Seismic design of RC buildings following ACI 318-14

Design outline

Seismic Design Category and Energy Dissipation Capacity

SDC – Seismic Design Category	Denomination (energy dissipation capacity)
A, B	Ordinary
C	Intermediate
D, E, F	Special

Seismic design requirements in ACI 318-14

Component resisting earthquake effect, unless otherwise noted	SDC			
	A (None)	B (18.2.1.3)	C (18.2.1.4)	D, E, F (18.2.1.5)
Analysis and design requirements	None	18.2.2	18.2.2	18.2.2, 18.2.4
Materials		None	None	18.2.5 through 18.2.8
Frame members		18.3	18.4	18.6 through 18.9
Structural walls and coupling beams		None	None	18.10
Precast structural walls		None	18.5	18.5[2], 18.11
Diaphragms and trusses		None	None	18.12
Foundations		None	None	18.13
Frame members not designated as part of the seismic-force-resisting system		None	None	18.14
Anchors		None	18.2.3	18.2.3

General Requirements

- Compressive strength of concrete f'_c larger than 21MPa
- Specified compressive strength of lightweight concrete less than 35MPa
- For computing the amount of confinement reinforcement, f_{yt} less than 700MPA
- Reinforcing steel must meet ASTM A706, if ASTM A615 is used, it must meet:
  - The actual yield strength based on mill tests does not exceed f_y by more than 125MPa
  - The ratio of the actual tensile strength to the actual yield strength is not less than 1.25
  - Minimum elongation in 200mm should be at least 14% (bar No. 10 to No. 19) and 12% (bar No. 22 to No. 36) and at least 10% (bar No. 43 to No. 57)

Ordinary moment frames

- Corresponds to SDC B
- Beams must have at least two continuous longitudinal bars along both top and bottom faces. These bars shall be developed at the face of support
- The design of beams in flexure and shear are governed by the requirements in ACI 318 chapter 9
- Columns having clear height less than or equal to five times the dimension c_1 (dimension of column in analysis direction)

Ordinary moment frames

- The design shear force is calculated as the lesser of

  - The shear V_u associated with the development of nominal moment strengths M_n of the column at each restrained end of the unsupported length due to reverse curvature

  - The maximum shear obtained from the design load combinations of ACI 318 chapter 5 that includes the earthquake effect E with Ω_o E substituted for E in the load combinations

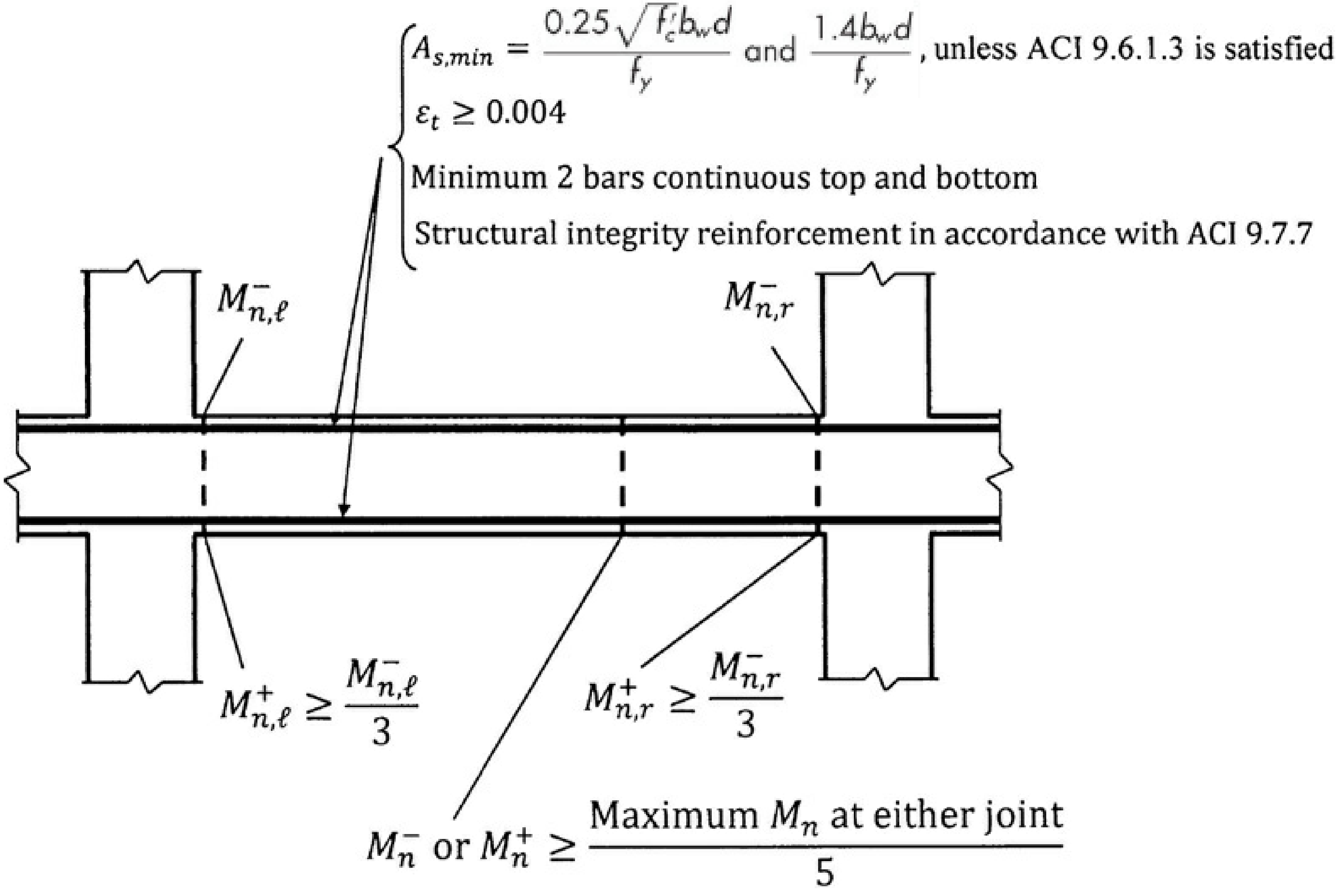
Intermediate moment frames

- Reinforcement details in a frame member shall satisfy beam requirements if the factored axial compressive load P_u does not exceed $A_g f'_c/10$

- When P_u is greater, reinforcing details must meet column requirements.

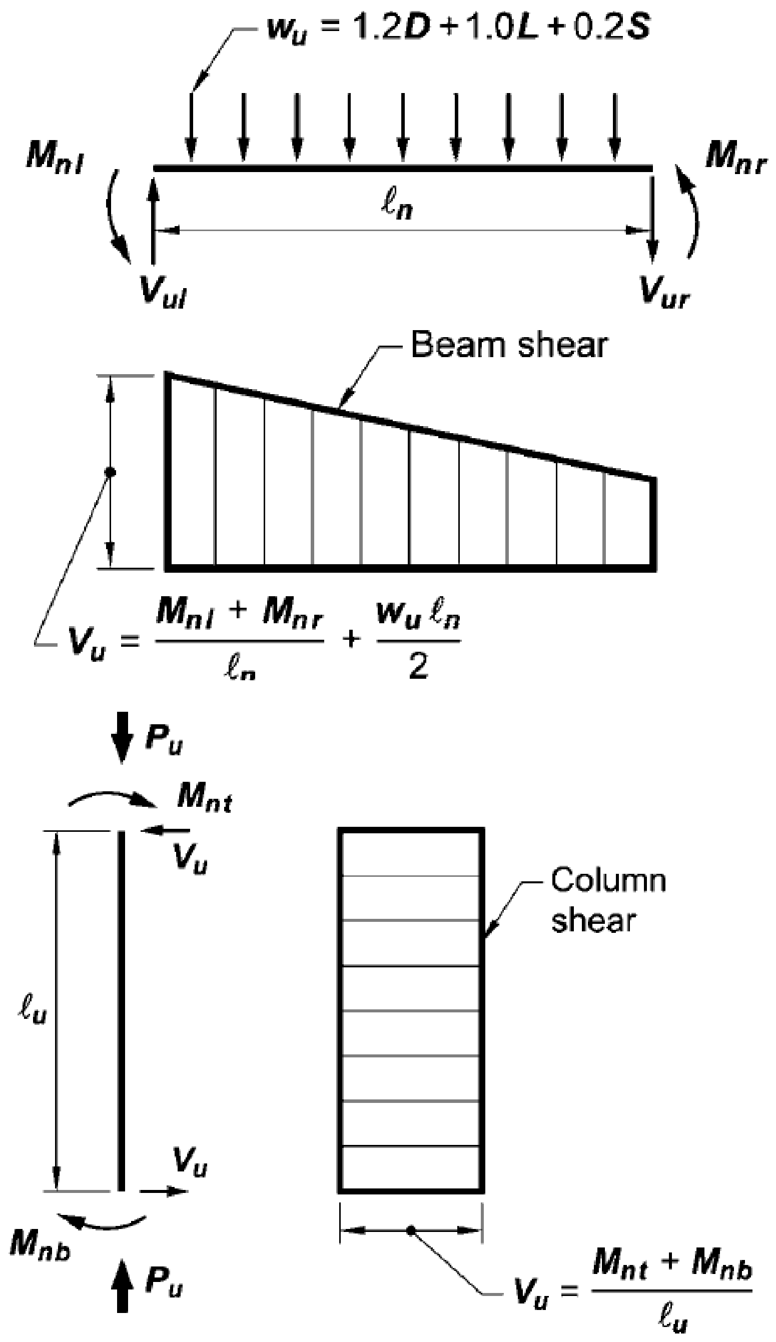
- When a slab-column system without beams is part of the seismic-force-resisting system, reinforcement details in any span resisting moments caused by seismic loads must satisfy Provision 18.4.5

