Lecture 05

Introduction to Earthquake Resistant Design of RC Structures (Part – II)

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Lecture Contents

- Behavior of RC buildings under Seismic loading
- ACI Special Provisions for Seismic Design of RC Buildings
- ACI Provisions for Concrete SMF
- ACI Provisions for Concrete IMF
- Example 5.2
- References

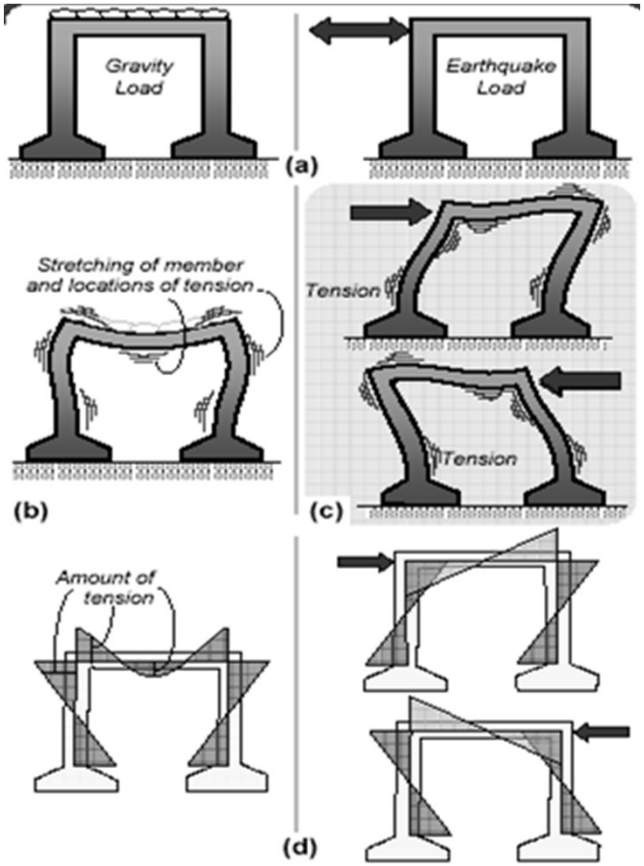
Learning Outcomes

- **At the end of this lecture, students will be able to;**
  - ***Outline*** ACI Provisions related to Earthquake resistant design of structures
  - ***Evaluate*** RC Members for Special Moment Frame Provisions

Behavior of RC buildings under Seismic loading

❑ Gravity loading vs Earthquake loading in RC buildings

- Under gravity loads, tension in the beams is at bottom midspan and is at top at the ends.
- On the other hand, earthquake loading causes tension in the beam and column faces at locations different from those under gravity loading.
- Hence steel bars are required on both faces of beams to resist reversals of bending moment.



Earthquake-Resistant Design of Buildings

❑ Seismic Force Resisting Systems

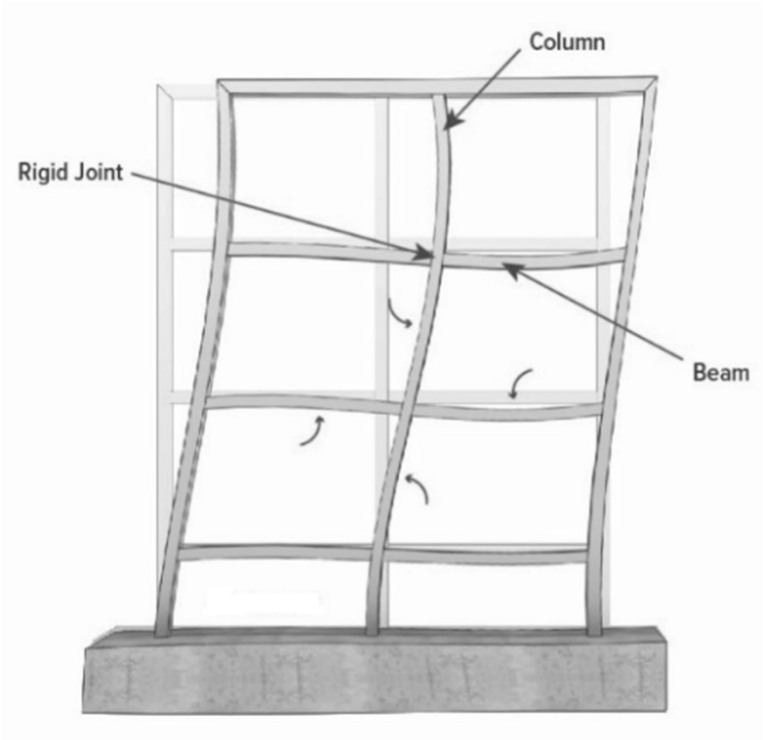
- The structural systems that are used to resist design earthquake forces are known as Seismic Force-Resisting Systems (SFRS).
- The four main categories of SFRS are:

1. Bearing Wall Systems
2. Building Frame Systems
3. Moment-Resisting Frame Systems
4. Dual Systems

Earthquake-Resistant Design of Buildings

❑ Moment-Resisting Frame Systems

- In Moment-Resisting Frame Systems (MRFS), both vertical and lateral resistance is provided by moment-resisting connections between the columns and beams.



Earthquake-Resistant Design of Buildings

❑ Moment-Resisting Frame Systems

- Based on the deformation capacity (ductility) , Moment-Resisting Frame Systems (MRFS) are further classified as:

Ordinary Moment-Resisting Frame (OMRF) or Ordinary Moment Frame (OMF)	Intermediate Moment-Resisting Frame (IMRF) or Intermediate Moment Frame (IMF)	Special Moment-Resisting Frame (SMRF) or Special Moment Frame (SMF)

Deformation capacity (Ductility)

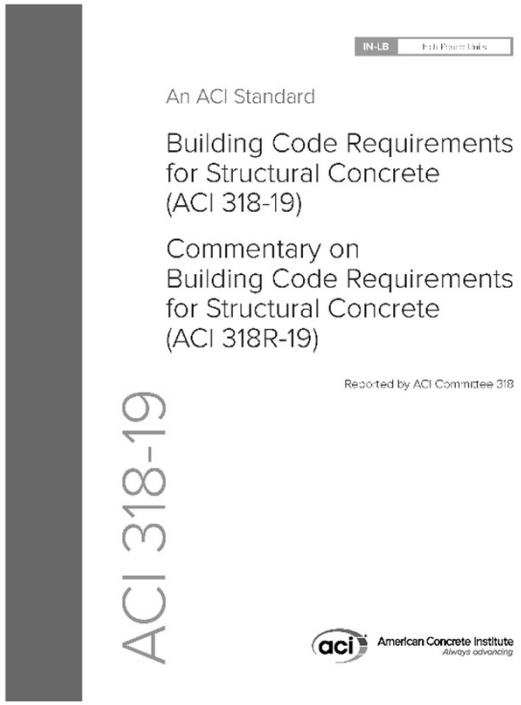
- The detailing and proportioning requirements of ACI become more stringent when moving from OMRF to SMRF.

ACI Provisions for Concrete SMF and IMF

ACI Provisions for Concrete SMF and IMF

❑ Aim of Special Provisions

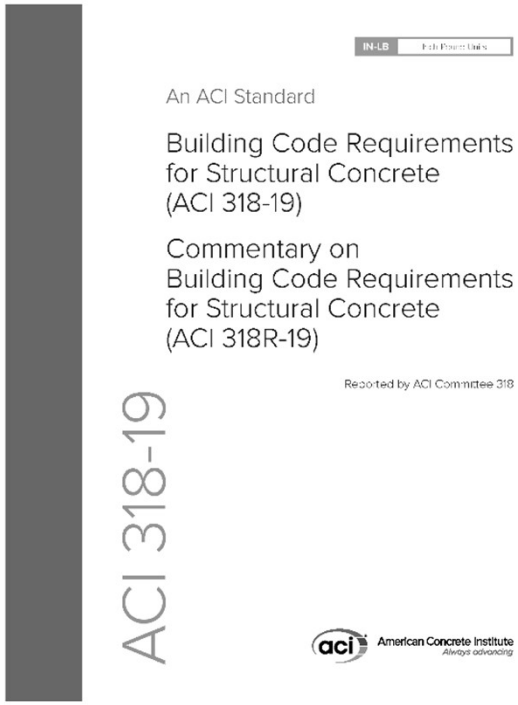
- The principal goal of the Special Provisions of ACI 318 is to ensure adequate toughness under inelastic displacement reversals brought on by earthquake loading.
- The provisions accomplish this goal by requiring the designer to provide adequate concrete confinement.



ACI Provisions for Concrete SMF and IMF

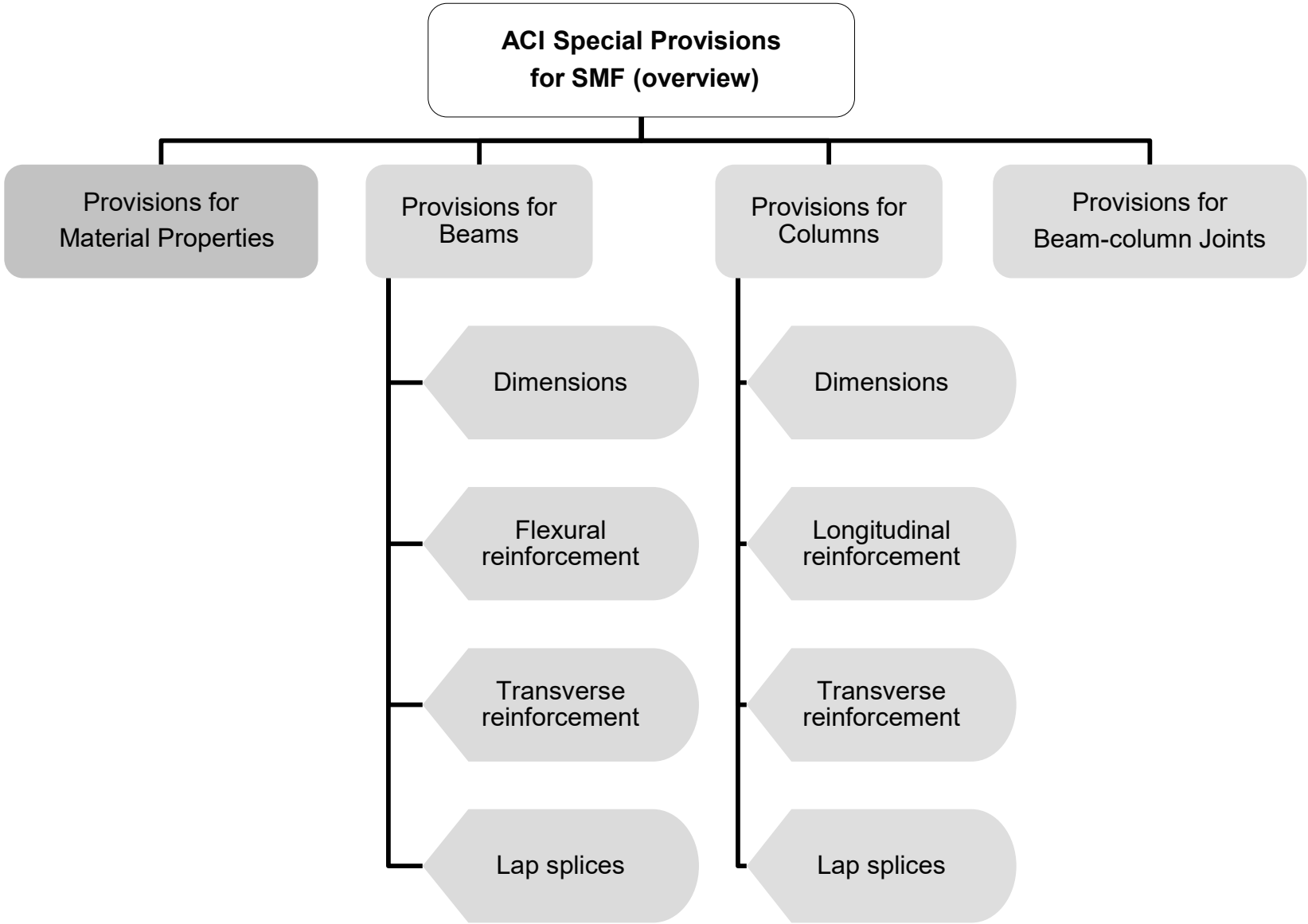
❑ Focus of this Lecture

- In this lecture, only few important provisions as specified in chapter 18 of ACI 318-19 will be discussed.
- For details, please refer to the stated chapter.



ACI Provisions for Concrete SMF

ACI Provisions for Concrete SMF



ACI Provisions for Concrete SMF

❑ Material Properties (20.2.2.5)

- Specified compressive strength of concrete in members resisting earthquake induced forces, shall not be less than 3000 psi (cylinder strength) as per Table 19.2.1.1.
- There is no limit on the maximum value of f_c' for normal weight concrete.

ACI Provisions for Concrete SMF

❑ Material Properties (20.2.2.5)

- Deformed longitudinal reinforcement resisting earthquake-induced forces in SMF shall be in accordance with (a) or (b):

  a) ASTM A706 (low alloy steel): Grade 60 and 80

  b) ASTM A615 (Billet steel):

  - Grade 80 is permitted only in certain applications (refer to Table 20.2.2.4a)
  - Grade 60 with certain conditions listed below.

