Steel & CFT Column Design

ดร.วศ. กิจพัฒน์ ภู่วรวรรณ

(kitjapat@hotmail.com)

ม.เกษตรศาสตร์

อนุกรรมการโครงสร้างเหล็ก วสท.

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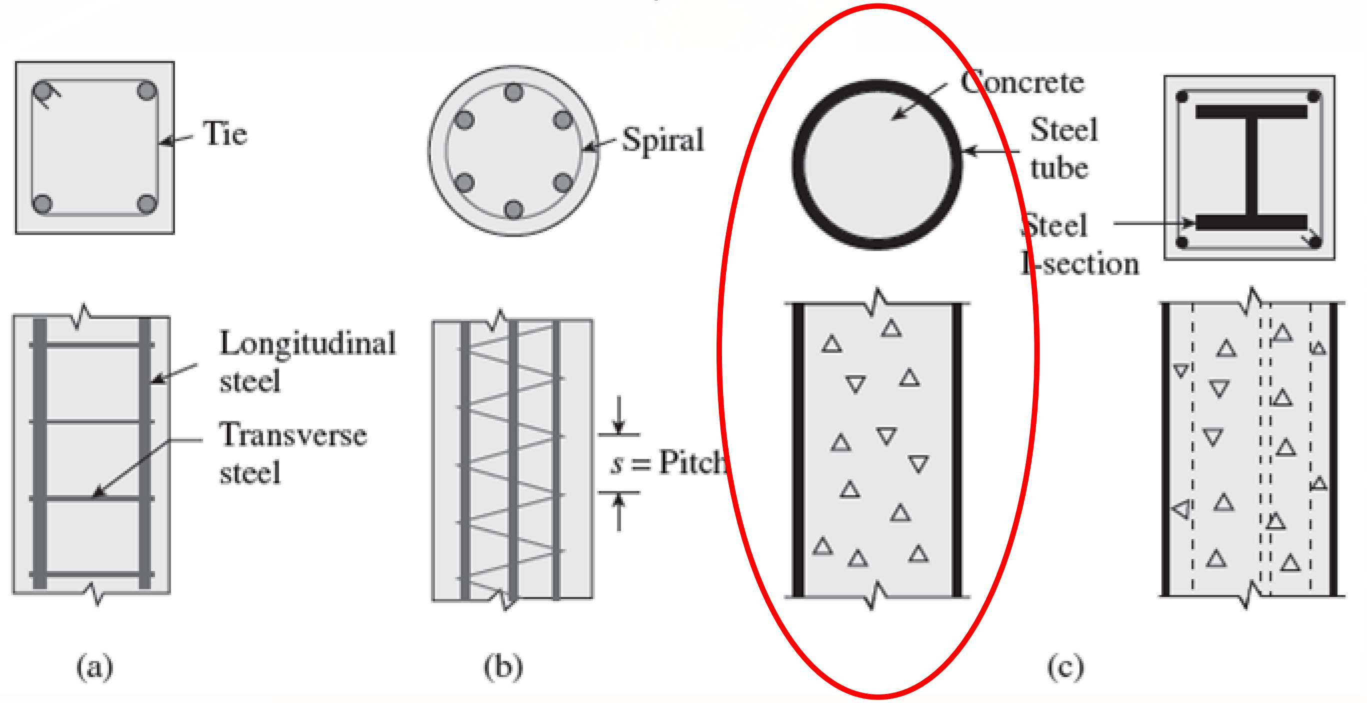
OUTLINE

- What is CFT?
- CFT Behavior
- Application of CFT
- Column Design Standards
- Column Design Example

What is CFT?

- CFT → Concrete-Filled (Steel) Tube
- Composed of: - Steel Tube

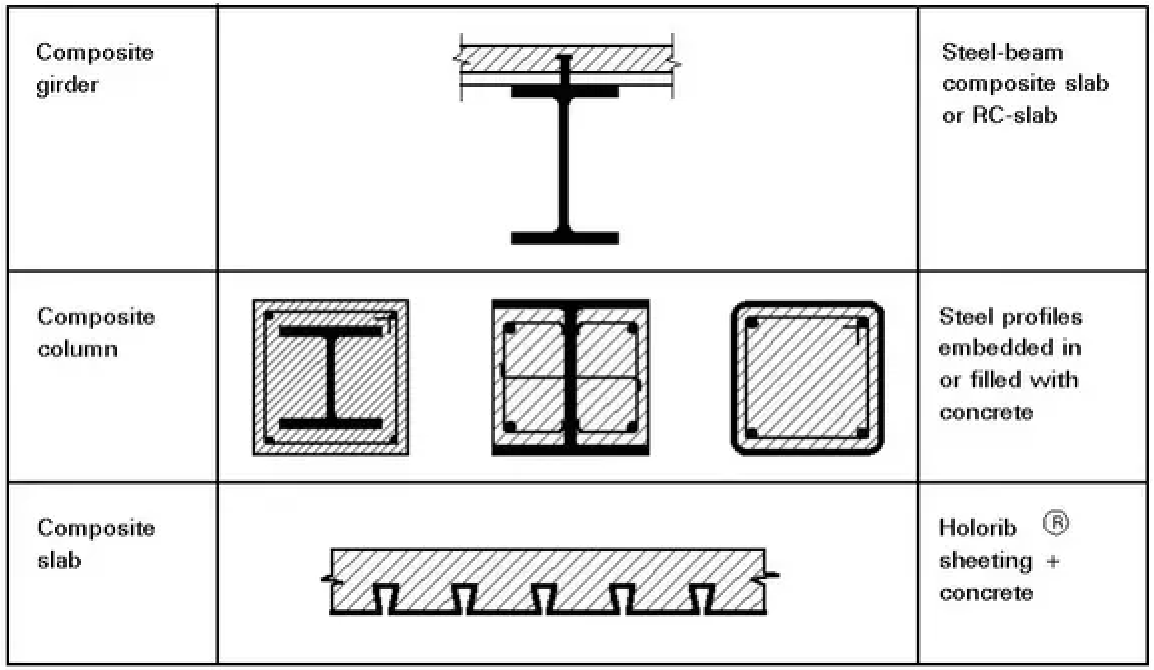
  - Filled Concrete (with or without Reinforcement)

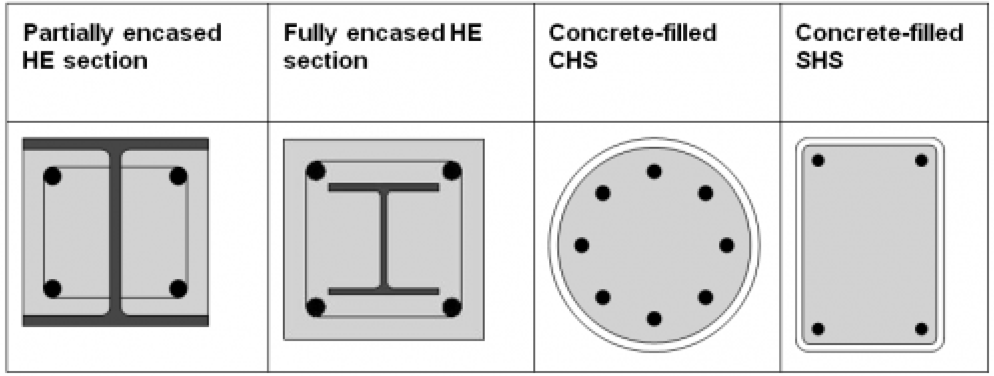


CFT

- Composite Structures:
  - Girders
  - Columns
  - Slabs

- Composite Columns:
  - Concrete Encased
  - Concrete Filled (CFT)





CFT Materials

- STEEL:
  - Mild steel / High strength steel / Fire resistant steel ..
  - In practical (but not limited to):
    - Diameter & Width should not be less than 100mm
    - Wall thickness should not be less than 3mm
    - Round: $D/t \leq 100(235/F_y)$
    - Rectangular: $B/t \leq 40(235/F_y)$

- CONCRETE:
  - Normal, Light weight concrete
  - Normal, High strength concrete
  - Water/Cement ratio should not exceed 0.4
  - Self-Consolidated Concrete (SCC) is preferred (but not required)
  - Strength of steel & concrete should be suitably matched
  - Combination of High strength concrete with High strength steel is preferred
  - For $235 \leq F_y \leq 345$ MPa steel → concrete should be $40 \leq f_c' \leq 60$ MPa

- **Features**

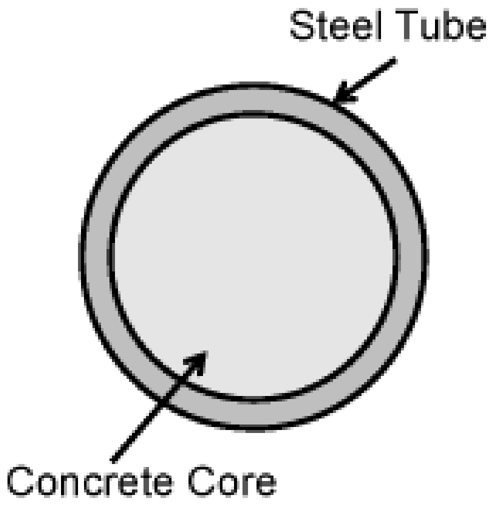
The CFT column has the combined effect of steel piping and concrete characterized by:

(1) Superior durability and modifiability.

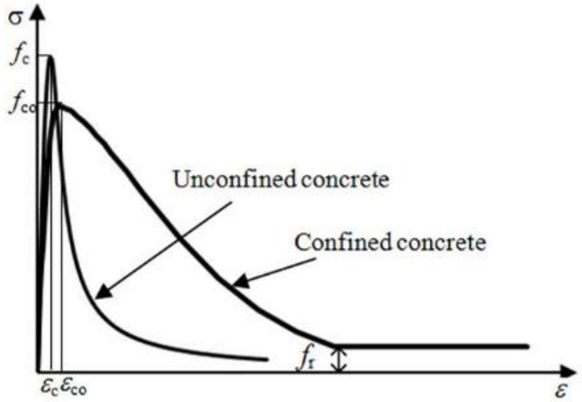
(2) Superior habitability.

