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Reinforced Concrete Requirements

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RC Requirements

- This presentation provides the specific requirements for designing a reinforced concrete building to resist progressive collapse.
- Appendix C in the UFC demonstrates the application of the reinforced concrete design requirements for a 5-story office building.

RC Requirements

- Composite Construction
  - ◊ Reinforced concrete is often used in composite construction, such as:
    - concrete deck slabs on steel beams,
    - sheet steel decking with an integral slab, and
    - columns reinforced with structural steel shapes,
  - ◊ For concrete/steel composite construction, the application of both the requirements of this chapter and those provided for steel in Chapter 5 are required.

RC Requirements

- Composite Construction, cont'd
  - ◊ For example, for a concrete deck slab on steel beam in which the slab is used to provide internal tie capacity, the floor system and roof system would be required to meet the internal tie requirements of this section, while the steel frame would be required to meet the other tie requirements (vertical, peripheral, and external column) and the AP requirements of Chapter 5.

RC Requirements

- Material Properties For Reinforced Concrete
  - ◊ Apply the appropriate over-strength factors to the calculation of the design strengths for **both** Tie Forces and the Alternate Path method.

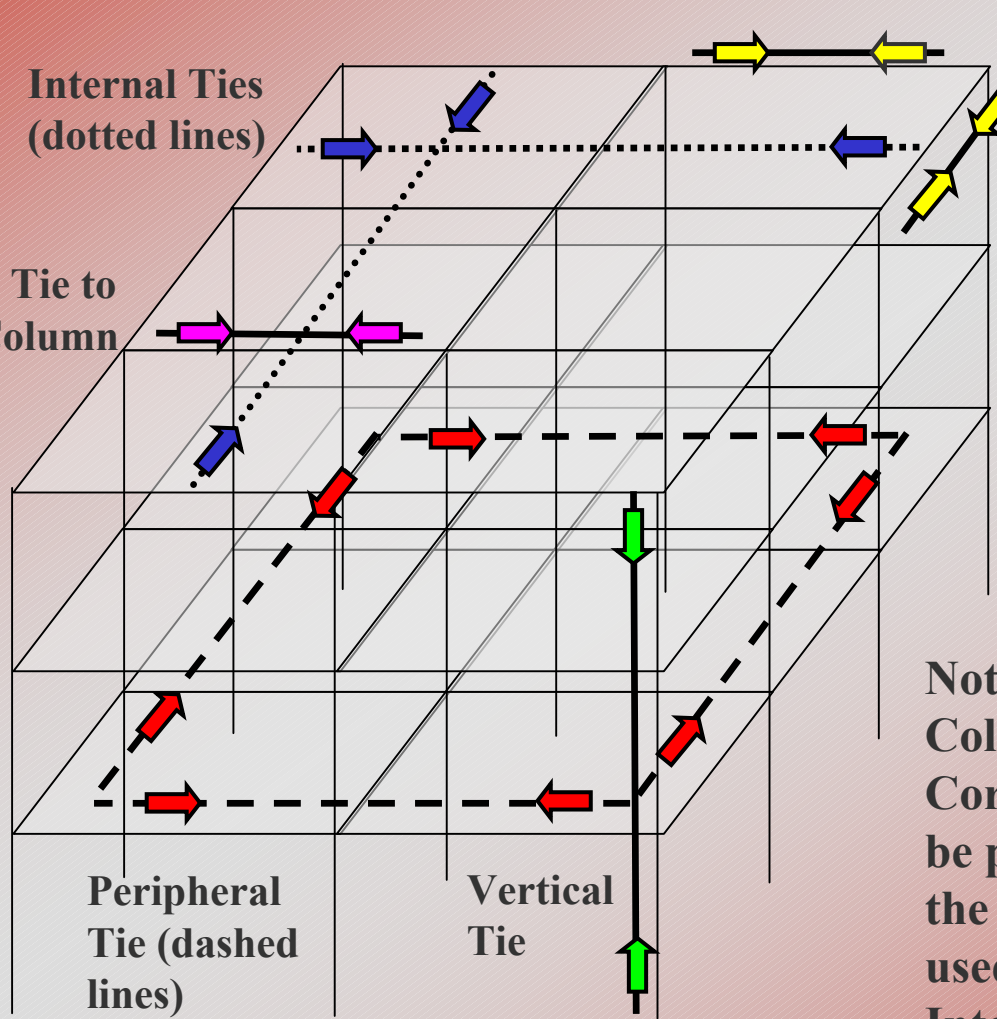
Over-Strength Factors for Reinforced Concrete

Reinforced Concrete	Over-Strength Factor, Ω
Concrete Compressive Strength	1.25
Reinforcing Steel (ultimate and yield strength)	1.25

RC Tie Force Requirements

- Reinforced Concrete Tie Force Requirements
  - ◊ General
    - Reinforced concrete structures must be designed with peripheral, internal, vertical, and horizontal ties to columns and walls, as applicable.
    - The required external column, external wall, and corner column tie forces may be provided partly or wholly by the same reinforcement that is used to meet the peripheral tie requirement.

RC Tie Force Requirements



Note: The required External Column, External Wall, and Corner Column tie forces may be provided partly or wholly by the same reinforcement that is used to meet the Peripheral or Internal tie requirement.

RC Tie Force Requirements

- Strength Reduction Factor Φ for Reinforced Concrete Tie Forces
  - ◊ The strength reduction factor Φ for properly anchored, embedded, or spliced steel reinforcement in tension is 0.75 (based on Section 9.3.2.6 of ACI 318-02 for strut-and-tie models).