ACI Provisions for Concrete SMF

❑ Material Properties (20.2.2.5)

a) ASTM A615 (Billet steel)

i. (Actual f_y − specified f_y) $\leq 18ksi$

ii. Ratio of actual ultimate tensile strength to actual yield strength shall be at least 1.25

iii. Minimum elongation in 8 inches long bar shall be at least

- 14% for #3 to #6
- 12% for #7 to #11
- 10% for #14 and #18

ACI Provisions for Concrete SMF

❑ Provisions for Beams (18.6.2)

1. Dimensional Limits (18.6.2.1)

a. Ratio of clear span l_n to the effective depth d shall be at least 4 $(l_n/d \geq 4)$

e.g., for L_n = 15 ft, d = 16″, L_n/d = 15 × 12/16 = 11.25 > 4, O.K.

b. Ratio of width b_w to depth h shall be at least 0.3 $(b_w/h \geq 0.3)$

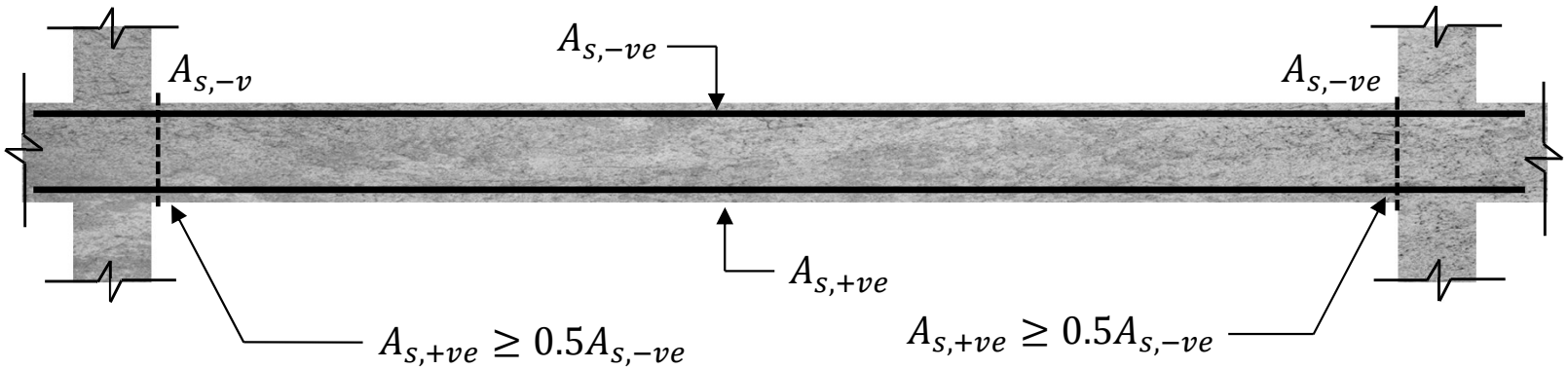
e.g., for width, b = 12″ and depth, h = 18″, b/h = 12/18 = 0.67 > 0.3, O.K.

c. Minimum width b_w shall not be less than 10″

ACI Provisions for Concrete SMF

❑ Provisions for Beams (18.6.2)

2. Flexural reinforcement (18.6.3)

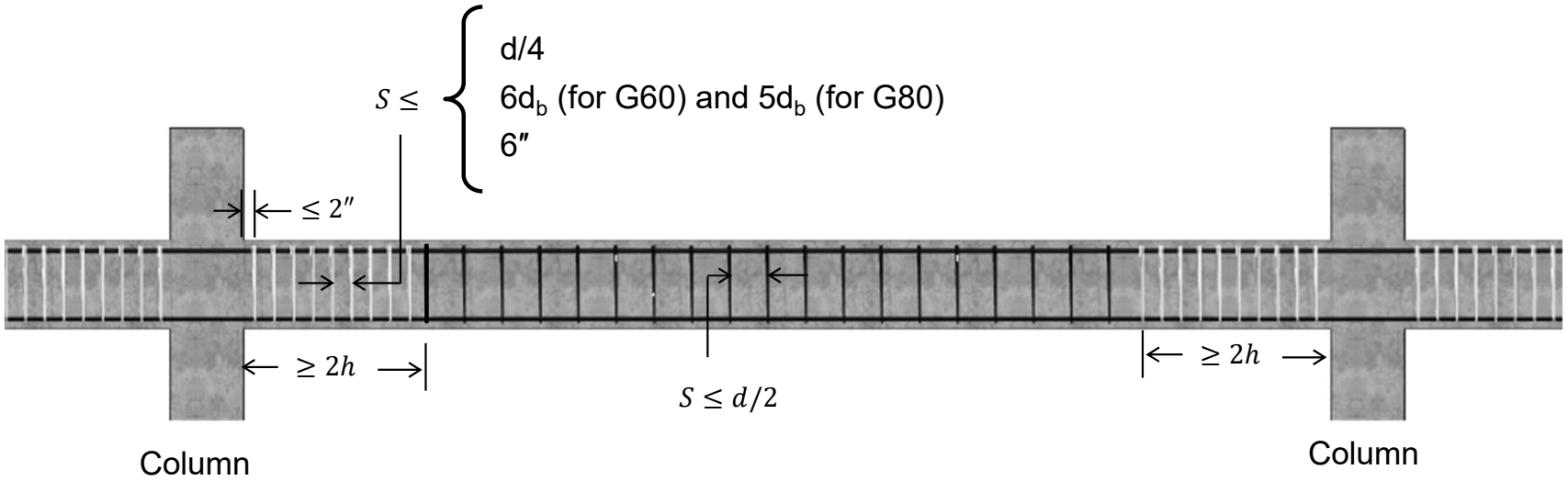


1. *Minimum 2 bars continous at all locations*
2. *At ends of beams;* $A_{s,+ve} \geq 0.5A_{s,-ve}$
3. $A_{s,-v}$ or $A_{s,+v}$ (at all sections) ≥ (maximum of A_s at either joint)/4
4. $A_{s,min} = larger\ of \left(\frac{3\sqrt{f_c'}}{f_y}, \frac{200}{f_y}\right) bd\ (at\ critical\ locations)$ and $A_{s,max} = 0.025bd\ (for\ Grade\ 60)$

ACI Provisions for Concrete SMF

❑ Provisions for Beams (18.6.2)

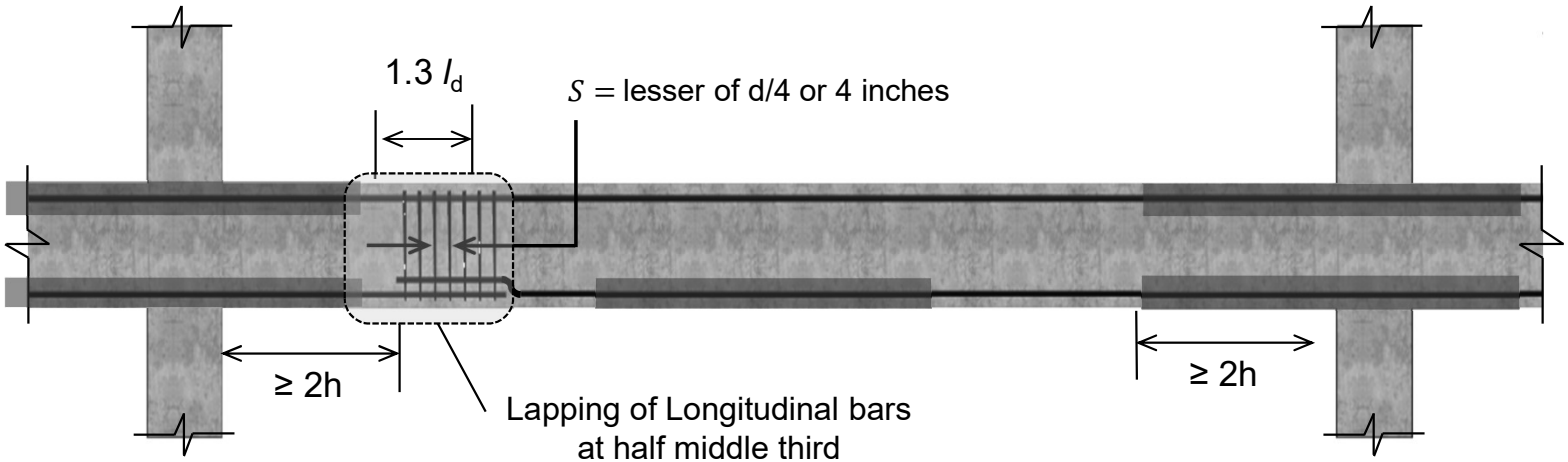
3. Transverse reinforcement (18.6.4)



ACI Provisions for Concrete SMF

❑ Provisions for Beams (18.6.2)

4. Splices (18.6.3.3)



Lapping is not allowed in regions where, longitudinal bars can yield in tension

Lap splice length = 1.3 l_d

$$l_d = \frac{f_y}{25\sqrt{f_c'}} d_b \ (\leq \#6) \qquad l_d = \frac{f_y}{20\sqrt{f_c'}} d_b \ (> \#6)$$

Taking f_c' = 3 ksi and f_y = 60 ksi

- **57 d_b** for bar size up to #6
- **71 d_b** for bar size greater than #6

ACI Provisions for Concrete SMF

❑ Provisions for Beams (18.6.2)

4. Splices (18.6.3.3)

- Mechanical (section 25.5.7) and welded splices (section 18.2.8) are permitted at the same half middle third location as shown on previous slide and should have strength of at least $1.25f_y$.

ACI Provisions for Concrete SMF

❑ Provisions for Columns (18.7)

1. Dimensional limits (18.7.2.1)

a) The shortest cross-sectional dimension shall be at least 12″

b) The ratio of the shortest cross-sectional dimension to the perpendicular dimension shall be at least 0.4

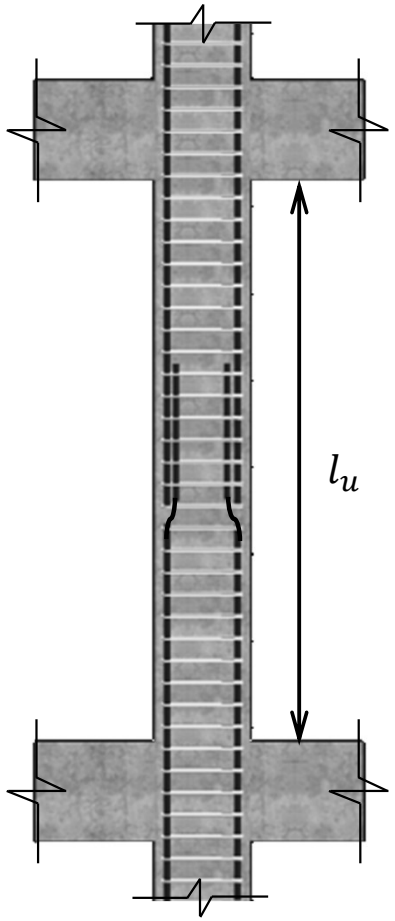
For example; 12/12, 12/18, 12/24 OK; but 12/36 is not O.K

ACI Provisions for Concrete SMF

❑ Provisions for Columns (18.7)

2. Longitudinal reinforcement (18.7.4)

a) Minimum area of longitudinal reinforcement, A_{st}, shall be at least $0.01A_g$ and shall not exceed $0.06A_g$.

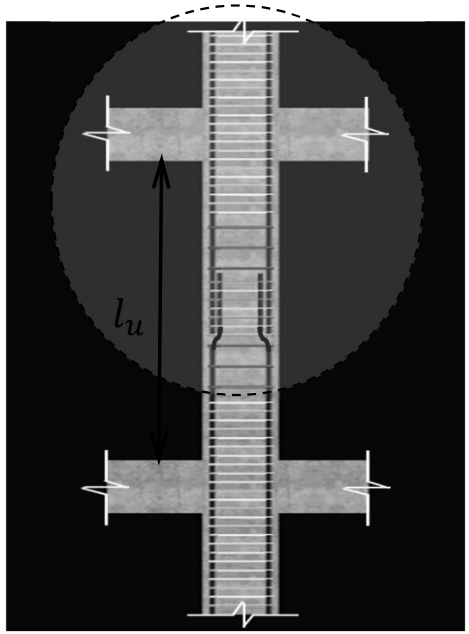


l_u is unsupported/clear height of column

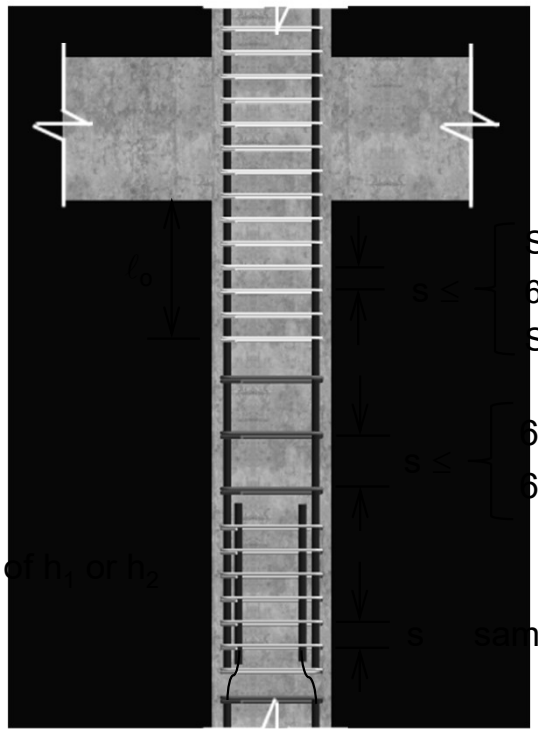
ACI Provisions for Concrete SMF

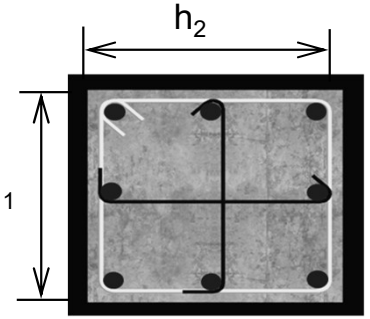
❑ Provisions for Columns (18.7)

3. Transverse reinforcement (18.7.5)



ℓ_o = max { Larger of h_1 or h_2 ; $l_u/6$; 18″





Smaller of $h_1/4$ or $h_2/4$
$6d_b$ for G60 and $5d_b$ for G80
S_o (defined on next slide)

