Requirements for Intermediate Moment Resisting Frames

A- Beams

1- General Requirements:
Requirements of ACI 21.3.2 are applicable for intermediate moment frame members proportioned primarily to resist flexure with factored axial forces \( \leq 0.1 f'_c A_g \). If such members are subjected to axial forces \( > 0.1 f'_c A_g \), they are treated as beam-columns.

2- Longitudinal Reinforcement:
- Positive moment strength at joint face is not to be less than \( \frac{1}{3} \) of the negative moment strength provided at the face of the joint.
- The negative or positive moment at any section along the member is not to be less than \( \frac{1}{5} \) the maximum moment strength provided at the face of either joint.

3- Transverse Reinforcement:
- At both ends of the member, hoops shall be provided over lengths equal to twice the member depth measured from the face of the supporting member toward midspan.
- The first hoop is to be located at a distance not more than 5 cm from the face of the supporting member. Maximum hoop spacing is not to exceed the smallest of: \( \frac{d}{4} \), \( 8d_b \) where \( d_b \) is the diameter of the
smallest longitudinal bar, 24 times the diameter of hoop bar, and 30 cm.

- Where hoops are not required, stirrups are spaced at not more than d/2 throughout the length of the member.

4- **Shear Strength Reinforcement:**

- $\Phi V_n$ of beams resisting earthquake effect, E, shall not be less than the smaller of (a) or (b):
  
  (a) The sum of the shear associated with development of nominal moment strengths of the member at each restrained end of the clear span and the shear calculated for factored gravity loads;

  (b) The maximum shear obtained from design load combinations that include earthquake effect E, with E assumed to be twice that prescribed by the legally adopted general building code for earthquake resistant design.
Design Shear, ACI 318-2008
B- Beam-Columns

1- General Requirements:
Requirements of ACI 21.3.5 are applicable for intermediate moment frame members proportioned to resist axial forces greater than \(0.1 f'c A_g\).

2- Transverse Reinforcement:

- At both ends of the member, hoops shall be provided at spacing \(s_c\) over a length \(l_c\) measured from the face of the joint.
  The length \(l_c\) shall not be less than the largest of:
  
  (a) \(1/6\) of the clear span of the member
  (b) Maximum cross-sectional dimension of the column
  (c) 45 cm.

- The spacing \(s_c\) shall not exceed the smallest of:
  (b) \(8d_b\)
  (c) 24 diameter of the hoop bar
  (c) One-half of the smallest cross-sectional dimension of the column
  (d) 30 cm.

- The first hoop shall be located at not more than spacing \(s_c/2\) from the joint face.

- Outside the length \(l_c\) spacing of the transverse reinforcement shall conform to ACI 7.10 (ordinary column ties) and ACI 11.4.5.1 (beam shear reinforcement spacing limits).
• Columns supporting reactions from discontinuous stiff members, such as walls, shall be provided with transverse reinforcement at the spacing, \( s_c \), as defined in 21.3.5.2 over the full height beneath the level at which the discontinuity occurs if the portion of factored axial compressive force in these members related to earthquake effects exceeds \( 0.1 f'_c A_g \). Where design forces have been magnified to account for the overstrength of the vertical elements of the seismic force-resisting system, the limit of \( 0.1 f'_c A_g \) shall be increased to \( 0.25 f'_c A_g \). This transverse reinforcement shall extend above and below the columns as required in 21.6.4.6(b).

3- Shear Strength Requirements:

• Design shear strength of columns resisting earthquake effect shall not be less than the smaller of (a) or (b):
  
  (a) The sum of the shear associated with development of nominal moment strengths of the member at each restrained end of the clear span and;

  (b) The maximum shear obtained from design load combinations that include earthquake effect \( E \), with \( E \) assumed to be twice that prescribed by the legally adopted general building code for earthquake resistant design.
C- Joints

- Joints of intermediate moment resisting frames are designed in a way similar to ordinary moment resisting frame joints.

Requirements for Ordinary Moment Resisting Frames

These provisions were introduced in the 2008 Code and apply only to ordinary moment frames assigned to SDC B.

21.2.1 — Scope
Requirements of 21.2 apply to ordinary moment frames forming part of the seismic-force-resisting system.
A- Beams

Based on 21.2.2, beams shall have at least two of the longitudinal bars continuous along both the top and bottom faces. These bars shall be developed at the face of support.

B- Columns

Based on 21.2.3, columns having clear height less than or equal to five times the dimension $c_1$ (in the direction of the span for which moments are being determined) shall be designed for shear in accordance with 21.3.3 (requirements for intermediate moment resisting frames).

Requirements for Structural Integrity

A structure is said to have structural integrity if localized damage does not spread progressively to other parts of the structure. Experience has shown that the overall integrity of a structure can be substantially enhanced by minor changes in detailing of reinforcement.