RC Tie Force Requirements

- Proportioning of Ties
  - ◊ Reinforcement that is provided for other purposes, such as flexure or shear, may be regarded as forming part or whole of the required ties.

RC Tie Force Requirements

- Continuity and Anchorage of Ties
  - ◊ Splices in longitudinal steel reinforcement that provide tie forces must be lapped, welded or mechanically joined with Type 1 or Type 2 mechanical splices, per ACI 318-02.
  - ◊ Splices must be located away from joints or regions of high stress and should be staggered.

RC Tie Force Requirements

- Continuity and Anchorage of Ties, cont'd
  - ◊ Seismic hooks, as defined in Chapter 21 of ACI 318-02, and seismic development lengths, as specified in Section 21.5.4 of ACI 318-02, must be used to anchor ties to other ties.
  - ◊ At re-entrant corners or at substantial changes in construction, care must be taken to insure that the ties are adequately developed.

RC Tie Force Requirements

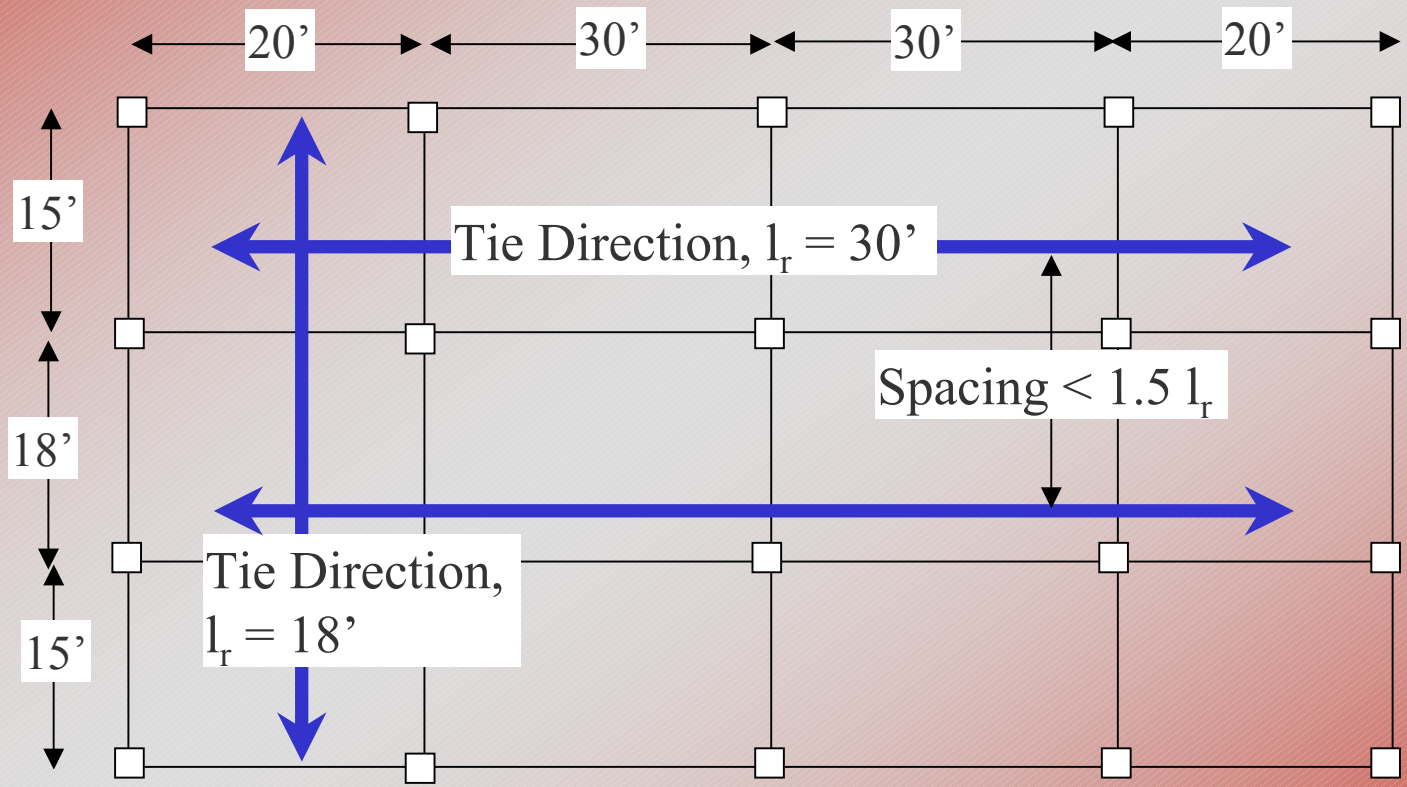
- Internal Ties
  - ◊ Internal ties are distributed at each floor and roof level in two directions approximately at right angles.
  - ◊ They must be made continuous from one edge of the floor or roof to the far edge of the floor or roof, using lap splices, welds or mechanical splices.
  - ◊ The internal ties must be anchored to peripheral ties at each end (unless continuing as horizontal ties to columns or walls).

RC Tie Force Requirements

- Internal Ties, cont'd
  - ◊ They may, whole or in part, be spread evenly in the slabs or may be grouped at or in beams, walls or other appropriate positions.
  - ◊ Spacings must not be greater than 1.5 l_r, where l_r is the greater of the distances between the centers of the columns, frames, or walls supporting any two adjacent floor spaces in the direction of the tie under consideration.
  - ◊ In walls, they must be within 0.5 m (1.6 ft) of the top or bottom of the floor slabs.

