is 15916:2010)	Recommendations To Indian (Standard Is 15916:2010) For Adoption.
1	Force Transfer Mechanism	-	Forces may be transferred between members by grouted joints, shear keys, mechanical connectors, reinforcing bar connections, welded or bolted connections reinforced topping, or a combination of these means.
2	Design Considerations	9.1 - The considerations for design of joints are: a) Feasibility, b) Practicability, c) Serviceability, d) Fire rating, e) Appearance	To control cracking due to restraint of volume change, and differential temperature gradients.
			To provide resistance against sliding, overturning and rocking.
3	Joint/Connection Requirements	9.2 (a) - It shall be capable of being designed to transfer the imposed load and moments with a known margin of safety.	
		9.2 (c) - It shall accept the loads without marked displacement or rotation and avoid high local stresses.	
		9.2 (e) - It shall require little temporary support, permit adjustment and demand only a few distinct operation to make.	
		9.2 (g) - It shall be reliable in service with other parts of the building.	
		9.2 (h) - It shall enable the structure to absorb sufficient energy during earthquakes so as to avoid sudden failure of the structure.	
4	Type Of Joints In Structure	9.2.1 - Continuous or hinged under lateral loading.	
5	Water Tightness Specifications	-	Water tightness provisions to be detailed.
6	Fire Resistance	9.1 (b) - The fire rating for joints of precast components shall be higher or atleast equal to connecting members.	
7	Detailing Specifications	Dry or wet joints as specified in cl. 9.3	
8	Jointing Systems	-	New Zealand code NZS 3101 part 1 have given the definitions of equivalent monolithic systems and jointed systems in a detailed manner. These are recommended for adoption in to IS codes.
9	Seismic Provisions (Ductility)	IS 13920:1993 suggest that precast and / or prestressed concrete members may be used only if they can be provided with the same level of ductility, as that of a monolithic reinforced concrete construction during or after an earthquake.	The definitions given for connections of limited ductility, ductile jointed connections and ductile hybrid connections as mentioned in NZS 3101 is recommended for adoption in to IS code.
10	Progressive Collapse	8.2 - Details about the requirement of safety against progressive collapse. Tie provisions horizontally and vertically are detailed with a tensile force of $F_t = 60 \text{ kN}$ or $(20+4N)\text{kN}$ whichever is less, where N is the number of storeys including basement. Key element identification is also indicated.	