The 1989 ACI Code introduced section 7.13, which provides details to improve the integrity of joist construction, beams without stirrups and perimeter beams. These requirements were updated in the 2002 ACI Code, and shown below.

- In detailing of reinforcement and connections, members of a structure shall be effectively tied together to improve integrity of the overall structure.
• In joist construction, at least one bottom bar shall be continuous and at non-continuous supports shall be terminated with a standard hook.
• Beams along the perimeter of the structure shall have continuous reinforcement consisting of:
  (a) at least 1/6 of the tension reinforcement required for negative moment at the support, but not less than 2 bars;
  (b) at least ¼ of the tension reinforcement required for positive moment at mid span, but not less than 2 bars.
- The above reinforcement shall be enclosed by the corners of U-stirrups having not less than 135-deg hooks around the continuous top bars, or by one piece closed stirrup with not less than 135-deg hooks around one of the continuous bars.
- Where splices are needed to provide the required continuity, top reinforcement shall be spliced at or near mid span and bottom reinforcement shall be spliced at or near the support. Splices shall be Class B tension splices or mechanical or welded splices.
Notes:  
(1) Larger of 1/4 (+As₁) or 1/4 (+As₂) but not less than two bars continuous or spliced with Class B splices or mechanical or welded splices. 
(2) Larger of 1/6 (-As₁) or 1/8 (-As₂) but not less than two bars continuous or spliced with Class B splices or mechanical or welded splices.
Diaphragm Key Components

Diaphragm Slab (Sheathing):
It is the component of the diaphragm which acts primarily to resist shear forces developed in the plane of the diaphragm.

Diaphragm Chords:
They are components along the diaphragm edges with increased longitudinal and transverse reinforcement, acting primarily to resist tension and compression forces generated by bending in the diaphragm.

Diaphragm Collectors:
They are components that serve to transmit the internal forces within the diaphragm to elements of the lateral force resisting system. They shall be monolithic with the slab, occurring either within the slab thickness or being thickened.

Diaphragm Struts:
They are components of a structural diaphragm used to provide continuity around an opening in the diaphragm. They shall be monolithic with the slab, occurring either within the slab thickness or being thickened.

Distribution of Forces:
For rigid diaphragms the distribution of forces to vertical elements will be essentially in proportion to their relative stiffness with respect to each other.
Diaphragm Chord / Beam Analogy

$H \left( \frac{k_1}{k_1 + k_2 + k_3} \right) H \left( \frac{k_2}{k_1 + k_2 + k_3} \right) H \left( \frac{k_3}{k_1 + k_2 + k_3} \right)$

$k_1, k_2$ and $k_3$ are lateral stiffness of walls 1, 2 and 3 respectively.
Diaphragm boundaries may not just occur at the perimeter of the diaphragm. Interior shear walls and drag members create diaphragm boundaries.
Requirements for Structural Diaphragms

Floor and roof slabs acting as structural diaphragms to transmit forces induced by earthquake ground motions in structures assigned to SDC D, E, or F shall be designed in accordance with this section 21.11 of ACI Code.

1- Scope:

Diaphragms are used in building construction are structural elements such as floors and roofs that provide some or all of the following actions:

- Support for building elements such as walls, partitions, and cladding resisting horizontal forces but not acting as part of the building vertical lateral force resisting system.
- Transfer of lateral forces from the point of application to the building vertical lateral force resisting system.
- Connection of various components of the building lateral force resisting system with appropriate stiffness so the building responds as intended in the design.

2- Minimum Thickness of Slab:

- Concrete slabs serving as structural diaphragms used to transmit earthquake forces shall not be less than 5 cm thick.

3- Reinforcement:
The minimum reinforcement ratio for structural diaphragms shall not be less than the shrinkage and temperature reinforcement ratio. Reinforcement spacing each way shall not exceed 45 cm.

Diaphragm chord members and collector elements with compressive stresses exceeding $0.2 f'_c$ at any section shall have transverse reinforcement over the length of the element as per transverse reinforcement of boundary elements of special shear walls. The special transverse reinforcement is allowed to be discontinued at a section where the calculated compressive stress is less than $0.15 f'_c$. Stresses are calculated for the factored forces using a linearly elastic model and gross-section properties of the elements considered.

4- Design Forces:

The seismic design forces for structural diaphragms shall be obtained from the lateral load analysis in accordance with the design load combinations.

5- Shear Strength:

Nominal shear strength $V_n$ of structural diaphragms shall not exceed

$$V_n = A_{cv} \left( 0.53 \lambda \sqrt{f'_c} + \rho_t f_y \right) \leq 2.12 A_{cv} \sqrt{f'_c}$$

where $A_{cv}$ is gross area of concrete section in the direction of shear force considered and $\rho_t$ is ratio of transverse reinforcement.
6- Boundary Elements:

- Boundary elements of structural diaphragms shall be proportioned to resist the sum of the factored axial forces acting in the plane of the diaphragm and the force obtained from dividing the factored moment at the section by the distance between the boundary elements of the diaphragm at that section.