(3) Superior fire-proof performance.

(4) Construction work efficiency.

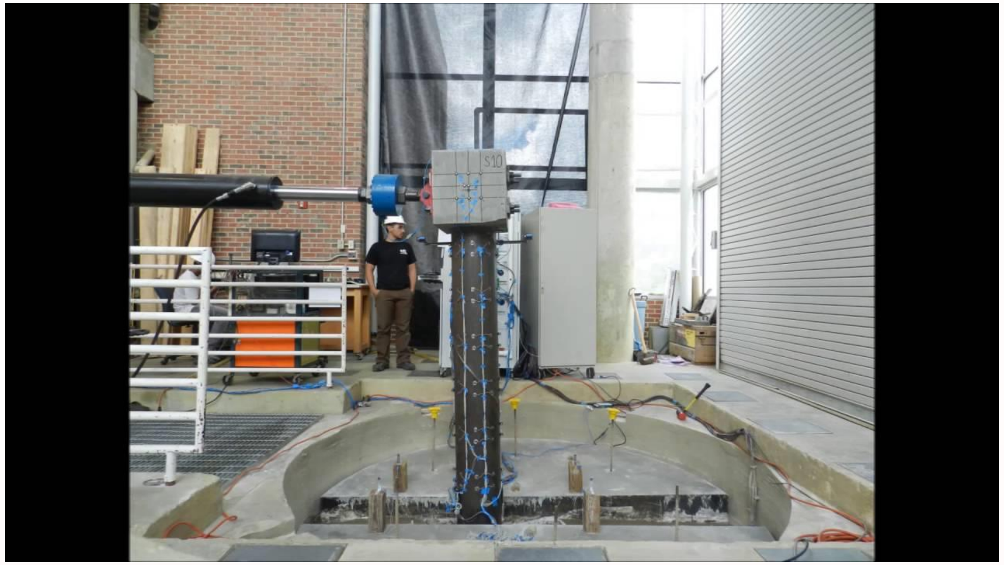


CFT Advantages & Limitations



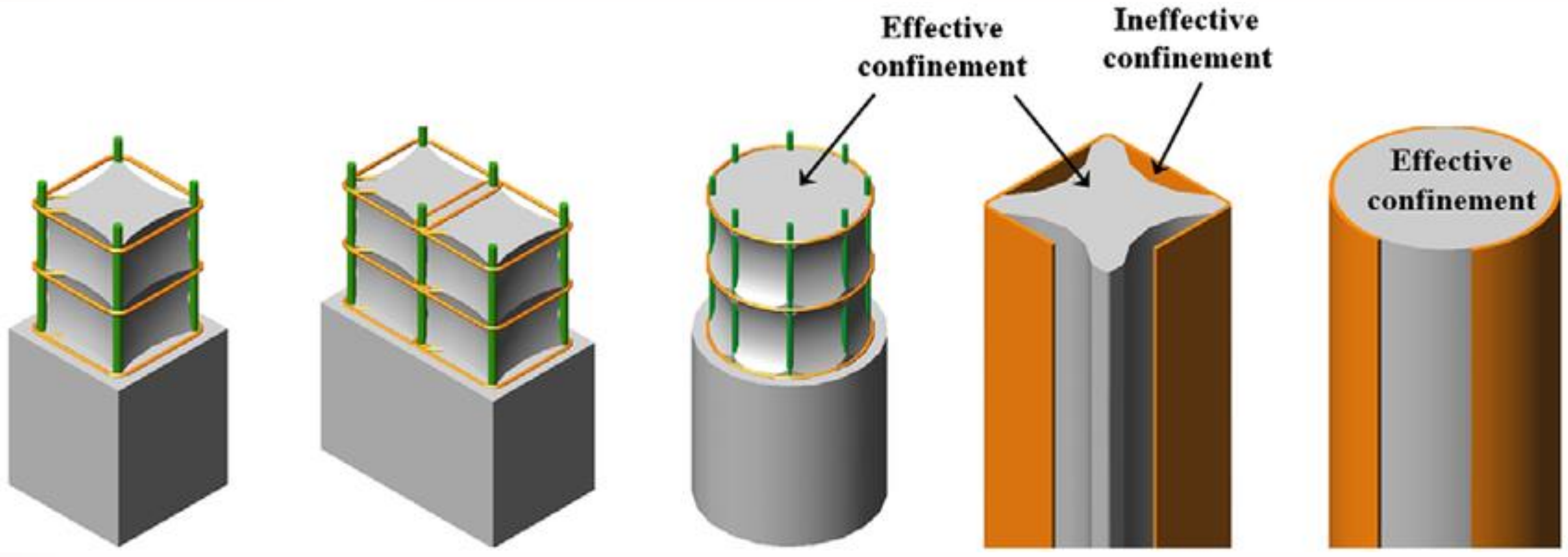
- Advantages
  - Large strength in Compression, Flexure, Shear
  - Large stiffness, Favorable ductility, Large energy absorption
  - Inherent stability: permits use of high-strength steel
  - Reduced labor cost & construction time relative to RC construction: Formwork or Reinforcing steel are eliminated
  - Better cost performance than ordinary steel
  - Column is smaller than ordinary RC. Usable floor area is increased.
  - ~50% lighter than RC. Foundation cost is reduced.

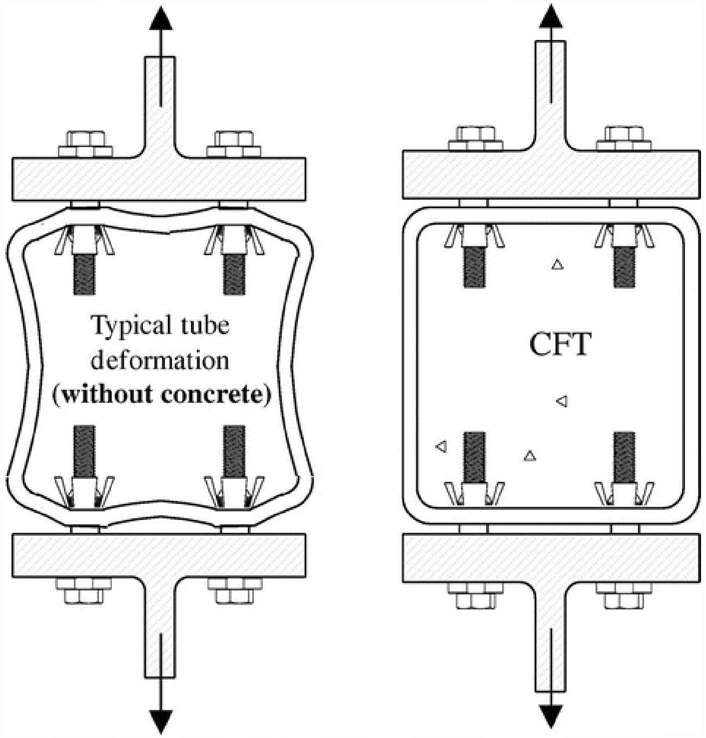
- Limitations (still in Research & Standard development)
  - Limited knowledge of CFT behavior
    - Interaction of the two materials (Combined properties: I, E)
    - Deformation capacity
  - Majority of tests on small specimens (generally 15cm dia. or less)
  - Strict D/t ratios
  - Design expressions
  - No standard connection designs