RC Tie Force Requirements

- Internal Ties, cont'd



RC Tie Force Requirements

- Internal Ties, cont'd
  - ◊ *In English units* and in each direction, internal ties must have a required tie strength (in kip/ft width) equal to the greater of:

a) $\frac{(1.0D + 1.0L)}{156.6} \frac{l_r}{16.4} \frac{1.0}{3.3} F_t$ (kip/ft)

or

b) $\frac{1.0}{3.3} F_t$ (kip/ft)

where: D = Dead Load (lb/ft^2)

L = Live Load (lb/ft^2)

l_r = Greater of the distances between the centers of the columns, frames or walls supporting any two adjacent floor spaces in the direction of the tie under consideration (ft)

F_t = "Basic Strength" = Lesser of $(4.5 + 0.9\ n_o)$ or 13.5

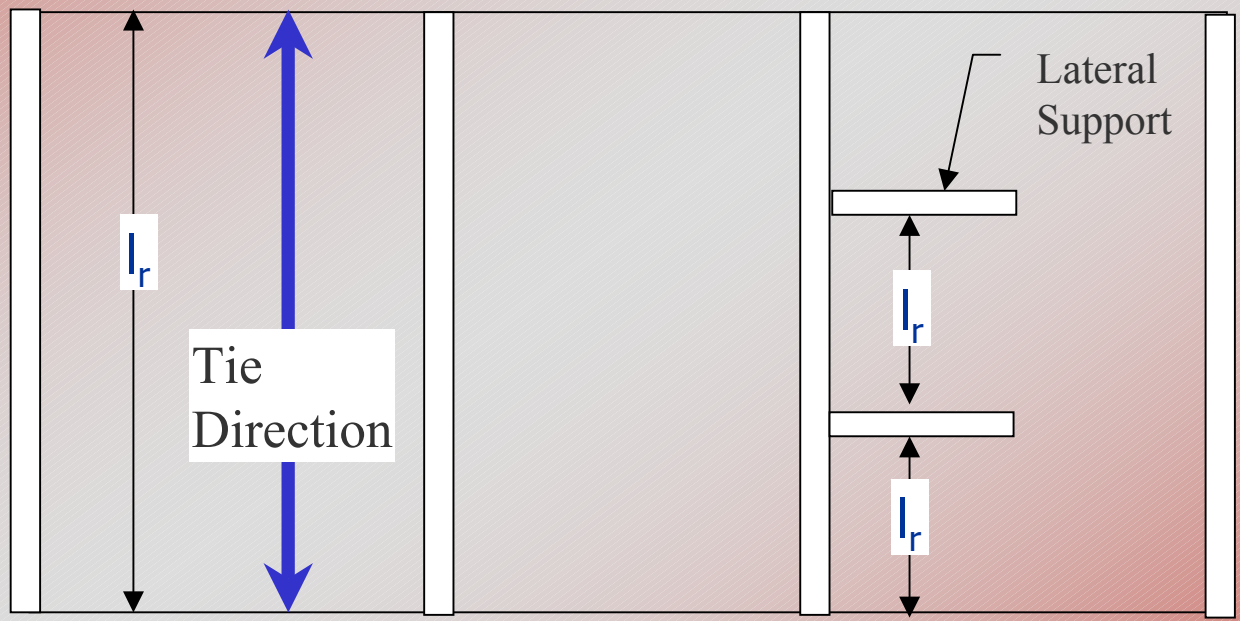
n_o = Number of stories

RC Tie Force Requirements

- Internal Ties, cont'd
  - ◊ Whenever walls occur in plan in one direction only (e.g. "cross wall" or "spine wall" construction), the value of l_r used when assessing the tie force in the direction parallel to the wall must be taken as either the actual length of the wall or the length which may be considered lost in the event of an accident, whichever is the lesser.
  - ◊ The length which may be considered lost is taken as the length between adjacent lateral supports or between a lateral support and a free edge, as defined in Table 4-2 (given later).

