Outline of Presentation

- Background & Applications
- Composite RCS Beam-Column Joints
- Large Scale Composite RCS Frame Test
  - Design/Construction/Testing
  - Analysis and Interpretation
- The New Frontier

Acknowledgments:
National Science Foundation (USA), National Science Council (TW)
Pacific Earthquake Engineering Research (PEER) Center
National Center for Research in Earthquake Engineering (TW)
Earthquake Engineering Research Institute
Nippon Steel Corporation, American Institute of Steel Construction

Early “Mixed” System

Texas Commerce Plaza
- 75-story, RC perimeter frame
- 1982, Houston, TX
- CBM Engineers, Houston

Three Houston Center
- 52-story RCS perimeter frame
- 1983, Houston TX
- Walter P. Moore Associates

Norwest Center Building
- Composite "Mega-Frame"
- Minneapolis, MN, 1987
- CBM Engrs., Houston, TX
**U.S. Design/ Construction Practice**

- Composite construction evolved as a variation of steel construction with most applications for mid-to high-rise building structures.
- Advantages of Composite:
  - Economy of concrete in vertical members
  - Speed of construction
  - Versatility in design and construction
- Disadvantages of Composite:
  - Mixing of construction trades
  - Lack of design standards, guidelines, etc.

**Japanese RCS Systems**

- Low-rise construction (3-5 stories)
  - Shopping centers and offices
  - About 100 RCS buildings in Japan
- Construction Methods:
  - Precast columns
  - Cast-in-place with rebar erection columns
- High-Seismic Regions
Advantages for Seismic Design “post-Northridge”

- Steel beam continuous through joint
- Avoids welding at location of maximum forces
- Stable hysteretic behavior

US Seismic Design Standards

  - Based on 1994 & 1997 NEHRP
  - General criteria for systems, members and connections
  - Based on 1994 NEHRP chapter on composite structures
  - Criteria for composite systems, members, connections
- AISC (2005) and ACI-318 (2005)
  - Steel and RC members and connections
  - Composite beams and columns (limited)

20 Story Design Example

Specifications
- 20-story “SAC” frame
- Perimeter frame system
- IBC 2006
  - \( S_1 = 1.5g \)
  - \( S_5 = 0.72g \)
  - \( R = 8, C_d = 5.5 \)

Mid-Rise: Competitive with Steel Frame

Controlling Design Criteria
- Strength
- Seismic
- Drift

Steel vs. RCS Design

RCS Frame Design
- Beams: W24 – W30
  - Steel quantity: 3.0psf
- Columns
  - 30” x 35”, 30” x 30”
  - Concrete quantity: 0.16\( \text{ft}^3/\text{ft}^2 \); rebar 1.4psf
- Gravity Framing
  - Steel quantity: 7.6psf

Steel Frame Design
- Beams: W24 – W30
  - Steel quantity: 3.0psf
- Columns
  - W24x335,W24x279
  - Steel quantity: 4.8psf
- Gravity Framing
  - Steel quantity: 7.6psf

Outline of Presentation

- Background & Applications
- Composite RCS Beam-Column Joints
- Large Scale Composite RCS Frame Test
  - Design/Construction/Testing
  - Analysis and Interpretation
- The Future Frontier
RCS Beam-Column Connection Tests & Design Guidelines

Research 1985 - 2004*:
- Transfer Mechanisms
- Details (band plates, etc.)
- Cyclic Behavior
- Exterior & 2-way joints
- Concrete Slab
- High Strength Concrete
- Fiber Concrete...

* total database of 400+ tests (world wide)

Connection Tests & Design Models

- US Research & Guidelines
  - Deierlein & Sheikh, UT Austin, 1989
  - Kanno & Deierlein, Cornell Univ., 1994
  - Parra-Montesinos and Wight, Univ. of Michigan, 2000
  - Bracci et al., Texas A&M, 2000

- Japanese Research & Guidelines
  - AIJ-SRC method (1987)
  - Modified AIJ-SRC (Iizaki et al., Sakaguchi, etc.; 1988-97)
  - Kim and Noguchi (1998)
  - Nishimura-Minami model (1989)


Composite Beam-Column Joint Tests

(Deierlein, 1989; Kanno, 1993)

- Typical Joint Detail
  - \( TJD = 0.01 \text{ rad} \) (after 2 cycles)
  - \( TJD > 0.05 \text{ rad} \) Exposed Core

Modes of Subassembly Failure

- Joint
- Mixed
- Beam

- Beam-Hinging
- Joint Panel Shear
Modes of Subassembly Failure

Beam Hinging Joint Shear

Displacement (mm)

Beam Shear (kN)

Connection Behavior & Design Model

Outer Panel Inner Panel Outer Panel

Inner Panel Failure Modes

Bearing failure Panel shear failure

Concrete crushing Kinking Panel shear yielding

Concrete crushing

Inner Panel Failure Modes

Panel shear failure Bearing failure

Typical Through-Beam Details

Face bearing plate (FBP) Steel band

Small column Vertical joint reinf. (VJR)

Steel band Transverse beam

Basic Equations for Model (Kanno)