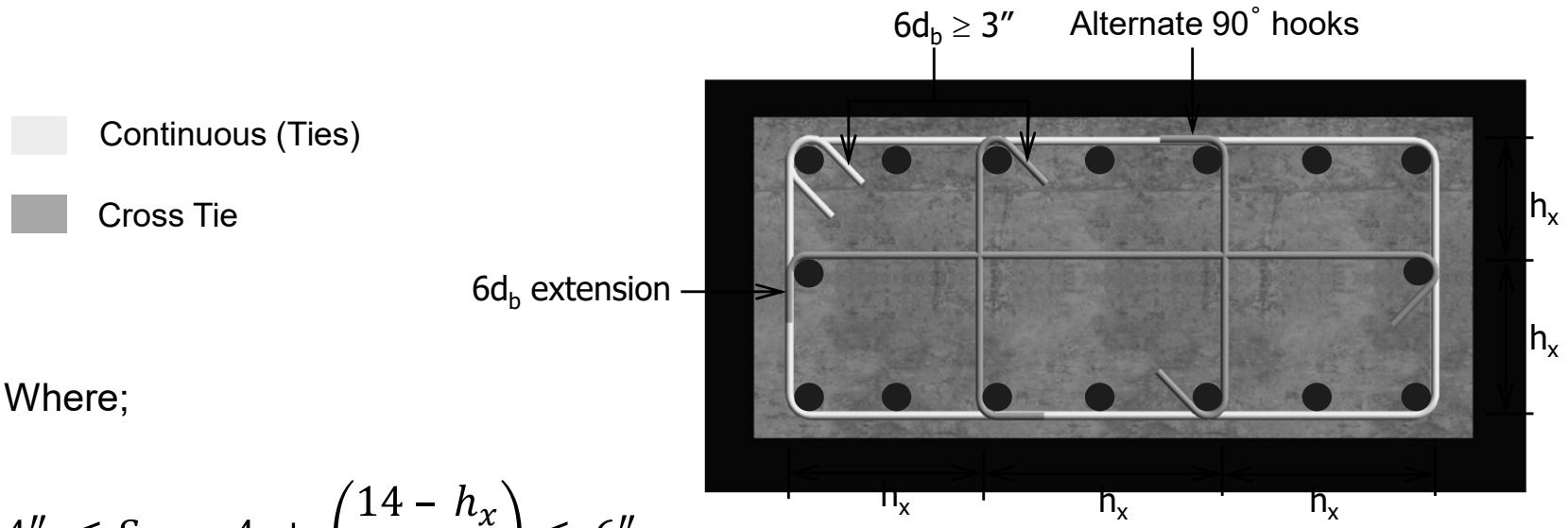
$6d_b$ for G60 and $5d_b$ for G80
6″

same as that of l_o region

ACI Provisions for Concrete SMF

❑ Provisions for Columns (18.7)

3. Transverse reinforcement (18.7.5)



Where;

$$4'' \leq S_o = 4 + \left(\frac{14 - h_x}{3}\right) \leq 6''$$

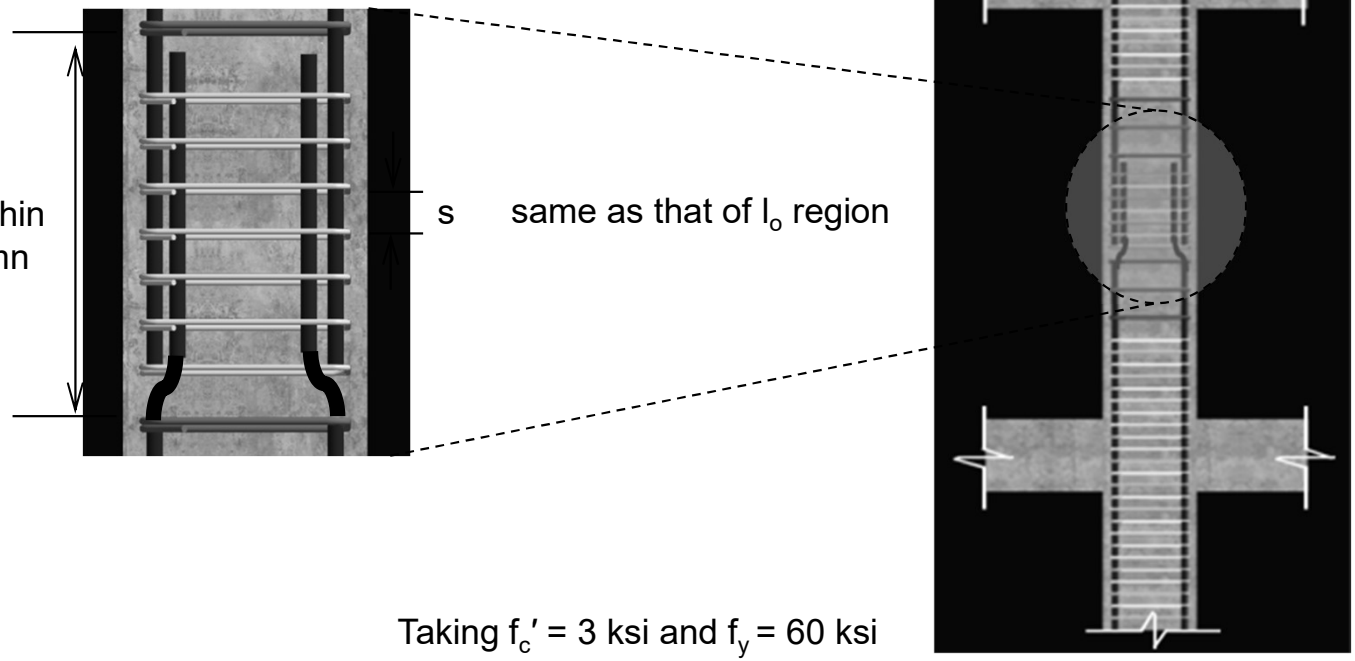
h_x = maximum value of h_x on all column faces

$h_x \leq 14''$

ACI Provisions for Concrete SMF

❑ Provisions for Columns (18.7)

3. Lap Splices (18.7.4.4)



Lap splice length = 1.3 l_d

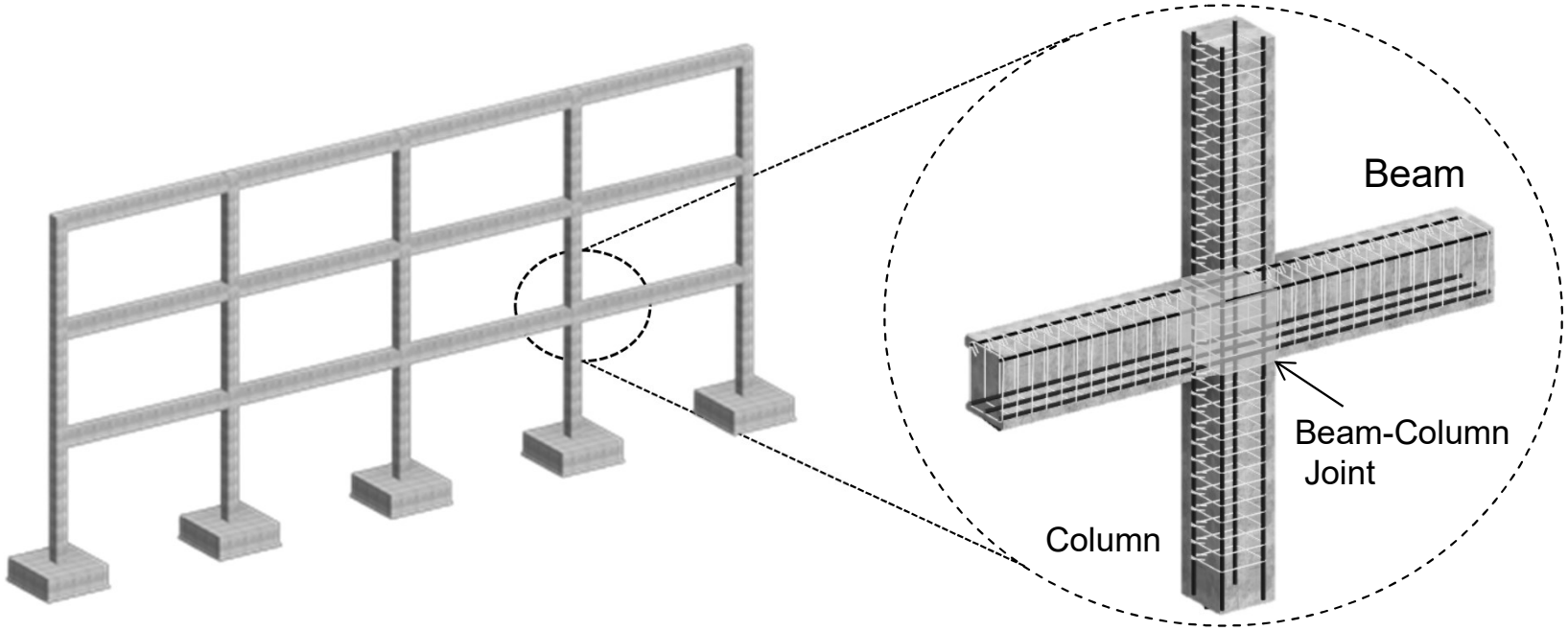
$$l_d = \frac{f_y}{25\sqrt{f_c'}} d_b \ (\leq \#6) \qquad l_d = \frac{f_y}{20\sqrt{f_c'}} d_b \ (> \#6)$$

Taking f_c' = 3 ksi and f_y = 60 ksi

- **57 d_b** for bar size up to #6
- **71 d_b** for bar size greater than #6

ACI Provisions for Concrete SMF

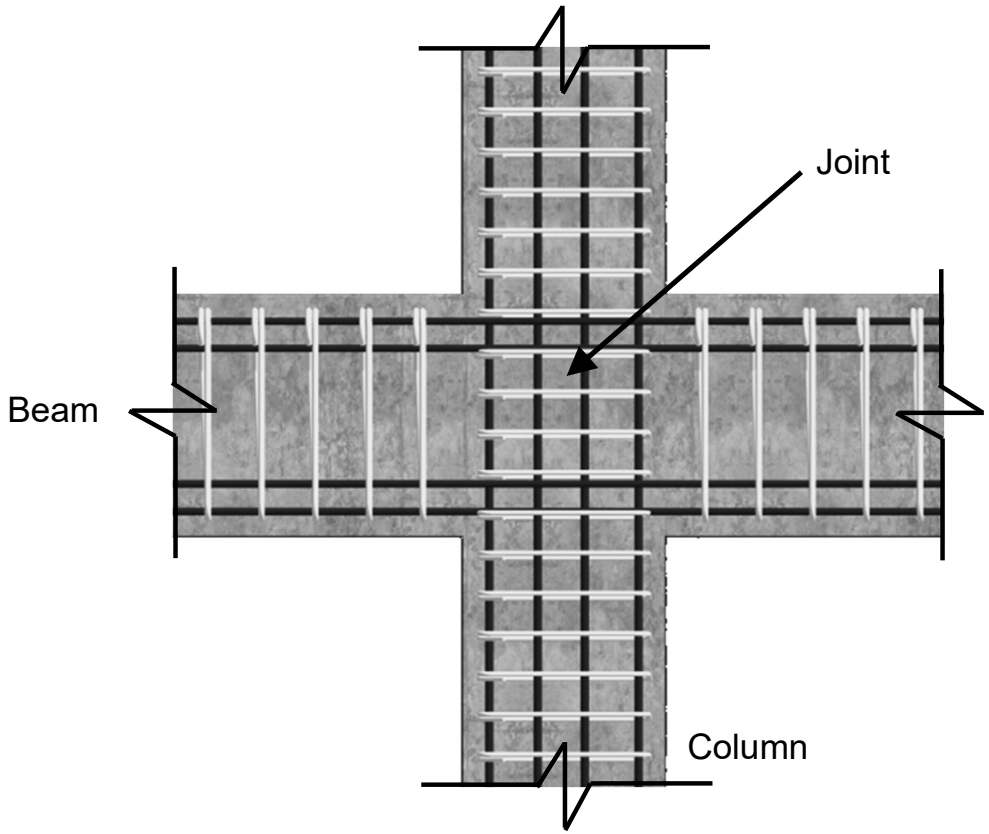
❑ Provisions for Beam-column Joints (18.8)



ACI Provisions for Concrete SMF

❑ Provisions for Beam-column Joints (18.8)

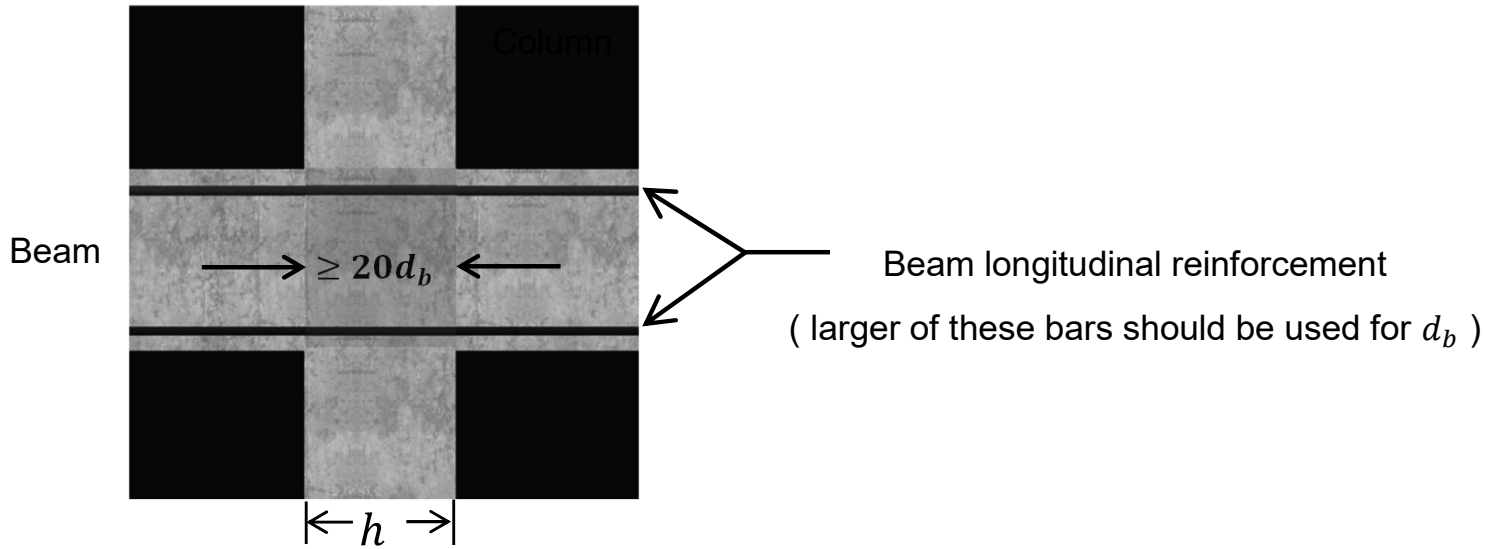
- Column ties (with 135deg hook) to be continued through joint.