Intermediate moment frames

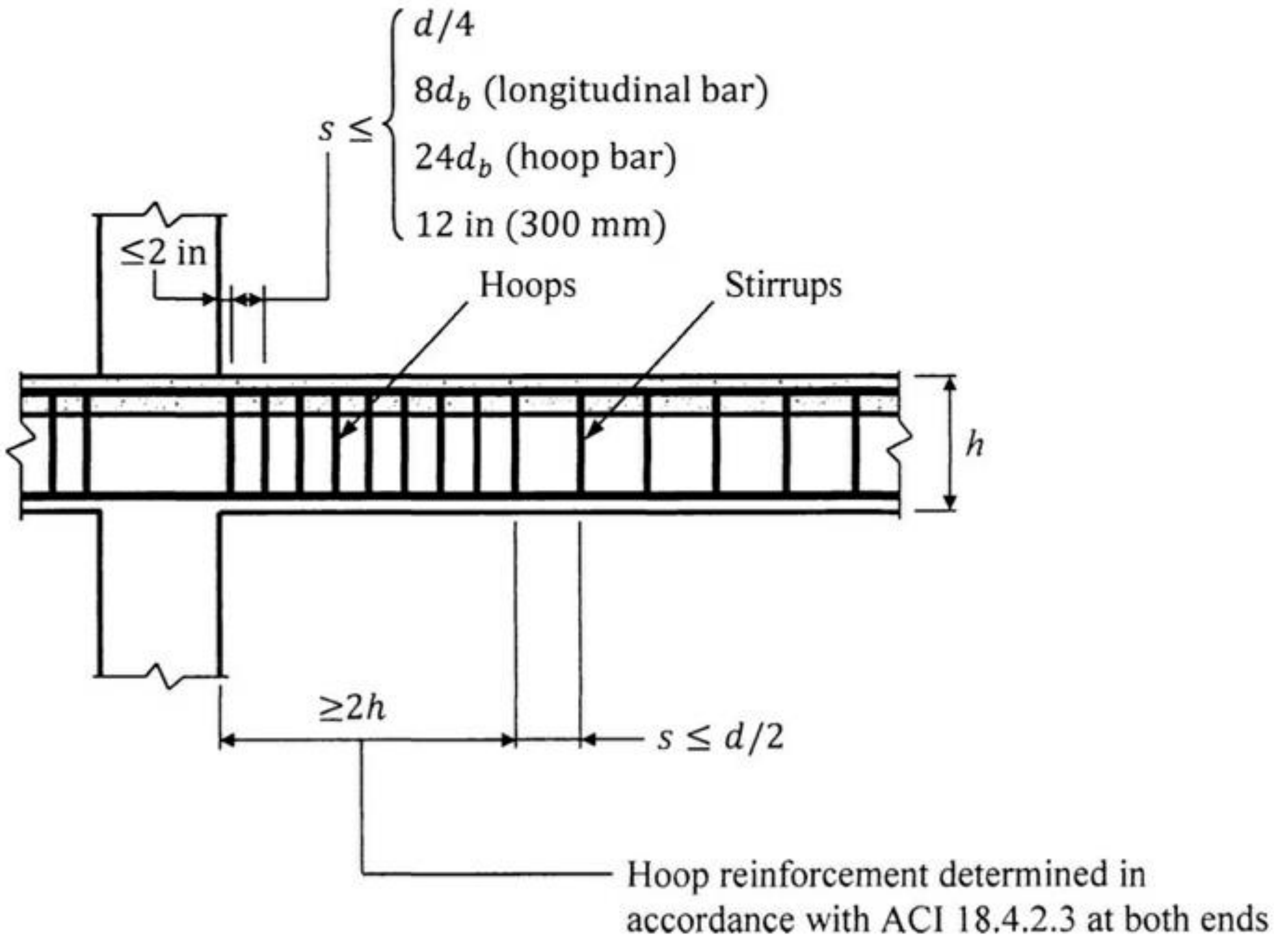


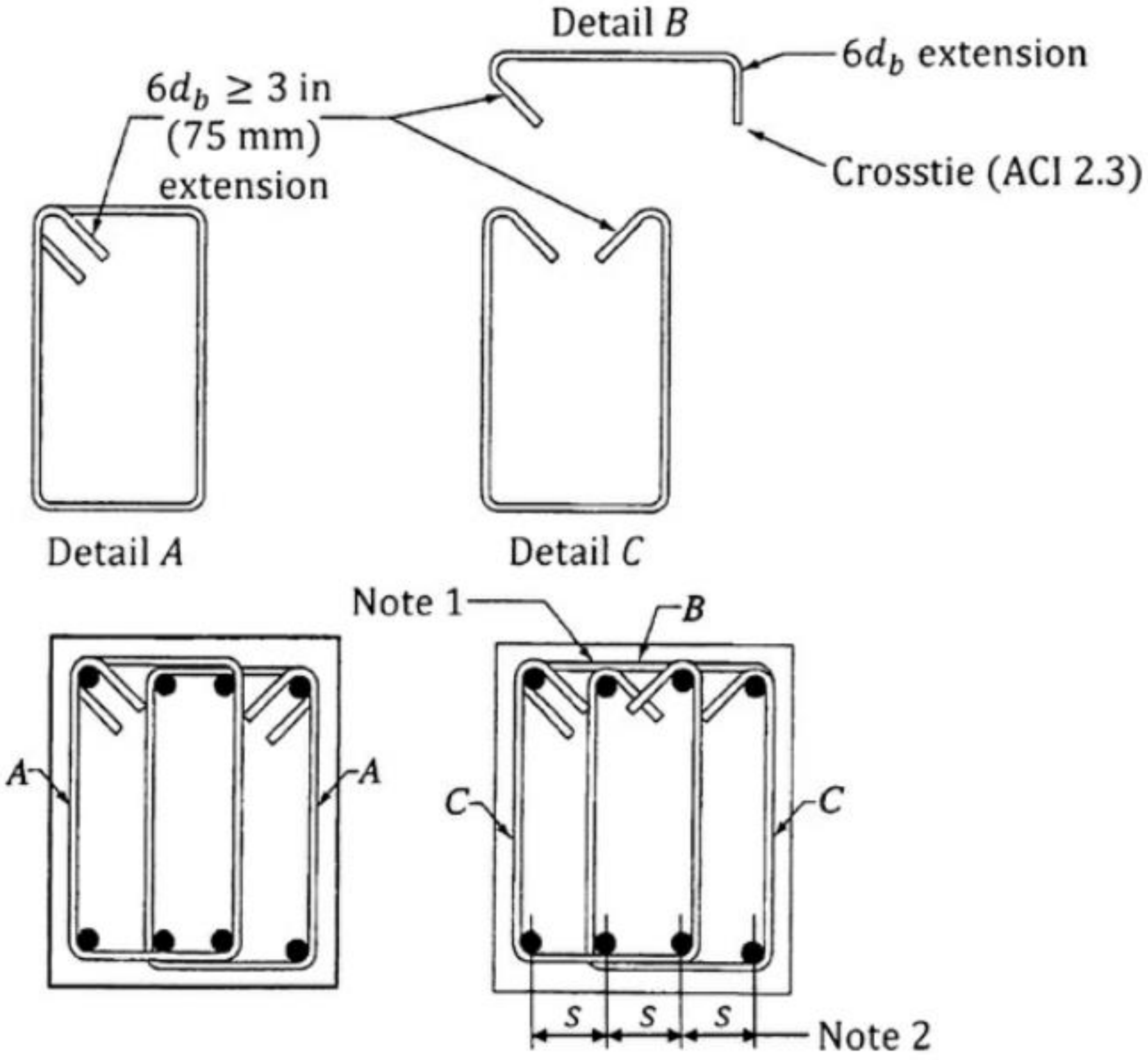
Intermediate moment frames

- Shear design of beams and columns, shear forces shall be at least the lesser of
  - The sum of the shear force associated with development of nominal strengths of members and the shear calculated for factored gravity loads (accounting for gravity is for beams only)
  - Maximum shear obtained from design load combinations taking (E) as (2E) for beams and (Ω_o E) for columns



Intermediate moment frames: shear reinforcement for beams





Notes
1. The 90-degree hooks of two consecutive crossties engaging the same longitudinal bars shall be alternated end for end.
2. Spacing s between longitudinal bars restrained by legs of crossties or hoops must not exceed 14 in (350 mm).

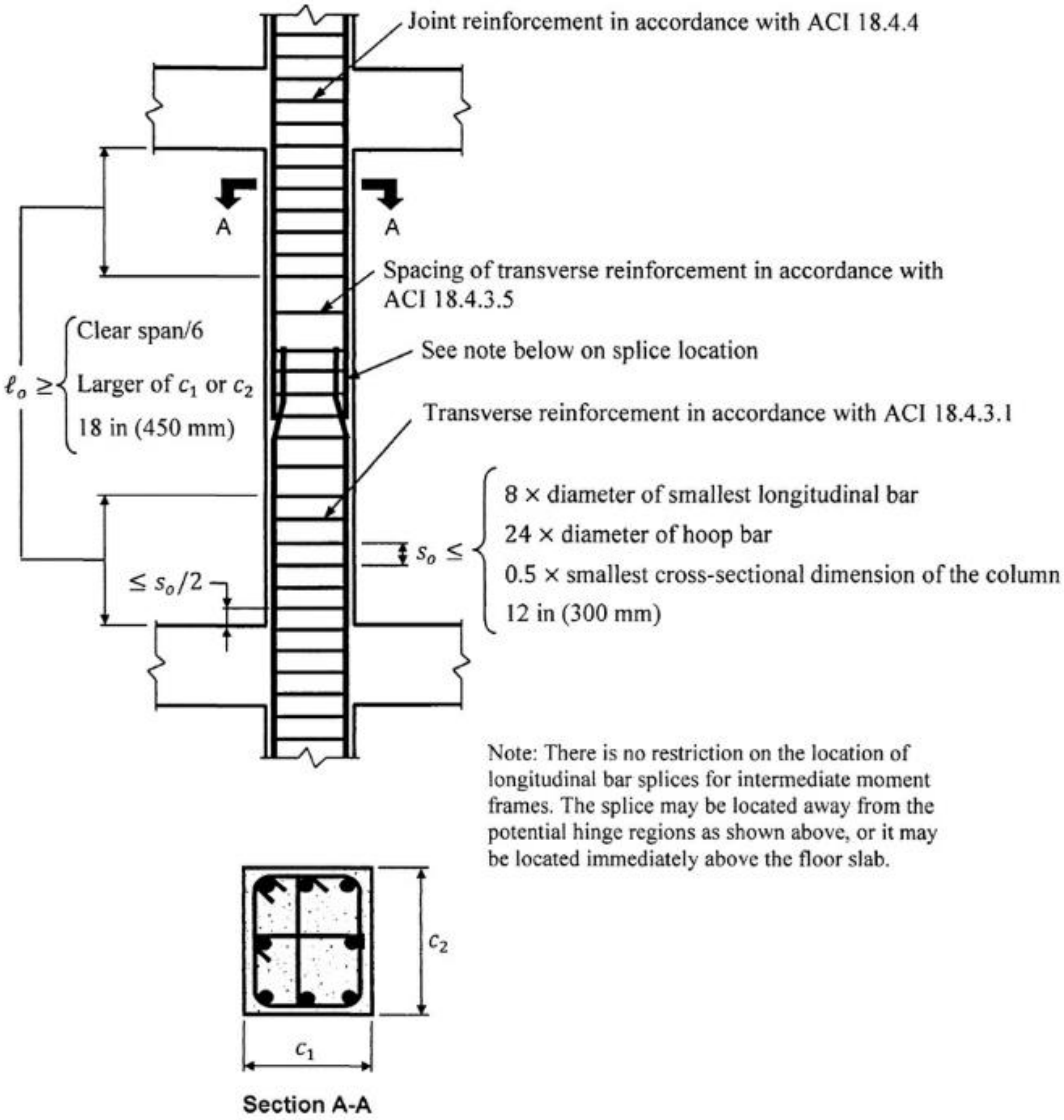
Intermediate moment frames: shear reinforcement for columns

Intermediate moment frames: transverse reinforcement in the joint

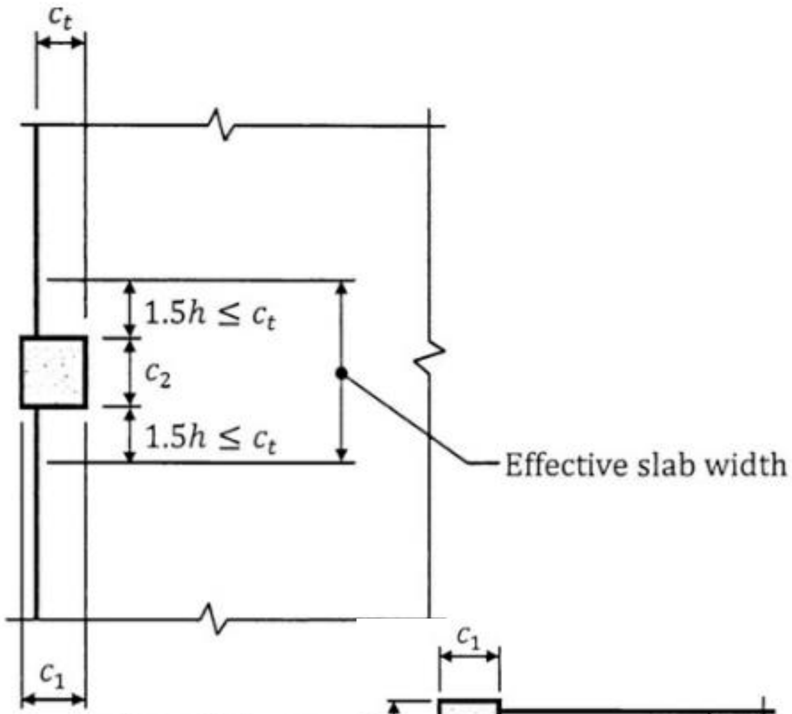
$$\frac{0.75\sqrt{f'_c}bs}{f_{yt}} \quad \left[\text{In SI: } \frac{0.062\sqrt{f'_c}bs}{f_{yt}}\right]$$

$$\frac{50bs}{f_{yt}} \quad \left[\text{In SI: } \frac{0.35\sqrt{f'_c}bs}{f_{yt}}\right]$$

