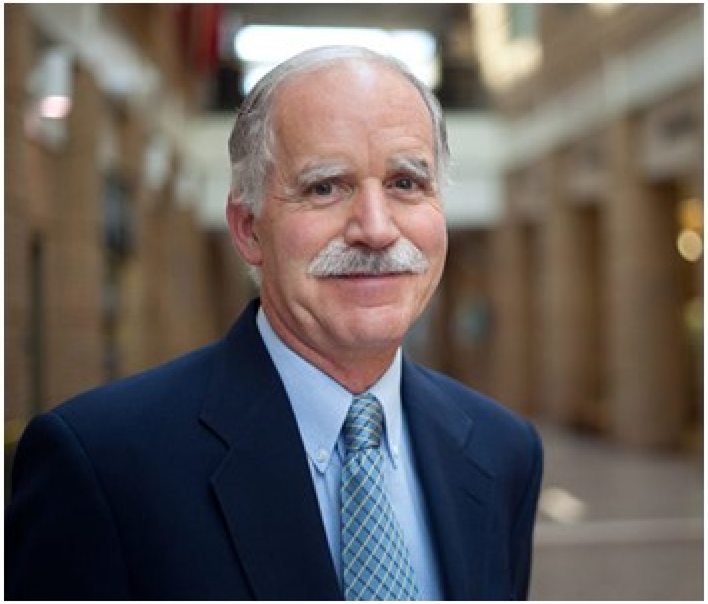
ACIES

Asociación Colombiana de Ingeniería Estructural

Presentación Técnica

"Strut-and-Tie Method for Analysis and Design of Concrete Members"



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Development of the Strut-and-Tie Method for use in ACI Building Code

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My introduction to the need for the strut-and-tie method:

Roof member collapse for a Combined Sewer Overflow (CSO) basin in Michigan

Roof consisted of precast double-tee sections with dapped ends designed following the PCI Design Handbook. Approximately 1 meter of soil was placed over top of basin. Collapse occurred as small earth-mover was smoothing soil fill.

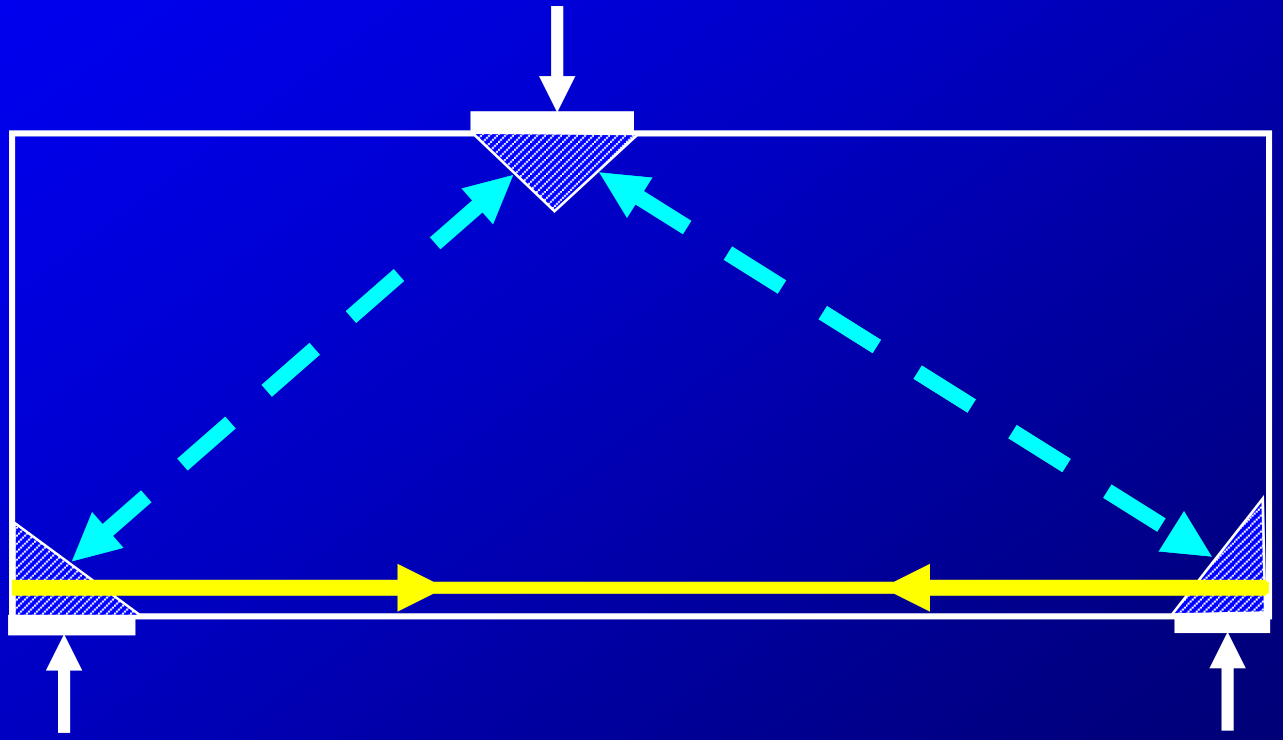
Double-Tee with dapped end; roof of CSO Basin

Adjacent uncollapsed roof members

Strut and Tie Models

Members or D-regions (disturbed regions) of members may be designed by idealizing the concrete and reinforcement as an assembly of axially loaded members, connected at nodes, to form a truss capable of carrying loads across a D-region or member.

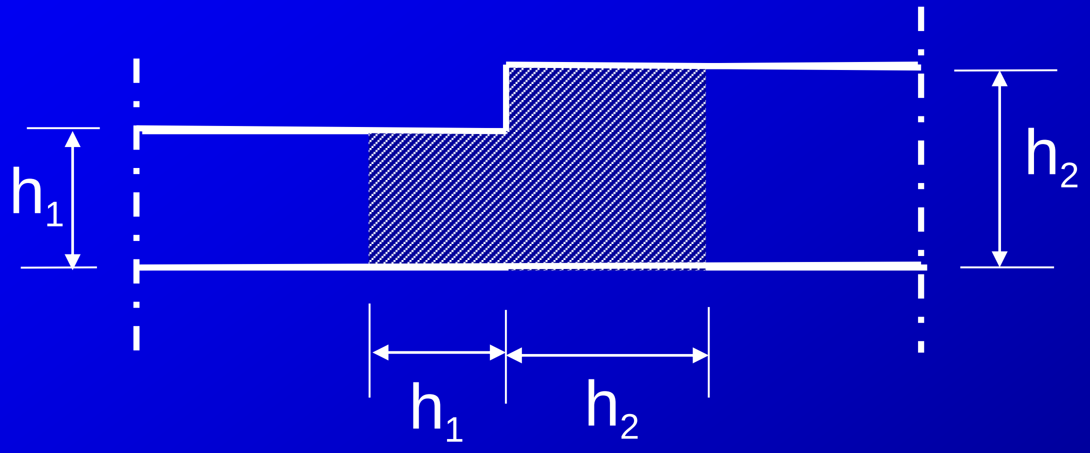
Components of Strut and Tie Models

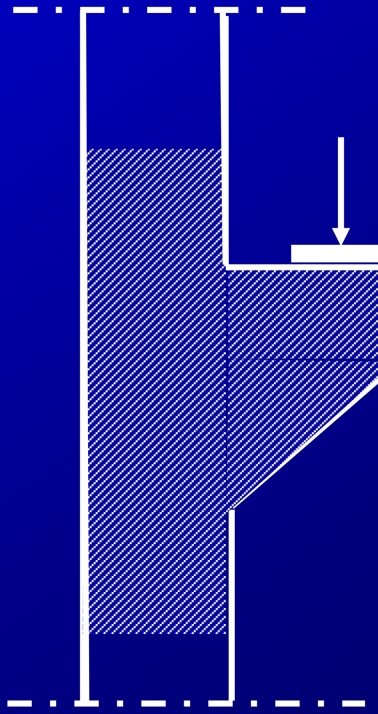


Steps to Build Strut & Tie Model

- Isolate member or D(disturbed) - region
- Compute forces or distribution of stresses on boundary
- Represent any stress distributions as forces
- Select a truss model to transmit these forces across the member or D-region

Concept of D-Regions (geometric discontinuities)

