DEVELOPMENTS IN COMPOSITE COLUMN DESIGN

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OVERVIEW

- Introduction
  - Advantages of composite columns
  - Applications in high-rise buildings
- Background to 2005 AISC Specification
  - Reason for changes
  - Reduction of conflicts with ACI 318
  - Issues for future work
- Experimental program
Composite Columns in Tall Buildings

- Four super-columns tied by 5-story Virendeel trusses provide all the lateral resistance to the Norwest Center in Minneapolis
- Speed of construction = gravity load system followed by lateral load system and building finishes
- Concrete in columns used mostly for stiffness

CBM Engineers - Houston
Column Details

Beam B2: W920 x 446

35M Dywidag bars to transfer bearing forces (B1 and B2)

Reinforcing Cage 1:
8 45M and 6 30M bars
(all exterior bars are 45M)

Shear studs to web of B1

Cage 3: 7 45M and 3 30M bars

Beam B1: W840 x 299

Shear studs to flange of B2

Cage 2: 14 45M and 6 30M bars

W360 x 421 column

P1 (FBP)
P2
P3
P4 (FBP)
P5
Frames with SRC columns

Phases in erection & construction

Source: Martinez-Romero, 2003
Construction Sequence

- **12**: Setting Steel
- **11-12**: Welding Frame
- **10**: Setting Metal Deck
- **9-10**: Derrick on 10
- **8**: Placing Studs
- **7-8**: Setting WWF
- **6-5**: Pouring Floors
- **5-6**: Setting WWF
- **4-3**: Tying Column Cage
- **3-4**: Setting Column Form
- **2-1**: Pouring Columns
Composite Columns in Tall Buildings

Building: Avantel
Use: Office
Location: Mexico City
Year: 1995

Firm: EMRSA
Floors: 28

Source: Martinez-Romero, 1999

Structural steel: ASTM A-572-50
Concrete: $f'_c = 5.7$ ksi
Reinf. steel: $F_y = 60$ ksi
Concrete: \( f_c' = 6 \text{ ksi} \)

Structural steel: ASTM A-572-50

Reinf. steel: \( F_y = 60 \text{ ksi} \)

Source: Martinez-Romero, 1999
Uses for Composite Columns

• Extra capacity in concrete column for no increase in dimension
• Large unbraced lengths in tall open spaces
  – Lower story in high rise buildings
  – Airport terminals, convention centers
• Corrosion, fireproof protection in steel buildings
• Composite frame – high rise construction
• Transition column between steel, concrete systems
• Toughness, redundancy as for blast, impact

(from Larry Griffis)
Applications around the world

Full-scale 3stor, 3-bay braced frame tested in Taiwan
Applications around the world

Rectangular or circular composite columns with external diaphragms
Transition Floors

From concrete walls and columns to steel columns

S.D. Lindsey & Assoc.
Composite or hybrid system (concrete & steel)

System which combines the advantages of concrete and structural steel

**Concrete**
- Rigid
- Fire resistant

**Structural steel**
- High strength
- Ductile

**Frames with CFT columns**
- Steel tube *confines* concrete
- Concrete restricts the local buckling of the steel tube
- Increase in strength & deformation of the concrete
- Delay in the global buckling of the steel tube

**Frames with SRC columns**
- Steel element supports the construction loads
- The concrete gives final stiffness and fire resistant
- Shear connections become FR once concrete is cast
- System fast to erect & build
- Redundancy & robustness
Configurations for Composite Columns

a) SRC

b) Circular and Rectangular CFT

c) Combinations between SRC and CFT
Design Guide 6

- Concrete encased WF shapes
- Based on 1986 LRFD Spec
- 5, 8 KSI NW concrete
- A36, A572 Gr 50 WF
- 1%-4% Rebar patterns
Design Guide 6

Adjust $\phi_c$ factor 0.85 to 0.75; $\phi_b=0.9$ same

$M_{ui}(AISC05) = M_{ui}(Design\ Guide) \times 0.75/0.85$
AISC Spec. (2005)
New Composite Column Provisions

- Changes in materials permitted
- Relaxation of slenderness limits
- New strength provisions for encased columns
- New strength provisions for CFT columns
- New provisions for force transfer
- New expressions for flexural stiffness

\[ \Phi_c = 0.75 \ (LRFD) \ (\text{Change from 0.85}) \]
\[ \Omega_c = 2.00 \ (ASD) \]
Composite Column Database