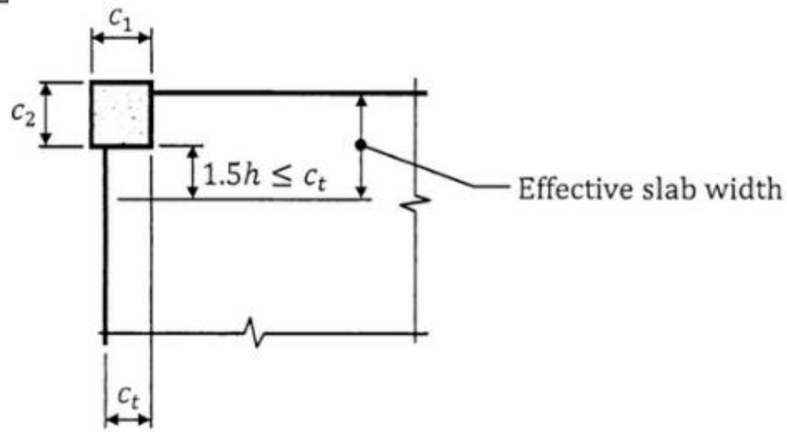
where **b** is the column's dimension perpendicular to direction of analysis and **s** is the spacing of the of hoops, s is less than half depth of smaller beam framing the joint



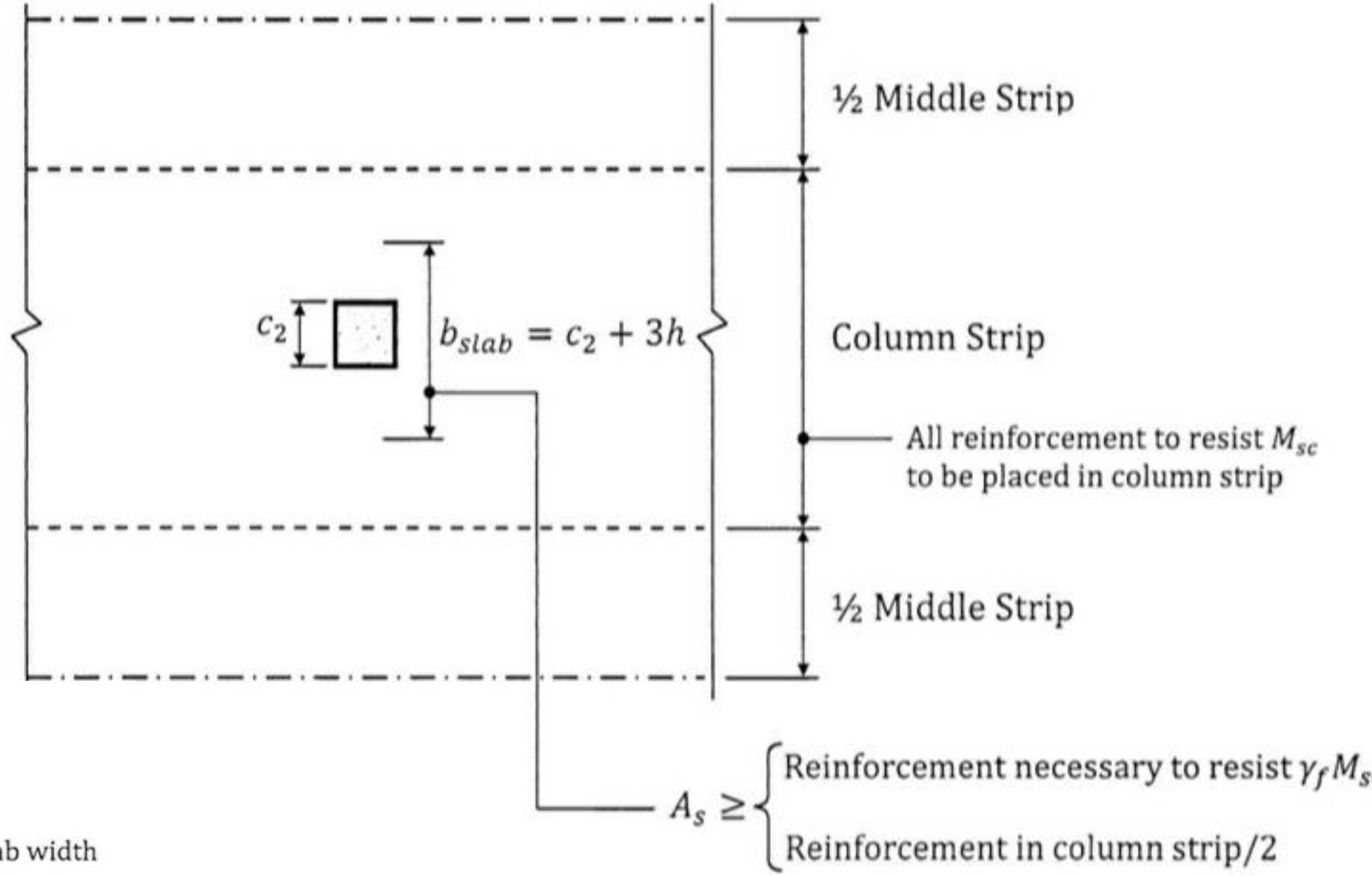
Intermediate moment frames: two way slabs – reinforcement



Edge Column



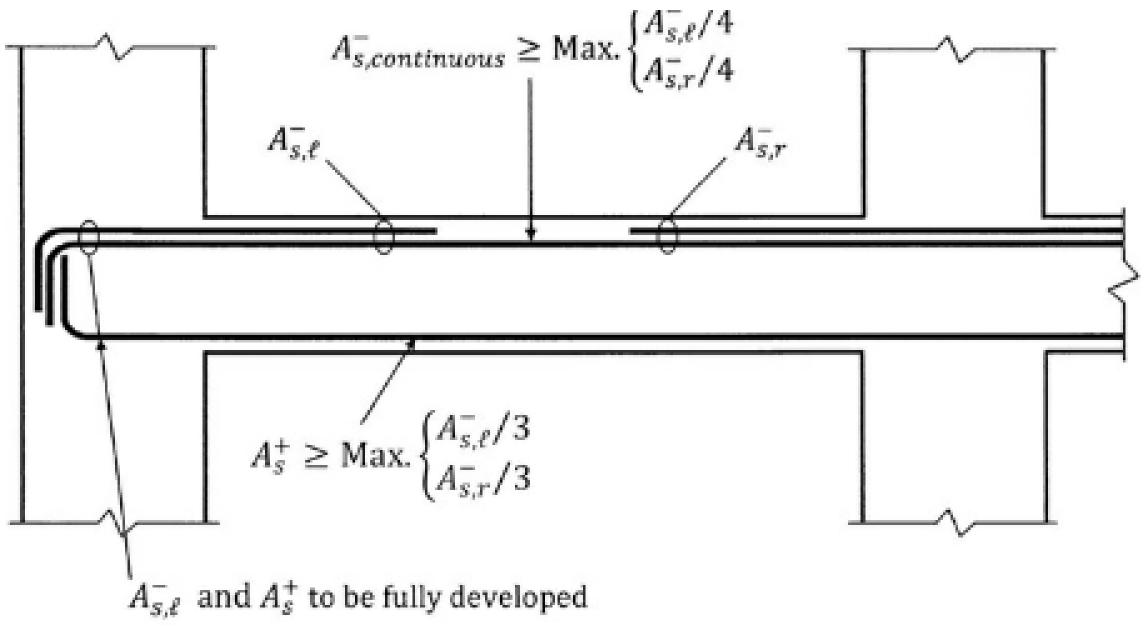
Corner Column



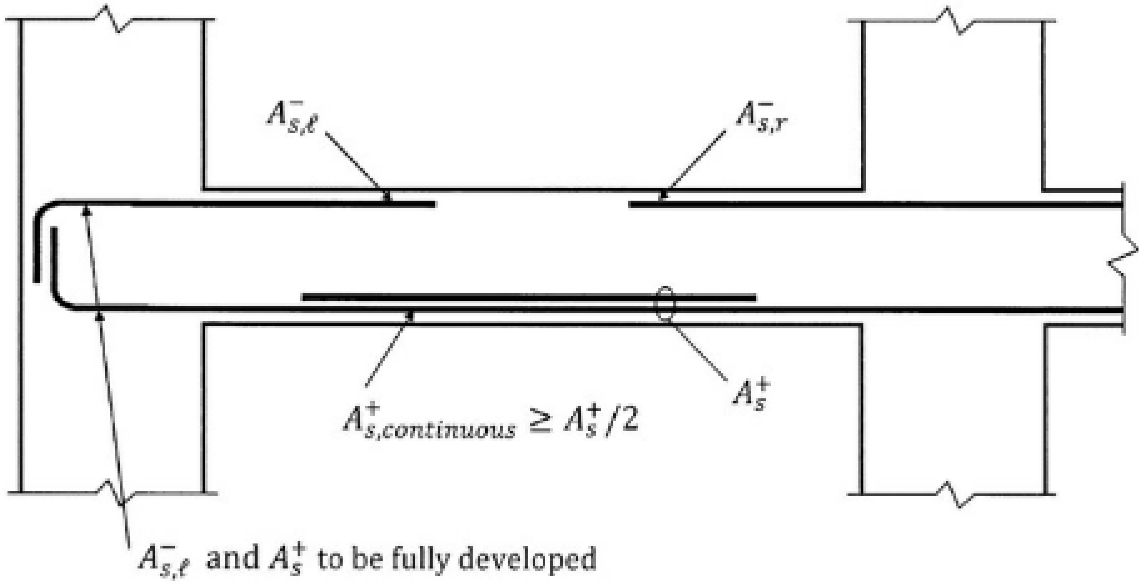
Note: Applies to both top and bottom reinforcement

$$\gamma_f = \frac{1}{1 + (2/3)\sqrt{b_1/b_2}}$$

Intermediate moment frames:
two way slabs - flexural capacity



Column Strip



Middle Strip

Intermediate moment frames: two way slab – shear design

Two way slab without beams

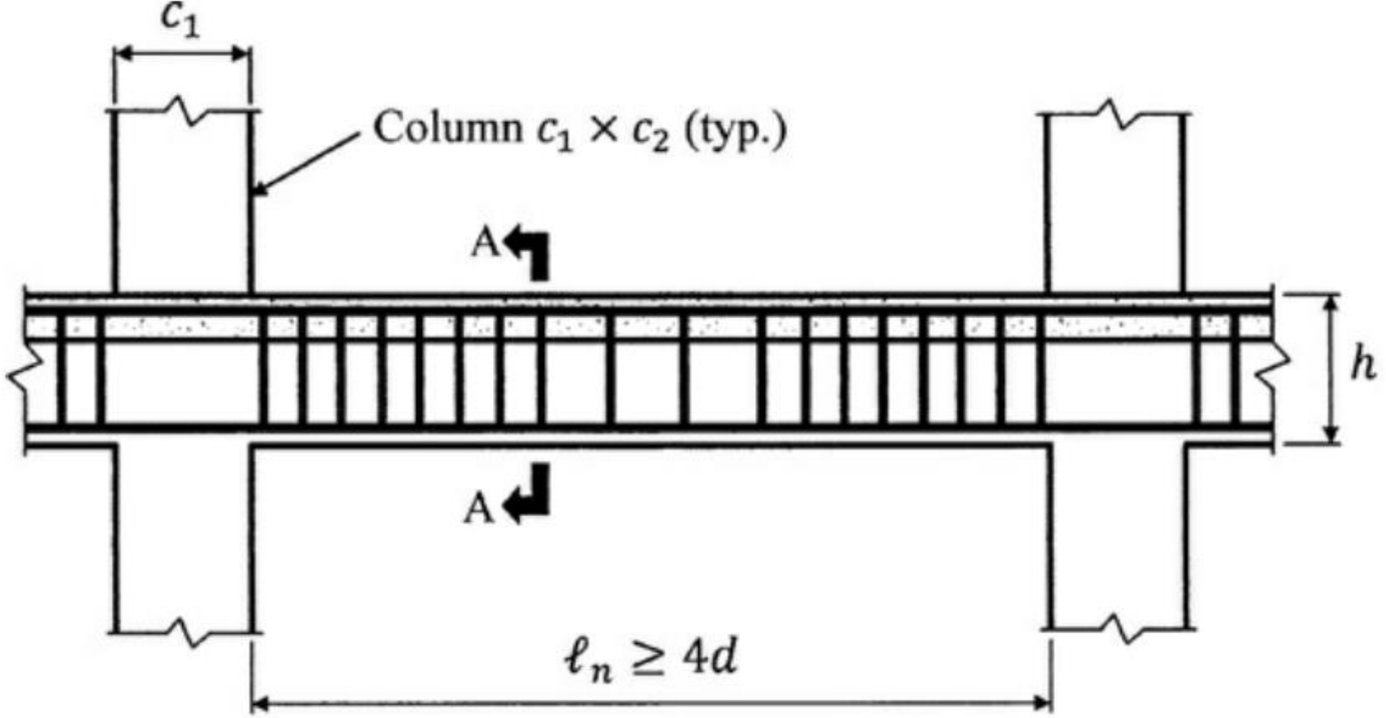
- Two way shear caused by factored gravity loads shall not exceed $0.4\Phi V_c$, where V_c shall be calculated in accordance with 22.6.5.