RC Tie Force Requirements

- Internal Ties, cont'd
  - ◊ l_r for cross wall or spine wall construction

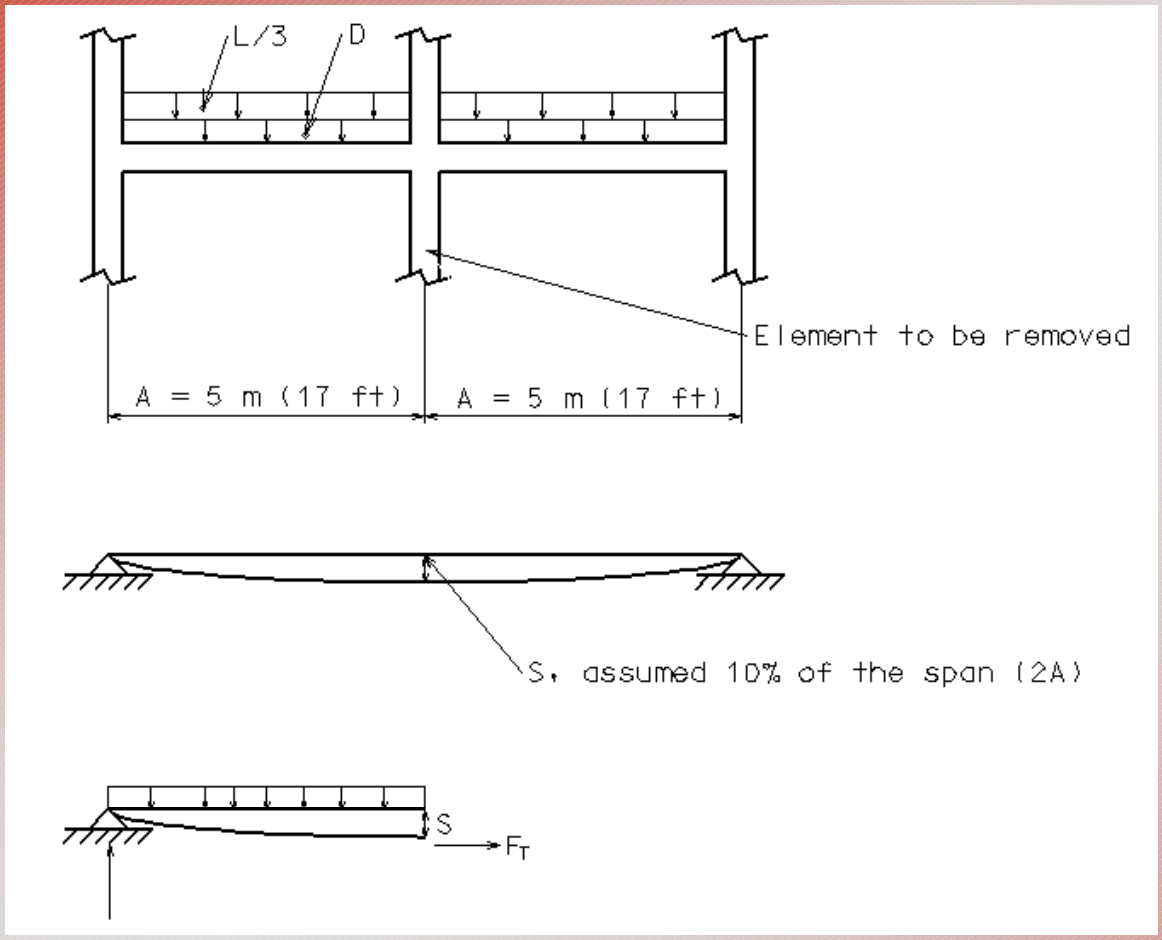


RC Tie Force Requirements

- Internal Ties, cont'd
  - ◊ Background:
    - As mentioned previously, the Tie Force requirements are taken from the British Standards, developed in the late 60's and early 70's.
    - A review of the 1972 British Standard Code of Practice CP110 is provided in *The Avoidance of Progressive Collapse: Regulatory Approaches to the Problem* (Burnett 1975) which discusses the origins or logic used to develop the reinforced concrete tie force requirements.

RC Tie Force Requirements

- Internal Ties, cont'd
  - ◊ Background, cont'd
    - Burnett indicates that the upper limit of F_t (13.5) can be derived from two scenarios.
      - First, this magnitude is equivalent to the internal member force created by catenary action of the floor after an intermediary load-bearing element is removed; see next slide.



$$\sum M = F_T * S = \frac{(D + \frac{L}{3})}{8} * (2A)^2$$

$$F_T = \frac{(D + \frac{L}{3}) * A^2}{2S}$$

Typical British Construction circa 1970:

A=5 m (17 ft)
S=A/5
D=3.6 kN/m^2 (75 psf)
L=3.6 kN/m^2 (75 psf)

Thus, F_t=60 kN/m (4.1 kip/ft or 13.5 kip/3.3-ft)

RC Tie Force Requirements

- Internal Ties, cont'd
  - ◊ Background, cont'd
    - Burnett indicates that the upper limit of F_t (13.5) can be derived from two scenarios, cont'd
      - Second, the upper limit of F_t can be related to the forces applied to a typical wall panel loaded with a 34 kN/m^2 (5 psi) static pressure, which is notionally equivalent to the overpressure that was thought to exist in the Ronan Point gas explosion.
      - Discussions with British engineers suggest that the first approach (catenary action) is the mechanism that the internal tie forces were intended to resist.

RC Tie Force Requirements

- Internal Ties, cont'd
  - ◊ Background, cont'd
    - The Basic Strength, F_t, is a function of the number of stories, which, according to Burnett 1975, "reflects that the probability of occurrence of an abnormal loading increases with building height".
    - Discussions with British engineers suggest that the dependence on number of stories was imposed to provide a smooth transition between 5 stories, where tying was not required, and 10 stories where the maximum value was required.

RC Tie Force Requirements

- Internal Ties, cont'd
  - ◊ Background, cont'd
    - In requirement a) above, the factors 156.6 and 16.4 are scaling factors, to account for larger loads and spans.
      - The 156.6 factor reflects the typical Dead plus Live Load value (7.2 kN/m^2 or ~150 psf) that was in effect in Britain at the time CP110 was instituted.
      - The 16.4 factor reflects the typical span length of 5 m (16.4 ft).
    - Lastly, it is noted that un-factored loads are used to scale the internal tie forces.

