Designing for Construction Productivity and Safety

Jared M. Reigstad, P.E., P.Eng.
Vice President
jmreigstad@pourstrip0.com
651-248-0593
In the United States, labor productivity in construction has declined since 1968, in contrast to rising productivity in other sectors.
PRO: An ACI Center of Excellence for Advancing Productivity is a catalyst for solving the barriers of constructability to advance concrete construction productivity.

Vision

According to McKinsey Global Institute, construction productivity lags behind other sectors. With a single focus to quickly stimulate industry change, PRO aims to increase the value of structural concrete to project owners.

The Center envisions a concrete industry where the productivity potential of contemporary materials and construction systems is fully realized and continually advanced.
INCREASE PRODUCTIVITY
REDUCE COSTS
ACCELERATE CONSTRUCTION
IMPROVE SAFETY
HIGHER QUALITY CONCRETE
Eliminates pour strips, wall leave-outs, and expansion joints while maintaining structural integrity and allowing for volume change. Using proven coupler technologies recognized worldwide, featuring a thread on one end and a grout-filled sleeve on the other. The system is an ACI 318 code compliant full-tension mechanical Type 1 and Type 2 rebar splice, is ICC approved and made in the USA.
The Main Issue
  • Volume change

Location Matters
  • Inflection point
  • Mid-span

Slab-to-Slab Connectors
  • Concrete anchors
  • Mechanical couplers
WHAT IS A POUR STRIP?

- A temporary leave-out
- Post-tensioned separately
- Allows for volume change
- A complete break in the structure
- 3-ft to 4-ft wide, or wider
- Poured back later
- 28-days to 120-days, or more
- Used in PT and RC
WHAT IS A POUR STRIP?

- Formwork left in place or reformed
- ACI lap splice
- Provides load transfer
- Provides diaphragm continuity
- Provides ACI integrity
- Safety hazard
- Critical path
- Delays other trades
- Most expensive concrete
WHAT IS A POUR STRIP?
WHAT IS A POUR STRIP?
THE MAIN ISSUE

Volume change
• Shrinkage
• Temperature
• Elastic shortening – PT
• Creep – PT

Restraint to shortening (RTS)
ACI 209 – CREEP AND SHRINKAGE IN CONCRETE

- 8-in PT slab
- 100-ft long
- No restraint
- RH = 75%
- P/A = 200 psi
- $f'_c = 3,000$ psi (release)
- $f'_c = 5,000$ psi
- Temperature change = 70°F

Estimated Long-Term Shortening (25-yrs)
- ES (Elastic Shortening) = 0.07-in
- SH (Shrinkage shortening) = 0.5-in
- CR (Creep Shortening) = 0.11-in
- T (Temperature shortening) = 0.5-in
- Total without T = 0.68-in
  - Total with T = 1.18-in

Estimated Short-Term Shortening (28-days)
- 40% of long-term
- Total without T = 0.26-in
  - Total with T = 0.46-in
4.1.1 – Pour Strips

The separation allows each region to independently undergo its shortening. After a time period ranging anywhere from 14 to 60 days, the gap between the two post-tensioned slab regions (the pour strip) is closed by placing non-shrink concrete.

Time to casting of pour strip
The time necessary to keep a pour strip open is determined by the extent of shortening deemed necessary before the two slab regions are tied together. Many practicing engineers use 0.25 in. (6 mm) as the hypothetical displacement which can be accommodated in a post-tensioned structure without significant impairment to its serviceability. For example, the casting of the pour strip concrete should be placed at a time when the remaining calculated displacement of the slabs at each side of the pour strip is 0.25 in. (6 mm). Obviously, once the two slab regions are tied through the pour strip, the deferred displacement cannot take place. It is recognized that this is an empirical procedure backed by the satisfactory performance of pour strips in place. Section 3.2.1 discusses a simple method for estimating the closing time of a pour strip and Section 6 presents a detailed approach.
VOLUME CHANGE – PTI DC20.2-22

- 28-Days - 40%
- 120-Days - 70%

Diagram showing percentage of final shrinkage and creep shortening over time.
RESTRAINT TO SHORTENING (RTS)

- Stiff elements
- Building geometry

It gets complicated!
RESHORES – ACI 347
• Shores placed snugly under a stripped concrete slab or other structural member after the original forms and shores have been removed from a full bay, requiring the new slab or structural member to deflect and support its own weight and existing construction loads to be applied before installation of reshores.