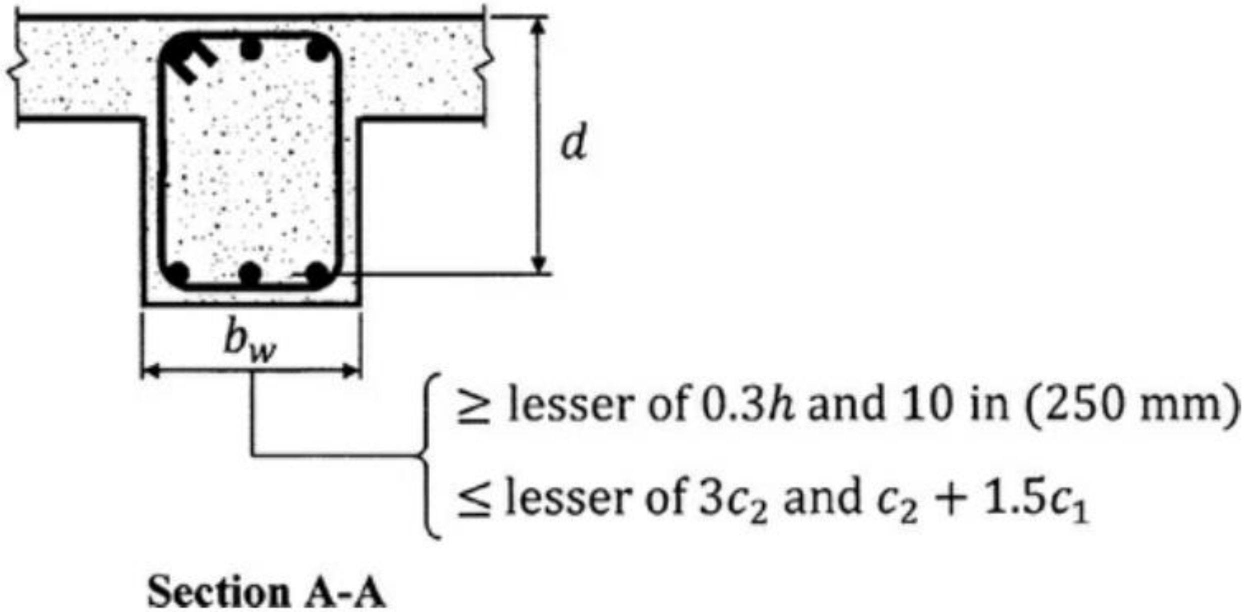
- This requirement may be waived if the slab complies with provision 18.14.5. This provision is related to the requirement of members not designated as part of lateral resisting system

Special moment frames: flexural members

- Dimensional restrictions

- Axial force, P_u must not exceed $0.1f'_cA_g$

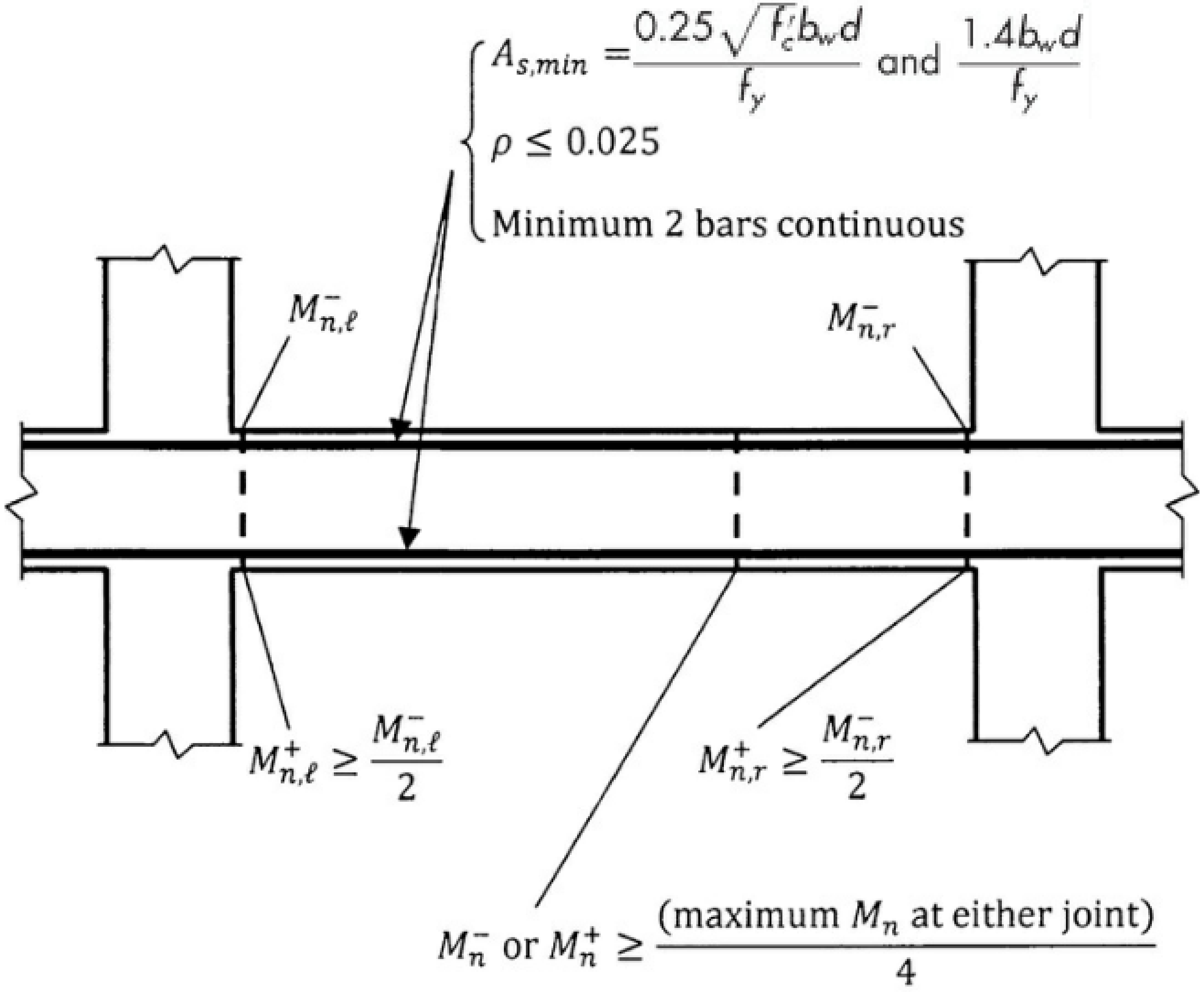




Special moment frames: flexural members

Requirements on:

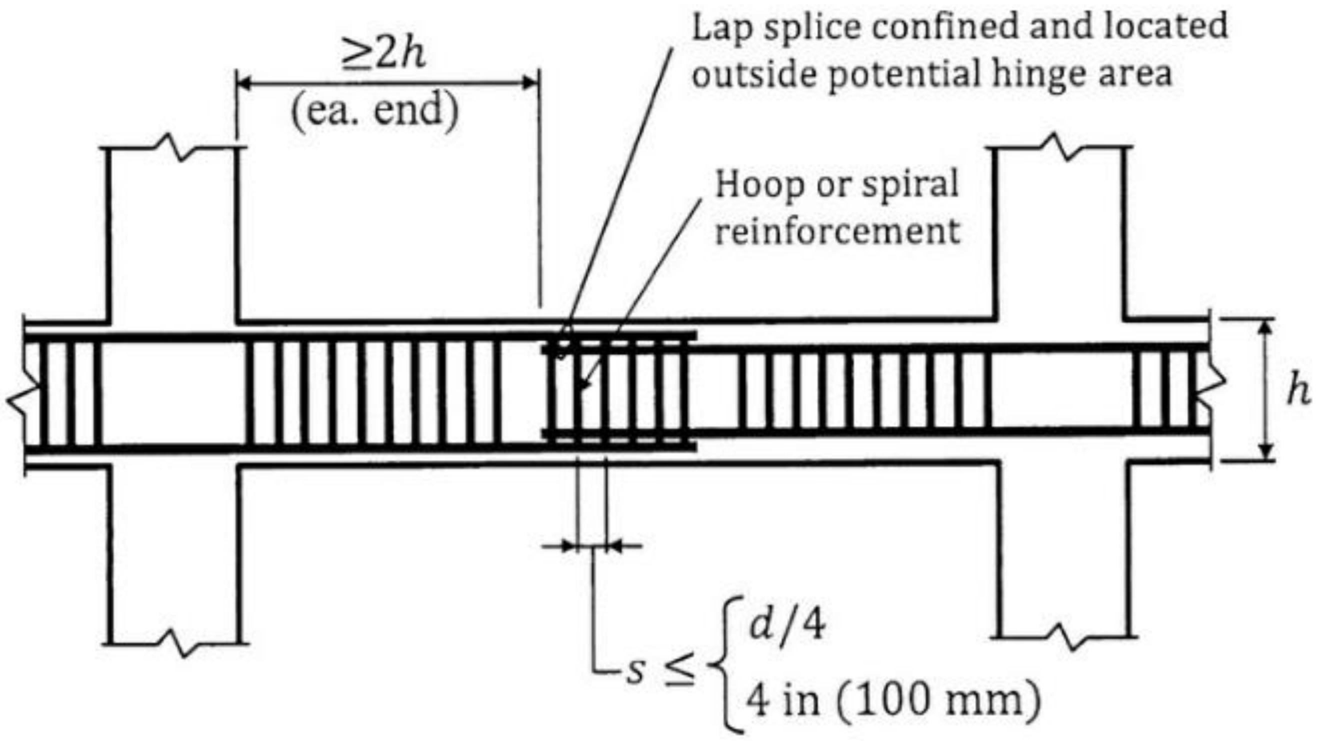
- member's reinforcement
- the moment strength of beam members – capacity checks



Special moment frames: flexural members

Requirements on:

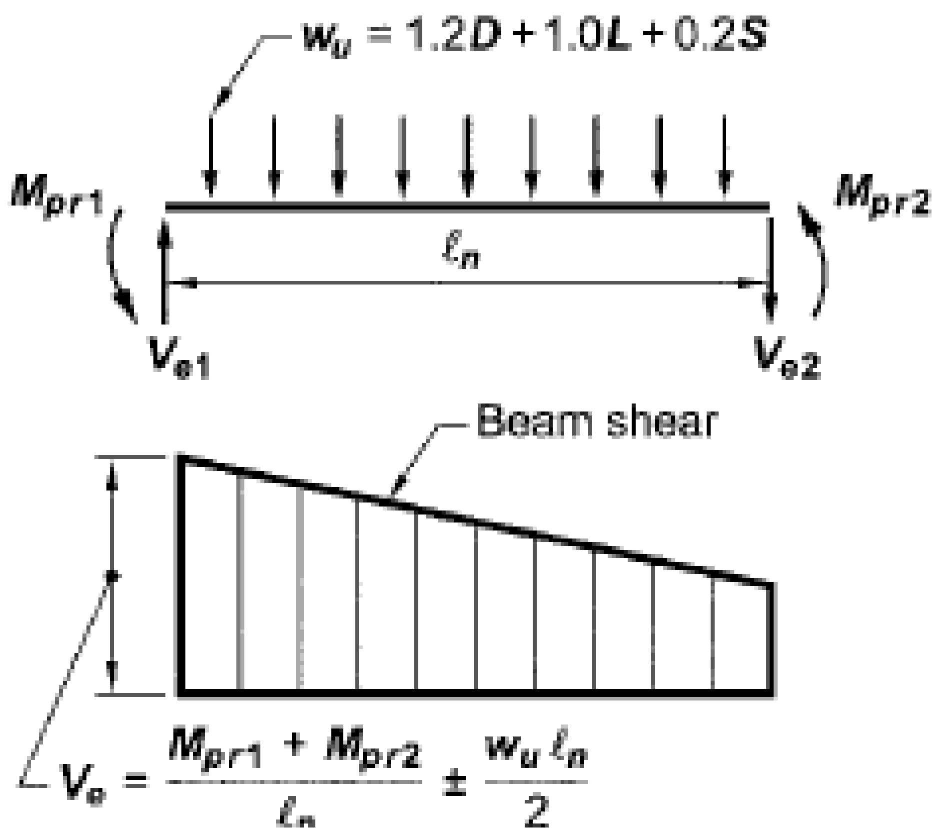
- Lap splices for longitudinal reinforcement