RC Tie Force Requirements

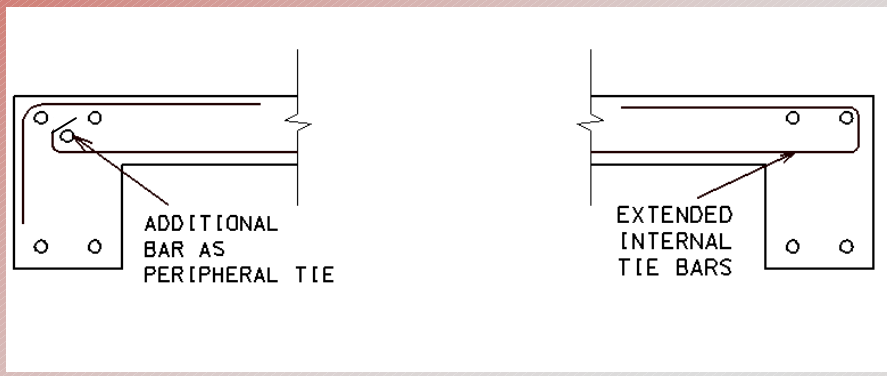
- Peripheral Ties
  - ◊ At each floor level and roof level, an effectively continuous peripheral tie must be provided, capable of providing a required tensile strength equal to 1.0 F_t, in kN (kip), located within 1.2 m (3.9 ft) of building edges or within the perimeter wall.

RC Tie Force Requirements

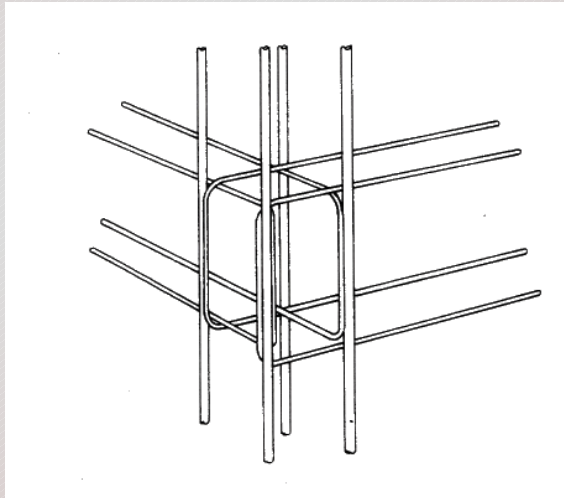
- Peripheral Ties, cont'd
  - ◊ Background
    - The peripheral ties are intended to keep the perimeter of the building together.
    - The peripheral ties also provide a means to anchor the internal ties and column/wall ties.
    - Two details are shown on the next page, suggested by Burnett 1975, for effectively anchoring internal tie bars to peripheral tie bars; also shown is a peripheral tie detail for corner columns.
    - There are numerous other ways to achieve anchorage of internal and peripheral ties.

RC Tie Force Requirements

- Peripheral Ties, cont'd



Details for Anchoring Internal Ties to Peripheral Ties



Peripheral Tie Detail for Corner Columns

RC Tie Force Requirements

- Horizontal Ties to External Columns and Walls
  - ◊ *In English units*, each external column and, if the peripheral tie is not located within the wall, every 3.3 ft length of external wall carrying vertical load must be anchored or tied horizontally into the structure at each floor and roof level with a tie with a required tie strength (in kips) equal to the greater of:

    a) the lesser of $2.0\ F_t$ or $(l_s/8.2)\ F_t$ (kip)

    or

    b) 3% of the largest factored vertical load, carried by the column or wall at that level, due to conventional design load combinations (kip)

    where: l_s = the floor to ceiling height (ft).
  - ◊ Where the peripheral tie is located within the wall, provide only such horizontal tying as is required to anchor the internal ties to the peripheral ties.

RC Tie Force Requirements

- Horizontal Ties to External Columns and Walls, cont'd
  - ◊ Background
    - The justification for these values appears to be engineering judgment as to the forces that are required to keep a column or wall vertical (i.e., minimizing the possibility of a large P-Δ effect).
    - Note that the second portion of requirement a) is scaled by the floor to ceiling height, to account for larger story heights; 2.5 m or 8.2 ft was a typical British floor height.

RC Tie Force Requirements

- Corner Column Ties
  - ◊ Corner columns must be tied into the structure at each floor and roof level in each of two directions, approximately at right angles, with ties having a required tensile strength equal to the greater of a) or b) from Section 4-2.7.1 (Horizontal Ties to External Columns and Walls).

RC Tie Force Requirements

- Vertical Ties
  - Each column and each load-bearing wall must be tied continuously from the lowest to the highest level.
  - *The tie must have a required strength in tension equal to the largest factored vertical load received by the column or wall from any one story, due to conventional design load combinations.*
  - Between floor levels, the column reinforcement must be spliced at the third points of the floor height, not at the intersection with the floors nor at mid-height.

RC Tie Force Requirements

- Vertical Ties, cont'd
  - When a column or a wall at its lowest level is supported by an element other than a foundation, a general check for structural integrity must be made (i.e., a careful check must be made and appropriate action taken to insure that there is no inherent weakness of structural layout and that adequate means exist to transmit the dead, live, and wind loads safely from the highest supported level to the foundations).

RC Tie Force Requirements

- Vertical Ties, cont'd
  - ◊ Background
    - Vertical ties must have a required strength in tension equal to the maximum factored sum of the dead and live load received by the column or wall from any one story, due to conventional design load combinations.
    - The justification of this is straightforward:
      - if the column section at a floor level is not supported by the column below that floor level, then it must be able to carry in tension the dead and live load applied by the floor.
    - As discussed with British engineers, this allows the loads to be redistributed up the building in catenary or Vierendeel action.

RC Tie Force Requirements

- Elements with Deficient Vertical Tie Forces
  - ◊ If it is not possible to provide the required vertical tie force in any of the load-bearing elements, then the Alternate Path method is applied for each such deficient element.
  - ◊ Remove each deficient member from the structure, one at a time in each story, in turn, and perform an AP analysis to verify that the structure can bridge over the missing member.

