Basic precast concrete structural systems

Precast concrete buildings are composed of some basic types of structural subsystems. These systems can be combined in different ways to obtain an appropriate and effective structural concept that fulfils the needs of specific buildings. The most common systems are:

- Beam and column systems (beam elements, column elements, connections)
- Floor and roof systems (floor elements, roof elements, connections)
- Bearing wall systems (wall elements, connections)
- Facade systems (facade wall elements, connections)

Skeleton structure: combination of columns, beams and floor elements

Central stabilizing core

Structure consisting of bearing facade elements and floors

Structure composed of walls and floors
Basic precast concrete systems

Beam and column systems
Connections in those systems:
- Beam to column
- Beam to beam
- Column to column
- Column to base

Floor and roof systems
Hollow core floor system
The prestressed hollow core elements carry the vertical load but are as well connected to act as a horizontal diaphragm.
Spans up to 20 m are possible.

Composite floor plate with lattices
Precast thin plates (50-60mm) are placed first.
At the construction site they are completed with a concrete layer. Latices and roughened surface make sure that the composite system works. The system is most suitable for short spans.
Basic precast concrete systems

Floor and roof systems

The Bubble deck system

The Bubble deck system is a variant to the hollow core slab. After placement at the site in-situ concrete is provided. The slabs carry, contrary to hollow core slabs, in 2 principal directions.

Prestressed double T beams with structural topping for large spans

Floor and roof systems

"Duct floor" (VBI)

The duct-floor is a prestressed concrete floor with an enlarged lower flange. In such a way ducts can be integrated in the floor.

Floor and roof systems

Infra+ floor

Infra+ floor consists of steel beams with a concrete lower flange. Ducts can be integrated. The top flange can be loaded.
Basic precast concrete systems

Floor and roof systems

The Wing floor with integrated installations

Basic precast concrete systems:

Wall systems:  Load-bearing walls

Load-bearing facade  Load bearing cross-walls

Connections required for:
- Wall to wall at interior and exterior vertical joints
- Wall to wall at interior and exterior horizontal joints
- Wall to base/foundations

Example of a non-bearing facade wall

The connections of non-bearing walls are mainly facade to beam. Non-bearing walls are normally designed to carry their own dead load. However, as an alternative, non-bearing facade walls can be connected to the adjacent load-bearing system in such a way that the dead load of each wall element is supported by the main system.
Basic precast concrete systems:

Wall systems: Example of a non-bearing facade wall

Prefabricated walls can be used as a part of the stabilizing system to resist horizontal loads in their own plane. In that case the precast wall should behave like one structural unit composed of interacting wall elements (lower figure). This structural interaction within the wall needs to be secured by structural connections that resist the required shear forces, tensile forces and compressive forces.

Basic precast concrete systems

Moment resisting frame systems

H-shaped elements and portal frame elements can be used for stabilization. The elements are connected in areas where flexural resistance is not required, at points of contraflexures. However, the frames are very sensitive to dimensional deviations. The transport limits the dimensions. Actually those systems are not often applied in non-seismic regions.

Basic precast concrete systems:

Cell systems:

Closed cell elements  Open cell elements with U-section  Elevator shaft cell

Precast concrete cell systems are composed of closed cell elements or open cell elements with U- or L-section. Complete structures can be made by combining cell-elements. However, it is more common to use cell elements for specific parts of the structure, for instance wet areas, and combine these with ordinary walls and floor systems.

The cell element system is not extensively used, because of transport problems and lack of flexibility in the layout of projects.
Structural systems: conceptual design

Stability of precast concrete structures requires due attention, since continuously, like for in-situ structures, does not exist automatically. The transmission of load should be enabled without too large deformations until the ground. Moreover the structure should be robust. Early interaction between architect and structural engineer is important. Important decisions at that stage are:
- Position and requirements for stabilizing elements
- Need for expansion joints
- Grid distances
- Span directions of slabs and beams
- Positions of columns and walls
- Use of loadbearing walls and/or facades

Structural systems: conceptual design

Reactions in shear wall due to horizontal load, a) When the resultant H of the horizontal load passes through the shear centre (S.C.) there is only translation.

b) Rotation is due to eccentric positioning of the stabilizing elements (the horizontal load resultant does not pass through the shear centre), the total deformation is translation + rotation.

