350 MISSION

HIGH PERFORMANCE FLAT PLATE POST-TENSIONED DESIGN WITH INNOVATIVE MULTI-STORY CONSTRUCTION METHODOLOGIES

SOM David Shook

WEBCOR CONCRETE Eric Peterson
FRAMING PLAN
TYPICAL FLOOR

RC Columns

11” Thick PT Flat Plate Slab

Ductile RC Core

60” Wide x 25” Deep Upturned PT Beam
BUILDING SECTIONS THROUGH CORE

RC Columns
42x42 to 26x26

RC Walls
33 in to 24 in

Slabs
PT Roof: 12 in
PT Typical: 11 in
Ground: 16 in
RC Bsmt: 10 in

Mat 10 ft
FRAMING SECTION

TYPICAL FLOOR
FRAMING SECTION
TYPICAL FLOOR
LONG-SPAN FLAT PLATE SLAB DESIGN

350 MISSION
**DESIGN CRITERIA**

**DESIGN LOADS**

Dead Load (DL)
- Post Tensioning (PT)

Superimposed Dead Load (SDL)
- Raised Floor, Ceiling, MEP

Live Loads (LL)
- Occupancy
- Partitions

Design Strength
- Rebar
  - ASTM A615 Gr 60
  - ASTM A706 Gr 60

As Required
- Post Tensioning (PT)

As Required
- Raised Floor, Ceiling, MEP

17 psf
- Live Loads (LL)
  - Occupancy
  - Partitions

50 psf
- Partitions

15 psf
- Partitions

5,000 psi
- Design Strength

Typical
- Rebar
  - ASTM A615 Gr 60
  - ASTM A706 Gr 60

At walls & columns
CONCEPTUAL DESIGN
CONCEPTUAL DESIGN
### DESIGN CRITERIA

#### DEFLECTION LIMITS

**Deflection Span Ratios**
- L/240 (43.5’ span) 2.2”
- L/360 (43.5’ span) 1.5”
- L/480 (43.5’ span) 1.0”

**Partitions Deflection Accommodation** 0.75”
**Curtain Wall Deflection Accommodation** 0.75”
**Level 5 Curtain Wall Deflection Accommodation** 0.375”

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**TABLE 9.5(b) — MAXIMUM PERMISSIBLE COMPUTED DEFLECTIONS**

<table>
<thead>
<tr>
<th>Type of member</th>
<th>Deflection to be considered</th>
<th>Deflection limitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat roofs not supporting or attached to nonstructural elements likely to be damaged by large deflections</td>
<td>Immediate deflection due to live load ( L )</td>
<td>( L/180 )</td>
</tr>
<tr>
<td>Floors not supporting or attached to nonstructural elements likely to be damaged by large deflections</td>
<td>Immediate deflection due to live load ( L )</td>
<td>( L/360 )</td>
</tr>
<tr>
<td>Roof or floor construction supporting or attached to nonstructural elements likely to be damaged by large deflections</td>
<td>That part of the total deflection occurring after attachment of nonstructural elements (sum of the long-term deflection due to all sustained loads and the immediate deflection due to any additional live load)(^1)</td>
<td>( L/480 )</td>
</tr>
<tr>
<td>Roof or floor construction supporting or attached to nonstructural elements not likely to be damaged by large deflections</td>
<td></td>
<td>( L/240 )</td>
</tr>
</tbody>
</table>

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\(^1\)Limit not intended to safeguard against ponding. Ponding should be checked by suitable calculations of deflection, including added deflections due to ponded water, and considering long-term effects of all sustained loads, camber, construction tolerances, and reliability of provisions for drainage.

\(^2\)Long-term deflection shall be determined in accordance with 9.5.2.5 or 9.5.4.3, but may be reduced by amount of deflection calculated to occur before attachment of nonstructural elements. This amount shall be determined on basis of accepted engineering data relating to time-deflection characteristics of members similar to those being considered.

\(^3\)Limit may be exceeded if adequate measures are taken to prevent damage to supported or attached elements.

\(^4\)Limit shall not be greater than tolerance provided for nonstructural elements. Limit may be exceeded if camber is provided so that total deflection minus camber does not exceed limit.
## DESIGN CRITERIA

### ANALYSIS

<table>
<thead>
<tr>
<th>Sustained Loads</th>
<th>1.0 DL + 1.0 PT + 1.0 SDL + 0.2 LL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rupture Strength of Concrete ( f_r )</td>
<td>( 4 \sqrt{f'_c} ) ACI 435 Table 4.1</td>
</tr>
<tr>
<td>( f'_c ) (design, for strength)</td>
<td>5,000 psi</td>
</tr>
<tr>
<td>( f'_c ) (based on testing, for deflection)</td>
<td>7,000 psi</td>
</tr>
<tr>
<td>Walls &amp; columns above/below modeled</td>
<td></td>
</tr>
<tr>
<td>Rigid zones over supports</td>
<td></td>
</tr>
</tbody>
</table>

Method 1: Cracked section analysis with long term multiplier

Long Term Creep Multiplier \( \lambda_t \) | 3.5 | ACI 435 Table 4.1

Method 2: Cracked section analysis with creep and shrinkage effects using variable \( E_c \)