RC Tie Force Requirements

- Elements with Deficient Vertical Tie Forces, cont'd
  - ◊ The specific details for AP analysis of reinforced concrete construction are provided in the next section.
  - ◊ The amount of the member to be removed from the structure is given in the next slide.

RC Tie Force Requirements

Removal of Deficient Reinforced Concrete Vertical Tie Members

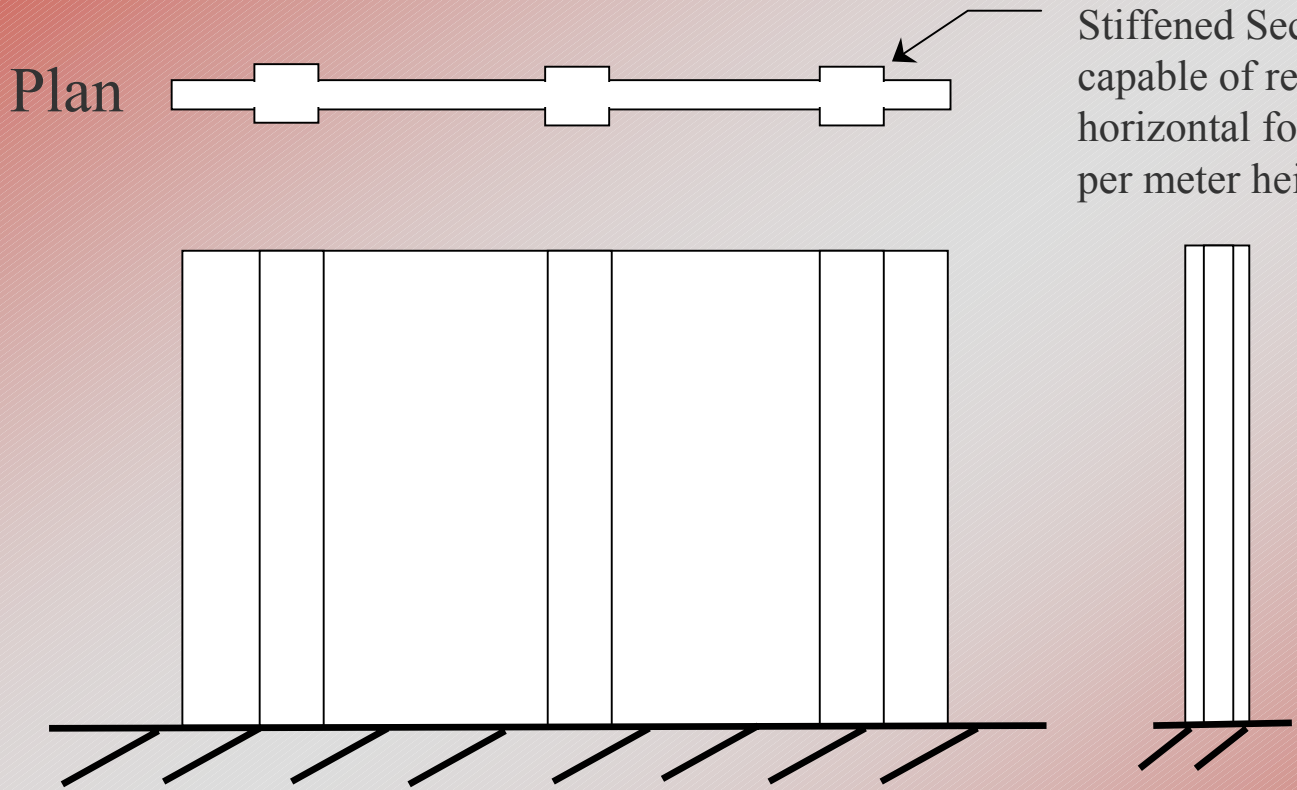
Vertical Load-bearing Element Type	Definition of Element	Extent of Structure to Remove if Deficient
Column	Primary structural support member acting alone	Clear height between lateral restraints
Wall	All external and internal load-bearing walls	Length between adjacent lateral supports[A] or between a lateral support and a free edge.

[A] Using the definition of F_t in Section 4-2.5, a lateral support is considered to be:

1) a stiffened section of the wall not exceeding 1.0 m (3.3 ft) in length, capable of resisting a horizontal force of 1.5 F_t, in kN per meter height of the wall (0.45 F_t in kips per foot height of wall), or,
2) a partition of mass not less than 100 kg/m^2 (20.6 lb/ft^2) at right angles to the wall and so tied to it as to be able to resist a horizontal force of 0.5 F_t, in kN per meter height of the wall (0.15 F_t in kips per foot height of wall).