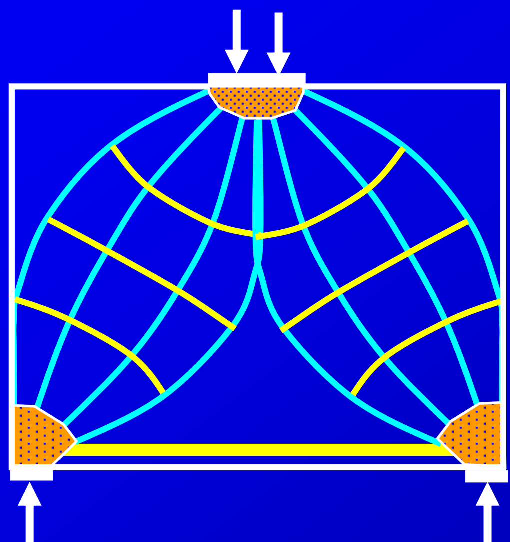




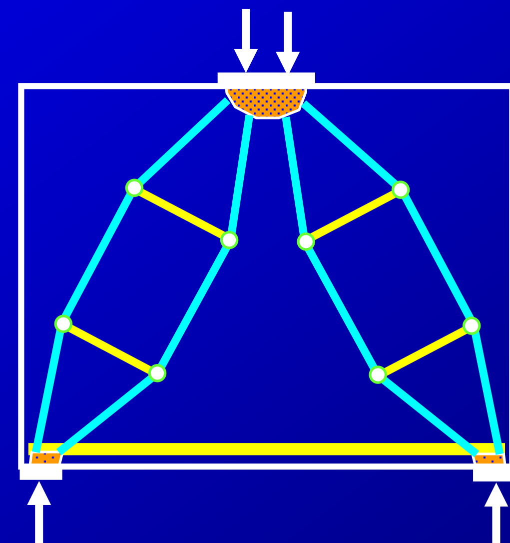
Basic Requirements for STM

- Model approximates stress flow across member or region
- Define truss component dimensions and strengths
- Define ϕ for STM and β factors for struts and nodes
- Analyze struts, ties and nodes
- Select reinforcement; check anchorage

Modeling Stress Flow

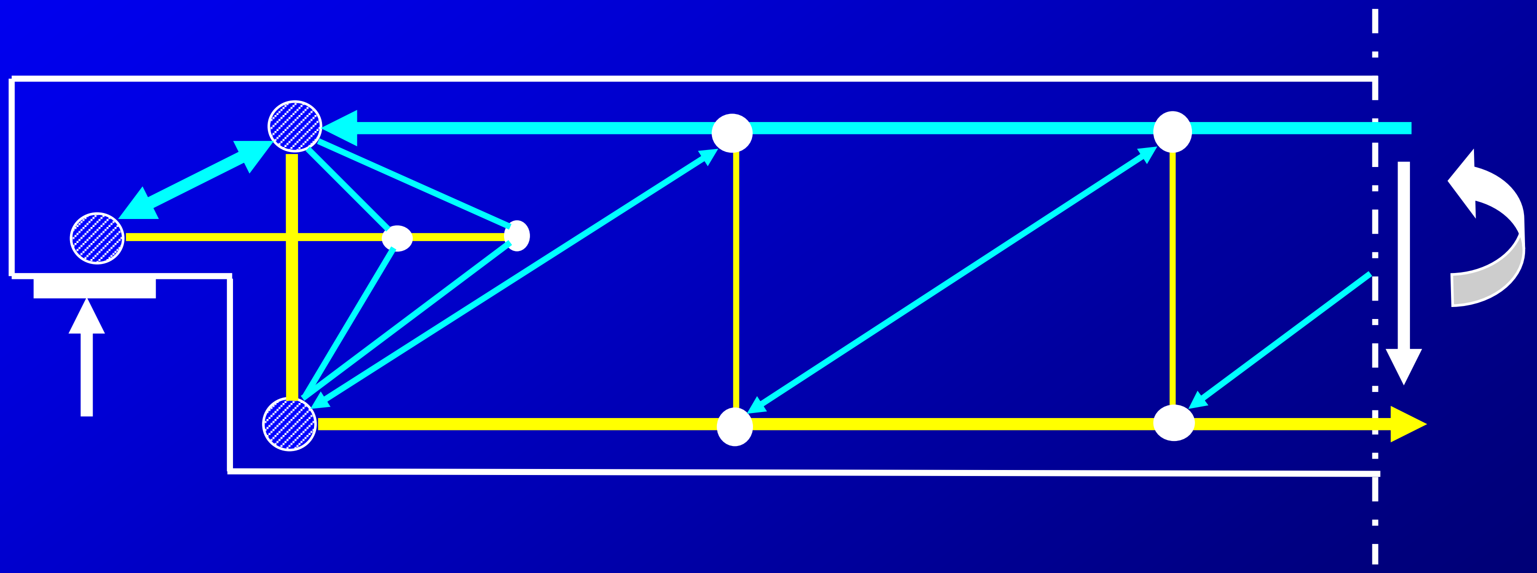


FE Analysis



Truss Model

Modeling Stress Flow in D-Regions (Dapped-End Beam)



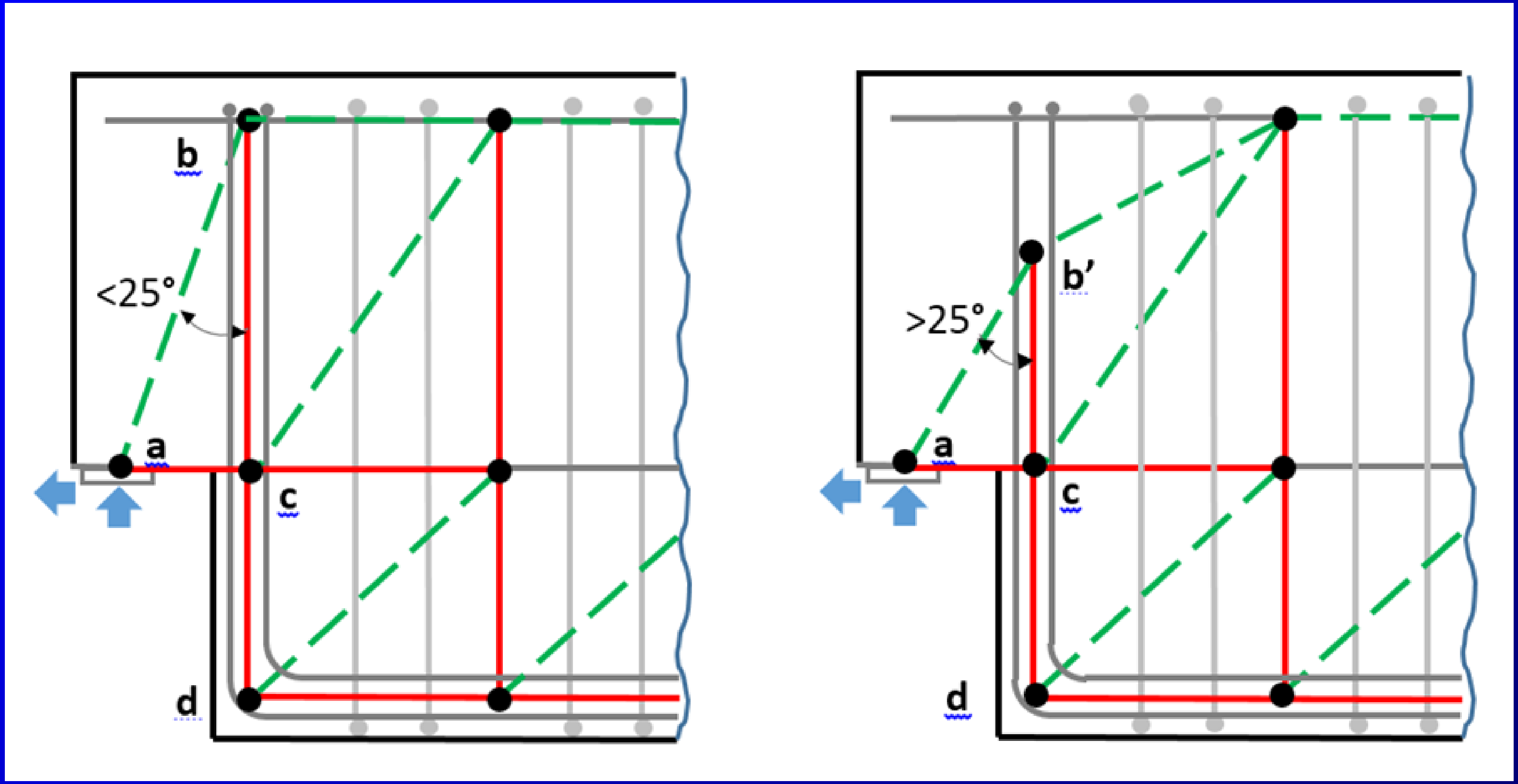
How to Select the “Correct” Strut-and-Tie Model

- Some researchers suggest using a finite element model to determine stress trajectories, then selecting a truss to “model” the stress flow.
- Generally, a STM that minimizes the required amount or reinforcement is close to an ideal model.