ACI Provisions for Concrete SMF

❑ Provisions for Beam-column Joints (18.8)

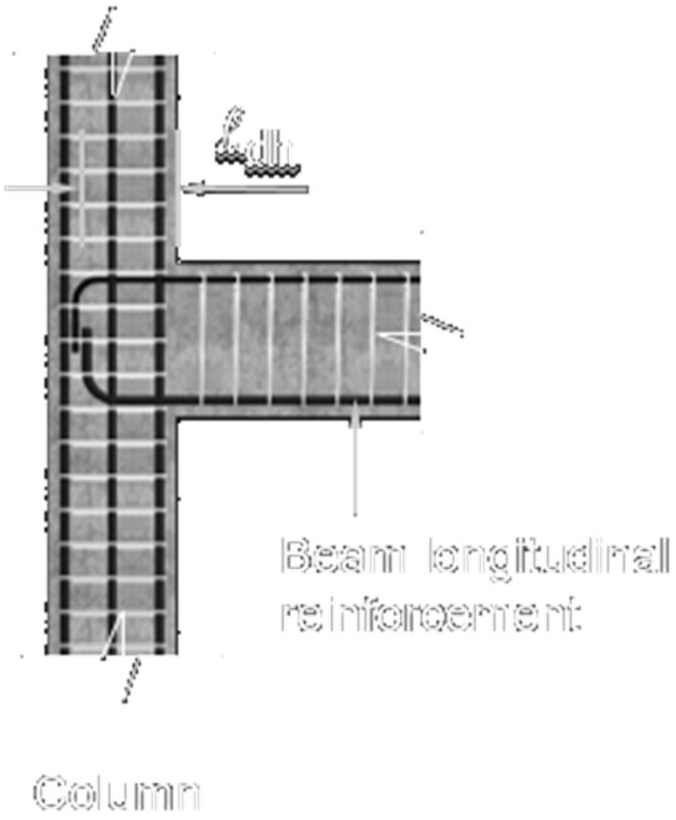
- The depth h of the joint parallel to the beam longitudinal reinforcement shall be at least 20 times diameter of largest Grade 60 longitudinal bar.



ACI Provisions for Concrete SMF

❑ Provisions for Beam-column Joints (18.8)

- Beam longitudinal reinforcement that is terminated within a column, must be extended to the far face of the column core.
- The development length l_{dh} of bars with 90° hooks must be not less than $8d_b$, 6″, or $f_y d_b / 65\sqrt{f_c'}$



For more details on Beam-column joints, please refer to **ACI 352R**.

ACI Provisions for Concrete SMF

❑ Provisions for Beam-column Joints (18.8)

Experimental test on beam-column joint

ACI Provisions for Concrete SMF

❑ Limitations of SMF Systems

- There are no limitations on use of SMF systems.
- They are permitted in all seismic zones (2A,2B,3 and 4) without any structural height restrictions.

ACI Provisions for Concrete IMF

ACI Provisions for Concrete IMF

❑ Material Properties

- There is are no special provisions/requirements for concrete in IMF.

ACI Provisions for Concrete IMF

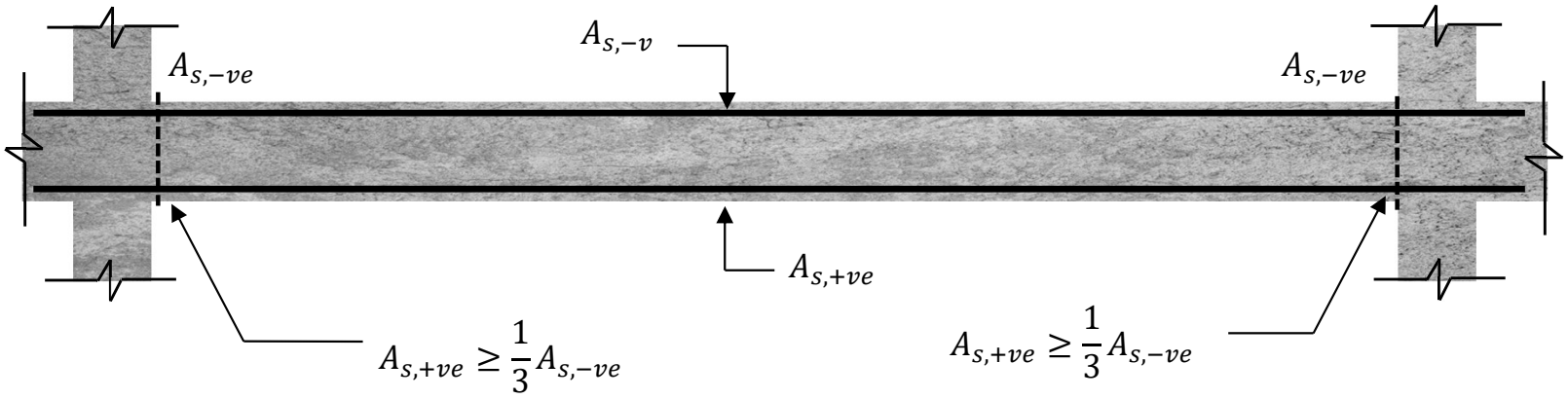
❑ Provisions for Beams (18.4.2)

- Size: No special requirements (just as ordinary beam requirements).
- Flexural reinforcement: Less stringent requirement as discussed next.
- Transverse reinforcement: Less stringent requirement as discussed next.
- Lap Splices: No special requirements (just as ordinary beam requirements).

ACI Provisions for Concrete IMF

❑ Provisions for Beams (18.4.2)

1. Flexural reinforcement (18.4.2.1 and 18.4.2.2)



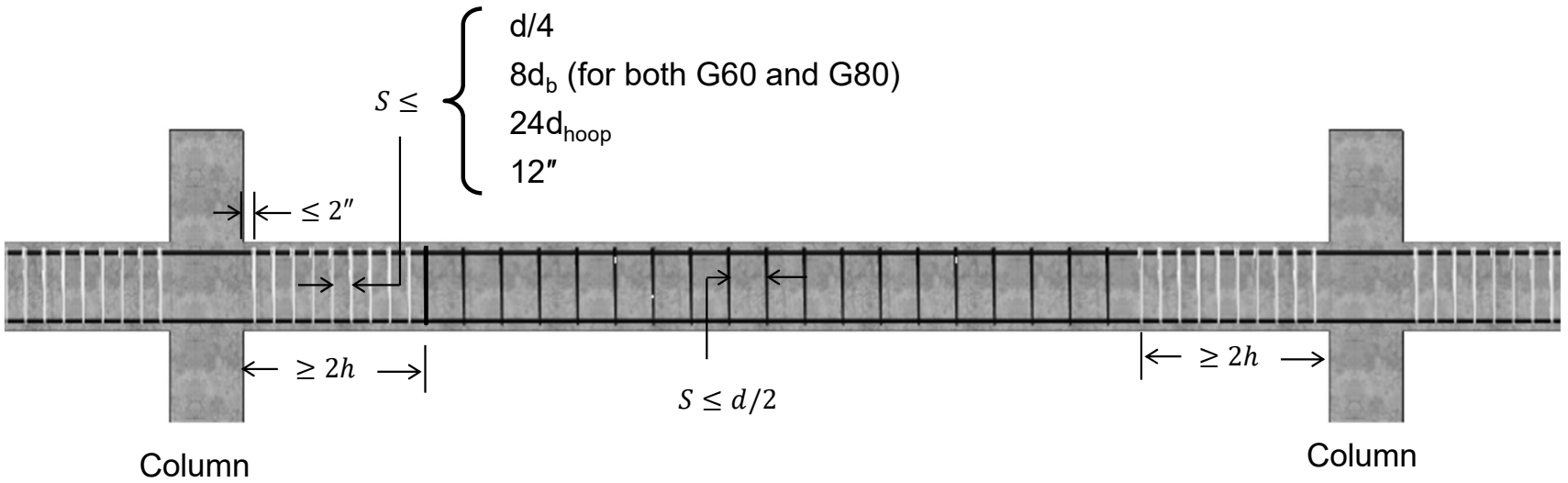
Minimum 2 bars continous at all locations

$A_{s,-ve}$ or $A_{s,+ve}$ (at all sections) ≥ (maximum of A_s at either joint) / 5

ACI Provisions for Concrete IMF

❑ Provisions for Beams (18.4.2)

2. Transverse reinforcement (18.4.2.4)



ACI Provisions for Concrete IMF

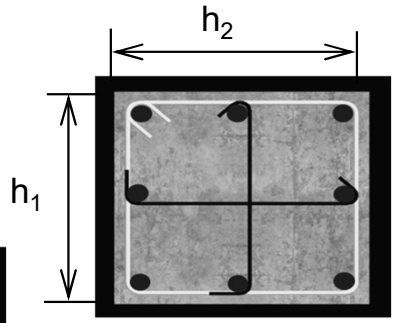
❑ Provisions for Columns (18.4.3)

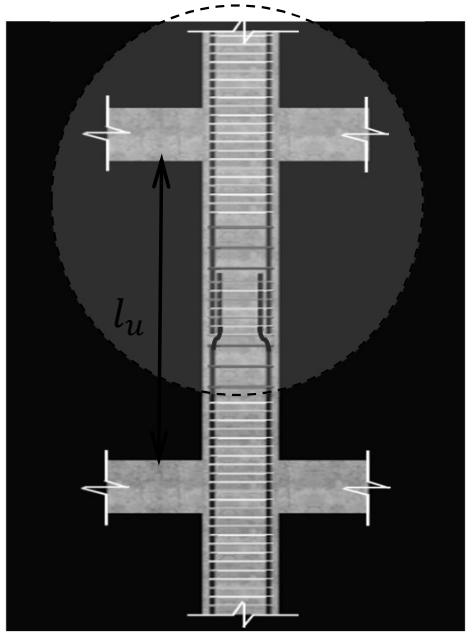
- Size: No special requirements
- Longitudinal reinforcement: No special requirements
- Transverse reinforcement: Less stringent requirement as given next.
- Lap: No special requirements

ACI Provisions for Concrete IMF

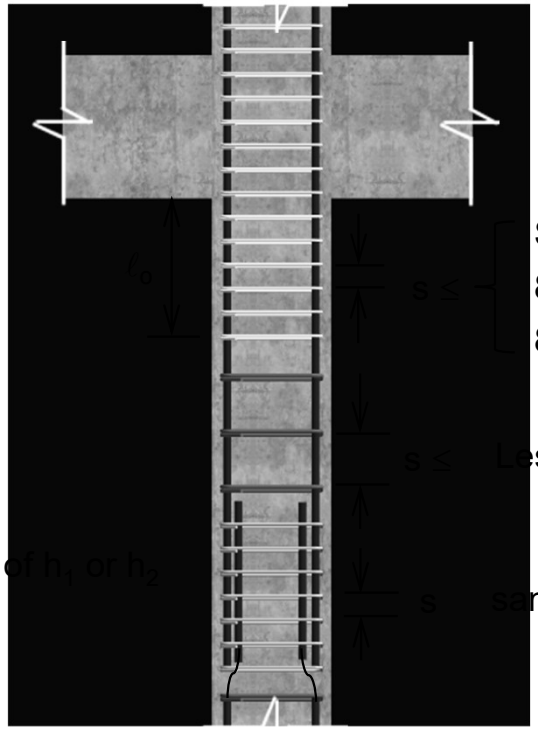
❑ Provisions for Columns (18.7)

1. Transverse reinforcement (18.4.3.3)





ℓ_o = max
- Larger of h_1 or h_2
- $l_u/6$
- 18″



- Smaller of $h_1/2$ or $h_2/2$
- $8d_b$ for G60 and $6d_b$ for G80
- 8″ for G60 and 6″ for G80

- Lesser d/2 or 24″

- same as that of l_o region

ACI Provisions for Concrete IMF

❑ Limitation of IMF Systems

- IMFs are not allowed in seismic zones 3 and 4.
- However, when used as dual systems (with special concrete shear walls), they are permitted with structural height up to 160 ft.
- Furthermore, it is to be noted that two-way slab system without beams are also not permitted in seismic zones 3 and 4.

Example 5.2

❑ Problem Statement

- A Reinforced concrete building frame is shown in figure 1 (a) on the next slide. All beams in the frame are 12″ wide and 18″ deep. All columns are 12″ square. f_c'= 3 ksi and f_y = 60 ksi.

  It is required only for frame BFGC to

  a) **Provide** suitable number of bars in beams and columns for the reinforcement results shown in figure 1 (b), using only #5 bars as main reinforcement and #3 bars as transverse reinforcement.

  b) **Provide** suitable spacing for stirrups and ties if shear reinforcement as per design is 0.23 in^2/ft in all parts of the frame.

  c) **Satisfy** all SMF requirements for beams and columns.

Example 5.2

❑ Problem Statement

d) **Present** appropriately proportioned structural details of beam and column. Also draw the beam-column joint detail at detail X as shown in figure.

