Accelerated Bridge Construction – Developments on the Earthquake Frontier

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ABC in Seismic Regions

- What are the challenges?
- Family of design concepts.
- Connections for emulative and other systems.
- Systems for enhanced seismic performance.
Challenges

- SPMT
- Lateral slide
- PBES
  - ABC
  - Bents
  - Superstructure
Challenges

PBES bent connections

ABC
- Easy to assemble.
- Generous tolerances.
- Fast in the field.
- Common materials.

Seismic
- Continuous load path.
- Robust.
- Avoid eccentricities.
- Energy Dissipation.
- Protect brittle elements.
- No stress concentrations.

So what is the problem?

Requirements for ABC and seismic often conflicting. Need approaches that solve both problems together.
Challenges

• Can ABC be achieved with the same seismic resistance as for conventional construction?
• Can we improve seismic performance with ABC?
• Present approach: Life Safety.
• Possible objectives (Immediate Operation):
  ❖ No residual drift.
  ❖ Low damage.
The field is yet young.

• Many ideas.
• Some: ABC = good, seismic = same.
• A few: Both = good.
• Combine concepts and details to suit particular project.
## Family of Connections

### Design Concept

<table>
<thead>
<tr>
<th>Connection Type</th>
<th>Emulative</th>
<th>Enhanced Seismic</th>
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</thead>
<tbody>
<tr>
<td>Socket</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Pocket</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Grouted duct</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Other</td>
<td>x</td>
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</table>

### Enhanced Seismic Design Concept

- UBPost-T
- UBPre-T
- SMA
- Other
Emulative Construction

• No new concepts to prove.
• Easier acceptance: “performs just like c.i.p.”
• But, use of precast shortens time on site.
Common connection concepts for emulative (and other) systems:

- Socket connections
- Pocket connections
- Grouted ducts and sleeves
- Other mechanical connections
Versatile Connections - Sockets

**WET SOCKET**
- **Column**: PC concrete or CFT
- **Footing**: cip concrete

**DRY SOCKET**
- **Column**: PC concrete or CFT
- **Footing**: PC concrete
- **Annular space**: cip grout or concrete

No steel crosses column-footing interface.
Quick to construct.
Best if $h_{\text{footing}} > 1.0 \ D_{\text{col}}$
Well suited to footings.
Vertical load can be carried by friction
Opening in Cap Beam. Fill with cip concrete

Corrugated steel pipe

PC Cap Beam.

Column – PC or cip
Pockets – Precast Concrete Cap Beam

**Critical node - CCT**

**Force transfer from column tension steel:**
- Occurs at top node.
- Helped by corrugated tube.

Connection good for cap beams, not footings.
Pockets – Precast Concrete Footings

No access for pouring the concrete!
Grouted sleeves vs. ducts

**SLEEVE:**
- Joins two bars in tension.
- Sleeve transfers load by tension in wall.
- Thick walls. Proprietary.
- Placement tolerances tight.

**DUCT:**
- Anchors bar in concrete.
- Duct not in axial tension.
- Can lap-splice other bars to outside of duct.
- More generous tolerances.
WHERE TO PLACE THEM?
Consider both strength and deformation capacity.

IN FOOTING
- Bars project from column. Potential difficulty in transportation.
- Debris in sleeves?
- Harder to access grout ports.

IN COLUMN
- Stiff sleeve inhibits plastic hinge formation.
- Tie fit problem.

Plastic zones
Grouted sleeves and ducts

WHERE TO PLACE THEM?
Consider both strength and deformation capacity.

- **Cover spalls.**
- **Bars more prone to buckling.**

- **Low moment.**
- **Bars may not yield.**

**Bar stress**

*Good confinement = good bond. Strain concentration.*
MECHANICAL CONNECTORS

- Tension butt-splice between bars.
- Shorter than sleeve. Less effect on plastic hinge zone.
- Need careful alignment.
**Emulative Systems Approach**

- Precast intended to achieve seismic response of c.i.p.
- Connection designed to be as strong as the column, so
- Inelastic action is forced into the column.

Thus the name: “EMULATION”
Precasting the cap beam is the biggest time-saver. Saves time for:
  • Shoring
  • Formwork
  • Rebar placement and fixing
  • Casting-curing cycle

Precasting the column saves time, but:
  • Many contractors prefer c.i.p. columns (keeps work in-house).
  • Time savings are less than with cap beam.
Emulative Systems – Grouted Ducts

EMULATIVE SYSTEM

- Precast column.
- Bars project into ducts in foundation/cap beam.
- Ducts grouted.
- All inelastic action in column. Just like c.i.p.
Emulative Systems – Grouted Ducts

Failure sequence same as in c.i.p.
- Longitudinal bars buckle.
- Spiral kinks, then fractures.
- Longitudinal bars re-straighten then fracture.
Precast cap beam on c.i.p. columns. (Contractor’s choice to save time).
SR 520, Redmond WA.
Emulative “Wet Socket” Connection

Headed bars

Roughened surface
Emulative Wet Socket Connection
After seismic testing. All inelastic action in column. Foundation undamaged.
Emulative Drilled-Shaft Connection
Emulative Drilled-Shaft Connection

DS-1

DS-2
CFTs can be used as foundation elements (piles, shafts) and piers in elevated bridges.
Connections in Emulative Systems – Summary

- All of the major connection types (Socket, Pocket, Grouted Sleeves or Ducts, Mechanical Connectors) have been tested under cyclic loading.
- All can provide sufficient strength.
- Most can provide ductility equal to or better than c.i.p. construction.
- Ductility depends strongly on details.
Enhanced Seismic

ABC

Enhanced seismic

Best of both worlds
Conventional, bonded, cip construction:

“So you want to protect the columns by deliberately inflicting damage on them?”