BACKSHORES – ACI 347
• Shores left in place or shores placed snugly under a concrete slab or structural member after the original formwork and shores have been removed from a small area, without allowing the entire slab or member to deflect or support its self-weight and construction loads.
RESHORING VS. BACKSHORING

VS.
RESHORING VS. BACKSHORING
LOCATION MATTERS

Inflection Point

OR

Mid-Span
4.1.1 – Pour Strips: Location

Location within a span and shoring
Between two adjacent supports, for regular conditions, the preferred location of a pour strip within a span is at midspan. For long spans, an alternate approach is to place the pour strip at the quarter span where the moments are typically small. It is important to carefully review predicted deflection at the end of the two cantilevers at the time the closure will be poured to ensure the closure is level and flat. The cumulative shoring requirements at all pour strip bays should be carefully reviewed. Other considerations, however, may dictate the location of the pour strip.
• Low bending moment
• High shear
• Tendons at mid depth
• PT/rebar most economical
• Not self-supporting
• Cannot be fully released
• Requires backshores
• Short cantilever lifts up
INFLECTION POINT
INFLECTION POINT

BACKSHORES – ACI 347

• Shores left in place or shores placed snugly under a concrete slab or structural member after the original formwork and shores have been removed from a small area, without allowing the entire slab or member to deflect or support its self-weight and construction loads.
MID-SPAN — NOT SELF-SUPPORTING

- High bending moment
- Low shear
- Tendons at bottom
- PT/rebar less economical
- Slabs cannot self-support
- Cannot be fully released
- Requires backshores
MID-SPAN – NOT SELF-SUPPORTING

BACKSHORES – ACI 347

- Shores left in place or shores placed snugly under a concrete slab or structural member after the original formwork and shores have been removed from a small area, without allowing the entire slab or member to deflect or support its self-weight and construction loads.
MID-SPAN – SELF-SUPPORTING

- High bending moment
- Low shear
- Tendons at bottom
- Added PT – higher stress
- PT/rebar least economical
- Slabs can self-support
- Slabs can be fully released
- No backshores
MID-SPAN – SELF-SUPPORTING

RESHORES – ACI 347

- Shores placed snugly under a stripped concrete slab or other structural member after the original forms and shores have been removed from a full bay, requiring the new slab or structural member to deflect and support its own weight and existing construction loads to be applied before installation of reshores.
SLAB-TO-SLAB CONNECTORS

Embedded Release Devices (PTI DC20.2-22)

- Concrete anchors
- Mechanical splices - PS=Ø®
POUR STRIP LAP SPLICE

- ACI-permitted splice
- Meets ACI integrity
- Shear friction
- Continuous rebar

- Yielding
- Ductility
- Fixed
- Fire rated
CONCRETE ANCHORS
CONCRETE ANCHORS

- Met local shear
- Did not meet local moment
- Did not transfer forces like a lap splice
- Did not meet ACI integrity
- Rebar not continuous
- Permanent hinge – expansion joint
- Required redesign of the slab and lateral system
- Uses epoxy grout – No fire rating
- Not ICC-approved
- Not an ACI-permitted splice
- Needed additional confinement steel
• Not ACI-permitted splice
• Does not meet ACI integrity
• No shear friction
• No continuous rebar
• No yielding
• No ductility
• Hinge
• Not fire rated

VS.