CFT Behavior

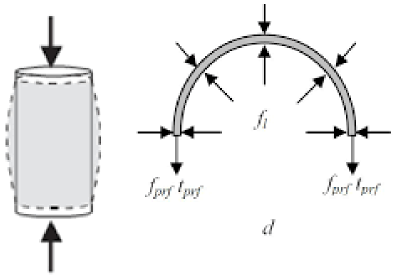
- Composited Column vs FRP vs CFT

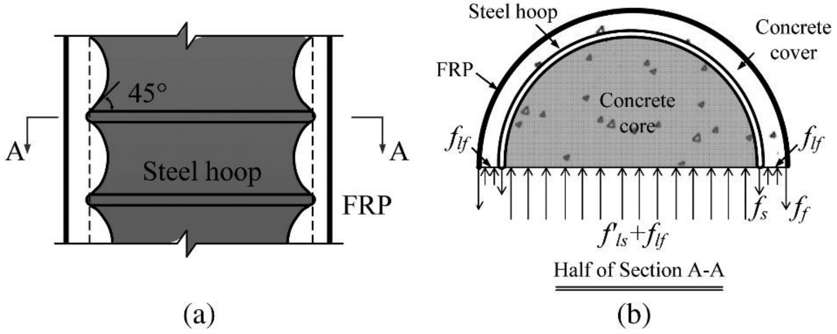




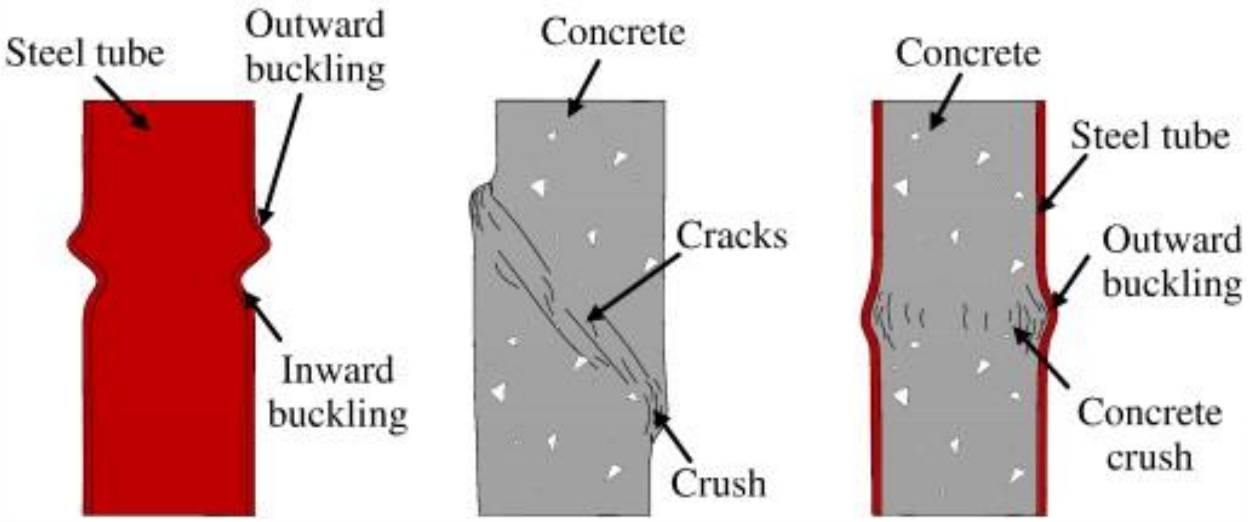
CFT Advantages: Behavior Aspects

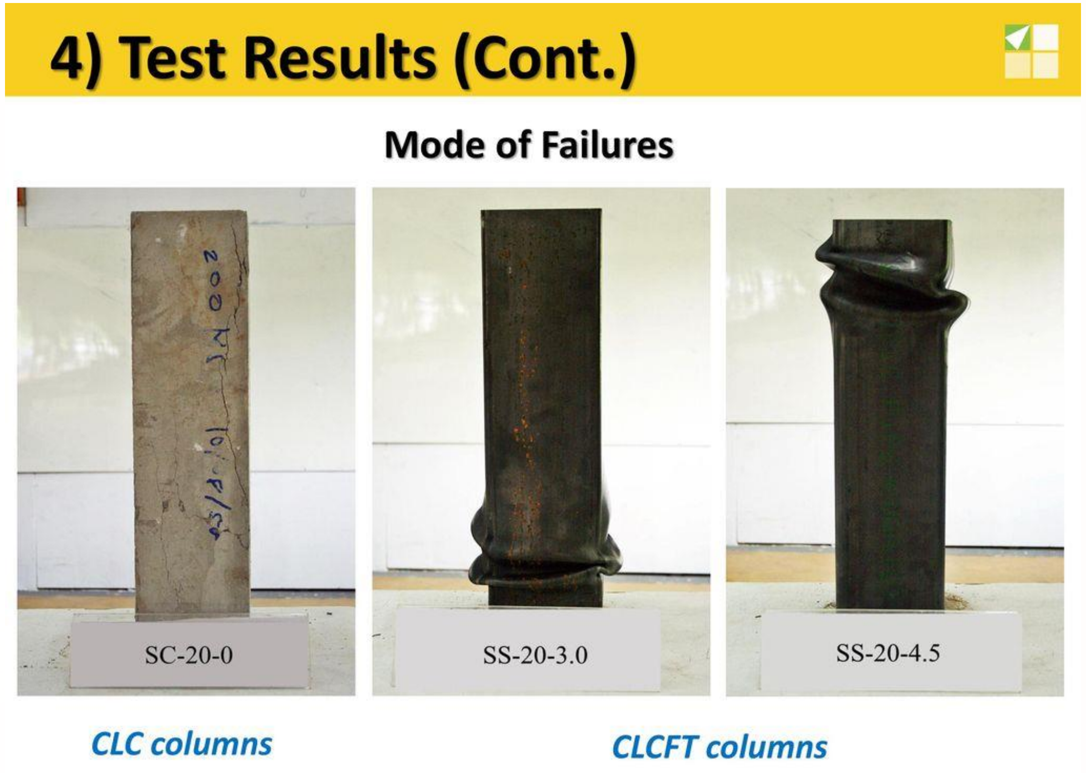
- Steel tube local buckling (LB) is delayed by concrete, and strength reduction after LB is moderated.
- Concrete strength is increased by confining of steel tube, and strength reduction is not very severe since concrete spalling is prevented by the tube.
- Drying shrinkage and creep of concrete are much smaller than ordinary RC.
- Concrete improves the fire resistance. The fireproof material can be reduced or omitted.
- Lighter than RC, EQ force is smaller.
- Safe and reliable in Seismic, since no brittle failure



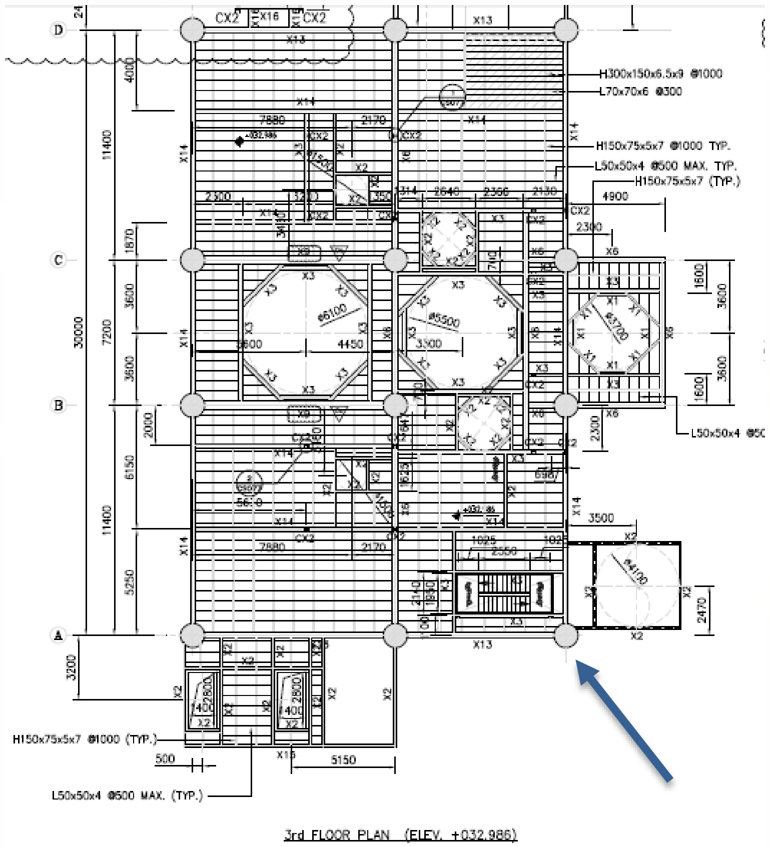


- CFT Failure Modes





Application of CFT



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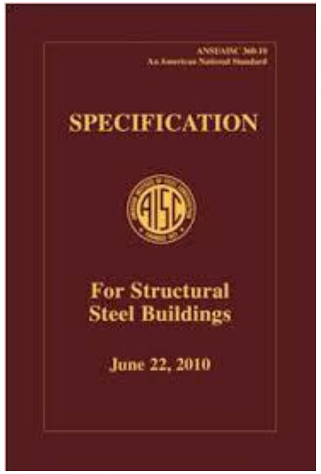
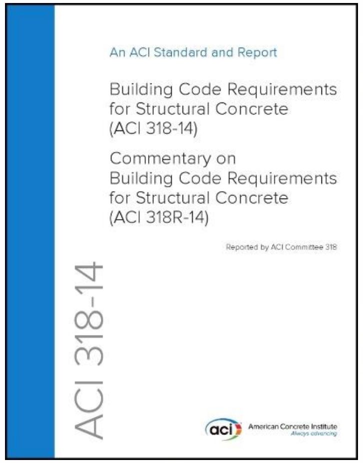
Column Design Standards

- AISC 2010 → Design for CFT (w/ & w/o Reinf.)
- AISI 2012 → Design for CFS (Cold-Formed Steel) Alone
- ACI318-14 → Design for RC (Reinf. Concrete) Alone

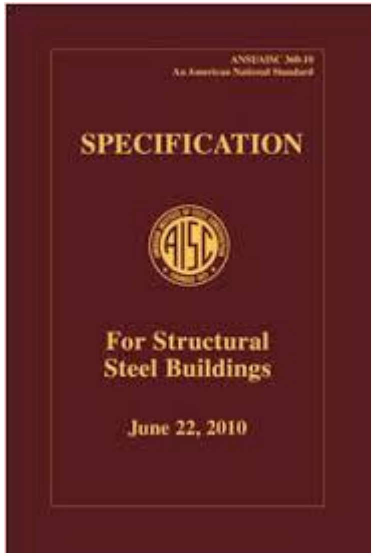


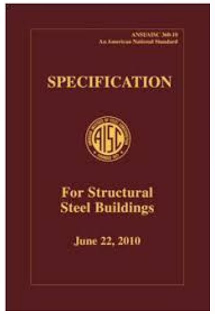


AISC-2010 Chapter I: Design of Composite Members

For:
– RC slab on steel beams
– Concrete-encased
– Concrete filled beams

Sections:
– Rolled
– Built-up
– Hollowed Steel Section (HSS)