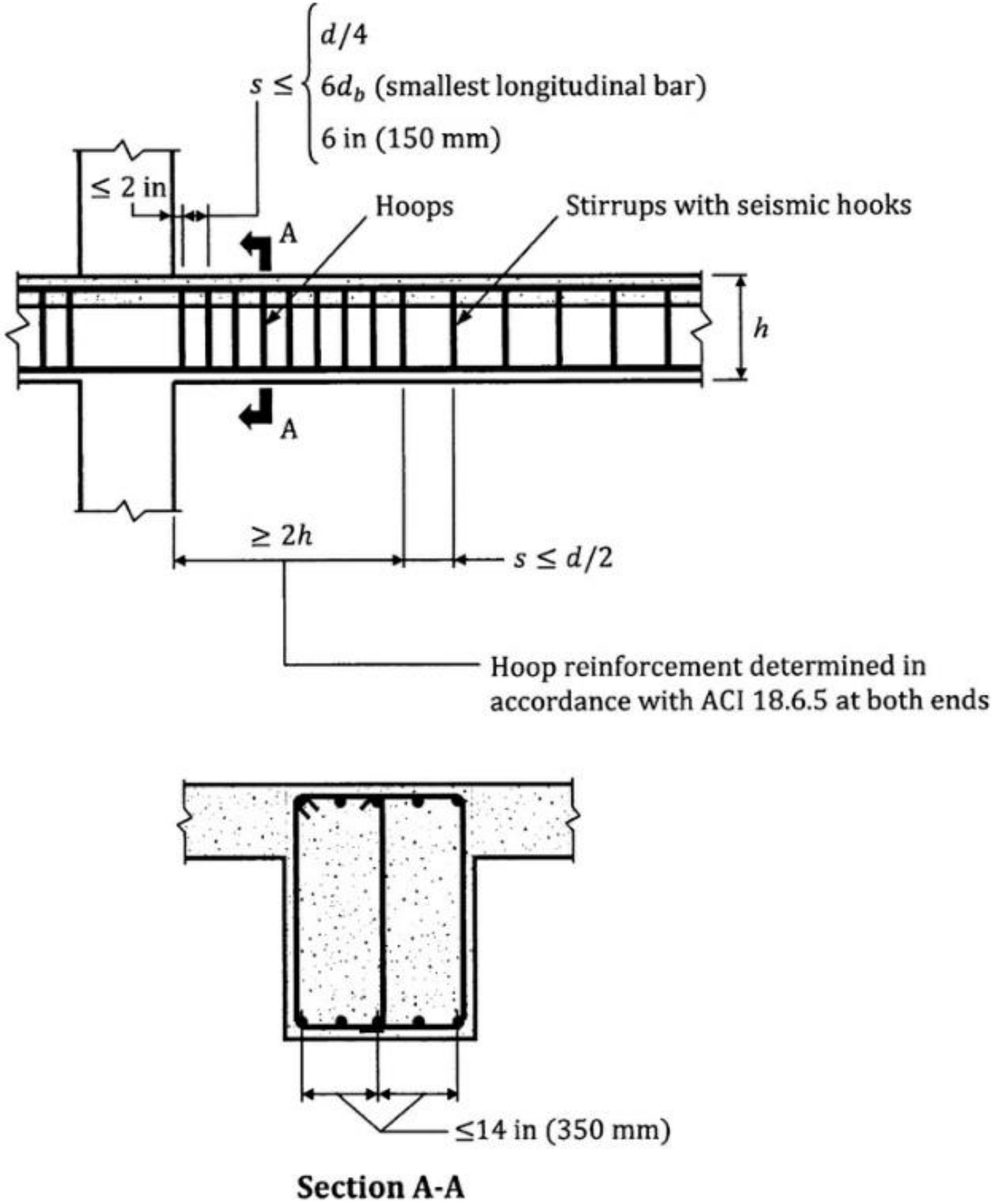
Special moment frames: flexural members – shear design values

- The design shear values are obtained from two sources, we design for the greater:
  - Analysis value from the load combinations
  - Based on flexural capacity of beams, M_{pr} computed using f_{ypr}=1.25fy and Φ is 1

- For the design of transverse reinforcement, V_c=0 if shear caused by lateral force is more than 50% of maximum required shear strength, and axial force is less than $0.05f'_c A_g$