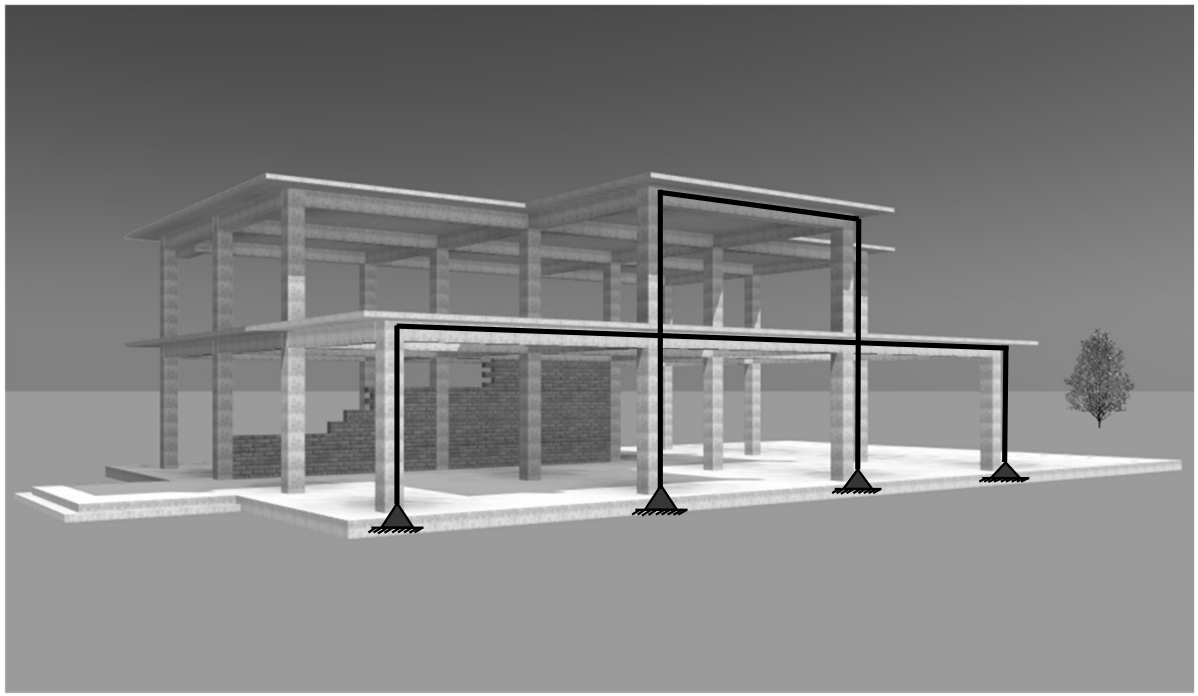
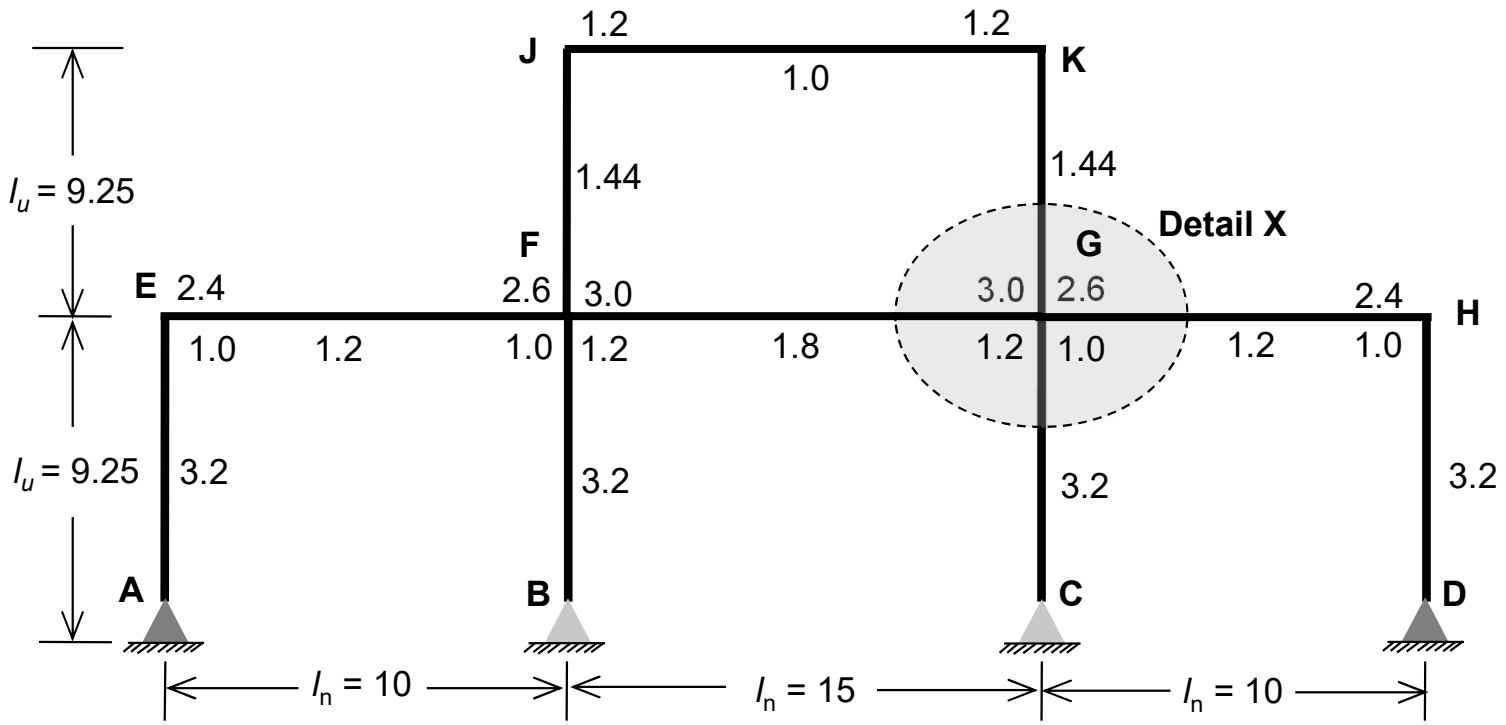


Figure 1 (a) : 3D RC Building Frame

Example 5.2

❑ Problem Statement



All reinforcement is in in^2

All lengths are in feet

Figure 1 (b) : Reinforcement Details

Example 5.2

❑ Solution

▪ Part (a): Flexural reinforcement detailing

For the given beam FG, we have;

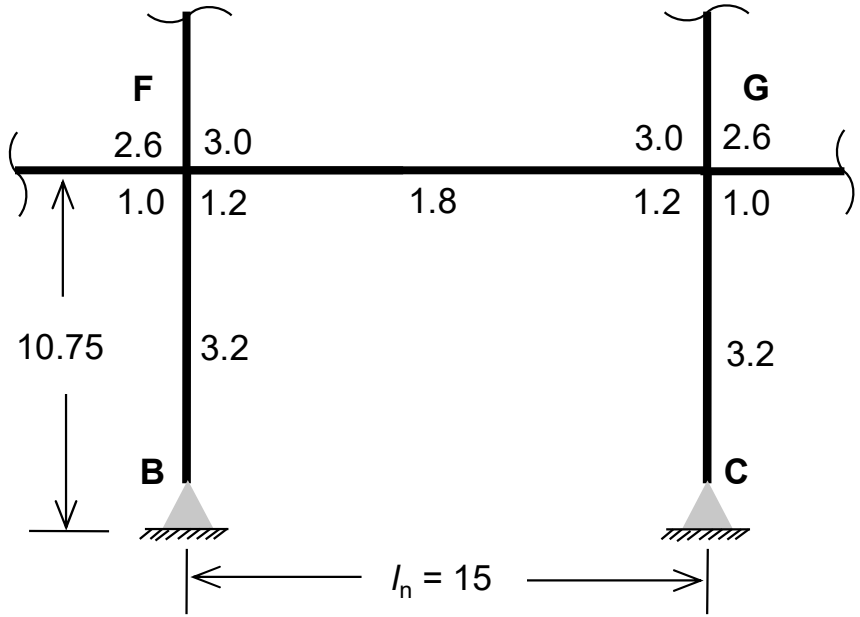
$$A_{s,min} = \frac{200}{60{,}000} \times 12 \times 15 = 0.6in^2$$

and

$$A_{s,max} = 0.025 b_w d$$

$$= 0.025 \times 12 \times 15 = 4.5in^2$$

Provided A_s at top and bottom is within the limits → OK!



Example 5.2

❑ Solution

- **Part (a): Flexural reinforcement detailing**

For the given columns BF and CG, we have;

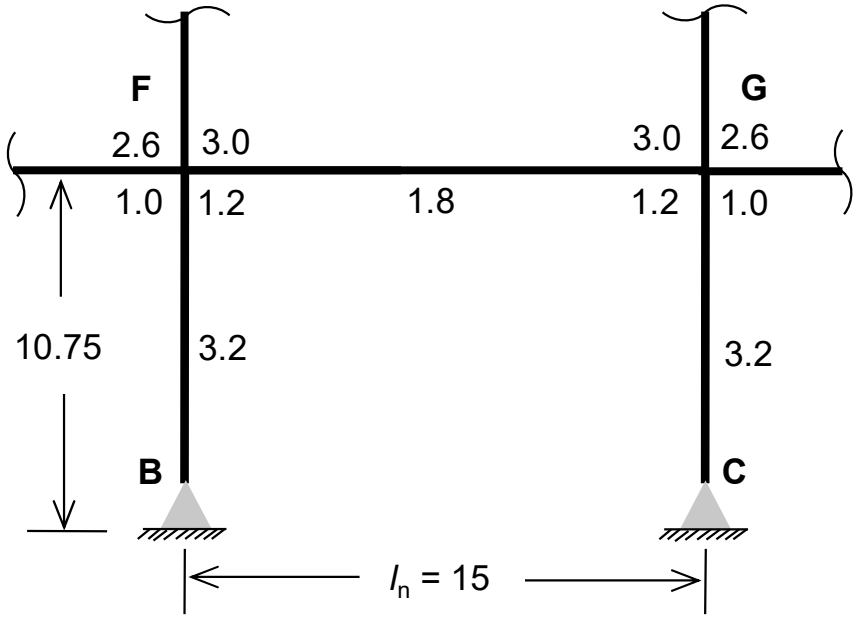
$$A_{s,min} = 0.01A_g$$

$$= 0.01 \times 12 \times 12 = 1.44in^2$$

and

$$A_{s,max} = 0.06A_g = 8.64in^3$$

Provided A_s of 3.2 in^2 is within the limits → OK!



Example 5.2

❑ Solution

- **Part (a): Flexural reinforcement detailing**

Determine number of bars using #5 bars with $A_b = 0.31 in^2$

a. Beam Positive reinforcement

At midspan: No. of bars = 1.8/0.31 ≈ 6 (provide in two layers, 4+2)

At ends: No. of bars = 1.2/0.31 ≈ 4 (provide in single layer)

b. Beam Negative reinforcement (at joints)

No. of bars = 3/0.31 ≈ 10 (provide in two layers, 5+5)

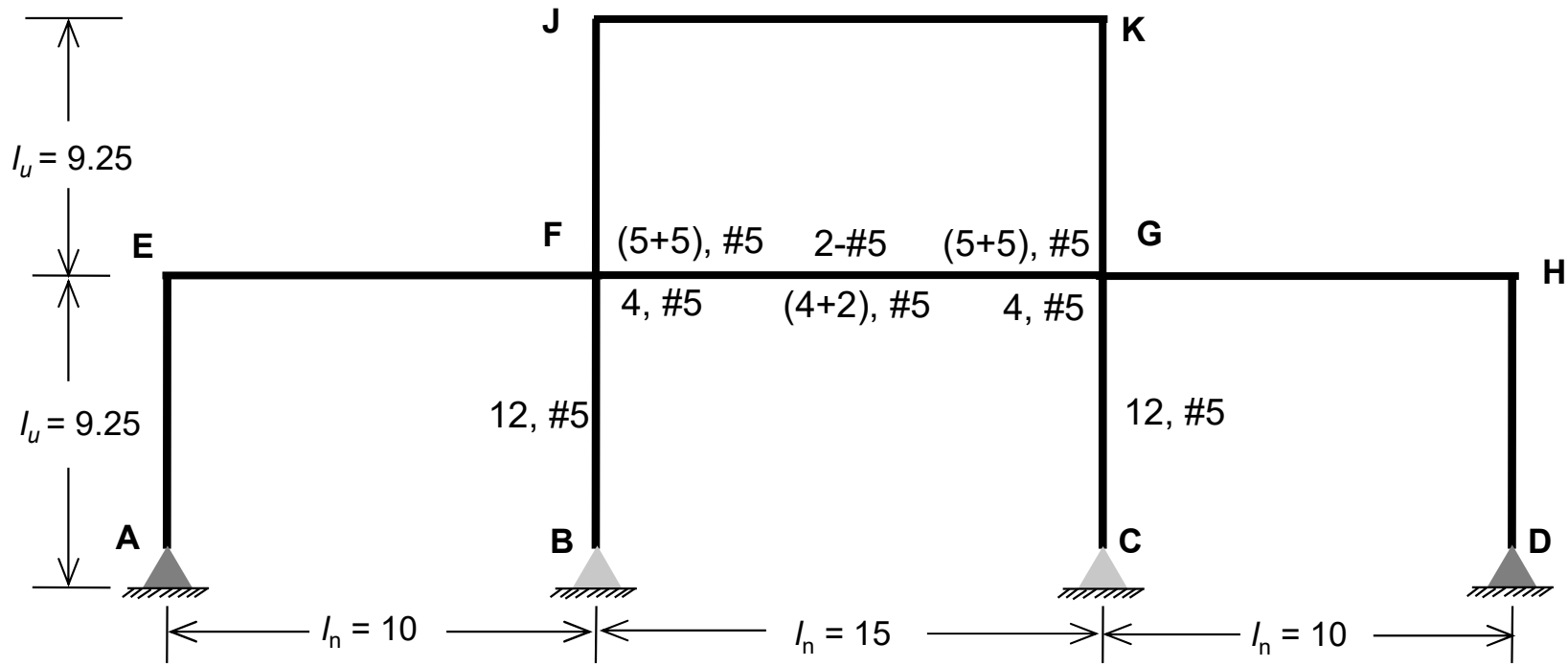
c. Column reinforcement

No. of bars = 3.2/0.31 ≈ 11 (provide 12 bars for even distribution)

Example 5.2

❑ Solution

- **Part (a): Flexural reinforcement detailing**



Example 5.2

❑ Solution

- **Part (b): Shear reinforcement detailing**

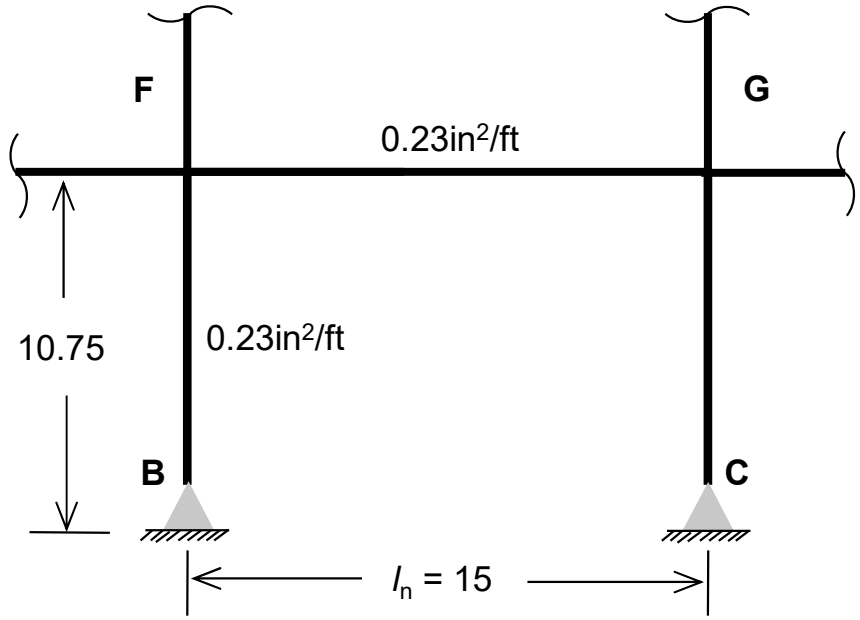
Determine spacing for transverse reinforcement #3 bars

a) Stirrup spacing for beam

$$S = \frac{12A_b}{A_s}$$

Using 2-legged #3 stirrups

$$S = \frac{12(0.22)}{0.23} = 11.5''$$



Example 5.2

❑ Solution

▪ Part (b): Shear reinforcement detailing

a) Stirrup spacing for beam

Maximum spacing S_{max} is given by

$$s_{max} = Least\ of \begin{cases} \dfrac{A_v f_y}{50 b_w} = \dfrac{0.22 \times 60{,}000}{50 \times 12} = 14" \\ \dfrac{A_v f_y}{0.75\sqrt{f_c'}\, b_w} = \dfrac{0.22 \times 60{,}000}{0.75\sqrt{3000} \times 12} = 17.9" \\ \dfrac{d}{2} = \dfrac{15}{2} = 7.5" \\ 24" \end{cases} \Rightarrow s_{max} = 7.5" < S$$

