Practical aspects

Precast concrete buildings in seismic areas

This report provides a short summary of work done by Task Group 6.10 of fib Commission 6 (Prefabrication) in collaboration with PCI. A more extended report on the work will be available in a joint fib/PCI publication that is expected to be issued by the end of 2015. It has been developed by selected experts from around the world and therefore combines a variety of precast experiences, design philosophies and construction techniques. The Task Group was convened by S.Tsoukantas, S.K.Ghosh, serving as liaison between fib Commission 6 and PCI, together with other distinguished PCI members and members of fib T.G. 6.10, ensured consideration, throughout the document, of U.S. design and construction practice for precast concrete structures. The general overview contained in the fib/PCI document intends to provide engineers, architects, clients, and end-users with a better appreciation of the wide range of applications that modern precast concrete technology is capable of in various types of construction from industrial to commercial as well as residential. Lastly, the emphasis on practical aspects, from conceptual design to connection detailing, aims to help engineers move away from blindly following prescriptive codes in their design to basic principles, in order to achieve a more robust understanding, and thus control, of the seismic behavior of the structural system as a whole, as well as its components and individual connections.

Basic Principles of Seismicity

In this chapter, the main principles and philosophy of seismic design are briefly reviewed with reference to performance requirements, seismic actions, design concept etc., with emphasis on precasting and relevant ductility properties of precast frame structures.

Basic Principles of Conceptual Design

This section emphasizes the major importance of the first step of the seismic design process, the so-called conceptual design. It is pointed out that every analysis has to be carried out on a preconceived structural system; several decisions have to be made prior to any analysis being carried out, so as to minimize uncertainties related to the seismic response of the structure.

Structural simplicity, vertical uniformity - regularity, bidirectional and torsional resistance together with proper stiffness and adequacy of foundations, should govern the architectural - structural concept for any structure subject to seismic excitations.

Precast Frame Systems

Reference is made to the different types of precast frame systems and guidance is provided to the selection of the force-response factors.

Hinged Beam-To-Column Connections

Such frame systems are used in low-rise buildings in areas of low or moderate seismicity. However they may also be integrated as gravity-dominated systems in buildings where the lateral loads are principally carried by fixed-connection frames, or by lateral force-resisting systems of other types, such as shear walls or dual systems (combining walls and frames).

Emphasis is given on the behaviour of hinged beam-to-column connections (see fig. 1 and fig. 2) in seismic situations, based on most recent experimental and theoretical research.

Precast Frames with Moment-Resisting Connections (FCF)

In this chapter various types of equivalent monolithic moment-resisting beam-to-column connections are presented by means of descriptions, connection details, construction steps, photos and comments with reference to relevant experimental research.

Fig. 1: Typical hinged beam-to-column connection with two parallel dowels (other reinforcements not shown for clarity).

Fig. 2: Hinged beam-to-column connection with two parallel dowels.

a) Actions in the plane of the frame

b) Actions perpendicularly to the plane of the frame
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Fig. 3: Classification of FCF considering in-plane lateral force resistance: a) one-way frame; b) one-way frame with pin-ended transverse beam; c) two-way frame

Fig. 4: Schematic representation of a moment-resisting connection using U-shaped precast beams (construction steps and typical reinforcement).

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e.g. SAS, the shuttering system for the manufacture of facades, sandwich walls, solid walls and floor systems, is available in lengths of up to 8000 mm and heights from 60 mm to 400 mm. The system is used in both manual handling and robot operation. The economic aspects are reduced consumption of shuttering timber, reduced shuttering and demoulding times, simplified cleaning and improved quality of the final product. Simple, flexible, fast, safe and efficient positioning is ensured by the switchable RATeC automatic system. RATeC magnetic components with adhesive forces from 450 kg to 2100 kg are used here depending on requirements.

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PRECAST CONCRETE ELEMENTS

For example:

Figure 4 shows a beam-to-column connection using U-shaped precast beams.

Figure 5 shows a beam-to-column connection with inverted T-shaped precast beam.