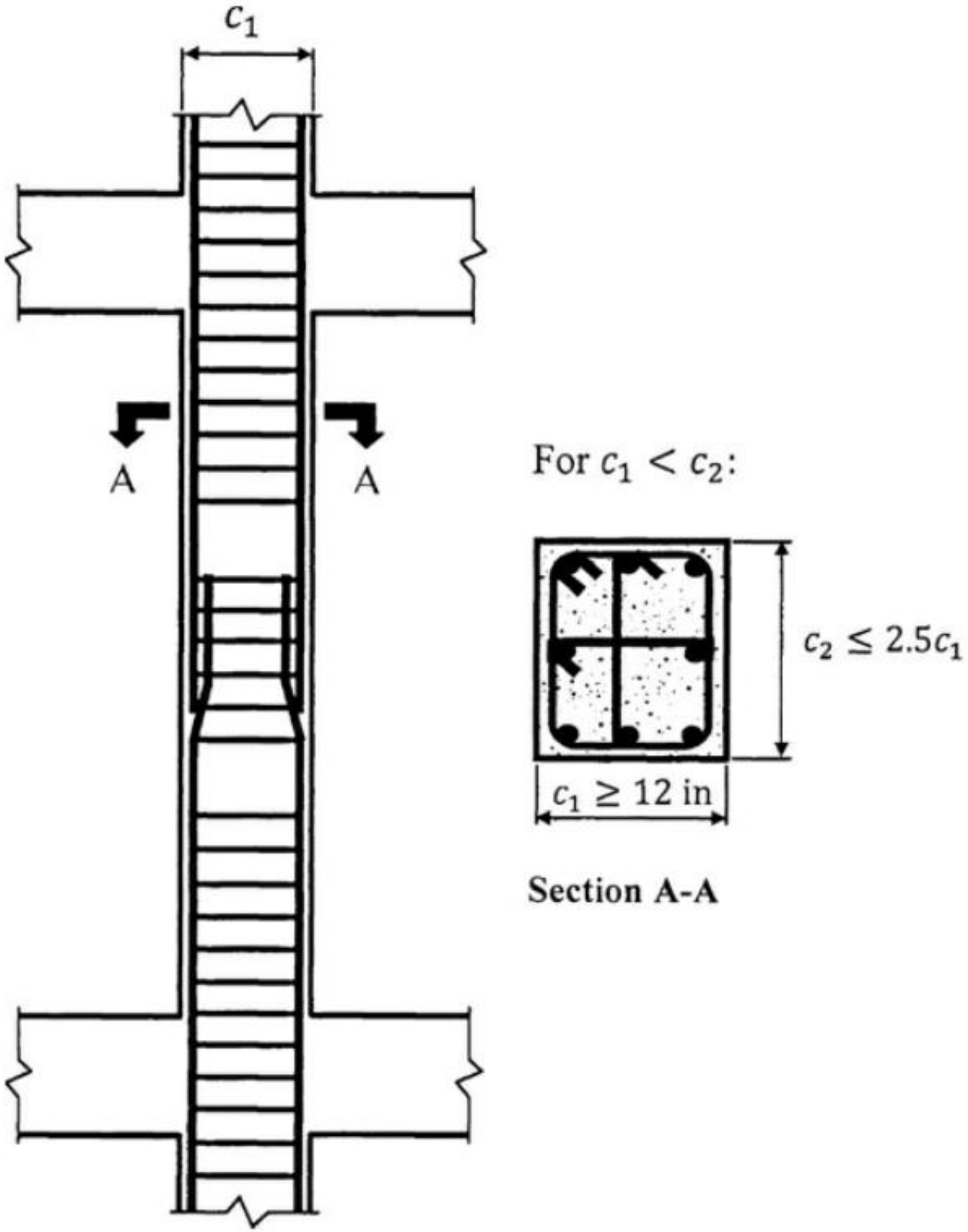


Special moment frames: flexural members – transverse reinforcement details

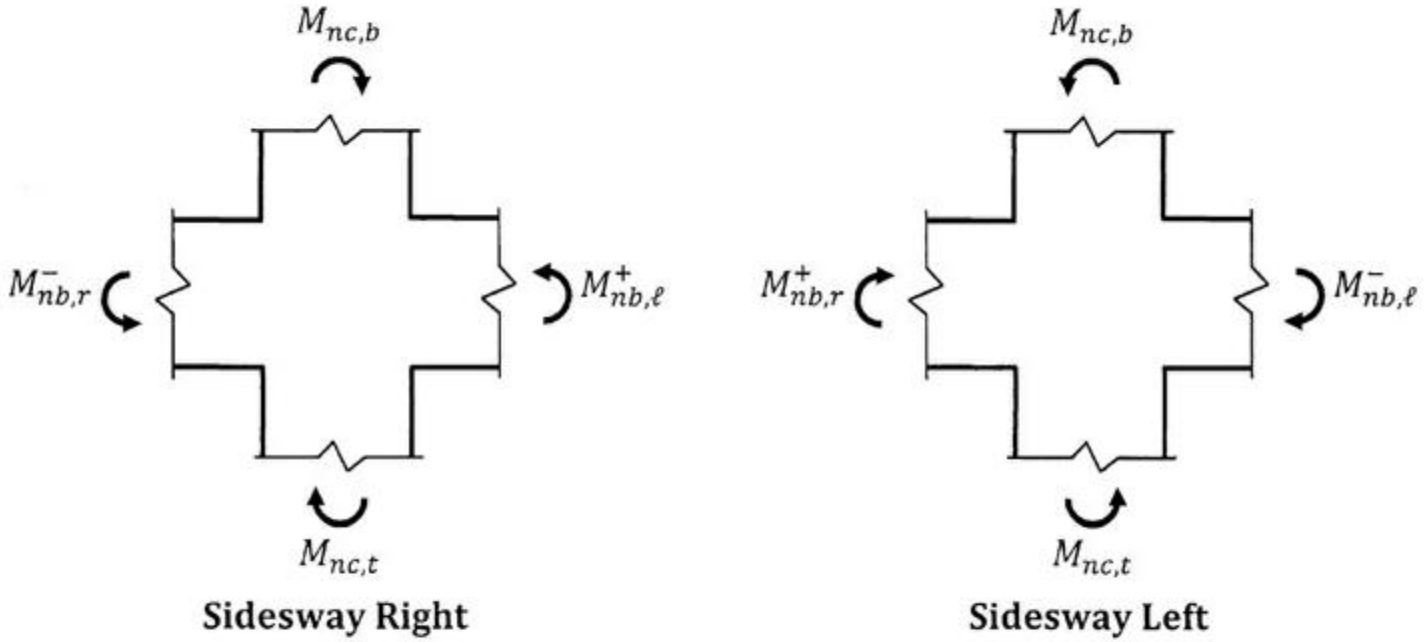


Special moment frames: column members

- Dimensional restriction
- Axial force greater than 0.10 $f'_c A_g$



Special moment frame: strong column – weak beam

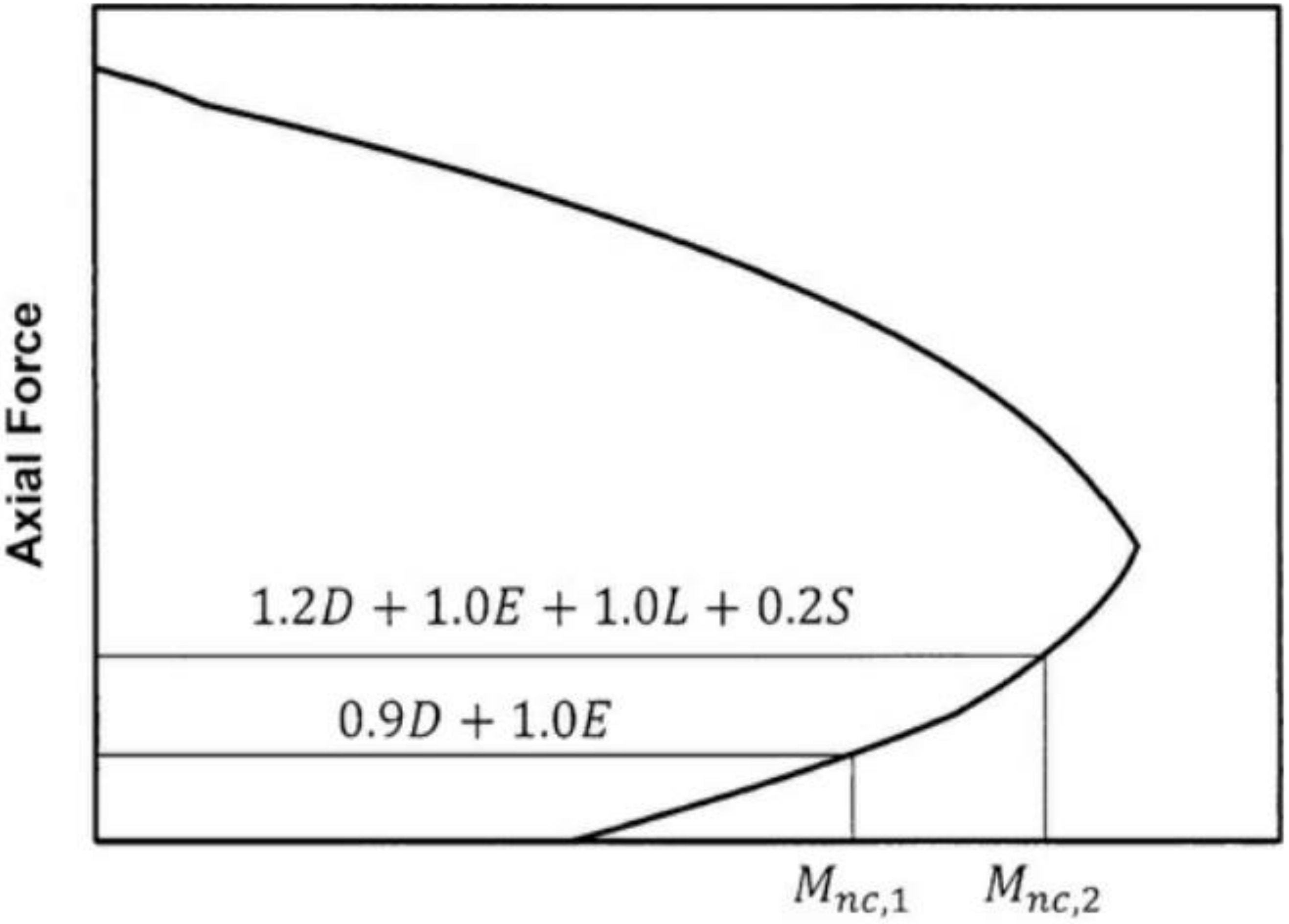


$$M_{nc,b} + M_{nc,t} \geq (6/5)\left(M^{+}_{nb,r} + M^{-}_{nb,\ell}\right)$$

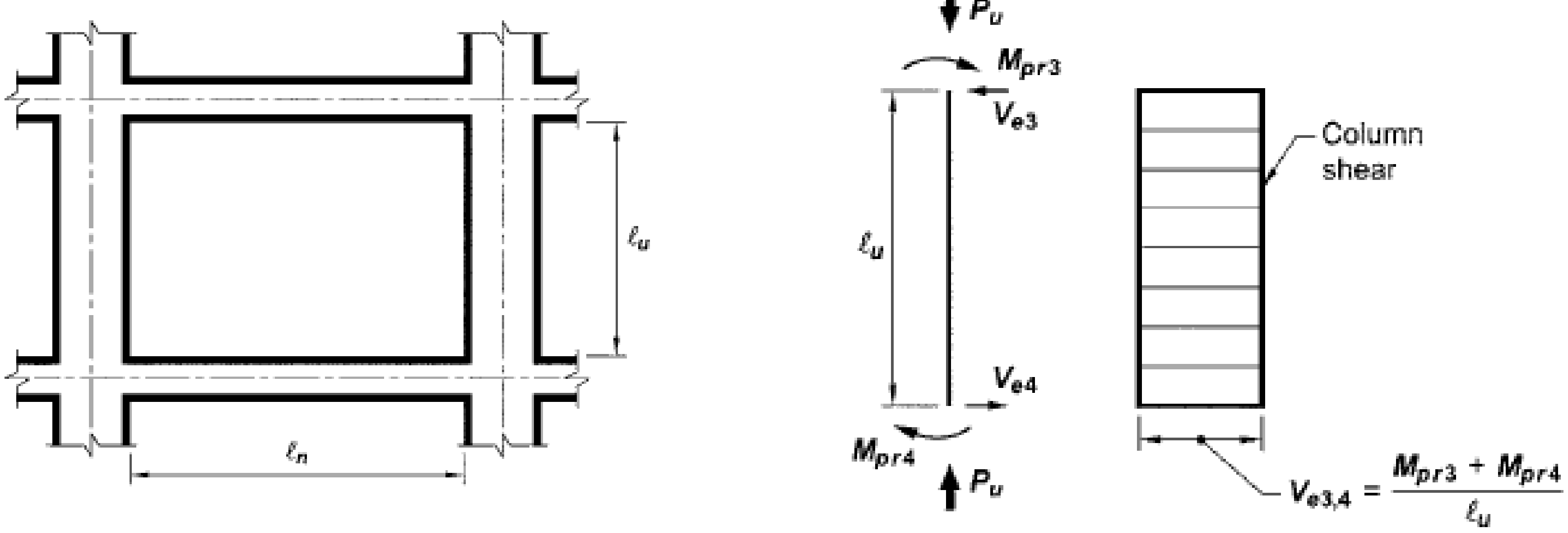
- Columns can be interior, edge and corner. The number of elements framing the joint and their reinforcement may differ
- The flexural capacity of the columns are dependent on the axial force in columns (corresponds to direction of analysis)

Special moment frame: column members

- The flexural capacity of the columns are dependent on the axial force in columns
- Do we consider lower or larger M_{nc}?



Special moment frames: column members – shear design value

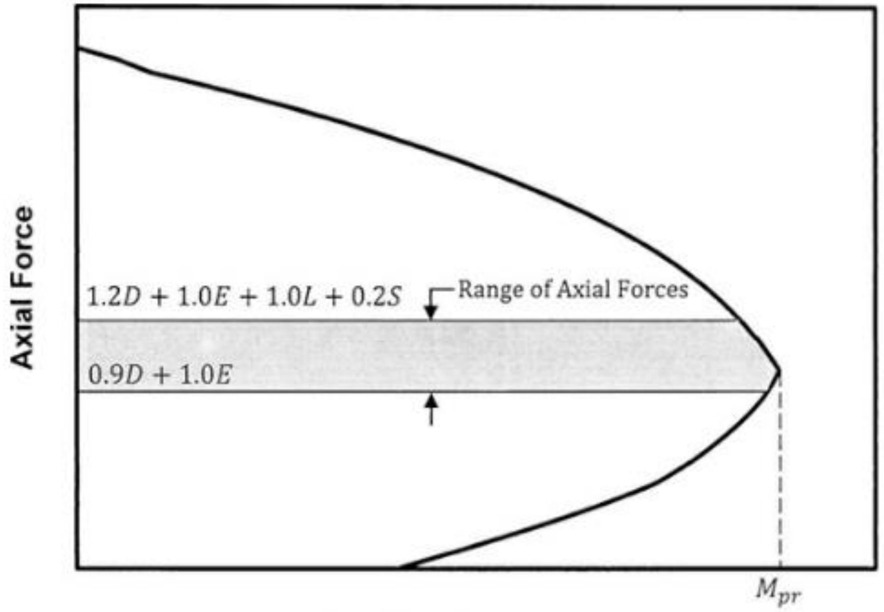


- The design shear values are obtained from two sources, we design for greater value:
  - Analysis value from the load combinations
  - Based on flexural capacity of beams, M_{pr} computed using f_{ypr}=1.25f_y and Φ is 1 P_u is considered to find M_{pr}
- For design, Vc=0 if shear caused by lateral force is more than 50% of required shear strength, and axial force is less than 0.05f'_c A_g

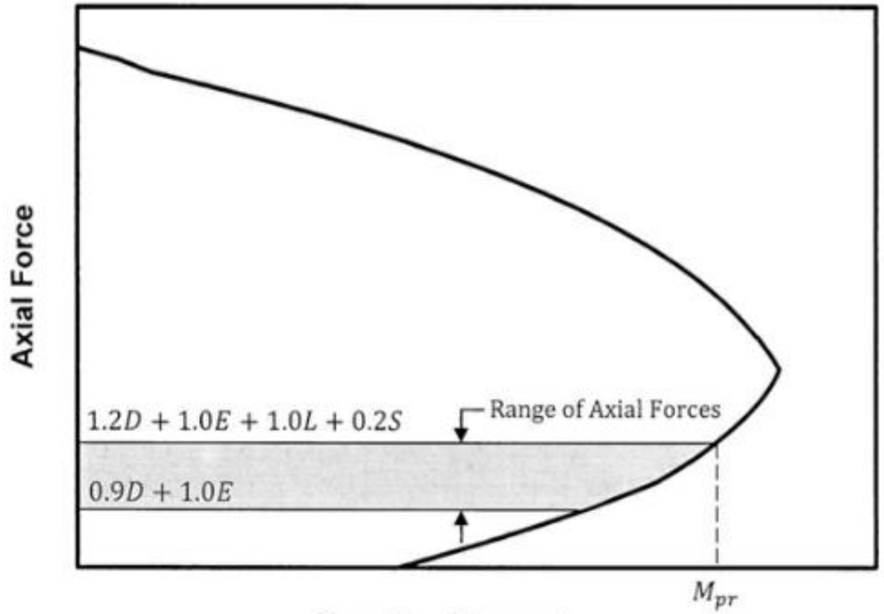
Special moment frames: column members –

how to find the bending capacity of the columns for shear design value

Do we consider lower or larger M_{pr}?