RC Tie Force Requirements

- Definition of Lateral Supports



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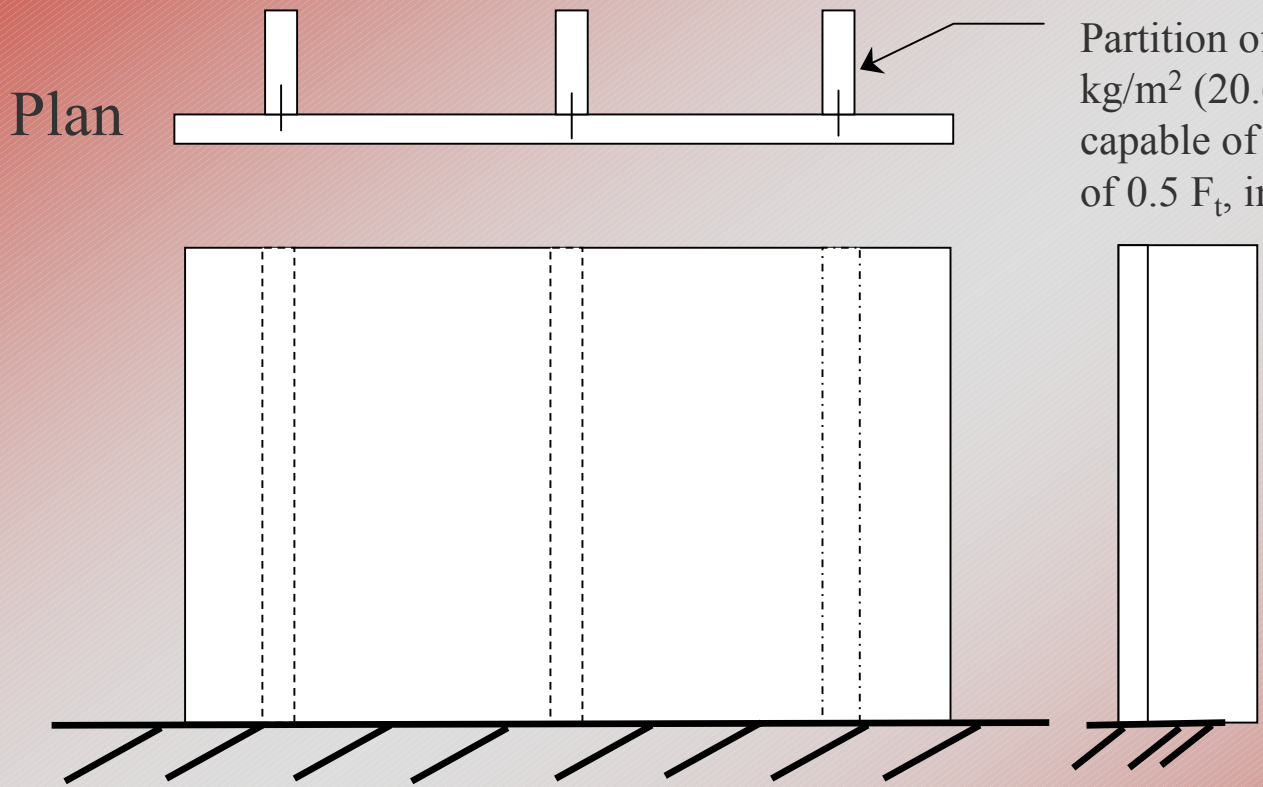
RC Tie Force Requirements

- Definition of Lateral Supports, cont'd



AP Method for RC

- Alternate Path Method For Reinforced Concrete
  - ◊ The Alternate Path method must be used to verify that the structure can bridge over removed elements.
  - ◊ The general procedure provided in Section 3-2 in the UFC must be followed.

AP Method for RC

- Acceptability Criteria for Reinforced Concrete
  - ◊ The acceptability criteria are provided in Table 4-3 and the design strengths must be calculated per ACI 318-02.
  - ◊ The subsequent actions for the AP model after violation of the acceptability criteria are detailed in the following slides.

AP Method for RC

Acceptability Criteria and Subsequent Action for Reinforced Concrete

Structural Behavior	Acceptability Criteria	Subsequent Action for Violation of Criteria
Element Flexure	ΦM_n^A	Section 4-3.1.1
Element Combined Axial and Bending	ACI 318-02 Chapter 10 Provisions	Section 4.3.1.2
Element Shear	ΦV_n^A	Section 4-3.1.3
Connections	Connection Design Strength[A]	Section 4-3.1.4
Deformation	Deformation Limits, defined in Table 4-4	Section 4-3.2

[A] Nominal strengths are calculated with the appropriate material properties and over-strength factor Ω; all Φ factors are defined per ACI 318-02.

AP Method for RC

- Flexural Resistance of Reinforced Concrete
  - For reinforced concrete, the flexural design strength is equal to the nominal flexural strength calculated with the appropriate material properties and over-strength factor Ω, multiplied by the strength reduction factor Φ.
  - Calculate the nominal flexural strength per ACI 318-02 procedures.

AP Method for RC

- Flexural Resistance of Reinforced Concrete, cont'd
  - ◊ For Linear Static Analysis:
    - If the required moment exceeds the flexural design strength and if the reinforcement layout is sufficient for a plastic hinge to form and undergo significant rotation, add an equivalent plastic hinge to the model, by inserting a discrete hinge at the correct location within the member.
    - For a connection with a plastic hinge, insert the hinge at the offset from the member end; use engineering analysis and judgment to determine the offset length, which must be less than ½ the depth of the member from the face of the column.
    - Also, apply two constant moments, one at each side of the new hinge, in the appropriate direction for the acting moment.

AP Method for RC

- Flexural Resistance of Reinforced Concrete, cont'd
  - ◊ For Nonlinear Static and Dynamic Analysis:
    - The software must be capable of representing post-peak flexural behavior.
    - The designer must ensure that shear failure will not occur prior to developing the full flexural design strength.
    - Additional guidance on the modeling of plastic hinges in reinforced concrete can be found in *Plastic Methods for Steel and Concrete Structures* by Moy (Moy 1996) and *Reinforced Concrete: A Fundamental Approach* by Nawy (Nawy 2000).