• Determine range of sizes and materials tested
• Assess robustness of data
• Extract useful information
• Determine types of tests needed

Leon and Aho, 2000
Databases in CCFT composite columns (Leon and Aho, 1996) (now: Goode et al., 2007 + Leon et al., 2005)

1375 Circular CFT
• 912 columns
• 463 beam-columns

798 Rectangular CFT
• 524 columns
• 274 beam-columns

267 Encased SRC
• 119 columns
• 148 beam-column
Material Limitations

• **Concrete Strength** $f'_c$
  - *NW*: 3 – 10 ksi
  - *LW*: 3 – 6 ksi
  - Higher values usable for stiffness

• **Structural Steel, Rebar**
  - $F_y = 75$ ksi max

• Higher strength materials by testing or analysis
Confinement Effects

Kent-Park’s model

Mander’s model

Sakino-Sun’s model

$0.95f'_c$ for CCFT only for simplicity
Encased Composite Columns
New Limitations

• Steel core = 0.01 x $A_g$ min
• 4 longitudinal continuous bars w/ ties or spirals
• Min transverse reinf $\geq$ 0.009 in$^2$ / in tie spacing
• Min reinforcement $A_{sr} / A_g = 0.004$
Filled Composite Columns
New Limits

- **HSS area** = 0.01 $A_g \text{ min}$
  (down from 0.04 in 1999)

- **Rectangular HSS:**
  \[ b/t \leq 2.26 \left[ \frac{E}{F_y} \right]^{0.5} \]
  = 54.4 for 50 ksi (+20%)

- **Round HSS:**
  \[ D/t \leq 0.15 \frac{E}{F_y} \]
  = 87 for 50 ksi (+50%)
**Slenderness**

For $P_e \geq 0.44 P_o$:

$$P_n = P_o \left[ 0.658 \frac{P_o}{P_e} \right]$$

For $P_e < 0.44 P_o$:

$$P_n = 0.877 P_e$$

$$P_o = A_s F_y + A_{sr} F_{yr} + 0.85 f'_c A_c$$

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

> Note similar format to all steel column
Moments of Inertia - Composite Columns

**SRC new effective stiffness:**

\[
E I_{\text{eff}} = E_s I_s + 0.5 E_s I_{sr} + C_1 E_c I_c
\]

\[
C_1 = 0.1 + 2 \left[ \frac{A_s}{A_c + A_s} \right] \leq 0.3
\]

(concrete effectiveness factor)

**CFT new effective stiffness:**

\[
E I_{\text{eff}} = E_s I_s + E_s I_{sr} + C_3 E_c I_c
\]

\[
C_3 = 0.6 + 2 \left[ \frac{A_s}{A_c + A_s} \right] \leq 0.9
\]

(concrete effectiveness factor)
Effective stiffness \( (EI_{eff}) \)

Mirza and Tikka (1999)
\[
EI_{eff} = \left( 0.313 + 0.00334 \frac{L}{h} - 0.203 \frac{e}{h} \right) E_c \left( I_g - I_{ss} \right) + 0.729 E_s I_s + 0.788 E_s I_{sr}
\]

\[
EI_{eff} = 0.9 \left( E_s I_s + E_s I_{sr} + 0.5 E_c I_c \right)
\]

AISC (2011?)
\[
EI_{eff} = E_s I_s + 0.5 E_s I_{sr} + \beta \cdot C_i E_c I_c
\]
\[
\beta = f (\text{creep} \& \text{shrinkage}) = f (\rho, KL/r) \leq 0.6-0.9 \,(\text{RFT-CFT}), \, 0.3 \,(\text{SRC})
\]

Alternatives:

**Concrete-only** or a **steel-only** (not unusual in practice, too conservative!)

**Fiber element analysis**: Nonlinearity \((\sigma - \varepsilon, \, P-\Delta, \, P-\delta)\), buckling, confinement (contact enforcement)

**Finite element analysis**: Local buckling, effective confinement, cracking.  
Steel-concrete contact (friction, bond stress, slip, adhesion, interference).
Design Methods
Encased Composite Beam Columns