Required Definitions for Code

- Geometric rules to follow when creating a strut-and-tie model.
- Component strengths for determining members sizes and final geometry of the model.

Minimum Angle between Struts and Ties



Codes with Rules for Use of Strut-and-Tie Models

- AASHTO LRFD Specification
- Canadian Code for Design of Concrete Structures
- FIP (fib) Recommendations for Design of Structural Concrete

Strength of Compression Struts (what to consider)

- Longitudinal cracking due to transverse tension strain
- Transverse tension forces
- Sustained compression (column design)
- Reinforcement grid crossing strut
- Confinement by concrete or steel

Effective Compressive Strength of Struts

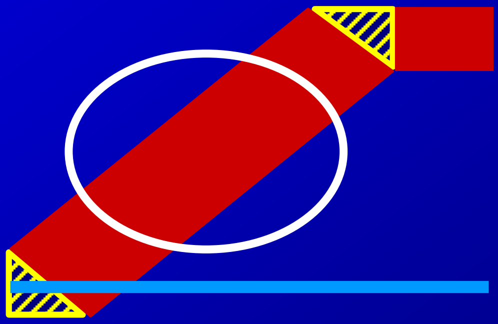
$$\phi F_{ns} \geq F_u$$

$$\phi = 0.75$$

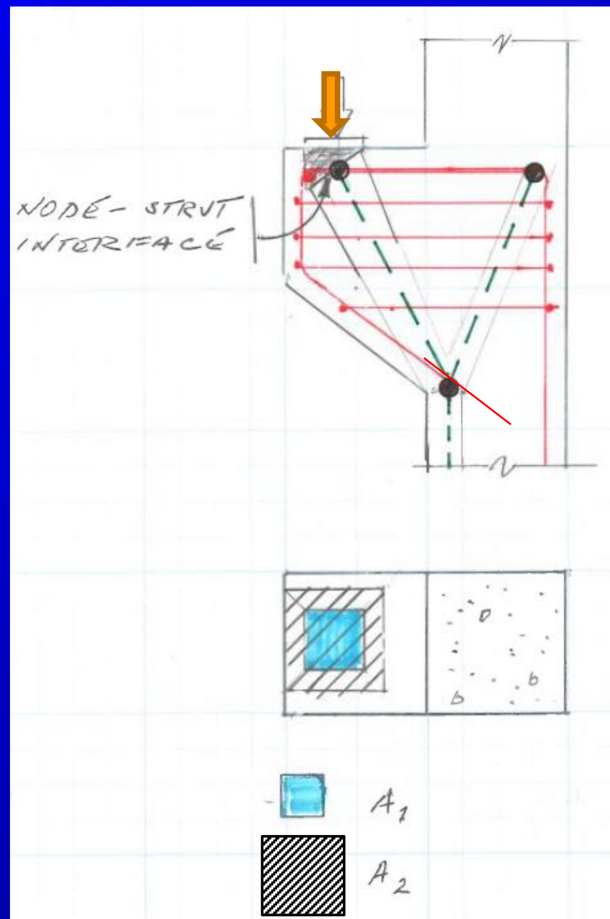
$$F_{ns} = f_{ce} A_c$$

$$A_c = \text{min. cross-sectional area of strut}$$

$$f_{ce} = 0.85 \beta_c \beta_s f_c'$$



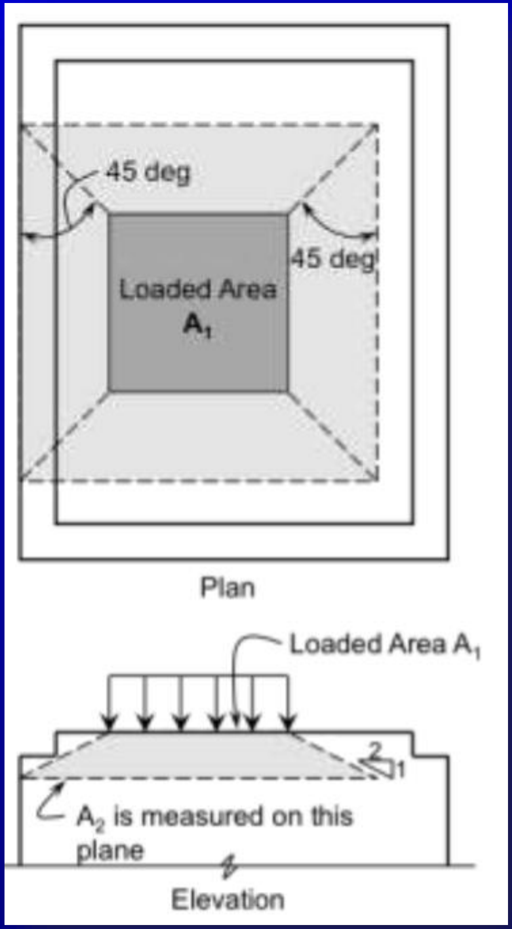
Confined Nodes (and Struts)



Confined Nodes (and Struts)

$$\beta_c = \sqrt{A_2 / A_1} \leq 2.0,$$

otherwise, $\beta_c = 1.0$



CSA Evaluation of Effective Concrete Strength

$$\beta_s f_c' = \frac{f_c'}{0.8 + 170\varepsilon_1} \le 0.85 f_c'$$

Transverse tension, $\varepsilon_1 = (\varepsilon_s + 0.002) \cot^2\theta_s$

θ_s = angle between strut and tie (steel)

ε_s = strain in steel tie

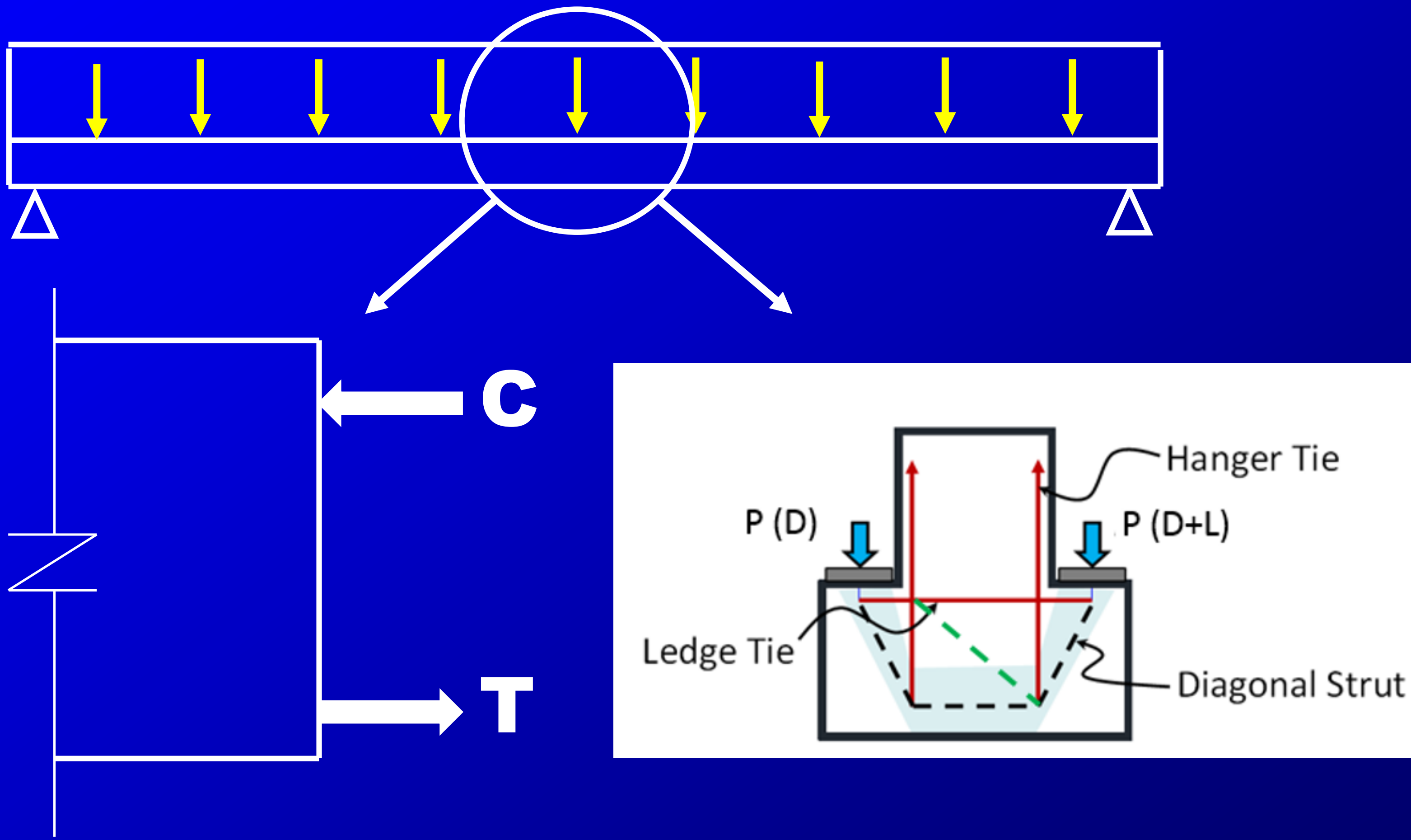
FIP Recommendations for β_s in Cracked Struts