I1 GENERAL PROVISIONS

I1.1 Concrete & Steel Reinforcement

Refer to ACI318 (Strength Design) except

- Criteria given in AISC-2010
- use LRFD Load Combination

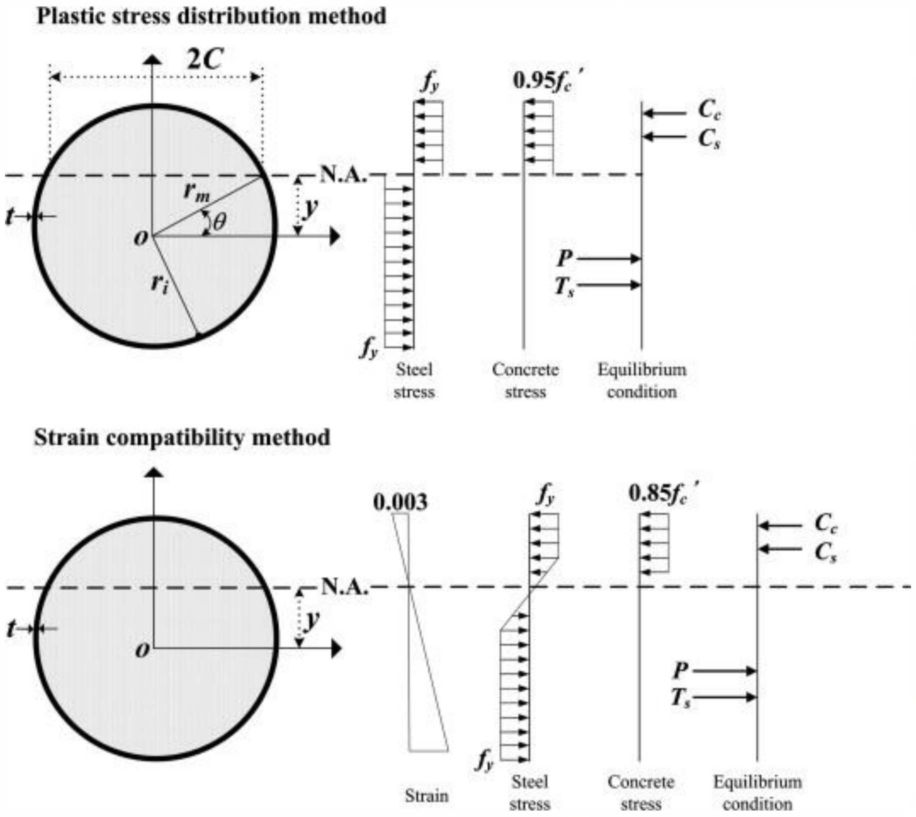
I1.2 Nominal Strength

I2.2a) Plastic Stress Distribution Method

- Steel reaches F_y (Tension & Compression)
- Concrete reaches:
  - » $0.85f_c'$ (Compression)
  - » $0.95f_c'$ (Compression) for HSS-CFT

I2.2b) Strain Compatibility Method

- Linear Distribution of Strains
- Max. Concrete Compressive Strain = 0.003
- Note: Can use for:
  - » Irregular Sections
  - » Steel is not elasto-plastic



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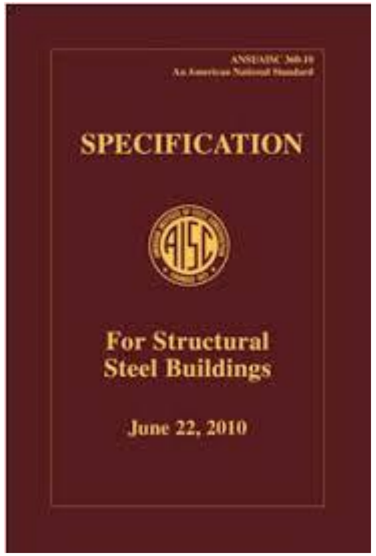
I1.3 Material Limitations

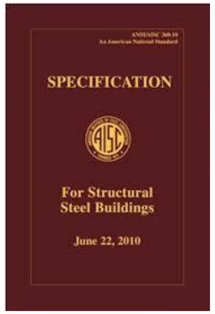
- Concrete Strength:
  - 21 MPa ≤ f_c' ≤ 70 MPa for Normal Weight Concrete
  - 21 MPa ≤ f_c' ≤ 42 MPa for Light Weight Concrete
  - Note: Higher f_c' can be used for Stiffness Calculation (but not for Strength)
- Structural Steel & Reinforcing Bars
  - F_y ≤ 525 MPa



I1.4 Classification of Local Buckling for CFT

- Use max. width-to-thickness ratio for classifications
- Classifications:
  - $^{w}/_{t} \leq \lambda_p$ → Compact Section
  - $\lambda_p < {^{w}/_{t}} \leq \lambda_r$ → Noncompact Section
  - $\lambda_r < {^{w}/_{t}} \leq Max.permitted$ → Slender Section

- Table for λ_p and λ_r and Max. Permitted



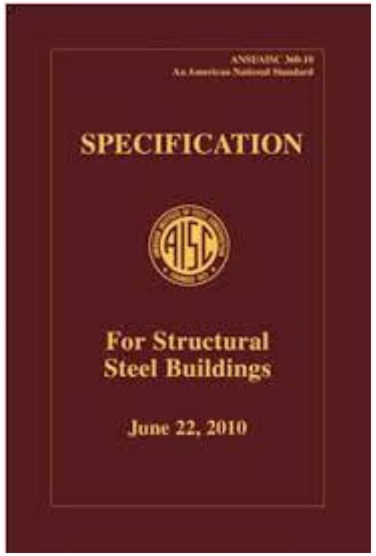
For Members subjected to	Element	Width-to-Thickness Ratio (w/t)	λ_p	λ_r	Max. Permitted
Axial Compression	Rectangular HSS	b/t	$2.26\sqrt{\frac{E}{F_y}}$	$3.00\sqrt{\frac{E}{F_y}}$	$5.00\sqrt{\frac{E}{F_y}}$
	Round HSS	D/t	$0.15\frac{E}{F_y}$	$0.19\frac{E}{F_y}$	$0.31\frac{E}{F_y}$
Flexure	Rectangular HSS: Flange	b/t	$2.26\sqrt{\frac{E}{F_y}}$	$3.00\sqrt{\frac{E}{F_y}}$	$5.00\sqrt{\frac{E}{F_y}}$
	Rectangular HSS: Web	h/t	$3.00\sqrt{\frac{E}{F_y}}$	$5.70\sqrt{\frac{E}{F_y}}$	$5.70\sqrt{\frac{E}{F_y}}$
	Round HSS	D/t	$0.09\frac{E}{F_y}$	$0.31\frac{E}{F_y}$	$0.31\frac{E}{F_y}$

I2 AXIAL FORCE

I2.1 ENCASED COMPOSITE MEMBER

I2.1a Limitations

- Steel Area Ratio
- Concrete must be RC (w/ Longitudinal bars & Ties/Spirals)
  - » Min. ties:
    - @305mm for d=10
    - @406mm for d=13+
  - » Ties spacing ≤ (least column dimension)/2
- Min. Longitudinal Rebar Ratio: $\rho_{sr} = 0.4\%$



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I2.1b Compressive Strength

For

- » Design Comp. Strength: $\phi_c = 0.75$ (LRFD)
- » Allowable Comp. Strength: $\Omega_c = 2.00$ (ASD)

– $$P_n = \begin{cases} P_{no}\left[0.658^{\left(\frac{P_{no}}{P_e}\right)}\right] & , \frac{P_{no}}{P_e} \le 2.25 \\ 0.877P_e & , \frac{P_{no}}{P_e} > 2.25 \end{cases}$$ $\geq P_n$ of bare steel (Chapter E)

Where:

$$P_{no} = F_y A_s + F_{ysr} A_{sr} + 0.85 f_c' A_c$$

$$P_e = \frac{\pi^2 EI_{eff}}{(KL)^2}$$

$$E_c = w_c^{1.5}\sqrt{f_c'} \text{ ksi} \quad (= 0.043 w_c^{1.5}\sqrt{f_c'} \text{ MPa}) \quad (= 15{,}100\sqrt{f_c'} \text{ ksc})$$

$$EI_{eff} = E_s I_s + 0.5 E_s I_{sr} + C_1 E_c I_c$$

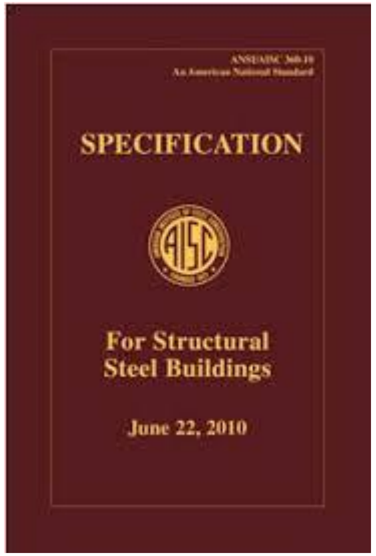
$$C_1 = 0.1 + 2\left(\frac{A_s}{A_c + A_s}\right) \le 0.3$$

Note:

sr = Steel Rebar

I is around NA. of Composite Section

E_s = 200,000 Mpa (= 2.04×10^6 ksc)



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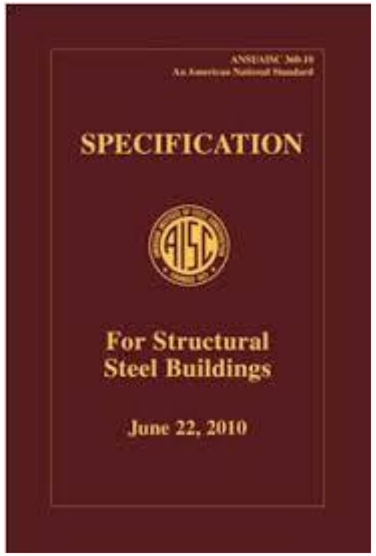
I2.1c Tensile Strength

- $P_n = F_y A_s + F_{ysr} A_{sr}$ (not consider Concrete)
- $\phi_t = 0.90$ (LRFD)
- $\Omega_t = 1.67$ (ASD)



I2.1d Load Transfer

- See section I6

I2.1e Detailing Requirements

- Clear Spacing between Steel core & Long. Rebar = $1.5d_{b,long.}$ (≥38mm)