• ACI-permitted splice
• Meets ACI integrity
• Shear friction
• Continuous rebar
• Yielding
• Ductility
• Fixed
• Fire rated
CONCRETE ANCHORS – COULD THEY WORK?

- Non seismic
- Non high wind
- Don’t need ACI integrity
- Don’t need ICC
- Don’t need continuous rebar
- Don’t need yielding
- Don’t need ductility

- Hinge – OK
- Don’t need tension like rebar splice
- Two separate lateral systems
- Cantilever column
- Shear only
- Don’t need a fire rating
  - See PTI DC20.2-22, 4.4 – Embedded Release Devices
4. **Lockable Dowels**

Dan Mullins provided a short presentation on the practical code implications of using “lockable dowels” for pour strips. Dan made the argument that although lockable dowels may meet localized shear and moment force transfer requirements, they do not meet continuity requirements. The committee agreed with Dan’s assessment, and the committee indicated that this topic should be considered for new business in the next code cycle.
**structural integrity**—ability of a structure through strength, redundancy, ductility, and detailing of reinforcement to redistribute stresses and maintain overall stability if localized damage or significant overstress occurs.

<table>
<thead>
<tr>
<th>Table 4.10.2.1—Minimum requirements for structural integrity</th>
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<tr>
<td><strong>Member type</strong></td>
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<tr>
<td>Nonprestressed one-way cast-in-place slabs</td>
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<tr>
<td>Nonprestressed two-way slabs</td>
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<tr>
<td>Prestressed two-way slabs</td>
</tr>
<tr>
<td>Nonprestressed two-way joist systems</td>
</tr>
<tr>
<td>Cast-in-place beam</td>
</tr>
<tr>
<td>Nonprestressed one-way joist system</td>
</tr>
<tr>
<td>Precast joints and connections</td>
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</table>
12.7.3.1 Except for slabs-on-ground, diaphragms that are part of floor or roof construction shall satisfy reinforcement detailing of one-way slabs in accordance with 7.7 or two-way slabs in accordance with 8.7, as applicable.

12.7.1.3 Splices of deformed reinforcement shall be in accordance with 25.5.
SPLICES – WHAT DOES ACI PERMIT?

• Lap splice
• End-bearing splice
• Mechanical splice
• Welded splice
ACI 318-19: MECHANICAL SPLICES

18.2.7.1 Mechanical splices shall be classified as (a) or (b):
(a) Type 1 – Mechanical splice conforming to 25.5.7
(b) Type 2 – Mechanical splice conforming to 25.5.7 and capable of developing the specified tensile strength of the spliced bars

25.5.7.1 A mechanical or welded splice shall develop in tension or compression, as required, at least $1.25f_y$ of the bar.

R25.5.7.1 To ensure sufficient strength in splices so that yielding can be achieved in a member and thus brittle failure avoided, the 25 percent increase above the specified yield strength was selected as both an adequate minimum for safety and a practicable maximum for economy.
MECHANICAL SPLICES

- Coupler for Thread-Deformed Bar
- Upset Straight Thread Coupler
- Non-Upset Straight Thread Coupler
- Cold-Swaged Threaded Coupler
- Taper-Threaded Coupler
- Straight Threaded Coupler with Upset Rebar Ends
- Grout-Filled Coupling Sleeve
- Combo Grout-Filled/Threaded Sleeve
- Steel-Filled Coupling Sleeve
- Cold-Swaged Coupling Sleeve
- Shear Screw Coupling Sleeve
- Extruded Coupling Sleeve
- Coupling Sleeve with Double Wedge
- Coupling Sleeve with Shear Bolt/Wedge
- Dowel Bar Mechanical Splice
- Compression-Only Mechanical Splices
Eliminates pour strips, wall leave-outs, and expansion joints while maintaining structural integrity and allowing for volume change. Using proven coupler technologies recognized worldwide, featuring a thread on one end and a grout-filled sleeve on the other. The system is an ACI 318 code compliant full-tension mechanical Type 1 and Type 2 rebar splice, is ICC approved and made in the USA.
Low bending moment
High shear
Tendons at mid-depth
PT, rebar most economical
Self-supporting
No Backshoring
PS=$\varnothing$ at mid-depth
**Shear Capacity Based on Concrete Break Out**