Bars must yield to dissipate energy, but Bar yielding causes large strains and damage.

Use of debonded reinforcement offers an alternative.
Most work has been done on
- Re-centering – “Zero residual drift”.
- Minimizing damage to columns – no bridge closure.
- Combinations of the two.

Re-centering can be achieved by
- Unbonded Post-tensioning.
- Shape memory alloy (SMA) reinforcement.
RE-CENTERING SYSTEMS

Unbonded Post-tensioned Bumble Bee
Re-centering system hysteresis Loops

Nonlinear elastic

% elastic

% yielding
**Generic Unbonded PT Bent**

PT, unbonded in the free height of the column. Remains elastic.

Bonded rebar yields cyclically, dissipates energy.

Column rocks as a rigid body:
- no curvature
- no strain
- no cracking

Local high stress at interface.
Unbonded PT (Rocking) Systems - End Protection

Conventional concrete only

HyFRC in plastic hinge region

Steel tube confinement
Unbonded PT (Rocking) Systems - Variations

Post-tensioning:
- cip or pc column.
- Site operation.
- Anchorage.
- Potential for corrosion.

Pre-tensioning:
- pc column only.
- Plant prestressing.
- No anchorages, no corrosion.
- Relies on bond.

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### Unbonded PT systems

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- **cip column**
  - ABC???

- **pc column**
  - Lifting weight
  - GCs prefer not

- **shell column**
  - Light weight
  - Need int. and ext. steel shells
  - PT corrosion?
  - GCs prefer not
Pre-T Precast system

Construction sequence
Footing Connection:
Wet Socket

Discontinuous reinforcing welded to plate

Steel confining tube with bottom plate

Pre-tensioned strands debonded in body of column bonded at the ends

Continuous rebars debonded locally at interface
Cap Beam Connection: Dry Socket & Grouted Duct.
Pre-T Precast system

Shaking Table Test: 1995 Kobe /Takatori (PGA=0.8g)
Unbonded Post-T: External Dissipaters

Post Tensioning
Armouring/Cover Confinement
External Dissipators

ABC Low Damage

Courtesy Allessandro Palermo, University of Christchurch, NZ
These dissipaters have the advantage of being completely dry. The fuse section touches in some discrete points the steel tube that prevent the buckling; Testing is still on going and the performance seems to be better and the cycles are more stable.

External Dissipaters: “BR bars”
Unbonded Post-T: External Dissipaters

Self-centring

Energy Dissipation

Hybrid system

Unbonded post-tensioned cables/tendons

Mild steel or dissipation devices

Low Damage Connections
Unbonded Post-T: External Dissipators

Field Implementation - Wigram Magdala Bridge: detail of dissipater assembly
Unbonded Post-T: External Dissipators

After installation
Low damage Unbonded Post-tensioned Dual Shell Columns.

Courtesy Jose Restrepo,
University of California San Diego
Unbonded PT Dual-Shell Column

Concentric Steel Shells
- Hollow-core composite section
- No need for formwork or rebars

Post-Tensioning System
- PT bar and polyurethane bearing in series.
- Prevents PT bar from yielding.

INTERNAL Energy Dissipators
- Unbonded stainless-steel dowels
- Grouted into column ducts
- Circumferential welds inside outer shell

EXTERNAL Energy Dissipators
- Buckling-restrained hysteretic devices
- Connected to outer shell and footing
- Allow rotation at connections

Courtesy Jose Restrepo, University of California San Diego
Unbonded PT Dual-Shell Column

**Shake Table Test Specimen**

- Cantilever test configuration
- Shear span: 96 in. (2.44 m)
- Column diameter: 16 in. (0.41 m)
- Outer shell thickness: 0.25 in. (6.4 mm)

- PT: single 1.75-in. (46-mm) threaded bar, A722 Gr. 150
- Energy dissipators: 8 #3 (9.5-mm) dowels, 316LN Gr. 75 stainless steel
- Mortar bed with polypropylene fibers
- Matching headed bars
- Inertial mass: 53 kips (236 kN)
Low damage Columns with ECC and Shape Memory Allow Bars.

Courtesy Saiid Saiidi,
University of Nevada Reno
Goal:
- Develop ABC columns with seismic performance better than CIP

Headed Coupler Columns tested by Haber et al. (2014), emulative performance

SMA-Reinforced ECC section

UHPC-Filled Duct Connection

Used eight different materials

Courtesy Saiid Saiidi, University of Nevada Reno
SMA bars - Precast Column

- Material Model
- Proposed a design specification
- SMA-Steel Bar Connections
Test Results: Force-Drift

Graph showing the force-drift relationship for SMA/ECC Column and Conventional Column.
Damage after undergoing 10% drift
SMA bars - Precast Column

*SMA bars achieve, in one element:*
- Re-centering,
- Energy dissipation.

Alternative to the unbonded PT/yielding rebar combination.

However:
- They are expensive,
- Difficult to form or machine.
The Lego Approach – Mix and Match
Thank You!

Questions ?