• *Method 1*: AISC Interaction Equations

• *Method 2*: Plastic Stress Distribution Method

• *Method 3*: Strain Compatibility Method
  (like ACI Column Design)
Encased Composite Beam Columns
Method 1 (Interaction Eq’s)

• *Uses AISC Beam Column Interaction Eq’s*
• *Strong and Weak Axis Bending*
• *Requires only pure axial, pure moment capacities (P₀, Mₙ)*
• *Conservative designs*
• *Can use existing Design Guide 6 (conservative answers)*
AISC Interaction Equations

- For $P_r/P_c \geq 0.2$,
  \[ -\frac{P_r}{P_c} + \frac{8}{9} \left( \frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}} \right) \leq 1.0 \]

- For $P_r/P_c < 0.2$,
  \[ -\frac{P_r}{(2P_c)} + \left( \frac{M_{rx}}{M_{cx}} + \frac{M_{ry}}{M_{cy}} \right) \leq 1.0 \]

- $P_r = \text{required axial compressive strength}$
- $P_c = \text{available axial compressive strength} (\phi_c P_n \text{ or } P_n/\Omega_c)$
- $M_r = \text{required flexural strength}$
- $M_c = \text{available flexural strength} (\phi_b M_n \text{ or } M_n/\Omega_b)$
- $\phi_c = \phi_b = 0.9$
Encased Composite Beam Columns
Method 2 (Plastic Stress Distr)

- **Plastic Capacity Equations**
  - *Points A,B,C,D (plus E weak axis only)*
  - *Defined on the Example CD (w/ manual)*
- **Strong and weak axis bending**
- **Bar placement must conform to equations**
- **Apply slenderness effects to P,M values**
- **More capacity than Method 1**
Rigid-plastic & strain-compatibility methods

**STEEL**

Interaction diagram: W8×31

\[
\frac{P_u}{P_n} + \frac{8}{9} \frac{M_u}{M_n} = 1 \text{ for } \frac{P_u}{P_n} \geq 0.2
\]

\[
\frac{P_u}{2P_n} + \frac{M_u}{M_n} = 1 \text{ for } \frac{P_u}{P_n} < 0.2
\]

Interaction diagram: (AISC Commentary, 2005)

**COMPOSITE**

Interaction diagram

(AISC Commentary, 2005)
Plastic stress distribution or rigid-plastic method

\[ P_D = 0 + \frac{0.85 A_c f'_c}{2} \]

\[ M_D = Z_s F_y + \left[ A_{sr} \left( \frac{h}{2} - c \right) \right] F_{yr} + \left( \frac{bh}{2} \cdot \frac{h}{4} \right) 0.85 f_c \]

\[ M_D = Z_s F_y + Z_r F_{yr} + \frac{Z_c}{2} (0.85 f'_c) \]
Plastic stress distribution or rigid-plastic method

\[ P_A = 0.85 A_c f_c' + A_s F_y + A_r F_{yr} \]

\[ M_A = 0 \]
**Plastic stress distribution method**

\[ P_B = \sum P_i = 0 \]

\[ P_C = \sum P_i \neq 0 \]

\[ P_C + P_B = P_C \]

\[ P_C = 0.85 f_c' A_c \]
Plastic stress distribution method

\[ P_B = \sum P_i = 0 \]

\[ P_C = \sum P_i \neq 0 \]

\[ P_C - P_B = P_C \]

\[ P_C = 2h_n \left( 0.85 f'c b + F_y \right) \]

\[ h_n = \frac{0.85 f'c A}{2(0.85 f'c b + F_y)} \]
Plastic stress distribution method

\[ M_B = M_C = M_D - \Delta M_{D-B} \]

\[ \Delta M_{D-B} = F_y \left(t_w h_n^2\right) + 0.85 f_c' \left(\frac{b h_n^2}{2}\right) \]

\[ M_D = Z_s F_y + Z_r F_{yr} + \frac{Z_c}{2} (0.85 f_c') \]  

\[ M_B = Z_s B F_y + Z_r B F_{yr} + \frac{Z_{cB}}{2} (0.85 f_c') \]
Composite Column Models

Calculate section strength
Reduce by length effect
Apply resistance factor

\[ \Lambda A = A_\lambda \]
\[ A_d = \phi_c A_\lambda \]
\[ \Lambda C = C_\lambda \]
\[ C_d = \phi_c C_\lambda \]