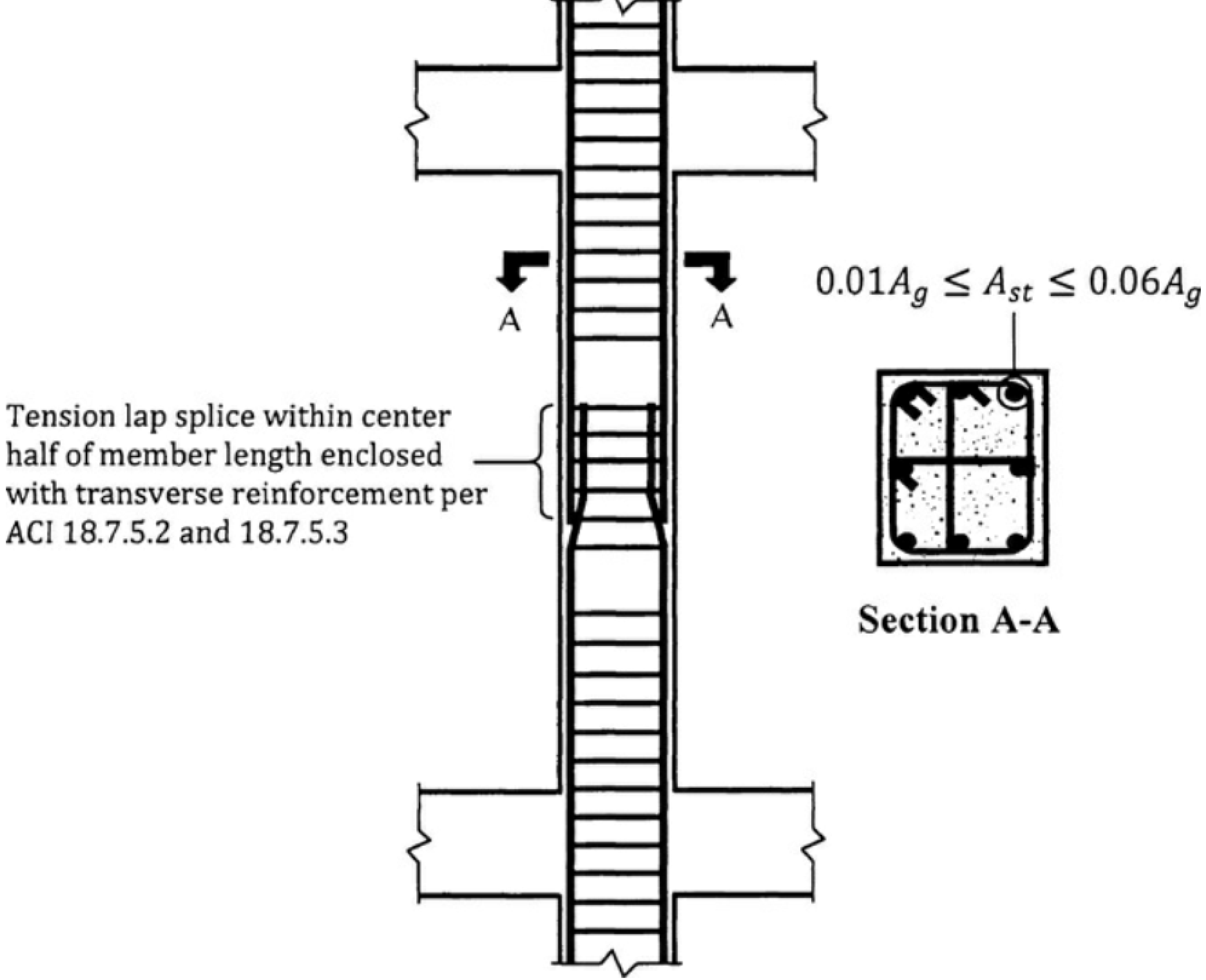


(a)

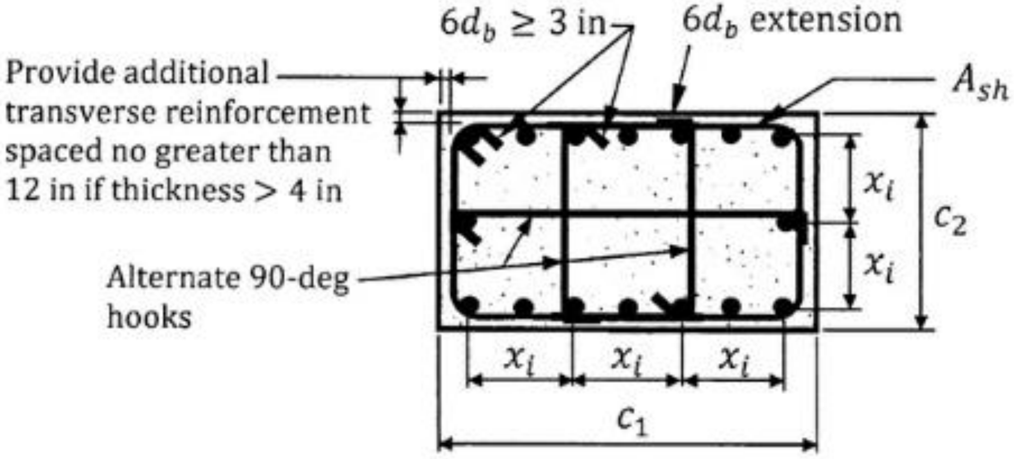


(b)

Special moment resisting frames: column's main and transverse reinforcement details

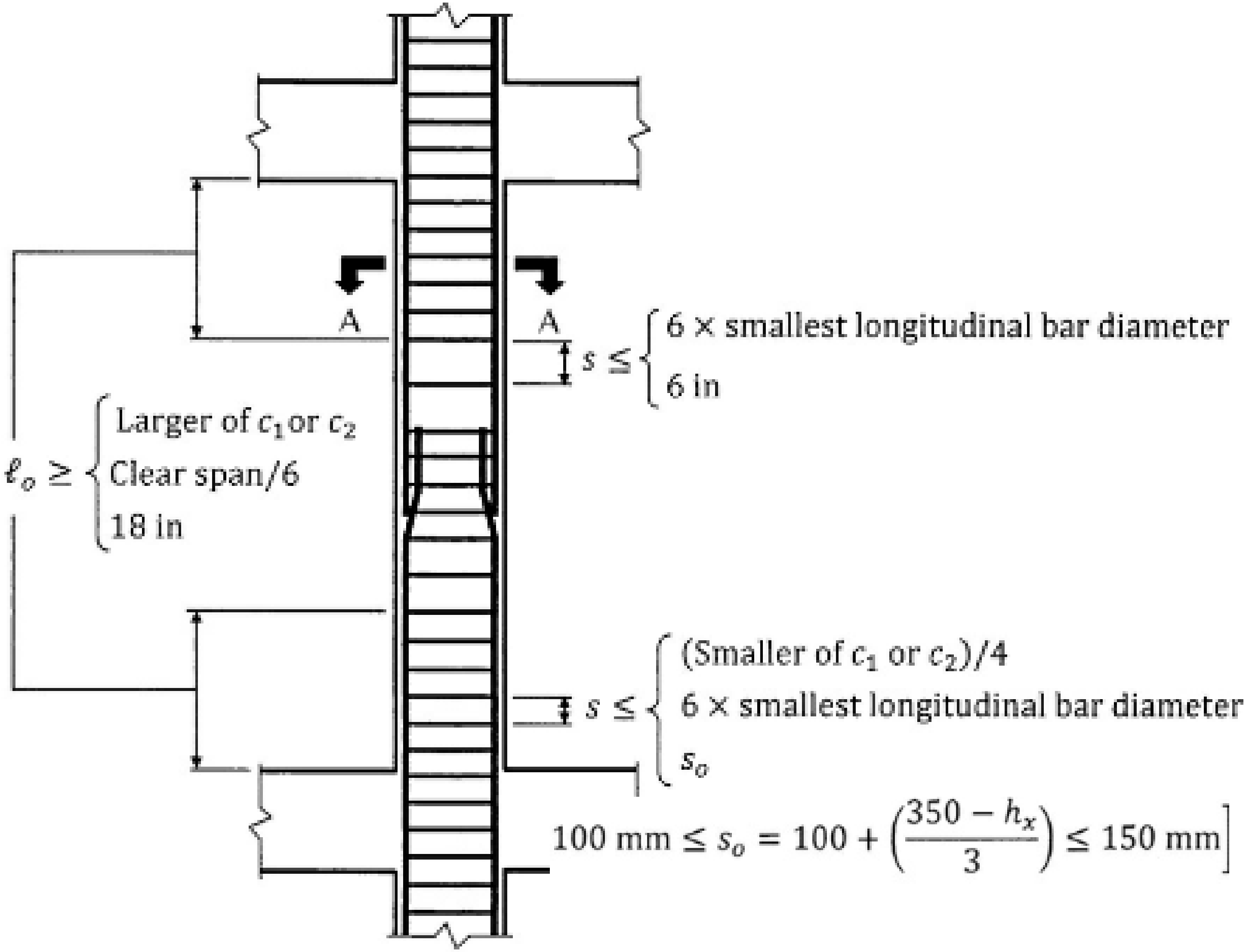


Special moment resisting frames: column main and transverse reinforcement details
for transverse reinforcement
$P_u < 0.3 A_g f'_c$ and $f'_c < 70$MPa



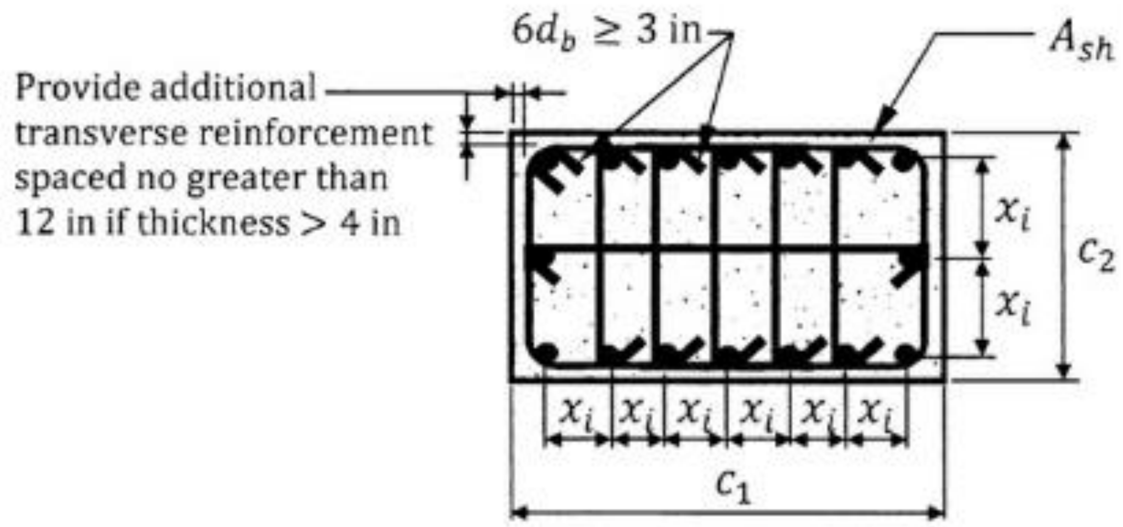
Section A-A

$$A_{sh} \geq \begin{cases} 0.3\left(\dfrac{A_g}{A_{ch}} - 1\right)\dfrac{f'_c}{f_{yt}} s b_c & \text{(a)} \\ 0.09\dfrac{f'_c}{f_{yt}} s b_c & \text{(b)} \end{cases}$$



x_i is less than or equal to 350mm, h_x in the equations of s_o is the largest of x_i
b_c is dimension of confined column that is perpendicular to the tie legs that make up A_{sh}

Special moment resisting frames: column transverse reinforcement details $P_u > 0.3A_g f'_c$ or $f'_c > 70\text{MPa}$



Section A-A

$$A_{sh} \geq \begin{cases} 0.3\left(\dfrac{A_g}{A_{ch}} - 1\right)\dfrac{f'_c}{f_{yt}} s b_c & \text{(a)} \\ 0.09\dfrac{f'_c}{f_{yt}} s b_c & \text{(b)} \\ \dfrac{0.2 k_f k_n P_u}{f_{yt} A_{ch}} s b_c & \text{(c)} \end{cases}$$

$$k_f = \frac{f'_c}{175} + 0.6 \geq 1.0$$

$$k_n = \frac{n_l}{n_l - 2}$$

where n_1 is the number of longitudinal bars

x_i is less than or equal to 200mm, h_x in the equations of s_o is the largest of x_i