Finally, provide #3 @ 7.5″ c/c

Example 5.2

❑ Solution

▪ Part (b): Shear reinforcement detailing

b) Ties spacing for columns

$$S = \frac{12A_b}{A_s} = \frac{12(0.22)}{0.23} = 11.5''$$

Maximum spacing is given by

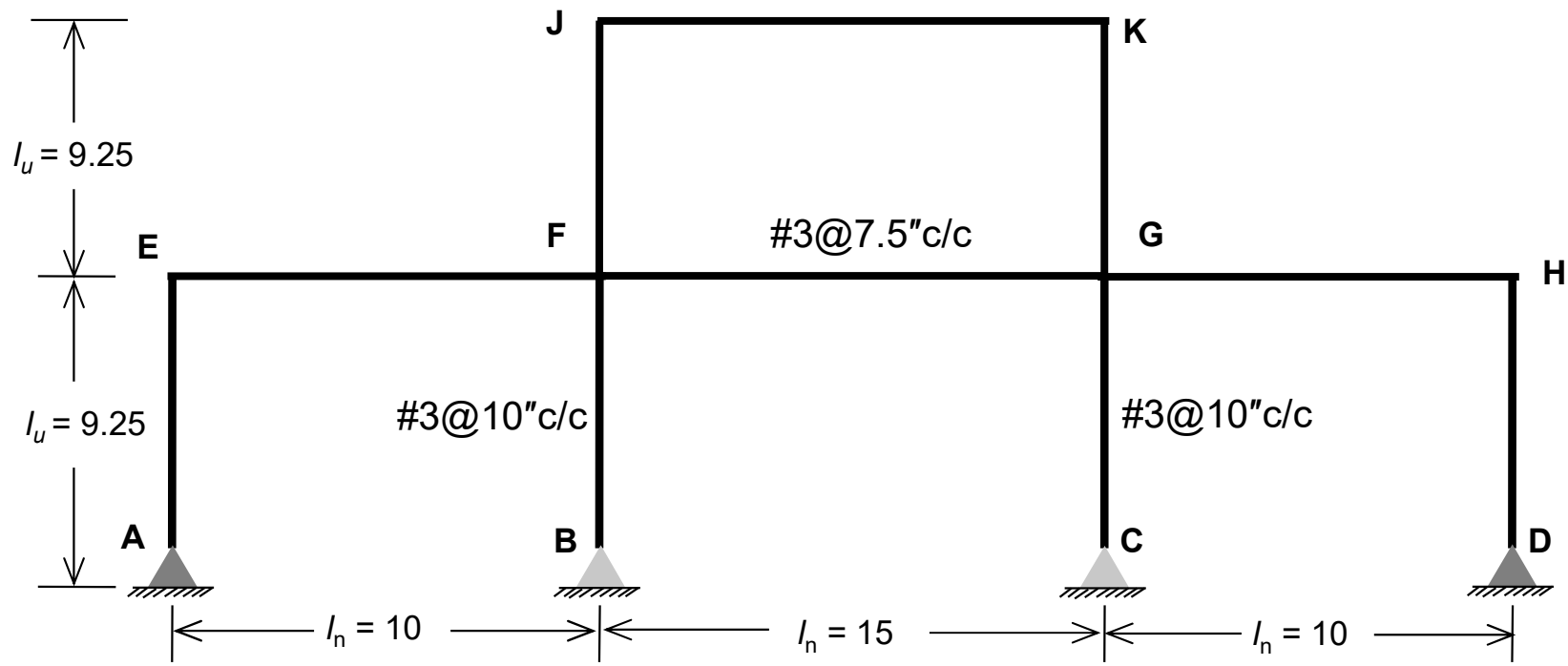
$$s_{max} = Min.of \begin{cases} 16d_b\ (main\ bar) = 16 \times 5/8 = 10" \\ 48d_b\ (hoop/tie) = 48 \times 3/8 = 18" \\ Least\ column\ dimension = 12" \end{cases} \Rightarrow s_{max} = 10" < S$$

Finally, provide #3 @ 10″ c/c

Example 5.2

❑ Solution

- **Part (b): Shear reinforcement detailing**



Example 5.2

❑ Solution

- **Part (c): SMF requirements Checklist**

a) Checklist for beams

i. Sizes

- l_n/d = 15 × 12/15 = 12 > 4 → OK!
- Width/ total depth = 12/18 = 0.67 > 0.3 → OK!
- Width = 12″ > 10″ → OK!
- Therefore 12″ wide and 18″ beams are OK.

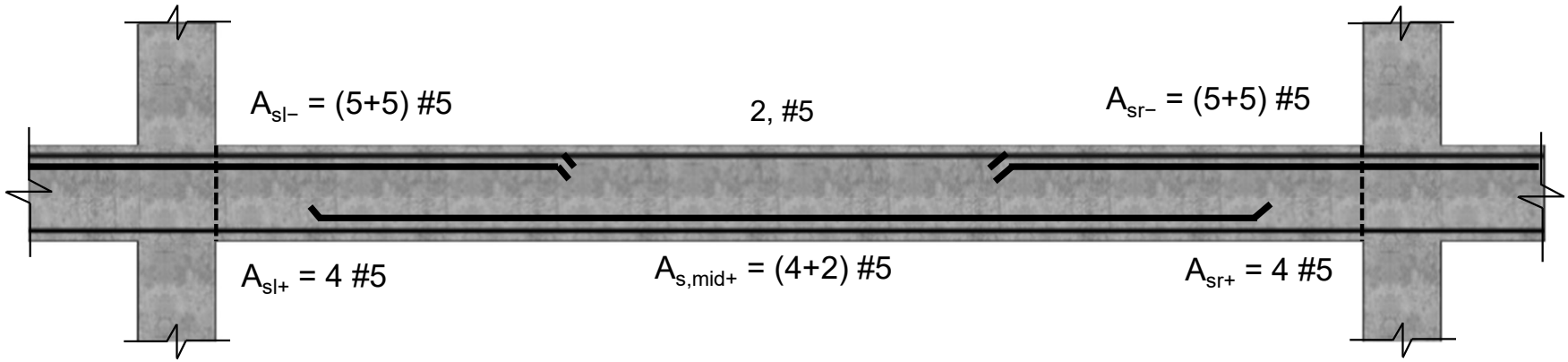
Example 5.2

❑ Solution

- **Part (c): SMF requirements Checklist**

a) Checklist for beams

ii. Flexural reinforcement



A_{s+} (at joints) ≥ ½ A_{s-} (at joints)

4 #5 bars are less than ½ {(5+5) #5 bars}

So, we must provide at least 5 bars at joint.