**ACI 318-19 Chapter 17**

**Case 1**
- Anchor is at Mid-Depth
  - Slab thickness, t = 10.38 in
  - Concrete strength, f'c = 3,000 psi
  - Rebar size, d_r = 7 in
  - Rebar diameter, d_r = 0.875 in

  
\[
\begin{align*}
V_{slab} &= \left( \frac{f'c}{d_r} \right)^{0.5} \sqrt{\frac{2}{3}} \sqrt[3]{\frac{1}{E}} \sqrt{\frac{1}{\rho}} (c_{at}^2) \frac{1}{3} \\
V_{bc} &= 9.0 \sqrt{\frac{f'c}{(c_{at}^2)}} \frac{1}{3}
\end{align*}
\]

**Case 2**
- Slab thickness, t = 10.38 in
- Concrete strength, f'c = 3,000 psi
- Rebar size, d_r = 7 in
- Rebar diameter, d_r = 0.875 in

**Table 1**

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<tr>
<td>(\psi_{w,v} = (1.5 d_r/t_0)^0.5)</td>
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<td>3,294</td>
<td><strong>4,077</strong></td>
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**Reduction factor**
- Edge factor for the slab if 1/2 < d < 1.5 c

**Breakout cracking factor**
- Breakout thickness factor

**\(\phi V_n = 4.077\) lbs**
ShearFrictionDesignMethod

ACI318-19, Sec 22.9

Assumed crack and shear plane

\[ \phi \cdot V_s = \phi \cdot A_s \cdot f_y (\mu \cdot \sin \alpha_t - \cos \alpha_t) \]
[22.9.4.3]

\[ \phi \cdot V_s = \phi \cdot A_s \cdot f_y \]
where \( \alpha_t = 60^\circ \) [22.9.4]

\[ \phi = 0.75 \] [T21.2.1]

Coef. of friction, \( \mu \) Against NOT intentionally roughened surface

\[ \mu = 0.6 \] [T22.9.4.2]

Concrete Type, \( \lambda = \) Normalweight

\[ \lambda = 1 \] [T19.2.4.1]

\[ f_y = 60 \text{ ksi} \]

\[ \alpha_t = 90^\circ \]

\[ A_s = 7 \text{ in}^2 \]

\[ n, \text{ number of bars} = 6 \]

\[ \lambda_{c, s} = 0.6 \text{ ksi} \]

\( \phi \cdot V_s = 16.20 \text{ kips/lb} \)

Total \( \phi \cdot V_s = 16.20 \text{ kips} \)

Shear Plan, Limit Based on Concrete:

\[ f_c = 5000 \text{ psi} \]

\[ t = 11 \text{ in} \]

\[ A_c = t \cdot D \]

\[ A_c = 100 \text{ in}^2 \]

\[ f_y = 60000 \text{ psi} \]

\[ f_c = 0.2 \text{ psi} \]

\[ 
\begin{align*}
\mu &= 1.4 \text{ or } 1.6 \\
\phi &= \mu \cdot f_{y,c} \min (0.2 \cdot f_c, 4000) \text{ AC, 1600 AC} \\
\phi &= 66.5 \text{ kips} \end{align*}
\]

\[ 
\begin{align*}
\phi \cdot V_{s, c} &= 71.26 \text{ kips} \end{align*}
\]

Use \( \phi = 16.20 \text{ kips/lb} \)

Shear friction reinforcement, \( A_s \)
Provide 1/2" chamfer each side of joint

Concrete slab (see structural)

First or second pour

Bulkhead

PS=Ø coupler

See plan for size & spacing

#X continuation bar inserted into PS=Ø coupler before second pour

See plan for rebar size, length, and shape

#X threaded bar

See plan for size, length, and shape
• ACI-permitted splice
• Meets ACI integrity
• Shear friction
• Continuous rebar
• Yielding
• Ductility
• Fixed
• Fire rated

VS.