Special moment frames: beam-column joints

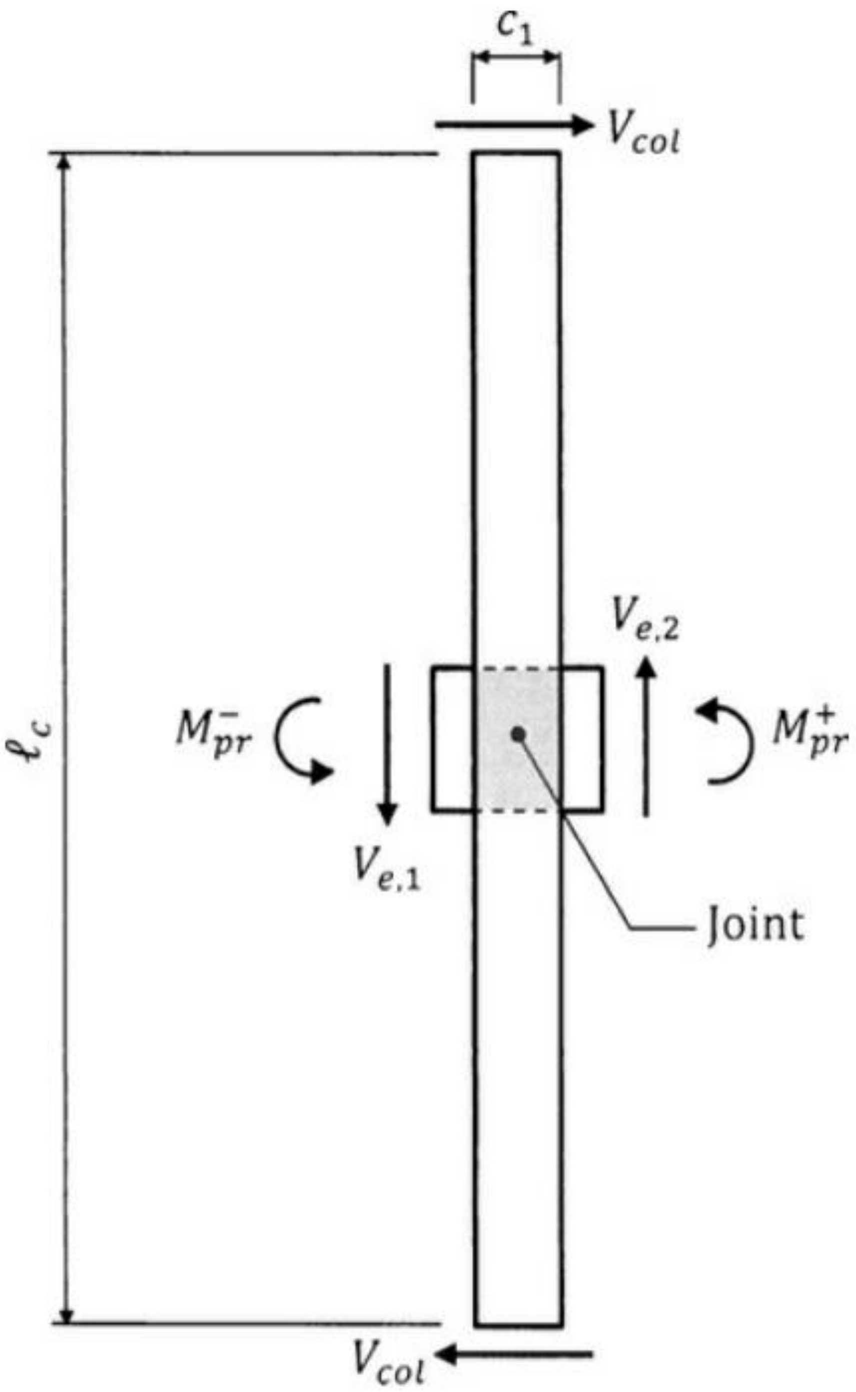
General requirements

- When computing shear strength within the joint in special frames all longitudinal reinforcement must be presumed to be stressed at $1.25f_y$
- Longitudinal reinforcement terminating at a joint must be extended to the far face of the column confined core and anchored in tension
- When the beam longitudinal reinforcement passes through the joint, the column dimension parallel to the reinforcement cannot be less that $20d_b$ for normal weight concrete and $26d_b$ for lightweight concrete

Special moment frames: beam-column joint

- The shear in the joint is calculated using M_{pr}

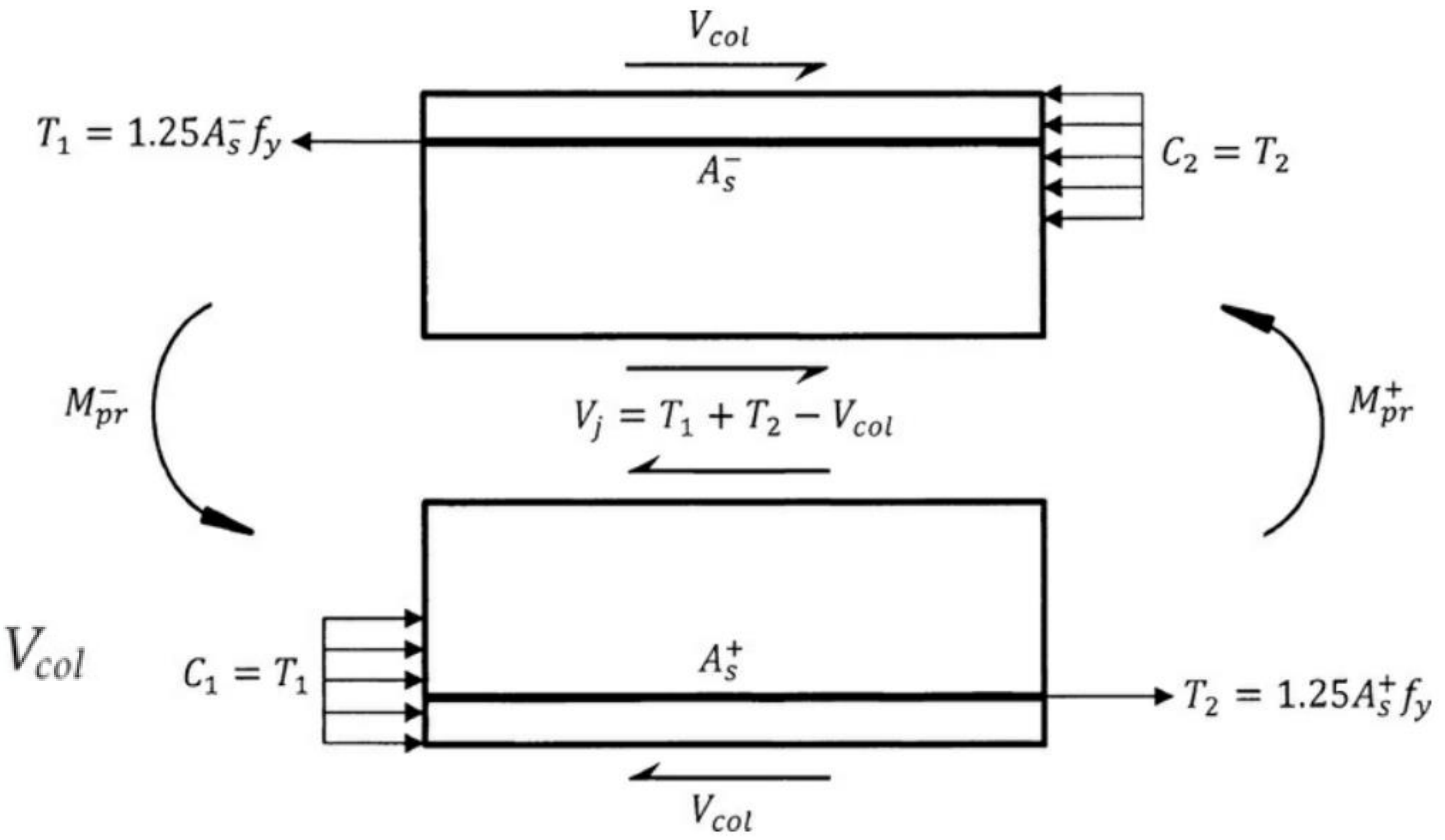
$$V_{col} = \frac{M_{pr}^{+} + M_{pr}^{-}}{\ell_c} + \frac{(V_{e,1} + V_{e,2}) \times (c_1/2)}{\ell_c}$$



Special moment frames: beam-column joint

- Computation of the shear demand on the joint Vj
- The shear in the joint is calculated using M_{pr}

$$V_j = 1.25 A_s^- f_y + 1.25 A_s^+ f_y - V_{col}$$



Special moment frame: beam-column joint

- The nominal shear strength of the joint is calculated following the table shown below, nominal strength factor is taken as 0.85

Table 18.8.4.1—Nominal joint shear strength V_n

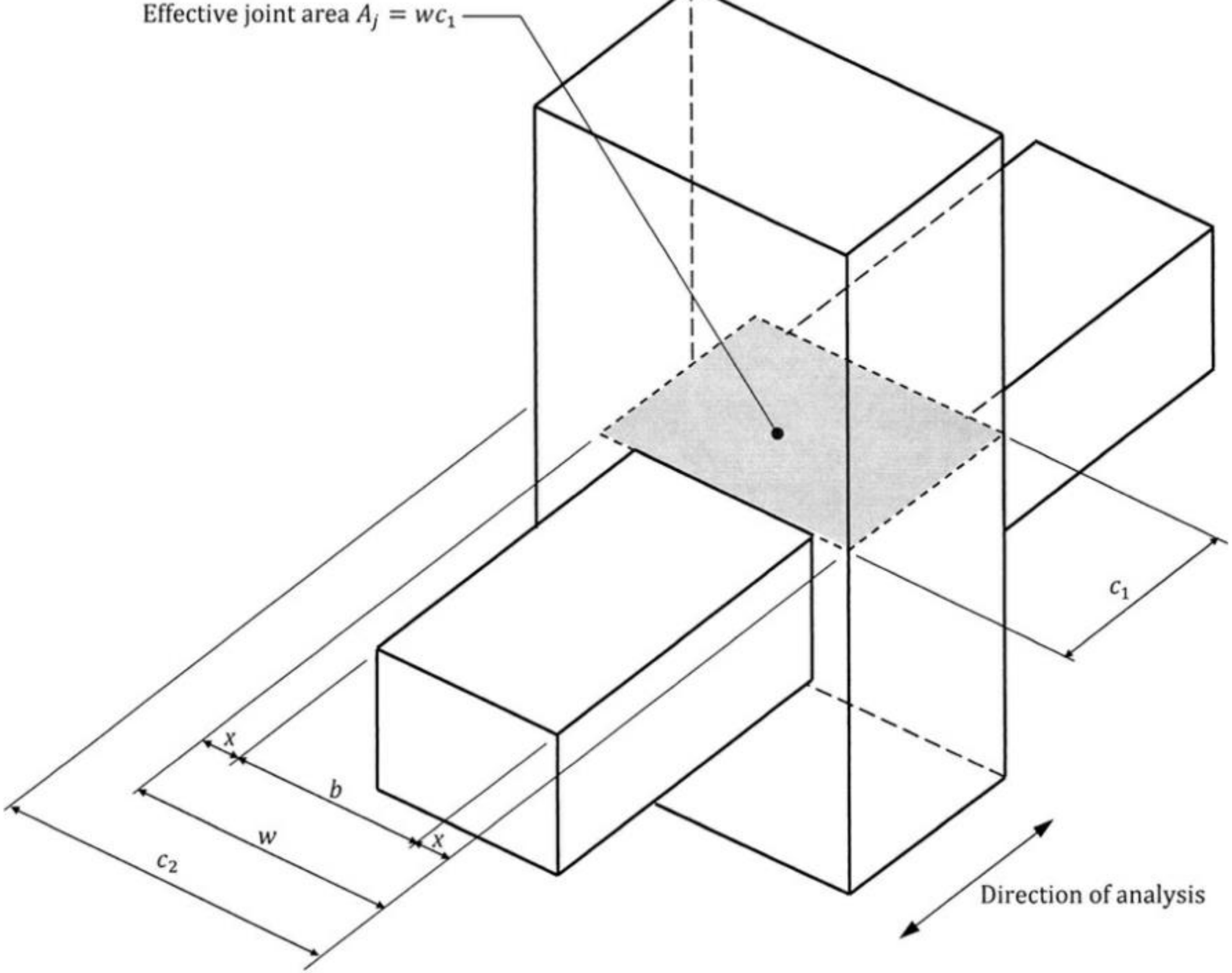
Joint configuration	V_n
For joints confined by beams on all four faces[1]	$1.7\lambda\sqrt{f_c'}A_j$ [2]
For joints confined by beams on three faces or on two opposite faces[1]	$1.2\lambda\sqrt{f_c'}A_j$ [2]
For other cases	$1.0\lambda\sqrt{f_c'}A_j$ [2]

[1] Refer to 18.8.4.2.

[2] λ shall be 0.75 for lightweight concrete and 1.0 for normalweight concrete. A_j is given in 18.8.4.3.

Special moment frame: beam-column joint

Effective area for nominal shear strength of the joint



Effective joint width w = smaller of $\begin{cases} b + c_1 \\ b + 2x \end{cases}$

Special moment frame: beam-column joint

- Development length of bars in tension

L_{dh} shall be at least the greater of $8d_b$ and 150mm for normal weight concrete

$$\ell_{dh} = f_y d_b / (5.4\lambda \sqrt{f_c'})$$

- The hook shall be located within the confined core of the column or boundary element