- 0.80 - struts with longitudinal cracking (splitting), but crossed by minimum reinforcement grid
- 0.75 - struts crossed by “normal” width cracks
- 0.60 - struts crossed by “wide” cracks

ACI Recommended β_s Values for Struts

- 1.0 – prismatic shape (constant width) over its length, similar to a flexural compression zone in a B-region
- 0.75 – inclined strut crossed by minimum reinforcement grid
- 0.75 – inclined strut confined by surrounding concrete; for example in a pile cap
- 0.40 – struts in flexural tension zones
- 0.40 – all other cases

Struts in a Flexural Tension Zone



Min. Reinf. Grid in other Codes

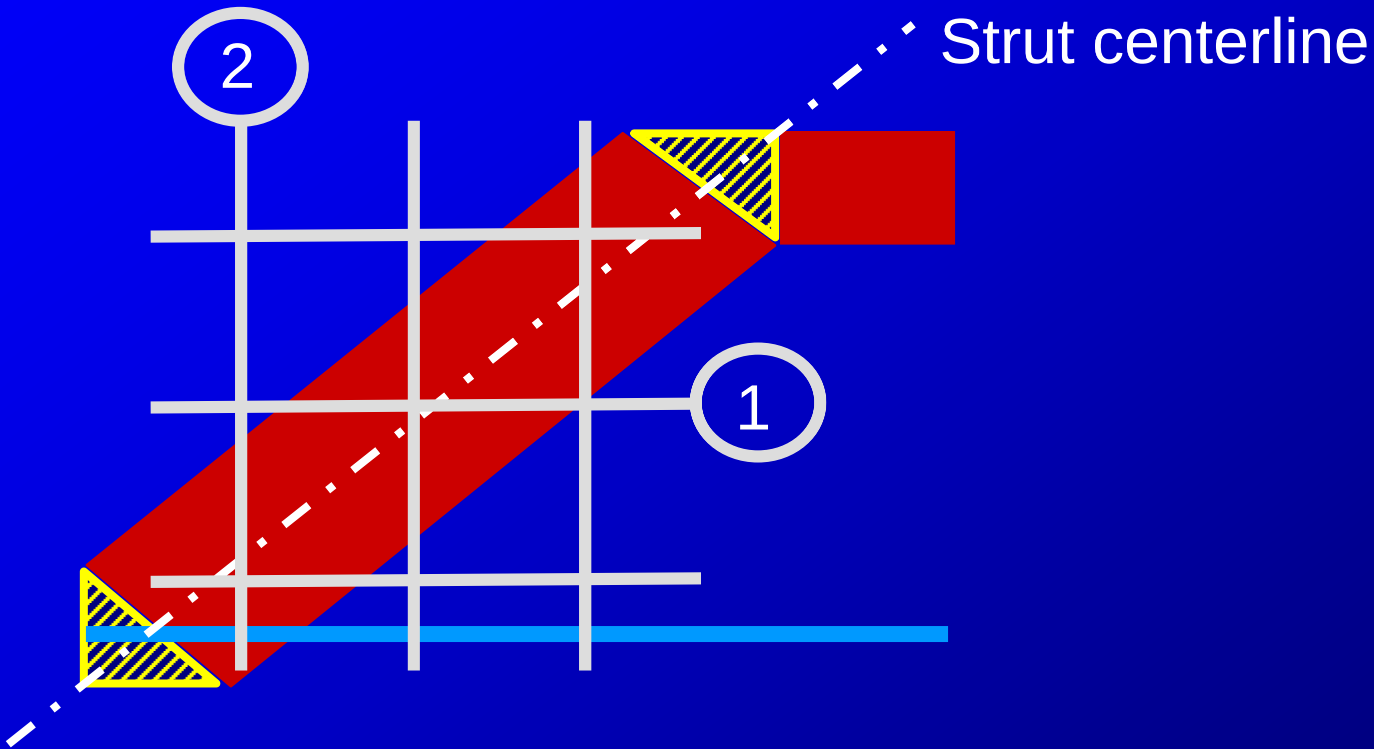
- AASHTO $\rho \geq 0.003$ EW
- CSA and FIP $\rho \geq 0.002$ EW

Minimum Reinforcement Grid – ACI Code

Deep Beams and Shear Walls with significant shear stresses

$$\rho_\ell \text{ and } \rho_t \geq 0.0025$$

Minimum Reinforcement Grid

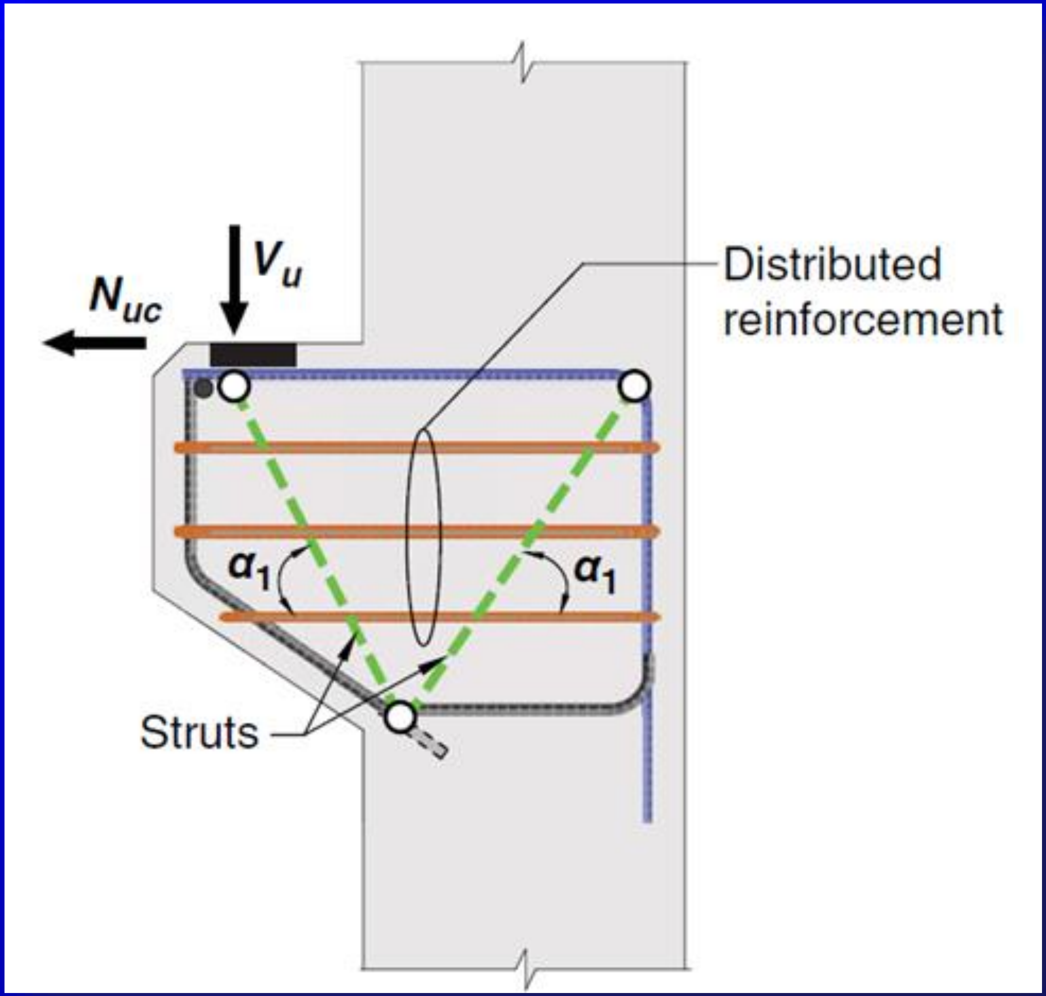


$$\rho_1 \text{ and } \rho_2 \geq 0.0025, \text{ and } s \leq 12 \text{ in.}$$

23.5.1 Minimum Reinforcement Crossing Struts in D-Regions

Reinforcement Configuration	**Min. Dist. Reinforcement Ratio**
Orthogonal Grid	0.0025 each direction
Reinf. in one direction crossing strut at angle α_1	$\dfrac{0.0025}{\sin^2 \alpha_1}$