The solution according to a) gives:
- Balanced design and repetition of connections in the stabilizing elements
- Equal horizontal sway
- Equal angle of rotation of the structural elements such as columns, walls, etc, follow the horizontal deformation of the stabilizing elements
- Uniform detailing

Structural systems: conceptual design

Position of cores/shear walls: most favourable if horizontal joints are in centric compression

a) Good
b) Good
c) Good
d) Satisfactory: two transversal walls have already moments due to eccentricity of the vertical load
e) Bad, almost no vertical load, and/or eccentric vertical load
f) Bad, almost no vertical load on the longitudinal shear wall.
Structural systems: conceptual design

Position of cores/shear walls:

In case of a small vertical load on the shear wall or core, the concrete section will crack resulting in larger deformations or more reinforcement needed.

The best design leads to full compression in the horizontal joints between the core- or wall elements.

Tensile forces require more complicated and time consuming connections, using for example reinforcing bars passing from one element to another, welding steel plates, bolted connections, post-tensioning etc.

In the case of full compression, a simple mortar joint will be sufficient.

Structural systems: stability considerations

It is appropriate to examine the flow of forces for the vertical and the horizontal loads separately and to superimpose the two solutions in the development of the structural system. The vertical loads are resisted by bridging elements (roof and floor elements, beams, stairs, etc.). With regard to the horizontal forces the structure should be provided with stabilizing units that are capable to resist the horizontal loads and link them to the reactions in the foundation. The following components can be part of the stabilizing system.

- Fixed-end columns (cantilever action)
- Fixed-end core (cantilever action)
- Fixed-end slender wall (cantilever action)
- Non-slender wall (diaphragm action)
- Frames with moment-resisting joints (frame action)
- Beams (frame and diaphragm action)
- Floors (diaphragm action)
- Roof (diaphragm action)

Precast structure with fixed end columns

Structural systems: stability considerations

Beam column frame with fixed end columns

Pocket foundation projecting reinforcement bolted connection
In multistorey structures the cores, staircase shafts or high slender walls can be used as stabilizing units. Such stabilizing units are often composed of precast wall elements designed as huge fixed-end cantilevered walls, secured by connections between the units. Staircase shafts can be composed by wall elements that are connected to become an interacting substructure. Solutions also exist where storey high cell-elements are placed in open box format (below).
Structural systems: stability considerations

For less slender walls, the flexural failure mode of behaviour is not as pronounced as in more slender walls, which resist horizontal load by cantilever action. In less slender walls, the shear capacity in joints and in the connections to the foundation can with relatively small measures be sufficient for stabilization by diaphragm action. For this reason the stabilization with diaphragm action in respect it is favourable that the walls are load-bearing, since they provide compression in the horizontal joints, reducing the need for tensile force transfer across the joints.

The horizontal loads must be transferred by diaphragm action in precast floors (and roofs) to the stabilizing units. Connections between the floors or roofs and the stabilizing units interact to resist the horizontal load as shown in the figure right.

Stabilization with diaphragm action in non-slender walls
Diaphragm action in precast floors and roofs

Structural sub-systems
Types precast floor and roof units

<table>
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<tr>
<th>Floor type</th>
<th>Dim. span m</th>
<th>Floor thickness mm</th>
<th>Unit width m</th>
<th>Unit weight kN/m²</th>
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<td>600-900</td>
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<td>200-800</td>
<td>2400</td>
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Floors composed with hollow core slabs

Production of prestressed hollow core slabs
The assembling of slabs should carry both the load in vertical direction and act as a diaphragm to transfer the horizontal loads on the structure to the stabilizing walls (and from there to the foundations).

Hollow core slabs should be designed for:
- Bending capacity
- Shear flexure capacity
- Shear tension capacity
- Anchorage capacity

Bearing capacity of hollow core slabs
Bearing capacity for vertical loads of a single slab in a system

If a single slab is loaded, it activates the neighbouring slabs, as a result of shear transmission across the joints. To carry this load, an equilibrium system is required, where the reinforcement in transverse direction (red lines) is necessary.

Transverse reinforcement between end faces of HC type of supporting beam

Transverse reinforcement between HC type and supporting facade element

Load distribution diagrams for hollow core slabs with and without structural topping (left) and with structural topping (right)

Diaphragm action of HC slab systems

Significance of assembling reinforcement

Tensile tie A

Tensile tie A
Diaphragm action of HC slab systems
Significance of assembling reinforcement

Tensile tie A

Solutions for tensile tie A

Tensile tie A
Diaphragm action of HC slab systems

Significance of assembling reinforcement

Shear connector A_s5

Further details about shear connector A_s5

Longitudinal connection of a hollow core slab with a wall: Shear connector A_s5

Design of slab for diaphragm action

For the calculation of tendons A_s1, the slab assembly is regarded as a deep beam: inner lever arm I = 0.8h, (with z ≤ 0.2l_s). The bending moment is M_d = \( \frac{1}{8} \times (q_{w1} + q_{w2} + q_{i}) \times l^2 \), where q_{w1} and q_{w2} are the design wind loads on the facades (compression and tension) and q_{i} is the design load due to unlimited column inclination (imperfection).
Design of slab for diaphragm action

The slab assembly may not be treated as a deep beam if it is shown that the shear force in the joints does not exceed a critical value (no shear slip in joints). The largest shear force \( V_{ed} \) is equal to:

\[
V_{ed} = \frac{1}{2} \left( q_{w1} + q_{w2} + q_{id} \right) l\]

occurs at the last joint before the stabilizing wall.