• ACI-permitted splice
• Meets ACI integrity
• Shear friction
• Continuous rebar
• Yielding
• Ductility
• Fixed
• Fire rated
HOW IT WORKS

1. Slab to Slab
2. Temporary Stressing Strip
3. Slab to Wall
4. Sequencing
5. Expansion Joints
SLAB TO SLAB

SECOND POUR

FIRST POUR

#x X'-X" CONTINUATION BAR INSERTED INTO PS=Ø COUPLER DURING SECOND POUR

SECOND POUR

FIRST POUR

BULKHEAD

PS=Ø COUPLER (MID-DEPTH) @ XX" O.C.

#x X'-X" THREADED BAR

SEE STRUCTURAL DRAWINGS FOR SLAB REINFORCEMENT

INFLECTION POINT
TEMPORARY STRESSING STRIP

SECOND POUR

FIRST POUR

SECOND POUR

THIRD POUR

FIRST POUR

BULKHEAD

SEE STRUCTURAL DRAWINGS FOR SIZE & SPACING

#X x X'-X" CONTINUATION BAR INSERTED INTO PS=Ø COUPLER DURING SECOND POUR

PS=Ø COUPLER (MID-DEPTH) @ XX" O.C.

#X x X'-X" THREADED BAR

INFLECTION POINT
SLAB TO WALL
SEQUENCING

SECOND SEQUENCE

FIRST SEQUENCE

SECOND POUR

FIRST POUR

#X x X"-X" CONTINUATION BAR INSERTED INTO P8xØ COUPLER DURING SECOND POUR

BULKHEAD
P8=Ø COUPLER (MID-DEPTH) @ XX" O.C.

#X x X"-X" THREADED BAR

SEE STRUCTURAL DRAWINGS FOR SLAB REINFORCEMENT

SLAB EQ.
BEAMS: PT and RC

NOTES:
1. APPLY NOX-创E硅酮经典脱模剂在第一和第二层之间。
2. THE PS-Ø RELIEF JOINT TO REMAIN OPEN FOR 28 DAYS (O.R. TO SPECIFY).
3. AFTER THE TIME PERIOD SPECIFIED ABOVE, THE PS-Ø COUPLERS AND JOINT TO BE GROUTED
   WITH BASE MASTERSWELL 88 HIGH PRECISION, NONSHRINK METALLIC AGGREGATE GROUT.
4. SEE PS-Ø MANUFACTURE DATA FOR MORE INFORMATION.

DETAIL - PT O STRESSING STRIP @ POST-TENSION BEAM

DETAIL - POST TENSION BEAM PROFILES w/PS-Ø COUPLERS
WHAT’S OFFERED

- Full tension mechanical splice
  - Type 1 & Type 2
  - #6 (Gr.60)
  - #7 (Gr.60)
  - #8 (Gr.60, Gr.80)
  - Epoxy coated

- Movement
  - Longitudinal
  - Transverse
WHAT’S INCLUDED

• Full package
  • Mechanical coupler
  • Torque wrench
  • Grout tubes with caps
  • Bond breaker
  • Sprayer for bond breaker
  • Non-shrink grout

• Full support
  • Technical
  • Shop drawings
  • On-site assistance
25 ft x 30 ft bays, 8 in. slab, 12 in. walls
PTI DC20.2-22: 7.2 – Model Examples – Model 1

Fully Connected at Final
25 ft x 30 ft bays, 8 in. slab, 12 in. walls
PTI DC20.2-22: 7.2 – Model Examples – Model 2

Fully Connected at 30 days
Fully Connected at Final
30 Days  Final
SALT LAKE CITY HOTEL
PTI DC20.2-22: 4 – CRACK MITIGATION DETAILS