I2.2 FILLED COMPOSITE MEMBER (CFT)

I2.2a Limitations

- Min. Steel Area Ratio = 1%
- Note: no min. rebar

I2.2b Compressive Strength (see “next Slide”)

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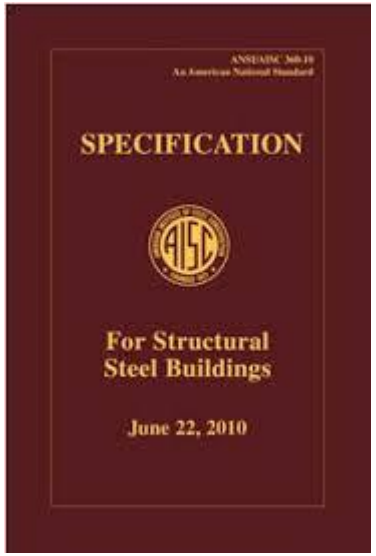
I2.2c Tensile Strength

- Follow I2.1c (Encased) → (not consider concrete)

I2.2d Load Transfer

- See section I6



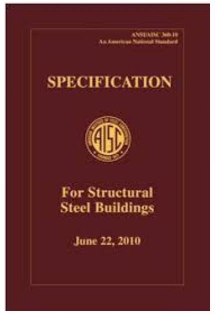
I2.2b Compressive Strength

- Follow section I2.1b (Encased) w/ modifications:

$$P_{no} = \begin{cases} P_p & \text{for Compact Sections} \\ P_p - (P_p - P_y)\left(\dfrac{\lambda - \lambda_p}{\lambda_r - \lambda_p}\right)^2 & \text{for Noncompact Sections} \\ F_{cr}A_s + 0.7f_c'\left(A_c + A_{sr}\dfrac{E_s}{E_c}\right) & \text{for Slender Sections} \end{cases}$$

where

- $P_p = F_yA_s + C_2f_c'\left(A_c + A_{sr}\frac{E_s}{E_c}\right)$ Note: Long.Rebar is not yielded
- $C_2 = \begin{cases} 0.85 & \text{for Rectangular Sections} \\ 0.95 & \text{for Round Sections} \end{cases}$ Note: Round = better / Rect. is same as Encased
- $P_y = F_yA_s + 0.7f_c'\left(A_c + A_{sr}\frac{E_s}{E_c}\right)$
- $F_{cr} = \begin{cases} \dfrac{9E_s}{\left(b/t\right)^2} & \text{for Rectangular Section} \\ \dfrac{0.72F_y}{\left(\frac{D}{t}\cdot\frac{F_y}{E_s}\right)^{0.2}} & \text{for Round Section} \end{cases}$
- $EI_{eff} = E_sI_s + E_sI_{sr} + C_3E_cI_c$ Note: CFT is better than Encased (C_3, I_{sr})
- $C_3 = 0.6 + 2\left(\frac{A_s}{A_c + A_s}\right) \leq 0.9$



AISI-2012 Closed Cylindrical Tubular Members: Compression (C4.1)

- Note: same as in AISI-2007 (EIT-2553)
- For: Manufactured/Fabricated (more imperfection) Tubes
- Compressive Strength
  - $P_n = F_n A_e$
  - $\phi_c = 0.85$(LRFD)
  - $\Omega_c = 1.80$ (ASD)
- Note: For Closed Section, there is no:
  - Torsional Buckling (TB)
  - Flexural-Torsional Buckling (FTB)
  - Distortional Buckling (DB)

- $F_n = \begin{cases} \left(0.658^{\lambda_c{}^2}\right) F_y & , \ \lambda_c \le 1.5 \\ \left(\dfrac{0.877}{\lambda_c{}^2}\right) F_y & , \ \lambda_c > 1.5 \end{cases}$

  Where

  $$\lambda_c = \sqrt{\frac{F_y}{F_e}}$$

  $$F_e = \frac{\pi^2 E}{\left(\frac{KL}{r}\right)^2}$$ (Section C4.1.1)

- $A_e = A_o + R(A - A_o)$ (Section C4.1.5)

  Where

  $$A_o = \left[\frac{0.037}{\left(\frac{D}{t}\right)\left(\frac{F_y}{E}\right)} + 0.667\right] A \quad (\le A)$$

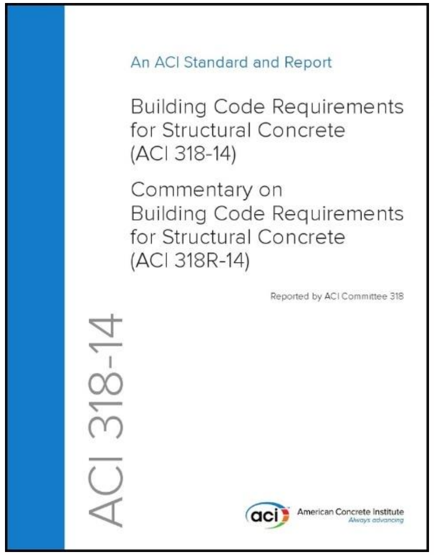
  $$R = \frac{F_y}{2F_e} \quad (\le 1.0)$$

AISI-2012 Closed Rectangular Tubular Members: Compression (C4.1)

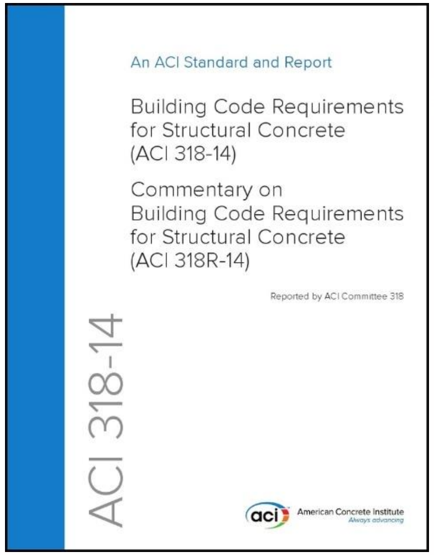
- Same as "Cylindrical" except A_e
- A_e = Effective Area using F_n
  - Effective Width using eqn:
  - $\rho = \frac{1-\frac{0.22}{\lambda}}{\lambda} \qquad (\leq 1.0)$
  - $\lambda = \sqrt{\frac{f}{f_{cr}}}$
  - Use $f = F_n$
  - $f_{cr} = \frac{k\pi^2 E}{12(1-\mu^2)}\left(\frac{t}{w}\right)^2 \qquad , k = 4.0 \qquad , \mu = 0.3$

ACI318-14 Chapter 10: Columns

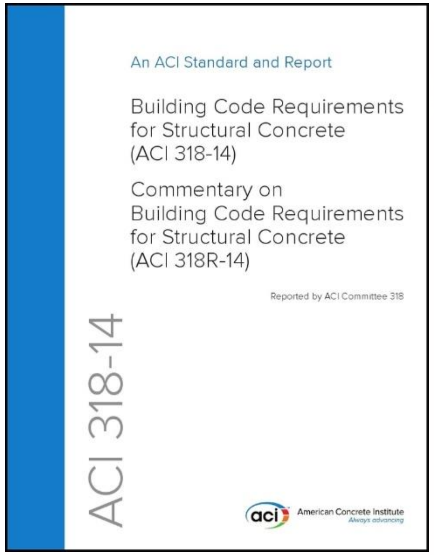
- 10.5 Design Strength
  - $\phi P_n \geq P_u$
  - P_u from Section 5.3: Load Factor (U = 1.2D +1.6L)
  - ϕ from Section 21.2
    - Compression Controlled (Section 21.2.2):
    - $\phi = 0.75$ for Spiral (see Section 25.7.3)
    - $\phi = 0.65$ for Others
  - P_n from Section 22.4: Axial Strength (or combined)
    - $P_n = \begin{cases} 0.80P_o & \text{for Ties (see Section 10.7.6.2 and 25.7.2)} \\ 0.85P_o & \text{for Spirals (see Section 22.4.2.5 and 25.7.3)} \\ 0.85P_o & \text{for Composite} \end{cases}$
    - $P_o = 0.85f_c'(A_g - A_{st}) + f_y A_{st}$
    - Note: st = Steel (Long. Rebar)



- 10.6 Reinforcement Limits
  - 10.6.1 Min. & Max. Long. Reinforcement
    - $\rho = \frac{A_{st}}{A_g}$
    - $\rho_{min.} = 1\%$
    - $\rho_{max.} = 8\%$
    - Note: For composite, use A_c instead of A_g

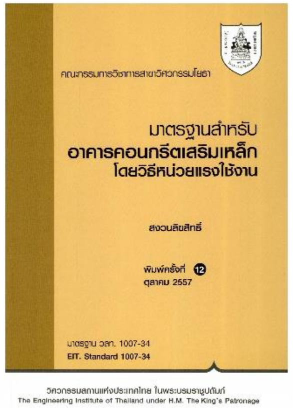


- Chapter 25 Reinforcement Details:
  - 25.7.2 Ties
    - $d_{b,tie}$ ≥ no.3 (9.5mm) for $d_{b,long.}$ ≤ no.10 (31.8mm)
      ≥ no.4 (12.7mm) for $d_{b,long.}$ ≥ no.11 (34.9mm)
    - $s_{min.}$ = Min.(16$d_{b,long.}$,48$d_{b,tie}$,b or h)
  - 25.7.3 Spiral
    - $d_{b,spiral}$ ≥ no.3 (9.5mm)
    - $s_{min.}$ = 1 in. (25.4mm) clear spacing → (EIT1007-34 = 3 cm)
    - $s_{max.}$ = 3 in. (76.2mm) clear spacing → (EIT1007-34 = 7 cm)
    - Volume, $\rho_s \geq 0.45\left(\frac{A_g}{A_{ch}}-1\right)\left(\frac{f_c'}{f_{yt}}\right)$
      - f_{yt} = f_y of trans. reinf.
      - A_{ch} = Area up to outer edge of trans. reinf.