A_s (any section) ≥ ¼ Max. A_s at joints

Provide at least 3 bars

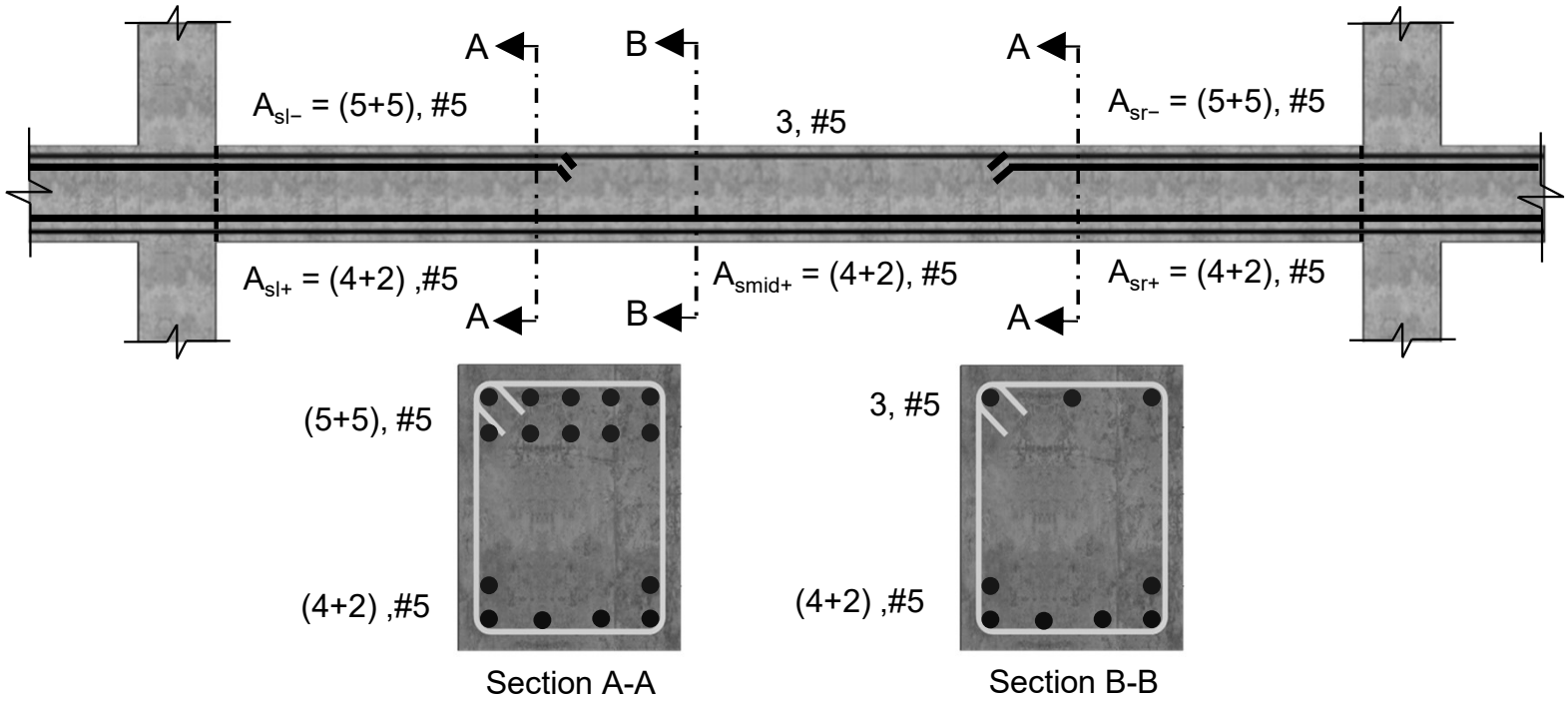
Example 5.2

❑ Solution

- **Part (c): SMF requirements Checklist**

a) Checklist for beams

- Recommended Flexural reinforcement



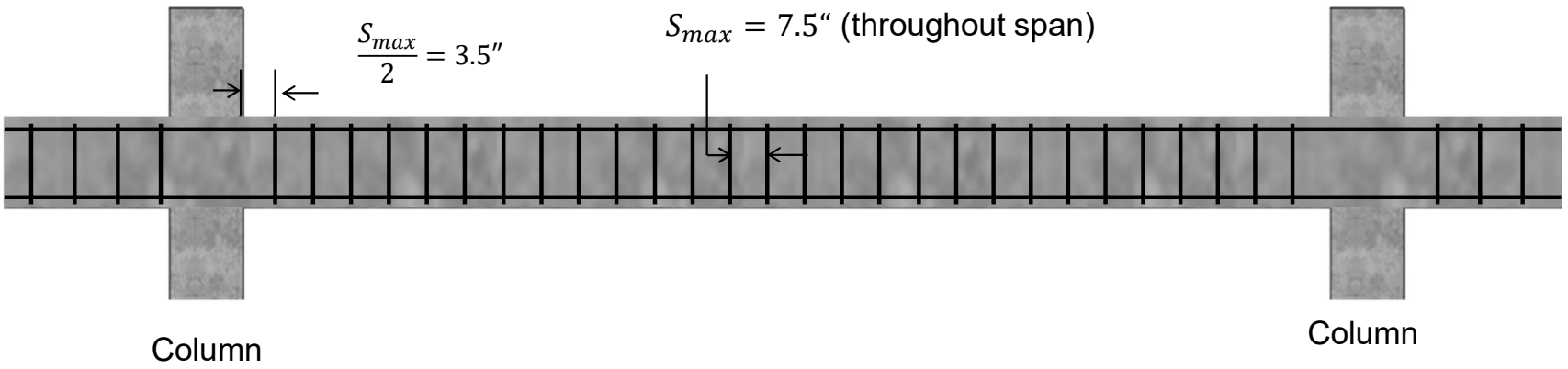
Example 5.2

❑ Solution

- **Part (c): SMF requirements Checklist**

a) Checklist for beams

iii. Transverse reinforcement



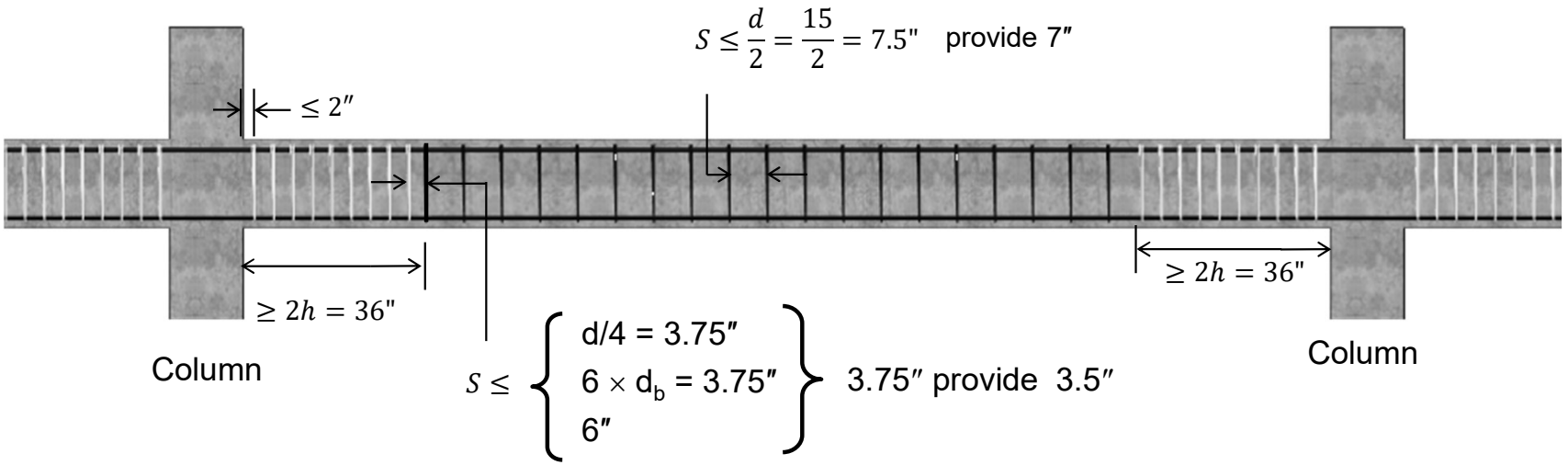
Example 5.2

❑ Solution

- **Part (c): SMF requirements Checklist**

a) Checklist for beams

iii. Recommended Transverse reinforcement



Example 5.2

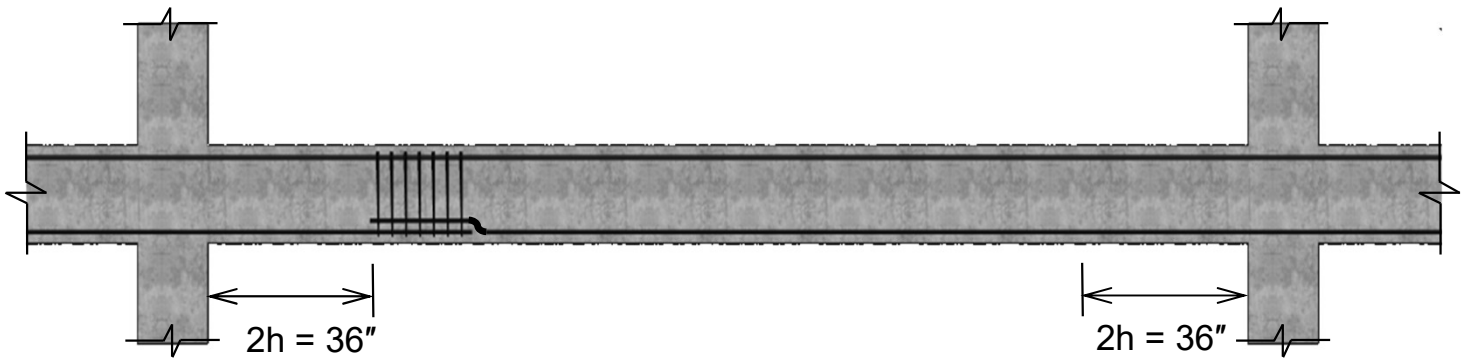
❑ Solution

▪ Part (c): SMF requirements Checklist

a) Checklist for beams

iv. Lap splices (if required)

- Not to be provided within joints and 2h region from face of the support.
- Spacing of hoops within lap = least of d/4 or 4″ c/c = 15/4=3.75 or 4″ so 3.75″ c/c
- Lap splice length (for bars ≤ #6) = $57d_b$ = 57 (5/8) = 35.6″ say 36″.



Example 5.2

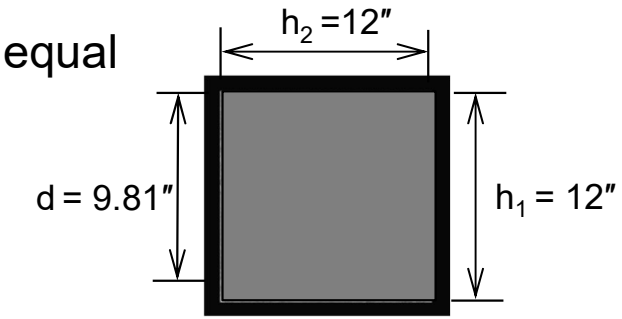
❑ Solution

- **Part (c): SMF requirements Checklist**

b) Checklist for columns

i. Dimensional limits

- All columns are 12″ square, which is equal to least required for SMF (i.e., 12″).



ii. Flexural Reinforcement

- All columns are reinforced with 12 #5 bars which gives

$$\rho_g = \frac{A_s}{A_g} = \frac{12 \times 0.31}{12 \times 12} = 0.026$$

which is within the specified range $0.01 \leq \rho_g \leq 0.06$.

Example 5.2

❑ Solution

- **Part (c): SMF requirements Checklist**

b) Checklist for columns

iii. Transverse reinforcement

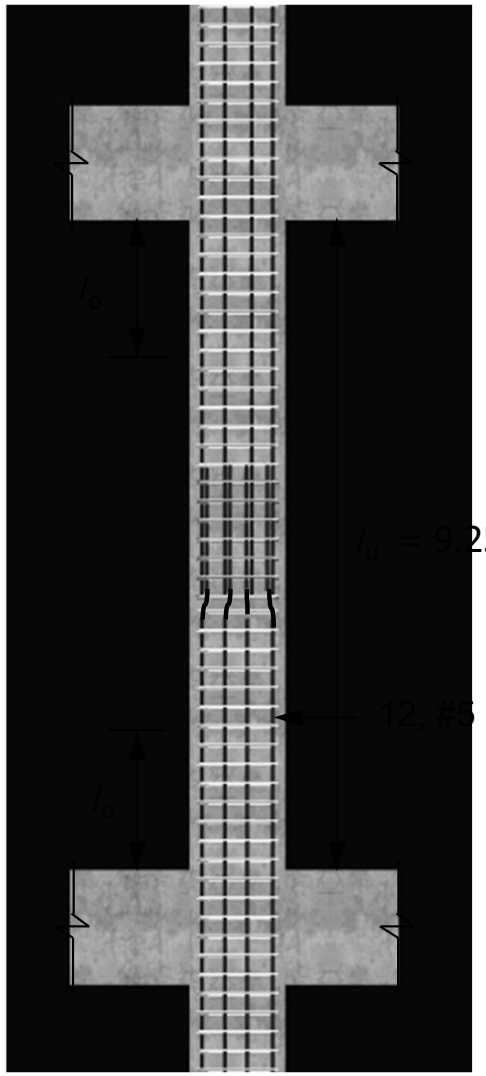
$$l_o = max(\, h_1 \; or \; h_2 \,, \frac{l_u}{6}, 18")$$

$$l_o = max(\, 12" \,, \frac{9.25}{6}, 18") = max(\, 12" \,, 18.5", 18") = 18.5"$$

Spacing of ties in l_o region is least of

- Smaller column dimension/4 = 12/4 = 3″
- 6 d_b = 6 × (5/8) = 3.75″
- $S_o = 4 + \left(\frac{14 - h_x}{3}\right)$

S_o is calculated next



Example 5.2

❑ Solution

- **Part (c): SMF requirements Checklist**

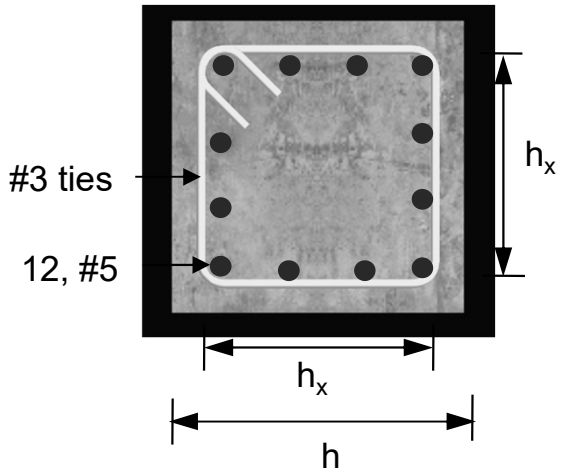
b) Checklist for columns

iii. Transverse reinforcement

$$h_x = h - 2\left(cc + d_{tie} + \frac{d_{long.bar}}{2}\right) = 7.62"$$

$$h_x = 12 - 2\left(1.5 + \frac{3}{8} + \frac{5}{16}\right) = 7.62"$$

$$S_o = 4 + \left(\frac{14 - 7.62}{3}\right) = 6.1 > 6",\ take\ S_o = 6"$$



Hence provide spacing of 3” in l_o region of 18.5” from both joint faces of column.

Example 5.2

❑ Solution

- **Part (c): SMF requirements Checklist**

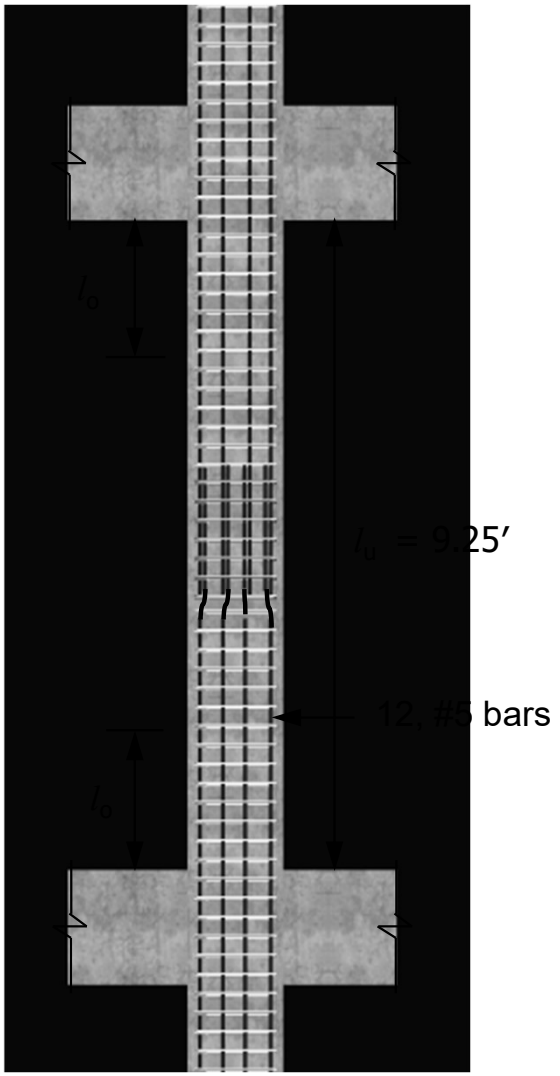
b) Checklist for columns

iii. Transverse reinforcement

Spacing other than l_o region will be least of

- 6 × long bar dia = 6 × (5/8) = 3.75″
- 6″

Provide spacing of 3.75” regions other than l_o



Example 5.2

❑ Solution

- **Part (c): SMF requirements Checklist**

b) Checklist for columns

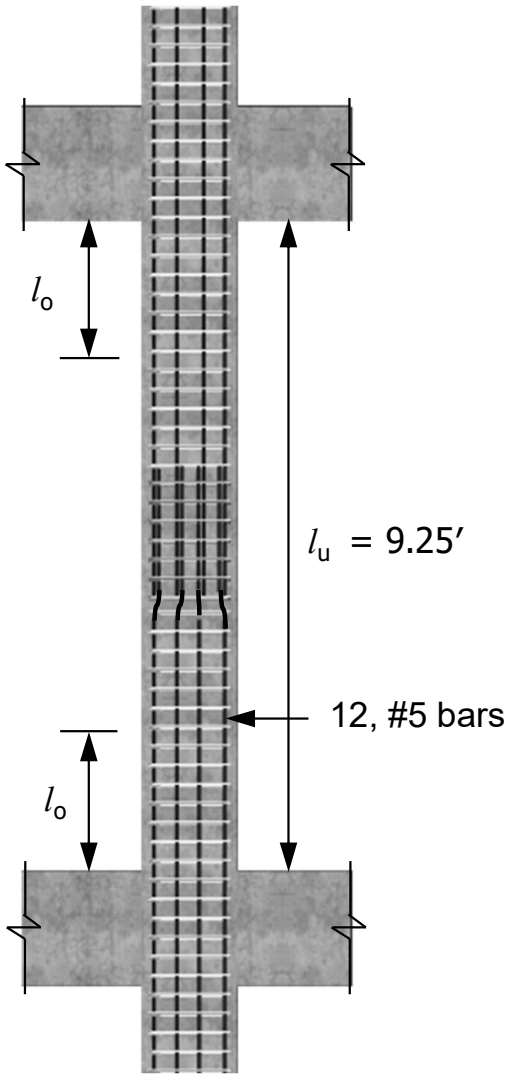
iv. Lap splice

Spacing within lap splice is the same as that of l_o region.

$S = 3"$

Lap splice length = $57d_b$

= 57 (5/8) = 35.6″ say 36″



Example 5.2

❑ Solution

- **Part (c): SMF requirements Checklist**

c) Checklist for Joints

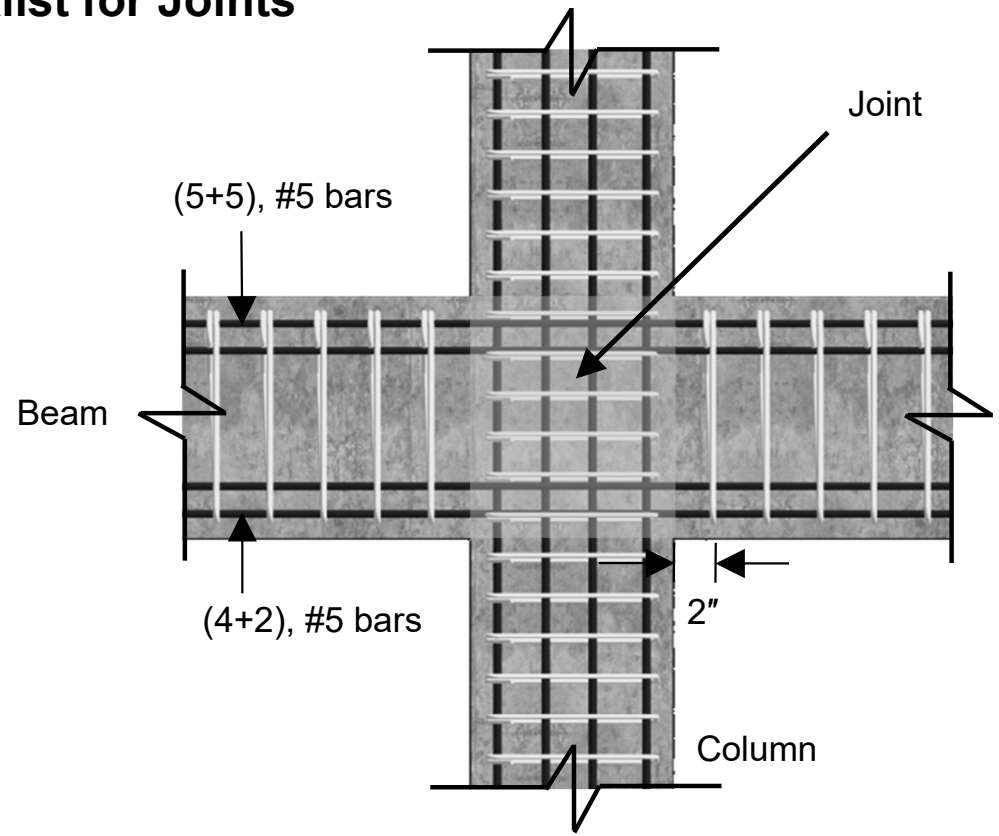
- The column dimension parallel to the beam reinforcement must be at least 20 times the diameter of the largest longitudinal bar for Grade 60 steel and normal weight concrete.
  - $20 \times 5/8 = 12.5'' > 12''$ → change size of column
  - Take column dimension parallel to beam long bar = 13.5″