- Each element strength is calculated by the smaller of two modes:
  \[ V_{bi} = \min \{ V_{be}^i, V_{swc}^i \} \]
  \[ V_{bo} = \min \{ V_{bo}^o, V_{scf}^o \} \]
- Strengths are added:
  \[ V_b = V_{bi} + V_{bo} \]
- Important aspect:
  - Simultaneous failure of inner and outer elements for entire joint failure
Joint Failure Models

- 1994 ASCE joint design model
  - Deierlein & Sheikh, UT Austin, 1989
- Follow-on studies
  - Kanno et al. 1994
  - Parra-Montesinos et al. 2000, 2003
  - Bracci et al. 2000
- 2007 Updated Guidelines
  - Synthesized past work
  - NCREE testing program results
  - Updated models and incorporated new details

Outline of Presentation

- Background & Applications
- Composite RCS Beam-Column Joints
- Large Scale Composite RCS Frame Test
  - Design/Construction/Testing
  - Analysis and Interpretation
- The Future Frontier

Rationale for Full-Scale Test

1. PROOF OF CONCEPT for innovative systems: construction, design, and performance
2. BEHAVIORAL EFFECTS: complete system study, precast & bolted splices, composite beam/slab, load introduction, etc.
3. CALIBRATION & VALIDATION of analysis models
4. DATA for performance-based earthquake engineering: (large deformations, immediate occupancy through near-collapse)
5. CAPSTONE project for past 20 years of research
6. DEMONSTRATE RELIABILITY for high seismic zones

Seismic Design Criteria

- IBC 2003
  - Design Hazard ($S_{md} = 1 g; 10\% $ in 50 year)
  - $R = 8$ (Composite Special Moment Frame)
  - Drift: $\Delta/v_C < 0.02h$
  - Period: $1.2T_a = 0.6$ sec
  - Accidental torsion (7.5\% increase in $V/W$)
- Design Base Shear
  - $V/W = (S_{md}/R)^*0.075 = 0.134$
  - $V = 261$ kips = 1163kN

Full Scale 3-Story Test

Collaborators: Dr. K.C. Tsai, C.H. Chen, W.C. Lai

- Designed per IBC 2003
- NCREE lab in Taipei, Taiwan
- 4 Pseudo-dynamic EQ’s and final static pushover
- Complementary subassembly tests

Columns - 650x650mm, $\rho_g = 0.03$
Beams - 1-600x200mm, 2-500x200mm, 3-400x200mm
Governing Criteria

- Beams
  - Sized for strength (1.42D+0.5L+E)
- Columns
  - Controlled by SCWB
- Composite Joints
  - Standard details (fulfills SJWB criterion)
  - Drift Criteria is automatically satisfied

1st Floor Beam-Column Modules

1st Floor Steel Beams

Lift steel beam into place

Fasten the beam splice connection

1st Floor Loading Beam

Loading Beam
Grouting 1st Floor Splice

2nd & 3rd Floors

Pseudo-Dynamic Testing Method

Input Ground Motions

Overview of Measured Response

- 3 Actuators per floor
- 1000KN, ±500mm stroke

- 50/50 Event
- 10/50 Event
- 2/50 Event
- 10/50 Event

- EQ#1 – 50/50 Chi-Chi Record
- EQ#2 – 10/50 Loma Prieta Record
- EQ#3 – 2/50 Chi-Chi Record
- EQ#4 – 10/50 Loma Prieta Record
- Final Static Pushover (RDR ~ 8%) (IBC 2003)
**Final Pushover**

<table>
<thead>
<tr>
<th>ACI/AISC SCWB Ratios</th>
<th>Per Joint: $\frac{\Sigma M_c}{\Sigma M_b} &gt; 1.2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel Strength</td>
<td>Steel Strength</td>
</tr>
<tr>
<td>Composite Strength</td>
<td>Composite Strength</td>
</tr>
</tbody>
</table>

**Local Buckling**

- **Full-Scale**
  - Continuity provided restraint against severe buckling
  - Large buckles straightened out on opposite cycles (esp. along side interior joints)

- **Subassembly**
  - Boundary conditions allow beam shortening
  - Buckles build up over each of the cycles
  - Overestimates amount of damage

**Slab Performance**

- **Full-Scale**
  - Exceeded expectations and remained intact
  - No shear stud fractures
  - Realistic load transfer alleviates stresses on slab

- **Subassembly**
  - Typically fails by local slab crushing and shear stud fractures
  - Slab failure initiates more buckling in top flange

**Analytical Modeling**

- **OpenSees**
  - Fiber Section
  - Beam-Column

**Fiber Element Calibration**

- Tsai 2002
  - Effective slab width: $b_{eff} = b_{col}$
Analytical Modeling
Composite Joint Calibration

Local Response from OpenSees

Ref: El-Tawil, Deierlein, Kanno

Analytical Modeling
50%in50 year Event

EQ01 – 50/50 TCU082

Maximum Response
- Displ. Error < 20%
- Shear Error < 10%
- Difference in period shift noticeable near latter half of event.