Effect of “bulge” is not used

\[ \phi_b B = B_d \]
### P-M Interaction anchor points  (*AISC Examples, 2005*)

#### Plastic Capacities for Rectangular, Encased W-Shapes Bent about the X-X Axis

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<th>Stress Distribution</th>
<th>Point</th>
<th>Defining Equations</th>
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#### Plastic Capacities for Composite, Filled Round HSS Bent about Any Axis

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<tr>
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</table>
Encased Composite Beam Columns
Method 3 (ACI Strain comp)

• Strain compatibility approach
• Linear strain diagram with 0.003
• Same as ACI Beam Column design
• Use AISC $\varphi$ factors ($\varphi_c=0.85$, $\varphi_b=0.9$)
• Can convert WF to equivalent bars
• Yields smaller values than Method 2
Fiber Element Analysis

\[ \delta_o = 0 \]

\[ \delta_o = L/1000 \]
Pure-compression (flexural buckling limit state)
Composite Sections (short columns)

\[ f'_c = 5 \text{ ksi} \]
\[ 34.5 \text{ MPa} \]

\[ E_s = 29000 \text{ ksi} \]
\[ 200 \text{ GPa} \]

\[ E_c = \text{From Code NTC (2004)} \]
\[ \text{AISC (2005)} \]
\[ \text{EC-4 (2004)} \]
\[ \text{AIJ (2004)} \]
Pure-compression-strength
AISC curve vs. fiber analysis results

a) Analysis without initial imperfection
b) Analysis with initial imperfection
P-M Interaction Diagram for CCFT20x0.375

- AISC (2005)
- AIJ (2001)
- Fiber Analysis
P-M Interaction Diagrams

- NTC (2004)
- AISC (2005)
- AIJ (2001)
$M_1$ and $M_2$ curves

(a) $L/D=8$

(b) $L/D=16$

(c) $L/D=24$

(b) $L/D=28$
Net $M_1$ and $M_2$ curves

(a) $L/D=8$

(b) $L/D=16$

(c) $L/D=24$

(b) $L/D=28$
Experimental Tests

NEES Project: Georgia Tech, U. Illinois, U. Minnesota

- 20 full-scale slender composite beam-columns (8 SRC, 4 CCFT, 4 RCFT, 4 SCFT)
- Data will fill gaps in U.S. database

*Multi-Axial Sub-assemblage Testing System (MAST-UMN)*
Preliminary Test Series

BC’s Configuration

Axial capacity of MAST System

Axial force, $P$

Moment, $M$

- Strain C.
- Plastic
- 2005Simp.
Actual Load Paths

Exterior Columns

6END-C7
1C3(B)

Interior Columns

6END-C7
1C3(B)
## Preliminary SRC Test Series

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<th>L (ft)</th>
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Inelastic Static & Dynamic Analysis
LA 3 & 20 Story SAC frames (FEMA 355C, 2000)

Steel Frame System

- W14x311
- W14x257
- W14x90

SRC Frame System

- 26x26in
- 12#10 (2.6%)
- #4@4in
- W14X90

CRC Frame System

- HSS-20x0.375
- f_c’ = 5ksi
- F_y = 42 ksi
$AF_M$ based on reduced $EI^*=0.8EI_{eff}$

(a) $L/D=8$

(b) $L/D=16$

(c) $L/D=24$

(d) $L/D=28$
Beam-column FEA (scaled displacements)

Local buckling

Flexural buckling
Encased Columns – Improve Reliability
Summary

New Composite Column Procedures

• Based on ultimate plastic capacity – simple plastic or strain compatibility (mechanistic approach / EC4)
• Provide transition from a RC to a composite column
• Maintain current length effects approach– adjust EI values
• Improve reliability (from $\beta = 2.4$ to 2.7)
• Relax local buckling - $b/t < 56$ (+20%); $D/t < 121$ (+50%)
• Relax concrete material limits = 70 MPa
• Relax steel material limits = 520 Mpa)
• Provide better force transfer guidelines
More Information

• EJ has two papers by Leon, Kim and Hajjar (4th Quarter, 2007) and Leon and Hajjar (1st Quarter, 2008) with all the details of the changes to the 2005 Specification