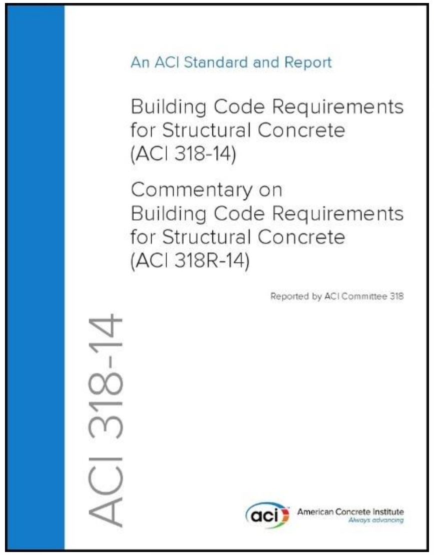


- Note: EIT1007-34 (Ties & Spiral)
  - $d_{b,trans.}$ = 6 mm for $d_{b,long.} \le 20$ mm
  - = 9 mm for $d_{b,long.}$ = 20-28 mm
  - = 12 mm for $d_{b,long.} > 28$ mm

  - Min. $d_{b,long.}$ = 12 mm



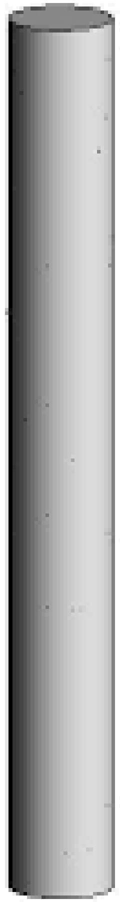
- 20.6 Durability of Steel Reinf.
  - 20.6.1 Concrete Covering
    - Exposed - no.6+ (19.1mm+) use 2” (5.08 cm)
    - - no.5- (15.3mm-) use 1.5” (3.81 cm)
    - Not Exposed - all $d_{b,long.}$ use 1.5” (3.81 cm)
  - Note:
    - กฎกระทรวง 6 = 4 cm
    - EIT1007-34 = 3.5 cm



Column Design Example

- Determine the Compressive Strength of the 6 m-length Column
  - Steel Alone
  - RC Alone
  - CFT (with and without reinforcement)

- Steel:
  - (Ref. Pacific Pipe B0113) EN10219 Grade S235JRH
  - F_y = 235 MPa, F_u = 340 MPa
  - d_o = 406.4 mm, t = 6.00 mm (w = 59.20 kg/m)
- Concrete:
  - (Ref. TIS213-2552) C23/28
  - f_c' = 240 ksc



- Calculated Properties:
  - $F_y = 235 \text{ MPa} \times \left(\frac{100}{9.806}\right) = 2{,}396 \text{ ksc}$
  - $f_c' = 240 \text{ ksc} \times \left(\frac{9.806}{100}\right) = 23.53 \text{ MPa}$
  - $E_s = 2.04 \times 10^6 \text{ ksc}$
  - $E_c = 15{,}000\sqrt{f_c'} = 15{,}100\sqrt{240} = 2.339 \times 10^5 \text{ ksc}$
  - $D_i = D_o - 2t = 40.64 - 2(0.6) = 39.44 \text{ cm}$
  - $D = D_o - t = 40.64 - 0.6 = 40.04 \text{ cm}$
  - $\frac{D}{t} = \frac{40.04}{0.6} = 66.73$
  - $A_s = \frac{\pi}{4}\left(D_o^2 - D_i^2\right) = \frac{\pi}{4}\left(40.64^2 - 39.44^2\right) = 75.47 \text{ cm}^2$
  - $I_s = \frac{\pi}{64}\left(D_o^4 - D_i^4\right) = \frac{\pi}{64}\left(40.64^4 - 39.44^4\right) = 15{,}128 \text{ cm}^4$
  - $A_c = \frac{\pi}{4}D_i^2 = \frac{\pi}{4}(39.44)^2 = 1{,}221.7 \text{ cm}^2$
  - $I_c = \frac{\pi}{64}D_i^4 = \frac{\pi}{64}(39.44)^4 = 118{,}773 \text{ cm}^4$

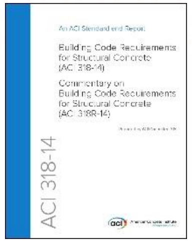
Steel Alone (AISI 2012)

- Limitation:
  - $\frac{D}{t}\ \ (= 66.73) \leq 0.441\frac{E}{F_y}\ \ \left[= 0.441\left(\frac{2.04\times10^6}{2396}\right)\ \ = 375.5\right] \Rightarrow \text{ok}$
- Nominal Compressive Strength:
  - $P_n = F_n A_e$
- Nominal Stress (F_n):
  - $F_n = \left(0.658^{\lambda_c^2}\right)F_y\ \ = \left(0.658^{0.4622^2}\right)(2396)\ \ = 2191\ \text{ksc}$
    - $\lambda_c = \sqrt{\frac{F_y}{F_e}}\ \ = \sqrt{\frac{2,396}{11,214}}\ \ = 0.4622\ \ (\leq 1.5)$
      - $F_e = \frac{\pi^2 E}{\left(\frac{KL}{r}\right)^2}\ \ = \frac{\pi^2\left(2.04\times10^6\right)}{\left(\frac{1\times600}{14.16}\right)^2}\ \ = 11,214\ \text{ksc}$
        - » $r = \sqrt{\frac{I}{A}}\ \ = \sqrt{\frac{15,128}{75.47}}\ \ = 14.16\ \text{cm}$

- Effective Area:
  - $A_e = A_o + R(A - A_o) \quad = 75.47 + 0.1068(75.47 - 75.47) \quad = 75.47\ \text{cm}$
    - $A_o = \left[\frac{0.037}{\left(\frac{D}{t}\right)\left(\frac{F_y}{E}\right)} + 0.667\right] \cdot A \quad = \left[\frac{0.037}{(66.73)\left(\frac{2{,}396}{2.04\times10^6}\right)} + 0.667\right](75.47) \quad = 85.97 \quad (> A)$

      use $A_o = A = 75.47\ \text{cm}^2$
    - $R = \frac{F_y}{2F_e} \quad = \frac{2{,}396}{2(11{,}214)} \quad = 0.1068 \quad (\leq 1.0)$
- Thus:
  - $P_o = F_n A_e \quad = (2{,}191)(75.47)/1000 \quad = 165.4\ \text{T}$
  - $\phi_c P_n = (0.85)(165.4) \quad = 140.6\ \text{T} \quad (LRFD)$
  - $\frac{P_n}{\Omega_c} = \frac{165.4}{1.80} \quad = 91.9\ \text{T} \quad (ASD)$

RC Alone (ACI318)



- Minimum Reinforcement:
  - Use minimum reinforcement, $\rho_{min.} = 1\%$
  - $A_{sr,min.} = (0.01)A_g = (0.01)(1221.7) = 12.22\ \text{cm}^2$
- Reinforcement Requirement:
  - Use covering = 3.5 cm
  - Longitudinal reinforcement → use 6-DB16 (SD40) (≥ 12mm → ok)
    - $A_{sr} = 6 \times \frac{\pi}{4}(1.6)^2 = 12.06\ \text{cm}^2 \ (\approx A_{sr,min.}) \quad \Rightarrow \text{ok}$
  - Transverse reinforcement: (say using “Hoop Ties”)
    - Diameter:
      - ACI318-14: Since $d_{b,long.}$ ≤ no.10 (25.4mm) → need no.3 (9.5mm)+
      - EIT1007-34: Since $d_{b,long.}$ ≤ 25mm → need 6mm+ → use RB6
    - Spacing:
      - $s_{max.} = min.\left(16d_{b,long.}, 48d_{b,tie.}, b \text{ or } h\right)$
      - $= min.\{16(16), 48(6), 394.4\}$
      - $= min.\{256, 288, 394.4\}$
      - $= 256\ \text{mm}$ → use RB6@250mm

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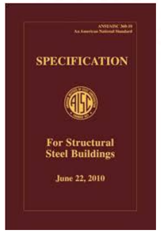
- Nominal Compressive Strength:
  - $P_n = 0.80\left[0.85f_c'\left(A_g - A_{st}\right) + f_y A_{st}\right]$
    - $= 0.80[(0.85)(240)(1{,}221.7 - 12.06) + (4000)(12.06)]/1000$
    - $= 0.80[246.8 + 48.2]$
    - $= 236.0\ \mathrm{T}$
  - $\phi_c P_n = (0.65)(236.0)\ = 153.4\ \mathrm{T} \quad (SDM)$

CFT (AISC 2010)



- Limitations:
  - For normal weight Concrete:
    - $21\ \text{MPa} \leq f_c'(= 23.53\ \text{MPa}) \leq 70\ \text{MPa}$ → ok
  - For Steel & Rebars:
    - $f_y\ (= 235\ \text{MPa}) \leq 525\ \text{MPa}$ → ok
  - Local Buckling Classification (Round HSS):
    - $\lambda_p = 0.15\frac{E}{F_y} = 0.15\left(\frac{2.04\times10^6}{2{,}396}\right) = 127.7$
    - $\lambda_r = 0.19\frac{E}{F_y} = 0.19\left(\frac{2.04\times10^6}{2{,}396}\right) = 161.8$
    - $\text{Max. Limit} = 0.31\frac{E}{F_y} = 0.31\left(\frac{2.04\times10^6}{2{,}396}\right) = 263.9$
    - Since $D/t\ (= 66.73) < \lambda_p(= 127.7)$ → Compact Section
  - Minimum Steel Ratio:
    - $\rho_s = \frac{A_s}{A_c} = \frac{75.47}{1221.7} = 6.18\% \quad (\geq 1\%)$ → ok

a) CFT (w/o Reinforcement)