Minimum Reinforcement of D Regions



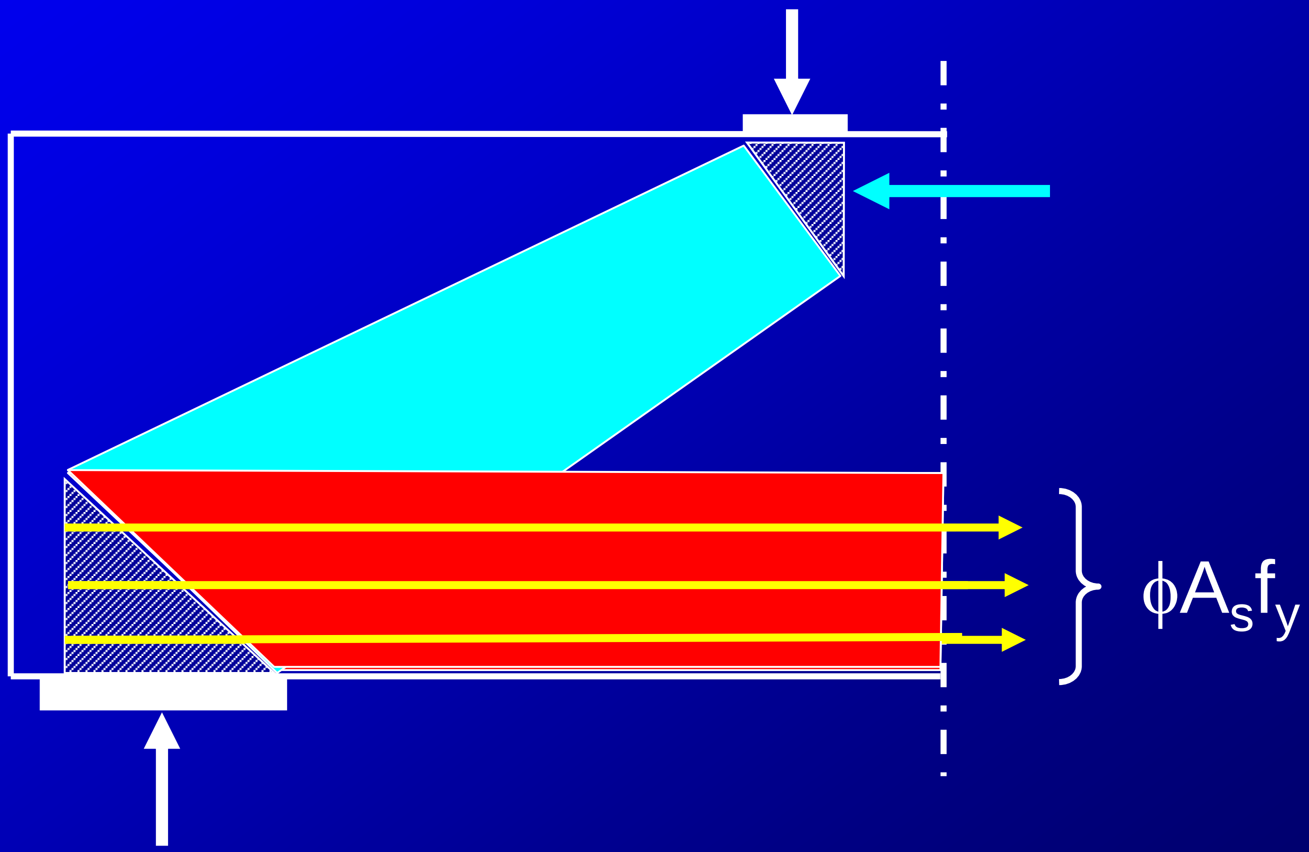
Note: $\alpha_1 > 40^o$

Smaller α_1 governs

Ties: Dimensions and Strength

- Out of plane - Full width of member
- In-plane width of tie is function of effective compression strength of nodal zone where tie is anchored
- Spread reinforcement throughout tie dimensions

Ties - Dimensions and Strength

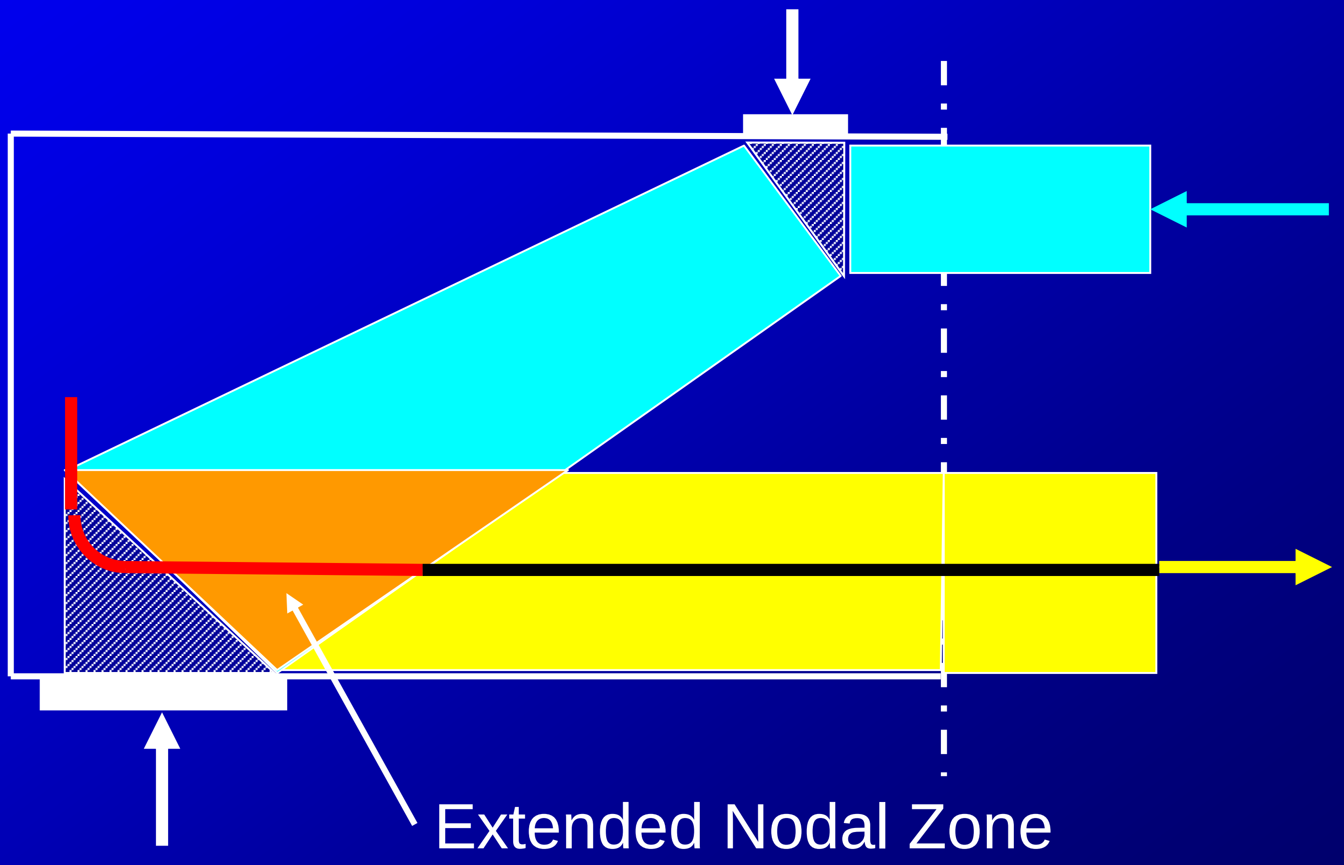


Strength of Ties

- Strength = $\phi A_s f_y$, where $\phi = 0.75$*
- Anchorage of ties at nodes is a major concern

**A constant value of $\phi = 0.75$ is to be used for sizing the strut-and-tie model.*

Ties - Anchorage Check



Nodal Zones: Dimensions and Strength

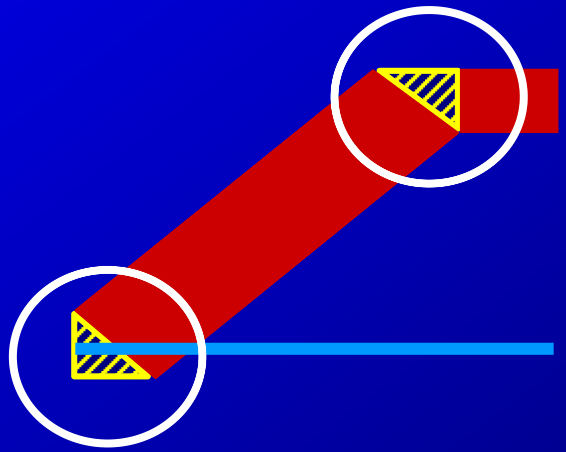
- Out of plane - Full width of member
- In-plane: Width of compression face is same as width of strut connecting to nodal zone (smaller allowable strength governs)
- Height of nodal zone is equal to tie force divided by effective compressive strength of the concrete in the node