AP Method for RC

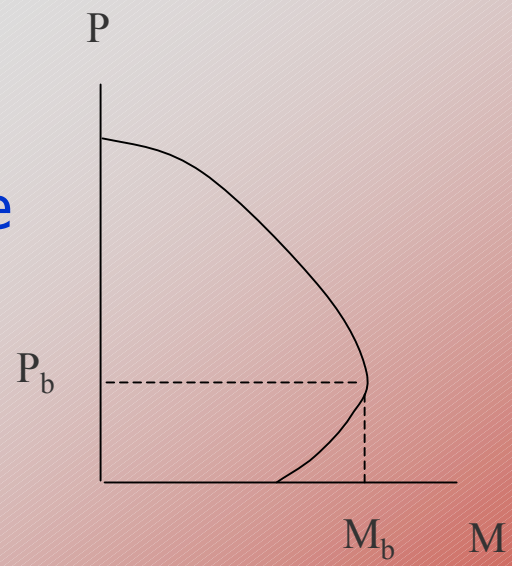
- Flexural Resistance of Reinforced Concrete, cont'd
  - ◊ If the structural element is not able to develop a constant moment while undergoing continued deformations, remove the element when the internal moment exceeds the flexural design strength.
  - ◊ Redistribute the loads associated with the element per Section 3-2.4.3.

AP Method for RC

- Combined Axial and Bending Resistance of Reinforced Concrete
  - ◊ The acceptability criteria for elements undergoing combined axial and bending loads are based on the provisions given in Chapter 10 of ACI 318-02, including the appropriate strength reduction factor Φ and the over-strength factor Ω.

AP Method for RC

- Combined Axial and Bending Resistance of Reinforced Concrete
  - If the combination of axial load and flexure in an element exceeds the design strength and the un-factored axial load is greater than the nominal axial load strength at balanced strain P_b, remove the element and redistribute the loads associated with the element per Section 3-2.4.3.
  - If the un-factored axial load is less than P_b, then insert an equivalent plastic hinge into the column, per the procedure discussed in Section 4-3.1.1.



AP Method for RC

- Shear Resistance of Reinforced Concrete
  - ◊ The acceptability criteria for shear is based on the shear design strength of the cross-section, per ACI 318-02, using the appropriate strength reduction factor Φ and the over-strength factor Ω.
  - ◊ If the element violates the shear criteria, remove the element and redistribute the loads associated with the element per Section 3-2.4.3.

AP Method for RC

- Connections
  - ◊ Calculate the design strengths for joints using ACI 318-02, including the appropriate strength reduction factor Φ and over-strength factor Ω.
  - ◊ The designer must consider the effects of embedment length, reinforcement continuity, and confinement of reinforcement in the joint when determining the joint design strength.
  - ◊ If the connection violates the criteria, remove it from the model.
  - ◊ If both connections at the ends of an element fail, remove the element and redistribute the loads associated with the element per Section 3-2.4.3

AP Method for RC

- Deformation Limits for Reinforced Concrete
  - ◊ The Deformation Limits are given in Table 4-4.
  - ◊ If an element or both connections at the ends of an element exceed a deformation limit, remove the element and redistribute the loads associated with the element per Section 3-2.4.3, before the analysis continues.
  - ◊ It is noted that Table 4-4 does not contain deformation limits for connections.
    - Per FEMA 356, monolithic joints between beams and columns or walls are represented as rigid zones.
    - Thus, the deformation limits are applied only to the structural elements.

Deformation Limits for Reinforced Concrete

Component	AP for Low LOP		AP for MLOP and HLOP	
	Ductility (μ)	Rotation, Degrees (θ)	Ductility (μ)	Rotation, Degrees (θ)
Slab and Beam Without Tension Membrane[A]				
Single-Reinforced or Double-Reinforced w/o Shear Reinforcing[B]	-	3	-	2
Double-Reinforced w/ Shear Reinforcing[C]	-	6	-	4
Slab and Beam With Tension Membrane[A]				
Normal Proportions ($L/h \geq 5$)	-	20	-	12
Deep Proportions ($L/h < 5$)	-	12	-	8
Compression Members				
Walls and Seismic Columns[D,E]	3	-	2	-
Non-Seismic Columns[E]	1	-	0.9	-

[A] Requirements for developing tension membrane response are provided in Park and Gamble 1999 and UFC 3-340-01; the tension membrane effect is an extension of the yield line theory of slabs and it increases the ultimate resistance. It cannot be developed when the slab has a free edge.

[B] Single-reinforced members have flexural bars in one face or mid-depth only. Double-reinforced members have flexural reinforcing in both faces.

[C] Stirrups or ties meeting ACI 318-02 minimums must enclose the flexural bars in both faces, otherwise use the response limits for Double-Reinforced w/o shear reinforcing.

[D] Seismic columns have ties or spirals in accordance with ACI 318-02 Chapter 21 seismic design provisions for special moment frames.

[E] Ductility of compression members is the ratio of total axial shortening to axial shortening at the elastic limit.

AP Method for RC

- Additional Ductility Requirements
  - For MLOP and HLOP structures, all perimeter ground floor columns and load-bearing walls must be designed such that the shear capacity is greater than the flexural capacity, including compression membrane effects where appropriate.
  - Methods for calculating the compression membrane effects can be found in *Reinforced Concrete Slabs* by Park and Gamble (Park and Gamble 1999) and UFC 3-340-01 *Design and Analysis of Hardened Structures to Conventional Weapons Effects*.

RC Requirements

Questions/Comments?