- Nominal Compressive Strength of Zero-Length (P_{no}):
  - $P_{no} = P_p$ for Compact Section

    $= F_y A_s + C_2 f_c' \left(A_c + A_{sr}\frac{E_s}{E_c}\right)$

    $= [(2{,}396)(75.47) + (0.95)(240)(1{,}221.7 + 0)]/1000$

    $= 180.8 + 278.5 \quad = 459.4 \text{ T}$

    - $C_2 = 0.95$ for Round Sections
- Elastic Buckling Load (P_e):
  - $P_e = \frac{\pi^2 EI_{\text{eff}}}{(KL)^2} = \frac{\pi^2(5.076\times10^{10})}{(1.0x600)^2}(10^{-3}) = 1{,}391.6 \text{ T}$
    - $EI_{eff} = E_s I_s + E_s I_{sr} + C_3 E_c I_c$

      $= (2.04 \times 10^6)(15{,}128) + 0 + (0.7164)(2.339 \times 10^5)(118{,}773)$

      $= (3.086 \times 10^{10}) + 0 + (1.990 \times 10^{10}) \quad = 5.076 \times 10^{10} \text{ kg.cm}^2$

      - $C_3 = 0.6 + 2\left(\frac{A_s}{A_c + A_s}\right) = 0.6 + 2\left(\frac{75.47}{1{,}221.7 + 75.47}\right) = 0.7164 \quad (\leq 0.9)$

- Nominal Compressive Strength:
  - $\frac{P_{no}}{P_e} = \frac{459.4}{1,391.6} = 0.3301 \quad \leq 2.25$
  - $P_n = P_{no}\left[0.658^{\frac{P_{no}}{P_e}}\right] = (459.4)\left(0.658^{0.3301}\right) = 400.1\ \mathrm{T}$
  - $\phi_c P_n = (0.75)(400.1) = 300.1\ \mathrm{T} \quad (LRFD)$
  - $\frac{P_n}{\Omega_c} = \frac{400.1}{2.00} = 200.1\ \mathrm{T} \quad (ASD)$

b) CFT (w/ Reinforcement:6DB16)

- Nominal Compressive Strength of Zero-Length (P_{no}):
  - $P_{no} = P_p$ for Compact Section

$$= F_y A_s + C_2 f_c' \left(A_c + A_{sr}\frac{E_s}{E_c}\right)$$

$$= \left[(2{,}396)(75.47) + (0.95)(240)[(1{,}221.7 - 12.06) + (12.06)\left(\frac{2.04\times10^6}{2.339\times10^5}\right)\right]/1000$$

$$= 180.8 + 299.8 \qquad = 480.6 \text{ T}$$

    - $C_2 = 0.95$ for Round Sections

- Elastic Buckling Load (P_e):
  - $P_e = \frac{\pi^2 EI_{\text{eff}}}{(KL)^2} = \frac{\pi^2(5.369\times10^{10})}{(1.0x600)^2}(10^{-3}) = 1{,}471.8 \text{ T}$
    - $EI_{eff} = E_s I_s + E_s I_{sr} + C_3 E_c I_c$

$$= (2.04\times10^6)(15{,}128) + (2.04\times10^6)(1{,}434.2) + (0.7164)(2.339\times10^5)(118{,}773)$$

$$= (3.086\times10^{10}) + (2.926\times10^9) + (1.990\times10^{10}) \qquad = 5.369\times10^{10} \text{ kg. cm}^2$$

  - $C_3 = 0.6 + 2\left(\frac{A_s}{A_c+A_s}\right) = 0.6 + 2\left(\frac{75.47}{1{,}221.7+75.47}\right) = 0.7164 \quad (\le 0.9)$
  - $I_{sr} = \sum Ad^2 = 4\left(\frac{\pi}{4}\right)(1.6)^2\left[\frac{\sqrt{3}}{2}\left(\frac{40.64}{2} - 3.5 - 0.6 - \frac{1.6}{2}\right)\right]^2 = 1{,}434.2 \text{ cm}^4$

- Nominal Compressive Strength:
  - $\frac{P_{no}}{P_e} = \frac{480.6}{1,471.8} = 0.3265 \quad \leq 2.25$
  - $P_n = P_{no}\left[0.658^{\frac{P_{no}}{P_e}}\right] = (480.6)\left(0.658^{0.3265}\right) = 419.2\ \mathrm{T}$
  - $\phi_c P_n = (0.75)(419.2) = 314.4\ \mathrm{T} \quad (LRFD)$
  - $\frac{P_n}{\Omega_c} = \frac{419.2}{2.00} = 209.6\ \mathrm{T} \quad (ASD)$

Comparisons (Steel vs. RC vs. CFT)

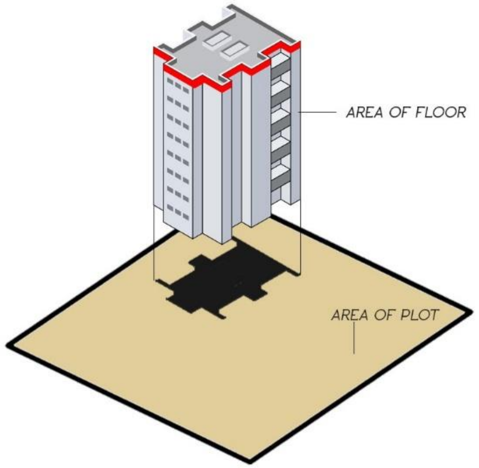
- Strength Comparison (LRFD, SDM):
  - Steel Alone: $\phi P_n = 140.6\ \mathrm{T}$
  - RC Alone (w/ ties): $\phi P_n = 153.4\ \mathrm{T}$

    (Steel + RC = 294.0 T)
  - CFT: $\phi P_n = 300.1\ \mathrm{T}$ (+2.07% increase)
  - CFT (w/ main reinf. 6DB16): $\phi P_n = 314.4\ \mathrm{T}$ (+6.90% increase)

- Weight Comparison:
  - Steel:
    - $V_s = \pi D t L \quad = \pi(0.4004)(0.006)(6) \ = 0.04528\ \mathrm{m}^3$
    - $W_s = V_s \rho_s \quad = (0.04528)(7850) \ = 355.5\ \mathrm{kg}$
  - RC:
    - $V_c = A_c L \quad = (0.12217)(6) \ = 0.7330\ \mathrm{m}^3$
    - $V_{sr,long.} = A_{sr} L \quad = (0.001206)(6) \ = 0.007236\ \mathrm{m}^3$
    - $V_{sr,tran.} = A_{tie} L_{tie} \left(\frac{L}{s_{tie}}\right) \quad = \frac{\pi}{4}(0.6)^2 \pi (39.44 - 2 \times 3.5 - 0.6) \left(\frac{600}{25}\right) / 10^6 \quad = 0.000216\ \mathrm{m}^3$
    - $W_c = V_c \rho_c \quad = (0.7330)(2400) \ = 1759.2\ \mathrm{kg}$
    - $W_{\mathrm{sr}} = \mathrm{V}_{\mathrm{sr}} \rho_s \quad = (0.007236 + 0.000216)(7850) \ = 56.8 + 1.7 \quad = 58.5\ \mathrm{kg}$
    - $W_{RC} = W_c + W_{sr} \quad = 1{,}759.2 + 58.5 \quad = 1{,}817.7\ \mathrm{kg}$
  - CFT:
    - $W_{CFT} = W_s + W_c \quad = 355.5 + 1{,}759.2 \quad = 2{,}114.7\ \mathrm{kg}$
    - $W_{CFT,reinf.} = W_s + W_c + W_{sr,long.} \quad = 355.5 + 1{,}759.2 + 56.8 \quad = 2{,}171.5\ \mathrm{kg}$

- Cost Comparison:
  - Assumptions:
    - Steel = 41 Baht/m^3 (material 29 + labor 12)
    - Concrete (240ksc) = 2,550 Baht/m^3
      - Formwork = 300 Baht/m^2
    - Reinforcement = 28 Baht/m^3 (material 24 + labor 4)
  - Steel:
    - $(355.5)(41) = 14{,}576$ Baht
  - RC:
    - $(0.7330)(2550) + \pi(0.3944)(6)(300) + (58.5)(28) = 1{,}833 + 2{,}230 + 1{,}638 = 5{,}701$ Baht
  - CFT:
    - (w/o reinf.) $= 14{,}576 + 1{,}833 = 16{,}409$ Baht
    - (w/ reinf.) $= 14{,}576 + 1{,}833 + 1{,}638 = 18{,}047$ Baht

- Structural Footprint Comparison:
  - Steel:
    - $A = A_s + A_c \quad = 75.47 + 1{,}221.7 \quad = 1{,}297.2\ \text{cm}^2$
    - $\left(A = A_s \quad = 75.47\ \text{cm}^2\right)$
  - RC:
    - $A = A_c \quad = 1{,}221.7\ \text{cm}^2$
  - CFT:
    - $A = A_s + A_c \quad = 75.47 + 1{,}221.7 \quad = 1{,}297.2\ \text{cm}^2$



Overall Comparison:

Structural Types:	ϕP_n (T)	Weight (kg)	Cost (Baht)	$\frac{\text{Load}}{\text{Weight}}$	$\frac{\text{Load}}{\text{Cost}}$ (kg/B.)	$\frac{\text{Load}}{\text{Footprint}}$ (ksc)	Construction Time	OVERALL PERFORMANCE
Steel	140.6	356	14,576	395 √√√	9.6 √	108 (1862) √√	√√√√	√√
RC (ties) *	153.4	1817	5,701	84 √	26.9 √√√	126 √	√	√√
CFT (w/o reinf.)	300.1	2115	16,409	142 √√	18.3 √√	231 √√√	√√√	√√√
CFT (w/ reinf.) **	314.4	2172	18,047	145 √√	17.4 √√	242 √√√	√√	√√