Effective Strength of Nodal Zones

- Function of type of members connected to the node
- Possible combinations are CCC, CCT and CTT
- Strength can be enhanced by confining concrete or confinement reinforcement

Strength of Nodes

$$\phi\ F_{nn} \geq F_u$$



$$\phi = 0.75$$

$$\mathrm{F}_{\mathrm{nn}} = \mathrm{f}_{\mathrm{ce}}\ \mathrm{A}_{\mathrm{n}}$$

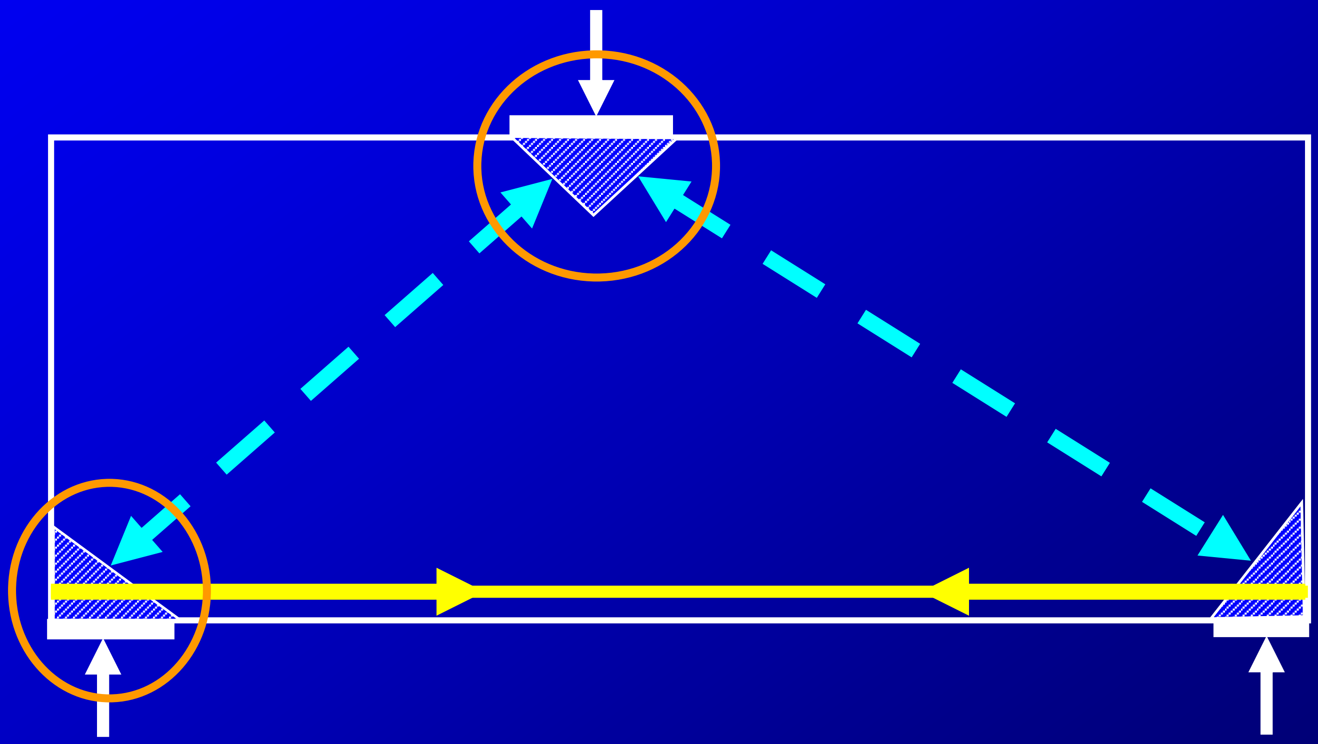
$$A_n = area\ of\ node\ face \perp to\ force\ F_u$$

$$\mathrm{f}_{\mathrm{ce}} = 0.85\,\beta_c\,\beta_{\mathrm{n}}\,\mathrm{f}'_{\mathrm{c}}$$

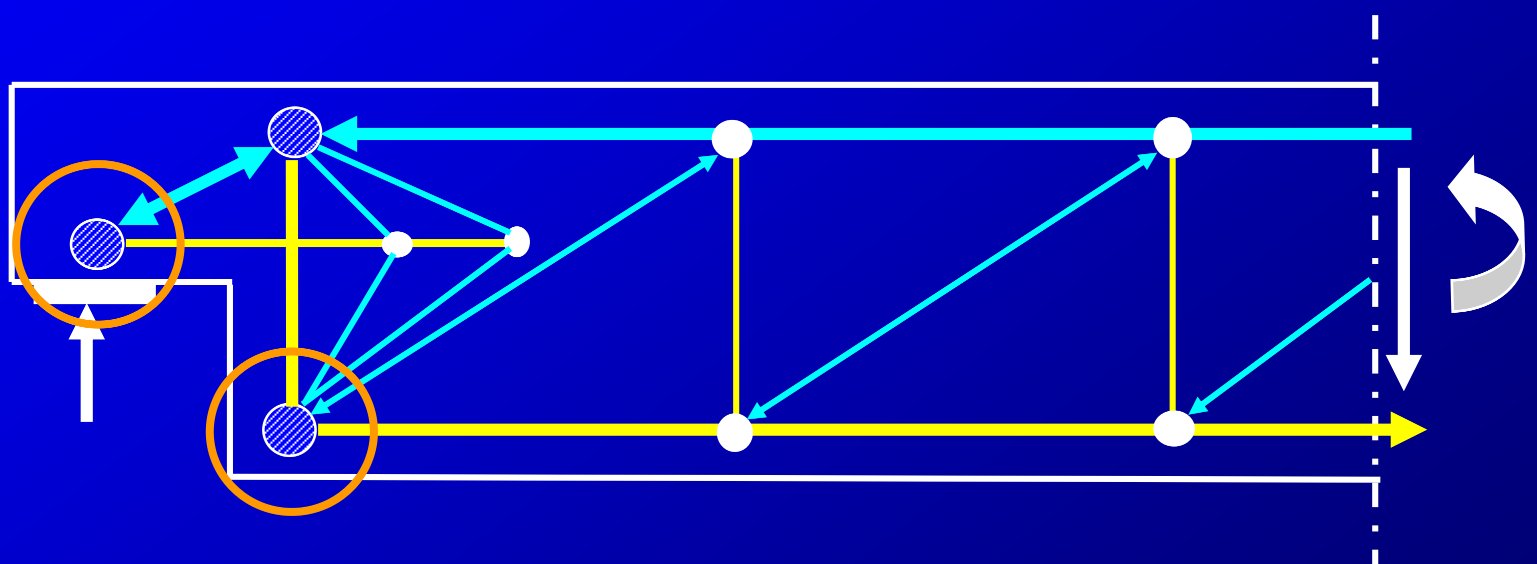
Recommended β_n Values (Nodes)

- 1.0 - CCC node
- 0.8 - CCT node
- 0.6 - CTT node

Examples of CCC and CCT Nodes



Examples of CCT and CTT Nodes



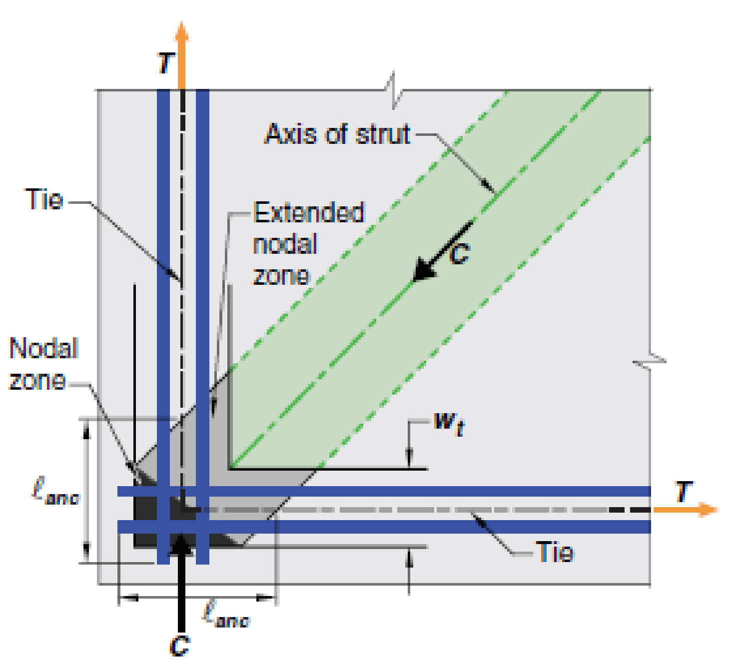
New Items in ACI 318-19

- Curved Bar Nodes
- Use in Earthquake Resistant Design

23.10 Curved-bar Nodes

Why curved-bar nodes?