Figures 6, 7 and 8 show a system in which the beam-to-column connections are made as follows: multi-story precast concrete columns are fabricated, each of which has an open gap at each floor level. The longitudinal bars are continuous and run through the gaps. Precast beams are placed between columns, seated on the cover concrete of the columns or on column corbels. The open gaps allow for the arrangement of the bottom and top beam reinforcement together with stirrups inside the joint core. A brief reference to hybrid frame and wall systems is also made (see fig. 9).

Different types of column-to-foundation connections are presented as, for example, the ones shown in fig. 10 and fig. 11 and are commented on.

Wall Systems – Large Panel Systems

Precast large-panel wall systems are mainly used in cases where there is no need for large open spaces, such as in apartment buildings, office buildings, hotels, housing, educational and administrative buildings and similar structures. Such systems are composed of precast large-panel load-bearing walls and precast concrete slabs. Usually, walls are story-high and both walls and slab panels are room-size. Walls might also be multi-story.

Alternatively, floors and roofs can be composed of precast components of other types such as hollow-core units, solid concrete units, plank-floor units, etc. In all cases, diaphragm action of the floors needs to be mobilized. This can be achieved by proper connections between precast slab elements and their supports or by using topping of proper thickness, or a combination of the above.

The seismic behaviour and structural integrity/robustness of such systems are discussed, together with possible mechanisms for dissipation of seismic energy.

Fig. 5: Construction steps of a beam-to-column connection with inverted T-shaped precast beams.
   a) Step 1: Placement of the column
   b) Step 2: Placement of one beam resting on the column
   c) Step 3: Placement of two beams resting on the column
   d) Step 4: Placement of the column ties into the joint and proper arrangement of the negative reinforcement of the connection

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Fig. 6: A precast project (Cummins) under construction in Pune, India. (courtesy of Precast India Infrastructures PVT LTD; photo by Nagesh Kole).

Fig. 7: Lifting of a column with two gaps after demolding, ready for transport, Cummins project, Pune, India (courtesy of Precast India Infrastructures PVT LTD; photo by Nagesh Kole).
**PRECAST CONCRETE ELEMENTS**

Requirements concerning details between precast walls (horizontal and vertical joints) are presented and commented on, covering techniques that are usually used in Europe (see fig. 12) and in the United States (see fig. 13).

Figure 14 shows an application of large panels by KEF Infra Precast Company for the construction of a nine-story-high residential building in Mangalore, India, using the U.S. technique.

**Wall Frame Systems**

Dual systems consist of a combination of shear walls and moment frames. A dual system is commonly used when the moment-resisting frames alone do not provide desirable lateral stiffness.

However, a probable lack of deformation compatibility in both elastic and inelastic

<table>
<thead>
<tr>
<th>Dual System Components</th>
<th>Description</th>
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<tbody>
<tr>
<td>Cast in-situ foundation</td>
<td>Precast column</td>
</tr>
<tr>
<td>Infill concrete</td>
<td>Precast socket</td>
</tr>
<tr>
<td>Precast column</td>
<td>Vertical stirrups</td>
</tr>
<tr>
<td>Vertical stirrups</td>
<td>Precast socket horizontal stirrups</td>
</tr>
<tr>
<td>Precast column</td>
<td>Precast socket vertical stirrups</td>
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**Fig. 8:** A column with two gaps in its final position, Cummins project, Pune, India (courtesy of Precast India Infrastructures PVT LTD; photo by Nagesh Kole).

**Fig. 9:** Jointed precast “hybrid” frame and wall systems developed in the PRESSS-Program (modified from fib, 2003; NZS3101:2006).

**Fig. 10:** Schematic representation of a socket foundation.
ranges between walls and frames should be visualized during the design; this is because walls and frames do not deform equally under normal or severe lateral loads. On the other hand, for the design of a lateral-force-resisting system for a precast/prestressed concrete building (which is made of precast walls and precast frames), it is important that the characteristics of the connections between walls and frames be such as to accommodate the different behavior of the two systems (walls and frames).