* w/ 6DB16 + RB6@250mm

** w/ 6DB16

- Comparison Notes:
  - Steel vs. RC:
    - For the same load, RC Weight = 4.7 (=395/84) times of Steel
    - For the same load, Steel Cost = 2.8 (=26.9/9.6) times of RC
    - Thus, for low LL structure, Steel = more advantage (4.7 vs. 2.8)
  - CFT vs. (Steel+RC):
    - CFT Load Capacity = 6.90% more than (Steel + RC w/ties)
  - Steel:RC*:CFT
    - 1 : 4.7 : 2.8 for Weight per Load Capacity
    - 2.8 : 1 : 1.5 for Cost per Load Capacity
    - 2.1 : 1.8 : 1 for Footprint per Load Capacity
    - 1 : 2.5 : 1.2 for Time@site per Load Capacity (estimated)

  - For the same Load Capacity:
    - CFT/RC* → -41% weight / +47% cost / -52% Footprint / ~-50% time
    - CFT/Steel → +178% weight / -48% cost / -44% Footprint / ~+20% time

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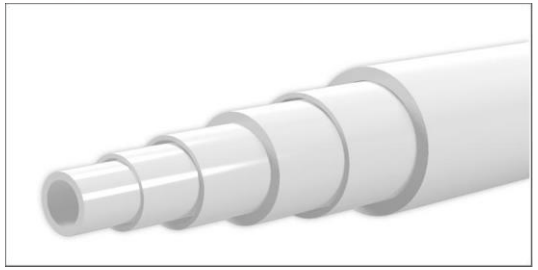
- Remarks:
  - RC:
    - In general $\rho > 1\%$ → become a lot more expensive

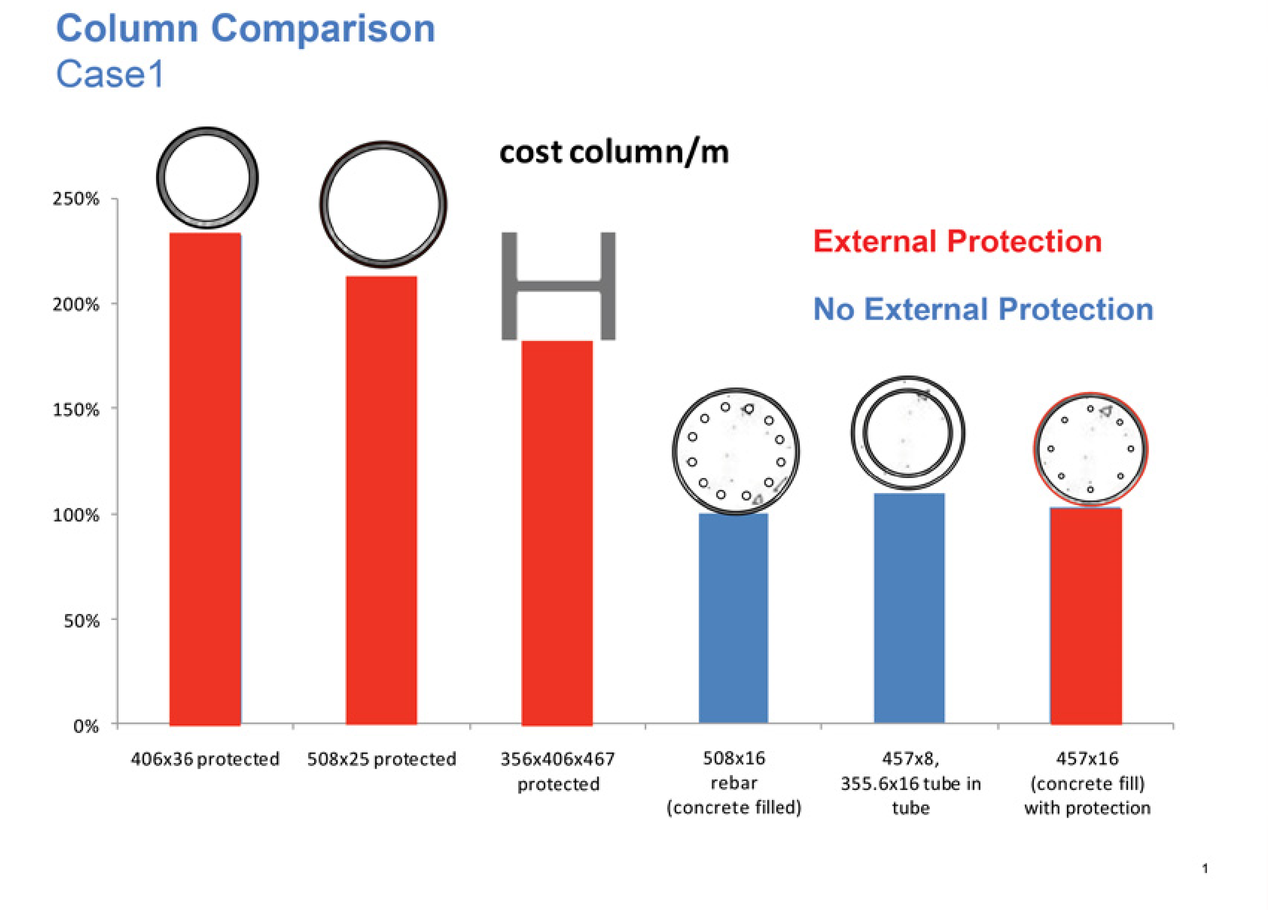
  - Steel:
    - $r \approx \frac{D}{2\sqrt{2}}$ $\quad r \propto D \quad (\text{but not } t)$
    - t may be reduced and F_n ($\propto \lambda_c \quad \propto F_e \quad \propto r$) is the same!
    - For no Local Buckling:
      - From $A_o = \left[\frac{0.037}{\left(\frac{D}{t}\right)\left(\frac{F_y}{t}\right)} + 0.667\right] A \quad (\leq A)$
      - No LB. when $\frac{0.037}{\left(\frac{D}{t}\right)\left(\frac{F_y}{t}\right)} + 0.667 \geq 1.0$ or $\left(\frac{D}{t}\right)\left(F_y\right) \leq 226{,}667$
      - Or when $F_y = 2396$ ksc (235MPa) → $D/t = 94.6$ → t can be 4.2 mm (70% of the available smallest t, 6mm)
      - Or when $F_y = 3620$ ksc (355MPa) → $D/t = 62.6$ → Can increase F_y to 355 MPa



  - CFT:
    - For No Local Buckling:

      - $D/t \leq \lambda_p \left(= 0.15\frac{E}{F_y}\right)$ or $\left(\frac{D}{t}\right) F_y < 306{,}000$
      - Or when $F_y = 2396$ ksc (235MPa) → $D/t = 127.7$ → t can be 3.1 mm (50% of the available smallest t, 6mm)
      - Or when $F_y = 3620$ ksc (355MPa) → $D/t = 84.5$ → t can be 4.7 mm (80% of the available smallest t, 6mm)

- General Column Cost Comparison:

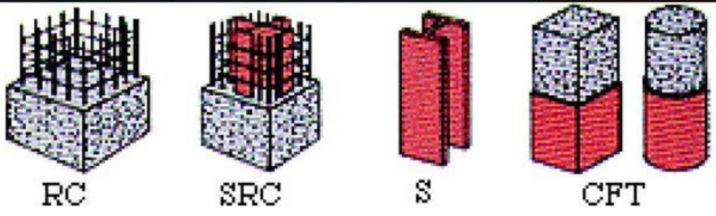


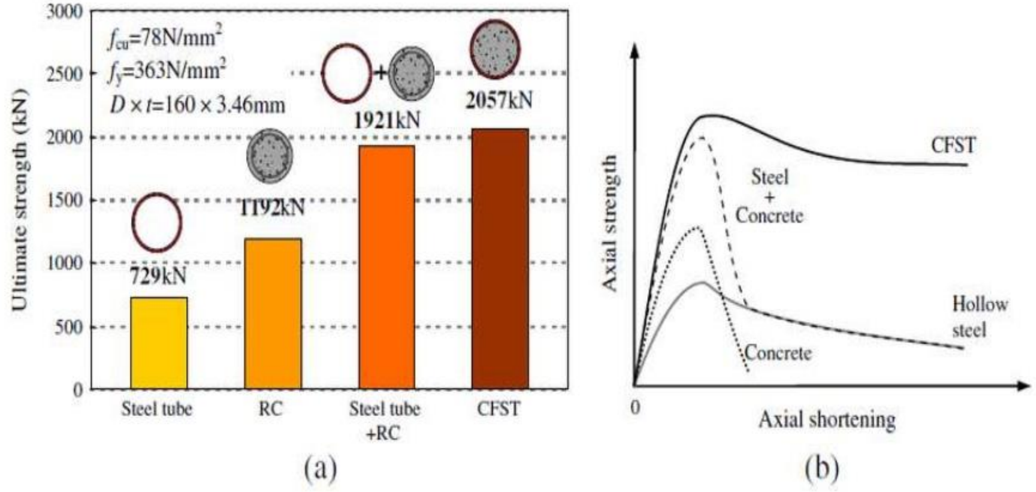
1) Statement (Cont.)

Comparisons of different types of columns

	RC structure	SRC structure	S structure	CFT structure
Flexibility	□	○	⊙	⊙
Rigidity, habitability	⊙	⊙	□	○
Fire resistance	⊙	⊙	□	○
Suitability for high-rise structures	□	○	⊙	⊙
Workability	○	□	⊙	⊙

⊙ Excellent
○ Good
□ Fair





Axial compressive behaviour of CFT column

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- AISC 2010
- AISI 2012
- ACI318-14