Period Elongation

- All records scaled to the spectral hazard ($S_a$) at the first natural period of frame ($T_1=1.0s$).
- The first event (50%in50yr) cause period elongation to 1.3 seconds.
- The following design level event (10%in50yr) actually represented a higher hazard level (~2%in50).
- Emphasizes importance of appropriate EQ intensity measures that captures spectral shape

Analytical Modeling
2%in50 year Event

Large local buckles in beam flanges

Local buckles not modeled

Shear Error < 10%

Relating Analysis to Physical Damage

Local Response from OpenSees

$$D_k = \frac{(\theta - \theta_0)\sum_{i=1}^n \theta_i' \mid \theta_i'}{(\theta - \theta_0)\sum_{i=1}^n \theta_i' \mid \theta_i'}$$

Mechanny & Deierlein 2001

$$0.0 \leq D_k \leq 1.0$$

- 0 – 0.5 Negligible damage
- 0.5 – 0.7 Moderate, repairable damage
- 0.7 – 0.95 Significant, questionable repair
- 1.0 Loss of capacity

Damage Indices

1st Floor Beam

26% in $S_d$

Loma Prieta, Scaled to 10/50

Emphasizes importance of appropriate EQ intensity measures

All records scaled to the spectral hazard ($S_a$) at the first natural period of frame ($T_1=1.0s$).

The first event (50%in50yr) cause period elongation to 1.3 seconds.

The following design level event (10%in50yr) actually represented a higher hazard level (~2%in50).

Emphasizes importance of appropriate EQ intensity measures that captures spectral shape.
# Performance & Modeling Implications

<table>
<thead>
<tr>
<th>EQ #2</th>
<th>EQ #3</th>
<th>EQ #4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damage Index (EDP)</td>
<td>Condition &amp; Consequence (DM)</td>
<td>Implications (DV)</td>
</tr>
<tr>
<td>0.5-0.7</td>
<td>Minor cracking &amp; spalling</td>
<td>Minor cost, No shutdown time</td>
</tr>
<tr>
<td>&gt;0.9</td>
<td>Severe cracking &amp; spalling</td>
<td>Is repair economically feasible?</td>
</tr>
</tbody>
</table>

## Strength Degrading Hinge Models

- Column Spring
- Beam Spring
- Joint Panel Spring

## Fiber versus NL Hinge Models

- Code Conforming 4-Story RC Frame
- Fiber Beam-Column Models

## Case Study Buildings

- 3, 6, and 20-story buildings
  - Composite beams controlled by strengths
  - RC columns controlled by SCWB
  - Joints satisfy strength requirements with standard details

### Design Details
- Column Sizes: 600x600mm – 1000x750mm  (ρ = 1.5-3%)
- Steel Beams: W450-750 (W18-W30)

## Incremental Dynamic Analysis

- 6-Story Frame
Summary Observations

- Even when designed to test the minimum limits of current building code, the RCS frame showed excellent behavior under various seismic demands.
  - Composite joints performed well
  - Composite beam action was maintained
  - Precast column splices and beam splices performed well
- Strong-Column Weak-Beam
  - Significance of composite beam action
  - Strength ratio criteria of 1.2 (6/5) is not necessarily a good measure to prevent story mechanisms.

Summary Observations, cont’d

- NL Fiber Analysis accurate up to 3% drift ratio
  - Accuracy degrades above 4% due to degradation effects that are not captured in model
  - Motivates use of degrading spring type models for >3%
- Importance of appropriate ground motion selection and scaling
- Full system versus subassembly testing
  - Damage in the slab and studs
  - Severity of local buckling

Future Research & Development

- Develop more cost-effective erection/construction methods (especially for low-rise)
- Improved models to simulate large deformations (including strength/stiffness degradation)
- Comprehensive performance-based assessment
- Continue to innovate new systems

Nanjing Financial Center
67 Story (339/450M) - 2007
Composite/Hybrid System
SOM

Outline of Presentation

- Background & Applications
- Composite RCS Beam-Column Joints
- Large Scale Composite RCS Frame Test
  - Design/Construction/Testing
  - Analysis and Interpretation
- The New Frontier
Composite/Hybrid Framing

<table>
<thead>
<tr>
<th>Graphic</th>
<th>Text</th>
</tr>
</thead>
</table>
| ![Diagram](image1.png) | Zhengzhou Tower  
55 stories (280m) - 2009  
Dual system: RC Core & Composite Perimeter Frame  
SOM |

<table>
<thead>
<tr>
<th>Graphic</th>
<th>Text</th>
</tr>
</thead>
</table>
| ![Diagram](image2.png) | Concrete Core  
Perimeter Moment Frame |

Zhengzhou Tower  
55 stories (280m) - 2009  
Dual system: RC Core & Composite Perimeter Frame  
SOM

- 32 Perimeter sloping columns per story  
- Column Diameter 750 - 1150 mm  
- Encased Steel Section: $A_c = 6.5\% - 8\%$  
- Steel Reinforcement: $A_r = 2.8\% - 3.5\%$

Innovations Closer to Home?  
e.g., New San Francisco Skyline

- High Density = Viable Community  
transportation – services – construction economics

Thank you!  
Questions ??