- Reinforcement for chord and collectors at splices and anchorage zones shall have either:
  (a) A minimum center-to-center spacing of three longitudinal bar diameters, but not less than 4 cm, and a minimum concrete cover of $2.5d_b$, but not less than 5 cm;
  (b) Transverse reinforcement as required per minimum shear reinforcement in beams, except where compressive stresses exceed $0.2f_c'$. 
Example (11):

Determine the diaphragm forces for the building shown in Example (1).

Solution:

\[ F_{P,x} = \frac{F_t + \sum_{i=x}^{n} F_i}{\sum_{i=x}^{n} W_i} w_{px} \geq 0.35 I Z w_{px} \]

\[ \leq 0.75 I Z w_{px} \]

**Diaphragm Forces:**

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Maximum forces occur at the seventh floor, where \( F_{P,x} = 12.86 \) tons

Load/m' = 12.86/18 = 0.714 t/m.

Chord forces:

\[ M_u = 0.75 (1.87) (0.714 (18))^2 / 8 = 40.55 \text{t.m} \]

\[ C = T = \frac{40.55}{18} = 2.253 \text{tons} \]

\[ A_{x,\text{required}} = \frac{2.253}{0.9 (4.2)} = 0.596 \text{cm}^2 \] (use minimum reinforcement)

For a beam 40 cm x 25 cm in cross section,

\[ f = \frac{2.253 (1000)}{40 (25)} = 2.253 \text{Kg/cm}^2 < 0.2 (300) \], i.e., no special transverse reinforcement required.
Collector Forces:

\[ V_u = \frac{12.86}{2} (0.75)(1.87) = 9.02 \text{ tons} \]

\[ V_n = A_{cv} \left( 0.53 \sqrt{f'_{c}} + \rho_n f_y \right) \leq 2.12 A_{cv} \sqrt{f'_{c}} \]

For a topping slab 5 cm in thickness,

\[ 2.12 A_{cv} \sqrt{f'_{c}} = 2.12 \left( \frac{1800}{1000} \right) \sqrt{300} = 330.47 \text{ tons} \]

\[ V_n = \left( \frac{1800}{1000} \right) \left[ 0.53 \sqrt{300} + 0.0018(4200) \right] = 150.66 \text{ tons} < 330.47 \text{ tons} \quad \text{O.K} \]

For seismic forces in the other orthogonal direction, chords and collectors trade places. For this condition, the same forces are evaluated.
Requirements For Foundations

Requirements for foundations supporting buildings assigned to high seismic performance or design categories were added to the 1999 Code. They represent a consensus of a minimum level of good practice in designing and detailing concrete foundations including piles, drilled piers, and caissons. The requirements for foundations are given in ACI 21.12, presented below.

- Longitudinal reinforcement of columns and structural walls resisting seismic forces shall extend into the footing, mat, or pile cap, and shall be developed for tension at the interface.
- Columns designed assuming fixed-end conditions at the foundation, and if hooks are required, longitudinal reinforcement resisting flexure shall have 90 deg hooks near the bottom of the foundation with the free end of the bars oriented toward the center of the column.
- Columns or boundary elements of special structural walls that have an edge within one-half the footing depth from the edge of the footing shall have transverse reinforcement provided below the top of the footing. This reinforcement shall extend into the footing a distance no less than the smaller of the depth of the footing, mat, or pile cap, or the development length in tension of the longitudinal reinforcement.
- Where earthquake effects create uplift forces in boundary elements of special structural walls or columns, flexural reinforcement shall be provided in
the top of the footing, mat, or pile cap to resist the design load combination, and shall not be less than minimum reinforcement in beams.

- Grade beams designed to act as horizontal ties between pile caps and footings shall have continuous longitudinal reinforcement developed within or beyond the supported column or anchored within the pile cap or footing at all discontinuities.

- Grade beams designed to act as horizontal ties between pile caps or footings shall be proportioned such that the smallest cross-sectional dimension shall be equal or greater than the clear spacing between connected columns divided by 20, but not greater than 45 cm. Closed ties shall be provided at a spacing not to exceed the lesser of one-half the smallest orthogonal cross-sectional dimension or 30 cm.

- Piles, piers, or caissons resisting tension loads shall have continuous longitudinal reinforcement over the length resisting design tension forces. The longitudinal reinforcement shall be detailed to transfer tension forces within the pile cap to supported structural members.

- Piles, piers, or caissons shall have transverse reinforcement in accordance with 21.12.2 at locations (a) and (b):
  (a) At the top of the member for at least 5 times the member cross-sectional dimension, but not less than 1.80 m below the bottom of the pile cap;
  (b) For the portion of piles in soil that is not capable of providing lateral support, or in air and water, along
the entire unsupported length plus the length required in (a).