Example 5.2

❑ Solution

- **Part (c): SMF requirements Checklist**

c) Checklist for Joints



Example 5.2

❑ Solution

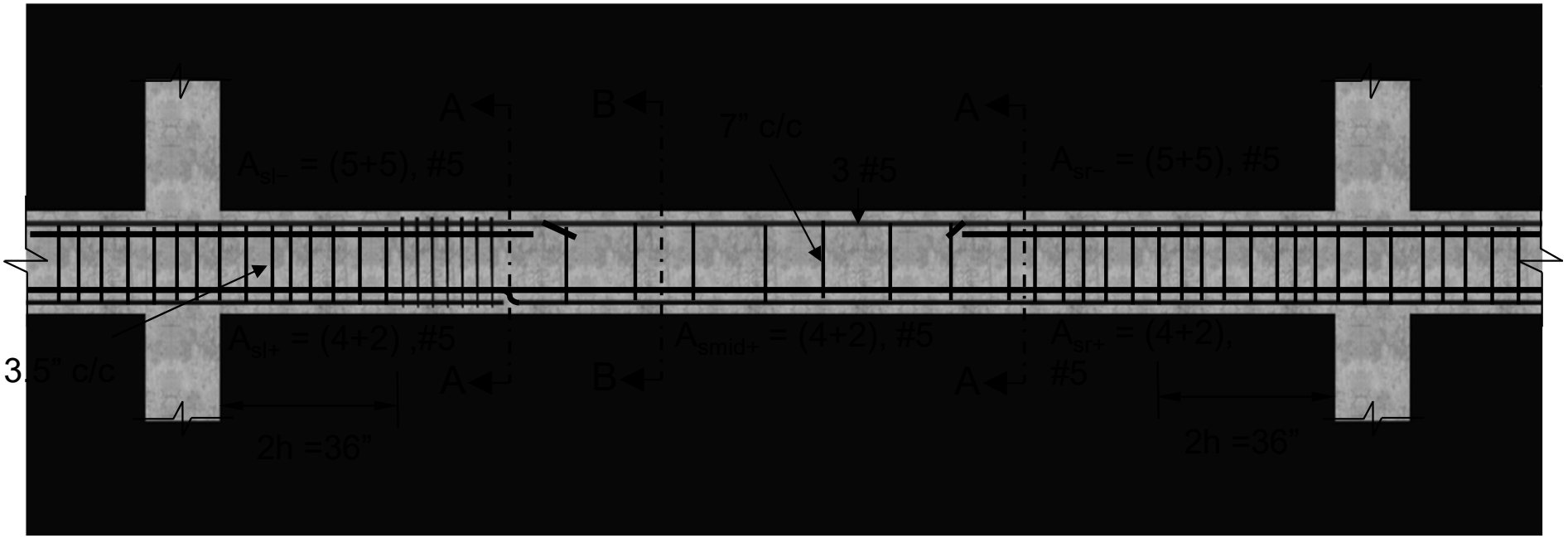
- **Part (d): Presentation of structural details**
  - In this part, structural drawings showing all calculated SMF details have been asked to draw. This has already been done in part (c) along with each member (beam and column) SMF checks.
  - However, in the examination, it is better to draw all drawings here in part (d) at the same place to avoid waste of time.

Example 5.2

❑ Solution

- **Part (d): Presentation of structural details**

a) Beam details

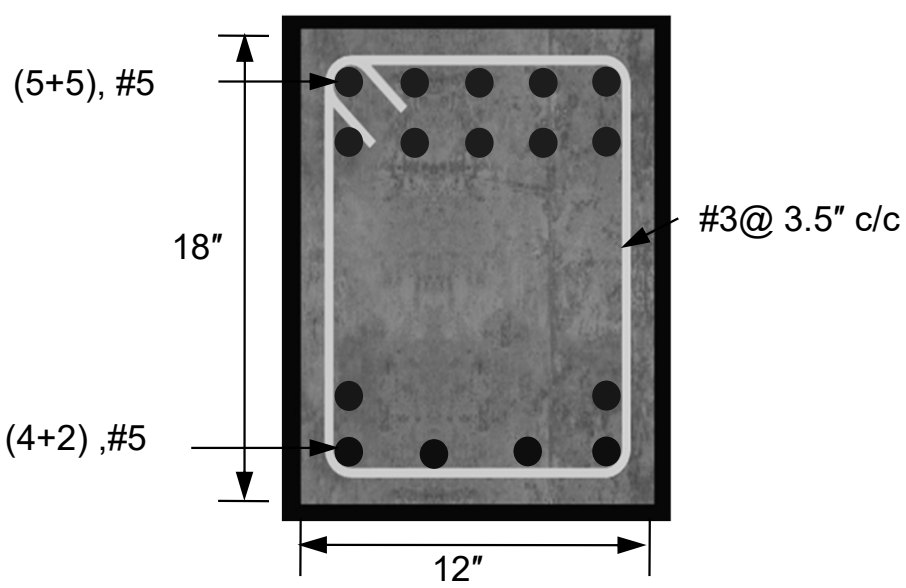


Example 5.2

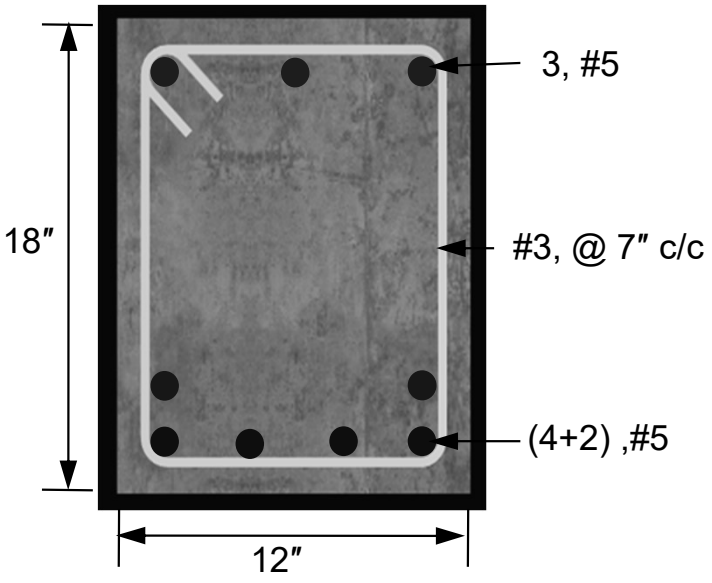
❑ Solution

- **Part (d): Presentation of structural details**

a) Beam details



Section A-A



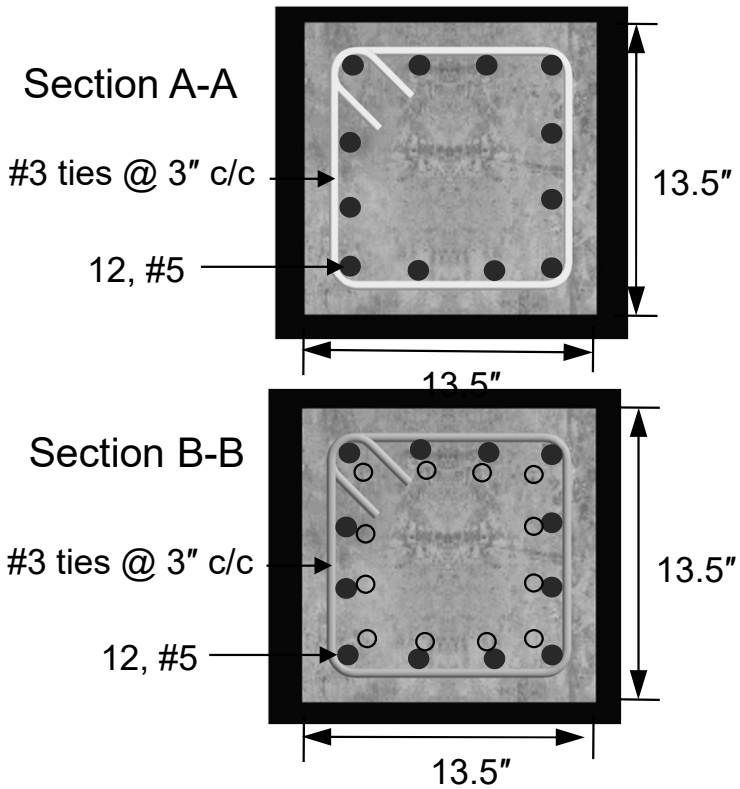
Section B-B

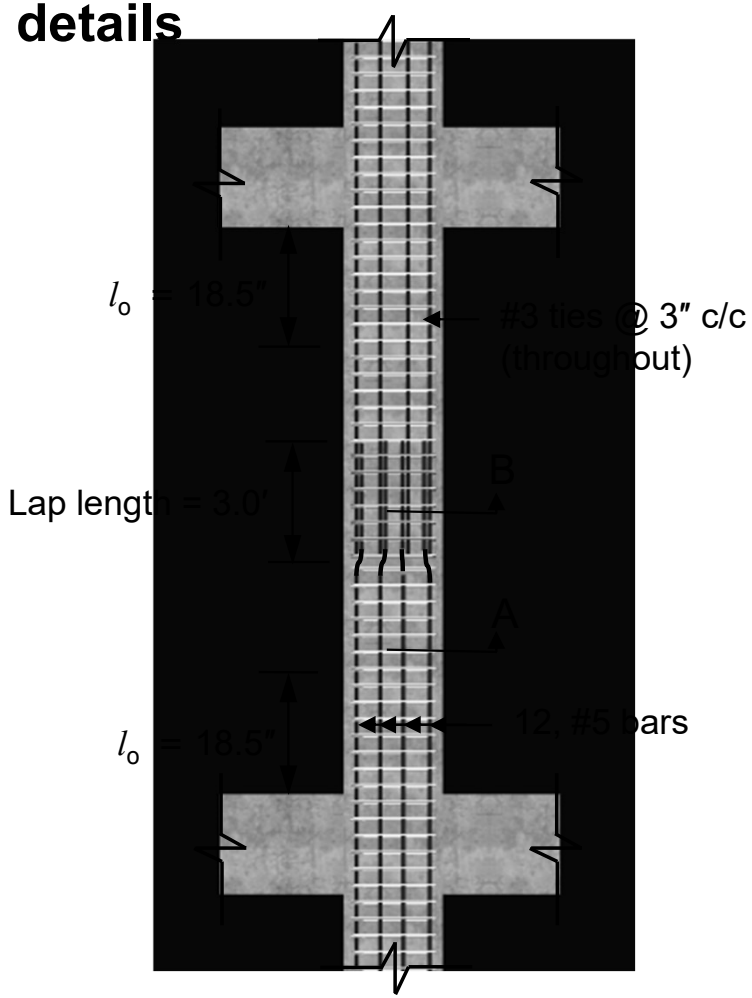
Example 5.2

❑ Solution

- **Part (d): Presentation of structural details**

b) Column details



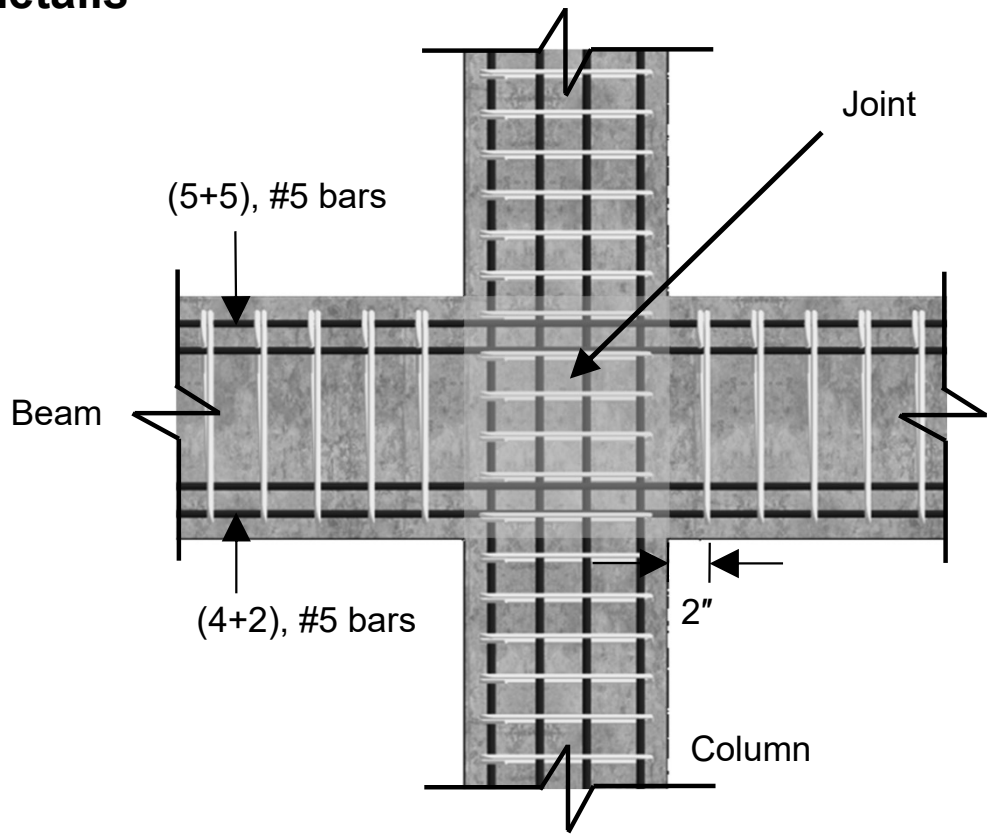


Example 5.2

❑ Solution

- **Part (d): Presentation of structural details**

c) Joint details



References

- Design of Concrete Structures 14th / 15th edition by Nilson, Darwin and Dolan.
- Building Code Requirements for Structural Concrete (ACI 318-19)