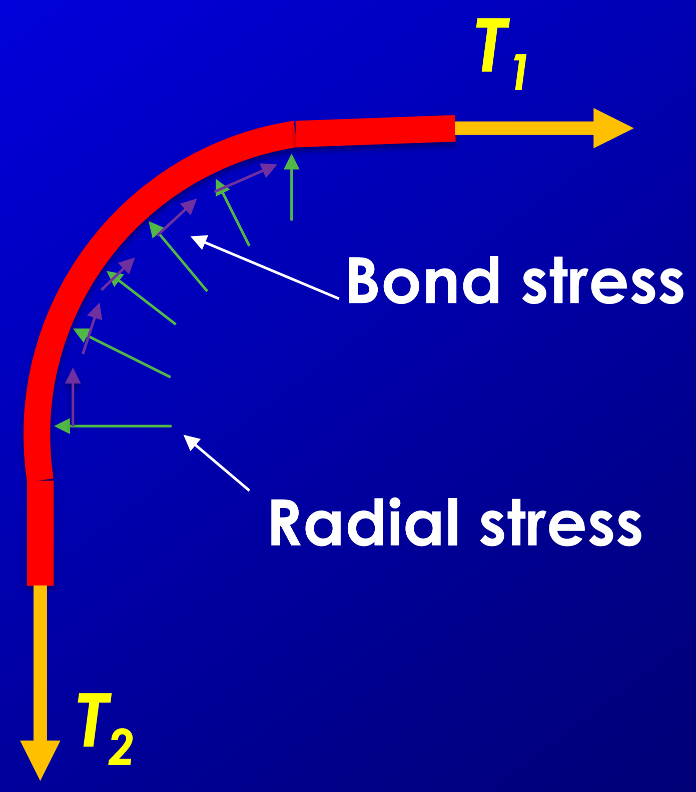
Nodal zones are sometimes <u>too small</u> to allow development



23.10 Curved-bar Nodes

Two issues that need to be addressed:

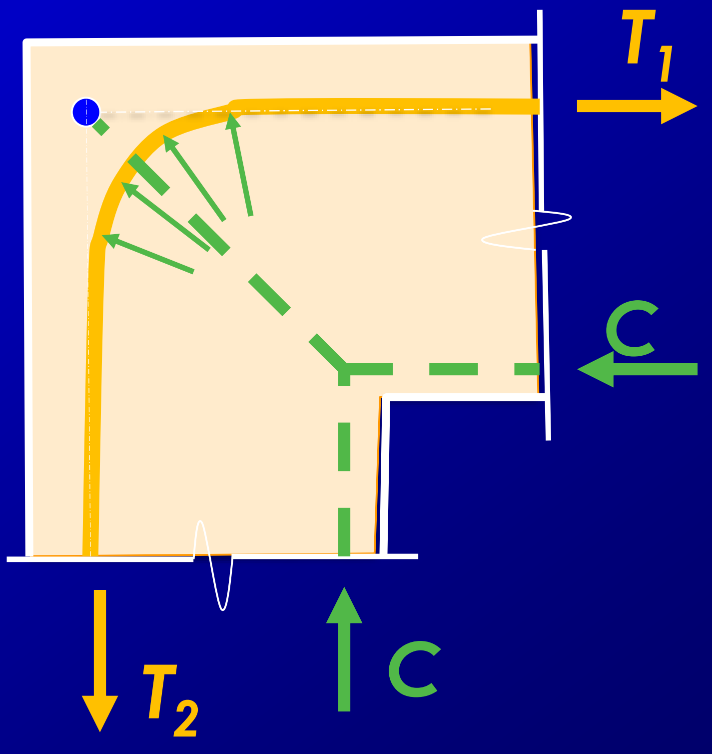
1. Slipping of bar, T_1 and T_2 are not equal.
2. Concrete crushing



23.10 Curved-bar Nodes

<u>1st Condition</u>

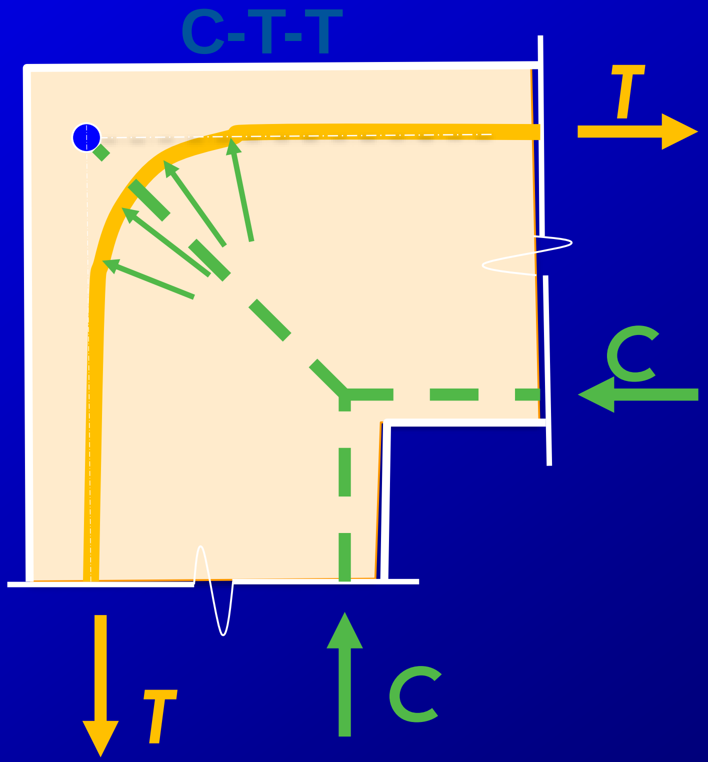
- θ < 180 degree bend
- $T_1 = T_2 = A_s f_y$
- Radial compression stresses are uniform
- Bond stresses = 0



23.10 Curved-bar Nodes

θ < 180 degree bend

$$r_b \geq \frac{2A_{ts}f_y}{bf_c'}$$



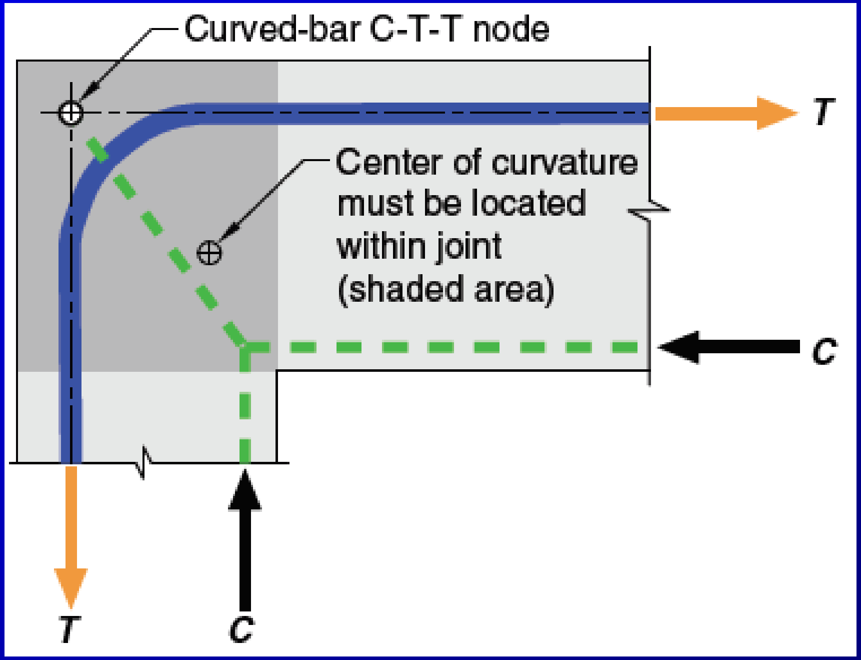
but not less than half bend diameter of Table 25.3; seldom governs!