Typically, the desired primary ductile behavior of precast shear walls emulating cast-in-place detailing is flexural yielding at the wall base (see fig. 15).

Because a small rotation in a wall will create a large bar elongation, the ductility at base is important. Ductility can be increased significantly by debonding bars into and out of the foundation, so that they can deform inelastically over a longer length, thus resulting in greater rotational ductility (see fig. 16).

Reinforcing steel specified for special walls should be ductile and have controlled strength properties.
Aspects of diaphragm behaviour in precast floor systems are treated by means of design rules, pictures and connection details (see fig. 17, fig. 18 and fig. 19) together with reference to displacement incompatibility issues between lateral force-resisting systems and precast floor diagrams (see fig. 20).
Double-Wall Systems

Double-wall precast systems are used for both low- and high-rise buildings such as residential and office buildings, housing, hotels, educational and administrative buildings.

Double-wall systems are normally built using an industrialized automatic production process. These are walls composed of two concrete layers, each usually 5 cm to 7 cm thick, with a gap of about 8 to 20 cm (see fig. 22). The two concrete layers are internally connected by means of reinforcement in the form of lattice girders at a spacing of about 40 to 80 cm. One layer of welded wire reinforcement is typically provided in each layer of the double-wall and acts as the main wall reinforcement. The gap between the two precast concrete layers is filled by cast-in-place concrete during construction, after placement of additional connection reinforcement where needed, and after placement of the installations.

Fig. 18: Typical details for a topped hollow-core slab to ensure full transfer of longitudinal shear across the interface with precast units.

Fig. 19: Typical range weld connection (concept according to PCI, 2010) – a) plan; b) forces; c) connection detail.

Fig. 20: Schematic example of vertical displacement incapability between floor and frame systems (modified from Matthews et al., 2003; NZS3101:2006).
Precast Cell Systems

Precast cells are industrially produced, completely finished, and fitted out at the precasting plant and delivered to the building site and installed in the building (see fig. 21). They are typically placed in one vertical line and usually form a self-supporting tower when properly connected together. Precast cell systems are also used for the construction of different types of buildings such as residential buildings, office buildings, hotels, educational facilities, correctional facilities, etc.

The cell units are completely constructed in the precast plant, ready for use after assembly on site, satisfying structural requirements and incorporating plumbing, electrical, and mechanical installations.

Fig. 21: Schematic representation of the deformation demand on and damage to a hollow-core unit sitting on a beam, due to the elongation of a plastic hinge and rotation of supporting beam under seismic excitation.
Cell systems are presented by means of texts and figures; fig. 25 is an example. Such systems are very suitable in cases where dismantling of a building is required for rebuilding at another location. Prestocked precast cell units are sometimes used to accommodate people after natural disasters.

**Advantages of cell systems are:**
- short construction time and good quality, since cells are finished and equipped at the factory;
- structural integrity of the final building if cell units are properly connected horizontally and vertically with each other;
- minimum risk of progressive collapse under accidental loading;
- good insulating properties; and
- cost savings due to industrialization of the production.

**Main disadvantages of cell systems are:**
- restriction on the sizes of the cell units, mostly on their widths, which are limit-
ed to about 3.6 m due to constraints on transport from the precast plant to the site;
- high self weight of the cell units, which may cause difficulties during transportation and erection; and
- limited architectural flexibility.

Appendices

The fib/PCI document contains three Appendices, as follows:

Appendix A: Structural ductility of precast frame systems
Appendix B: Behavior factors of precast frame systems
Appendix C: Design example of a one-story industrial building using Force-Based or Displacement-Based Design approaches

Conclusions

In this report, a short summary of the fib/PCI Bulletin of the same title is presented, in order to draw attention of the readers of this article to the variety and extent of the precast topics that are covered in the fib/PCI Bulletin. It is expected to be published by fib and PCI by the end of 2015.

Acknowledgements

To all those who participated in fib/PCI Task Group 6.10

References