Design of slabs for diaphragm action

Verification of shear capacity of longitudinal grouted joints between hollow core slabs

Tests at TU Delft showed that no shear slip will occur if the friction angle is below \( \mu = 1.0 \). If this is the case the following condition should be satisfied:

\[
\frac{V_{ud}}{A_d f_{yd}} \leq 1.0
\]

where:
- \( V_{ud} \) = design shear force in critical joint
- \( A_d \) = cross sectional area of reinforcement intersecting the joint
- \( f_{yd} \) = design yield stress of reinforcement
Design of slab for diaphragm action
Choice of the correct load bearing model

Diaphragm with opening:
For wind from the most favourable side an inner lever arm $z = 0.8h$ applies.

For wind from the other side the lever arm should be reduced to $z = 0.8h_{\text{red}}$.

Design of slab for diaphragm action
Choice of the correct load bearing model

Two options for bearing mechanisms:
- 2-arch system
- 1-arch system with larger inner lever arm

Design of slab for diaphragm action
Choice of the correct load bearing model

Left side: solution with strut and tie model
Right side: solution with arch
Design of slab for diaphragm action
Choice of the correct load bearing model

![Image of slab with load bearing model]

Design of precast walls
Stabilizing wall diaphragms are normally subjected to axial load and sustain higher stress than precast floor diagrams. The stiffness is an important parameter of shear walls. If cracks develop in horizontal joints, the stiffness is significantly reduced. Whenever possible, shear walls should be designed in such a way that tensile stresses are avoided in horizontal joints or only small tensile stresses occur. It is mostly economical to have as much as possible vertical load on shear walls in order to suppress tensile forces.

The walls in precast shafts can be designed either as individual shear walls or connected along the vertical joints to form a closed open cross section (see figure). Then the shaft will act as one unit in the stabilizing system. If this interaction between the walls is accounted for in the analysis, connections along the vertical joints should be designed to resist the corresponding shear forces and should be designed and detailed accordingly.
Design of precast walls

The connections at vertical joints are mainly of two types: cast-in-situ concrete filled joints with transverse reinforcement, or welded connections. In the concrete-filled joint, there is a continuous shear transfer along the joint, but with welded connections the shear transfer is intermittent. The concrete-filled joint can be plane or castellated. The transverse reinforcement can be well distributed or concentrated at the horizontal joints. Concrete joints are stiffer than steel connections, but those work immediately after mounting. Moreover they require fire protection and need finishing with regard to aesthetics.

Concrete-filled connection with shear keys

Welded steel connector

Design of precast walls

Besides solutions with welded connections and concrete-filled joints, one possibility is also to interlock elements. This provides a connection with high shear capacity.

The interlocking (masonry type) solution

Moment resisting frames

Moment resisting frames typically include moment resisting connections. Examples are H-frames or Π-frames (picture below). A typical solution for the connection, which should be able to transmit bending moments in the grouted sleeve – projecting bar solution (right). Dimensional tolerances deserve high attention for this way of building.

In-frame in old Delft office building

Grouted sleeve – projecting bar solution for moment resisting connection
Moment resisting frames

Application of H-frame with moment resisting connections. The system is applied if there is a high degree of repetition. High reliability is imposed on the accuracy of producing and placing (continuity of horizontal connection).

Moment resisting frames

H-frame used in multi-storey moment resisting frame for grandstands

Composite action and composite members

Composite action can be used to increase the flexural strength and stiffness of structural members. Typical precast concrete composite sections could be hollow core elements of double T-units with a structural topping, or composite floor-plate floors. The interface should be sufficiently rough to transfer the shear forces involved in composite action.
Composite action and composite members

Beams and slabs can be connected to composite bearing systems. In such a way the stiffness of the system can be considerably increased. On the other hand the composite action influences the state of stress in the floor elements, which should be regarded in design.

Demountable structures

Demountable system, CD20, The Netherlands

Demountable office building, Delft, The Netherlands