23.10 Curved-bar Nodes

23.10.2 Cover ≥ $2d_b$

23.10.3 Cover < $2d_b$

➔ r_b x $(2d_b / c_c)$



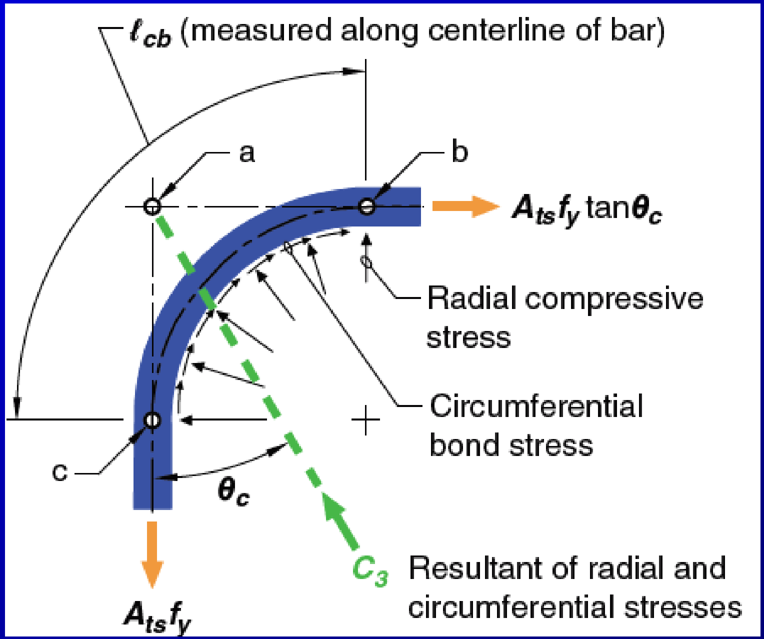
23.10.5 At frame corners, joint and bars must be proportioned such that center of bar curvature is located within the joint

23.10 Curved-bar Nodes

2nd Condition

Tie forces are not equal:

- **Compressive stress on the inside radius of bar varies**
- **Circumferential bond stress develops along bar**



$$C_3 = \frac{A_{ts} f_y}{\cos\theta_c}$$

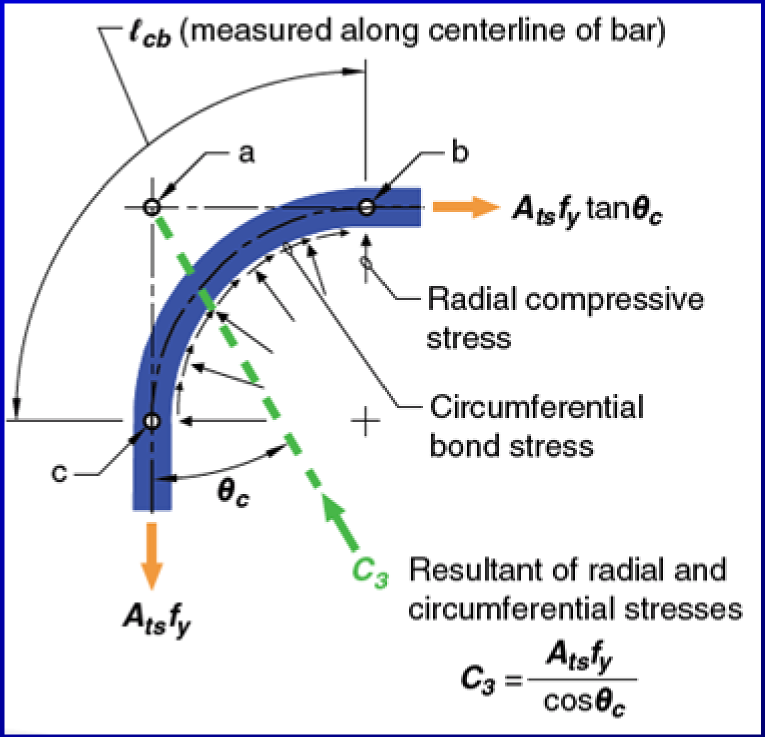
23.10 Curved-bar Nodes

23.10.6 The curve must be sufficient to develop difference in force

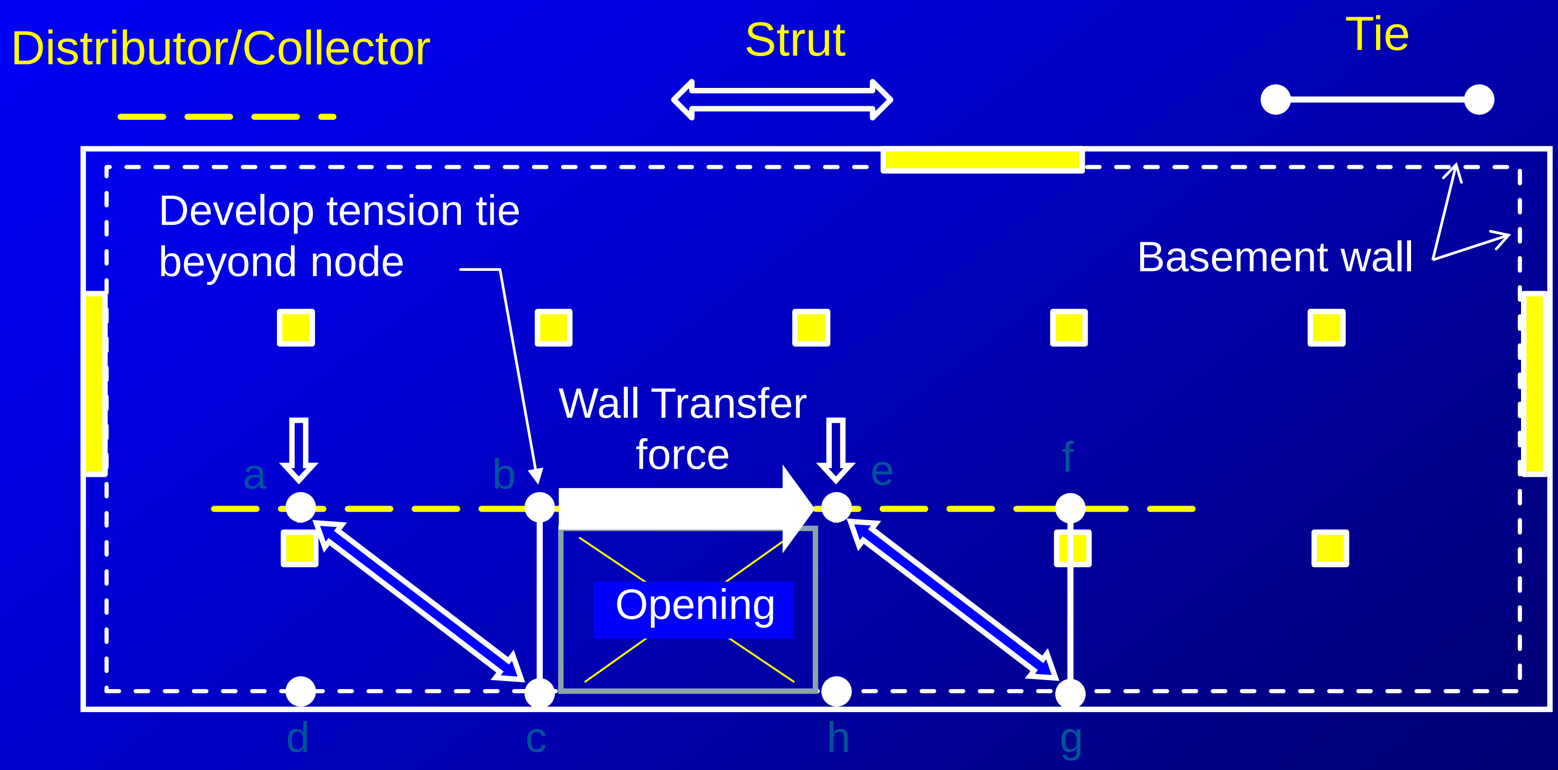
$$\ell_{cb} > \ell_d(1 - \tan\theta_c)$$

In terms of r_b

$$r_b > \frac{2\ell_d(1-\tan\theta_c)}{\pi} - \frac{d_b}{2}$$



23.11 Earthquake-resistant design using STM



Earthquake-resistant design using STM

Seismic-force-resisting system assigned to SDC D-F and designed with STM must satisfy:

1. **Chapter 18**
2. **Strut forces are increased by overstrength factor Ω_o = 2.5 or Ω_o < 2.5 if based on rational analysis**

23.11 Earthquake-resistant design using STM

If condition 2 is not satisfied then the following must be addressed, Provisions 23.11.2 - 23.11.5

<u>Reduce</u> <u>strut</u> and <u>node</u> effective compressive strength, f_{ce}, of concrete by <u>0.8</u>

$$f_{ce} = (0.8)(0.85\,\beta_c \beta_{s/n}\, f_c')$$

Use of STM in ACI 318-19

- Chapter 23 of ACI Code.
- STM is the required procedure for design of deep beams.
- STM is noted as alternate procedure in other sections of the code.
- Sect. 23.11 added for earthquake-resistant design.

Gracias

Questions?

Thank you for your attention