2" CORRUGATED METAL OR PLASTIC SLEEVE, FILL WITH NON-METALLIC, NON-SHRINK, CHLORIDE FREE GROUT AFTER PT-SLAB HAS BEEN STRESSED. DURATION AS DETERMINED BY L.D.P. (3 TO 7 DAYS)

SMOOTH TROWEL FINISH WITH (2) LAYERS OF HORIZONTAL BOND BREAKER

C.I.P. WALL BELOW

CONCRETE WALL

COMPRESSIBLE MATERIAL TO ALLOW HORIZONTAL SLAB MOVEMENT IN ANY DIRECTION

HORIZONTAL BOND BREAKER MATERIAL AT TOP OF ANGLE LEG

SLAB SOFFIT ENDED PLATE

POST-TENSIONED SLAB

WELD AFTER INITIAL SLAB SHORING PERIOD DETERMINED BY L.D.P. (19 TO 56 DAYS)

STEEL SUPPORT ANGLE, PROVIDE CORROSION AND FIRE RESISTANCE AS REQUIRED

WELD TOP AND BOTTOM PRIOR TO FORMWORK INSTALLATION

WALL EMBED PLATE
PTI DC20.2-22: 4 – CRACK MITIGATION DETAILS

- Stay form (by others): Place up against the vertical steel of wall to provide maximum bearing.
- Place P-T anchors right against wood form.
- Slab top & bottom steel; see plan.

- Pour wall as determined by L.D.P. (3 to 7 days) after post-tensioned slab has been stressed.
- Smooth trowel finish with (2) layers of horizontal bond breaker.
- Post-tensioned slab or beam.

- C.I.P. wall
- See struct. for rein.

- Concrete wall
PTI DC20.2-22: 4 – CRACK MITIGATION DETAILS
THE SMITH – BOSTON, MA

- 12-Story two-way PT
- Mid-span not self-supporting
- 45-day leave-out
- 2-Month schedule delay
- $1M liquidated damages

- PS=Ø® last 6 floors
- Savings
  - $160K/floor
  - 2-Months
LEVELS 1-6
LEVELS 7-12
VS.

Cost: $150 - $200/SF

Cost: $130/SF
• Mid-span not self-supporting
• 2-Month schedule delay
• $1M liquidated damages

• 1/5-span self-supporting
• 2-Month schedule saving
• $1M saved
MILL CREEK CITY HALL – MILL CREEK, UT

- 6-Levels two-way PT
- Inflection point
- 56-day leave-out
- Wall releases

- Savings
  - 2-Months
  - $1.2M
  - $200K/floor
• 56-day pour-back
• Backshoring
• 2-Month schedule delay
- 56-day grout-back
- No backshoring
- No schedule delay
PROVIDE 1/2" CHAMFER EACH SIDE OF JOINT

CONCRETE SLAB (SEE STRUCTURAL)

FIRST OR SECOND POUR

FIRST OR SECOND POUR

SLAB

EQ, EQ

t

#X CONTINUATION BAR INSERTED INTO PS=Ø COUPLER BEFORE SECOND POUR
SEE PLAN FOR REBAR SIZE, LENGTH, AND SHAPE

BULKHEAD

PS=Ø COUPLER SEE PLAN FOR SIZE & SPACING

#X THREADED BAR SEE PLAN FOR SIZE, LENGTH, AND SHAPE
HISTORICAL DATA - SAVINGS

Schedule Savings Range
• 2 to 4-Months

Cost Savings Range
• $100k/floor to $350k/floor
INCREASE PRODUCTIVITY
REDUCE COSTS
ACCELERATE CONSTRUCTION
IMPROVE SAFETY
HIGHER QUALITY CONCRETE
Questions?

Jared M. Reigstad, P.E., P.Eng.
Vice President
jmreigstad@pourstrip0.com
651-248-0593