- Creep Coefficient \( C_u \) | 2.35 | ACI 209R-92
- Shrinkage Coefficient \( \varepsilon_{sh} \) | 780 \times 10^{-6} | ACI 209R-92

Design Software – SAFE: Method 1 & 2 (CSI)
Verification Software – ADAPT Floor: Method 1 (ADAPT)
Table 4.1—Multipliers recommended by different authors

<table>
<thead>
<tr>
<th>Source</th>
<th>Modulus of rupture, psi</th>
<th>Immediate</th>
<th>Creep $\lambda_c$</th>
<th>Shrinkage $\lambda_s$</th>
<th>Total $\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sharounis (1984)</td>
<td>$f_{i}^{1/4}$</td>
<td>1.0</td>
<td>28</td>
<td>1.2</td>
<td>5.0</td>
</tr>
<tr>
<td>Branson (1977)</td>
<td>$f_{i}^{1/4}$</td>
<td>1.0</td>
<td>20</td>
<td>1.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Graham and Sauls (1966)</td>
<td>$4 f_{c}^{1/4}$</td>
<td>1.0</td>
<td>20</td>
<td>20</td>
<td>5.0</td>
</tr>
<tr>
<td>ACI Code</td>
<td>$f_{i}^{1/4}$</td>
<td>1.0</td>
<td>20</td>
<td>1.0</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Shrinkage warping deflections can also be determined using the equivalent tension force method outlined in ACI 209R.

The total deflection at any time is obtained by adding immediate deflection due to sustained load, creep deflection due to sustained load, shrinkage warping deflection, and deflection due to the part of the live load that is transient.

Sophisticated finite element models have been developed (ASCE 1982) to account for time-dependent deformations of two-way slabs caused by creep and shrinkage. These models are generally used for research purposes and are considered to be too complex for normal design applications, particularly when the high variability of creep and shrinkage properties is considered.

where restraint stresses are likely to have a significant effect on cracking, for example, large slab areas and stiff lateral restraint elements such as structure walls and columns, it is recommended that a reduced modulus of rupture given by $f_r = 4 \sqrt{f_c}$ psi (0.33 $f_c$, MPa) be used along with a long-term sustained-load multiplier of 2.5.

Values recommended in ACI 209R for ultimate creep and shrinkage coefficients are $C_{u} = 2.35$, and $\varepsilon_{sh,0} = 780 \times 10^{-6}$, respectively at standard conditions as discussed in Chapters 2 and 3. Sharounis (1984) has suggested that at standard conditions the long-term multipliers be modified if the concrete properties are known, and better estimates of ultimate creep, $C_{u}$ and shrinkage, $\varepsilon_{sh,0}$, are available. Thus,
Raised floor and curtain wall installed approximately **90 days** after casting concrete.

Therefore 50% of long-term creep and shrinkage has occurred when curtain wall installed.
SLAB DESIGN
MILD REINFORCEMENT

At Walls
Bottom Reinf: #5@12 (0.23%)
Top Reinf: #7@12 (0.49%)

At Wall Corners
Bottom Reinf: #5@12 (0.23%)
Top Reinf: #9@6 (1.51%)

At Mid-Span
Bottom Reinf: #5@6 (0.47%)
Top Reinf: #5@18 (0.15%)

At Columns
Bottom Reinf: #5@6 (0.47%)
Top Reinf: #5@6 (0.47%)

NO UNIFORM REINFORCEMENT
Mild Quantities: 3.7 psf
SLAB DESIGN
POST-TENSIONING

½" Diameter tendons

Unbonded tendons

Fully encapsulated

Tendons go through concrete walls and columns

PT Quantities: 1.3 psf
600 truck loads of concrete eliminated

5,400 cubic yards of concrete
SLAB DESIGN
ANALYSIS

FRAMING PLAN
REBAR PLAN
PT PLAN
SLAB DESIGN
DEFLECTION

SELF WEIGHT

SUPERIMPOSED DEAD

LIVE LOAD

0.7"

0.5"

0.1"

0.05"

0.3"

0.2"
SLAB DESIGN

DEFLECTION

SELF WEIGHT + PT

SERVICE LOADS (ELASTIC)

SERVICE (CRACKED)
SLAB DESIGN
DEFLECTION

TOTAL LONG TERM SERVICE – METHOD 1
\[ \lambda_t = 3.5 \ (2.5+1) \]
\[ f_r = \sqrt{4f'c} \]

TOTAL LONG TERM SERVICE – METHOD 2
\[ C_u = 2.35 \ & \ \epsilon_{sh} = 780 \times 10^{-6} \]
\[ f_r = \sqrt{4f'c} \]
SLAB DESIGN
DEFLECTION

AFTER NSC WITH LIVE – METHOD 1
\[ \lambda_t = 3.5 \ (2.5+1) \]
\[ f_r = \sqrt{4f'c} \]

AFTER NSC WITH LIVE – METHOD 2
\[ C_u = 2.35 \ & \ \epsilon_{sh} = 780 \times 10^{-6} \]
\[ f_r = \sqrt{4f'c} \]
CAMBER DESIGN
SHORING CONSIDERATIONS

350 MISSION – SAN FRANCISCO
SKIDMORE, OWINGS & MERRILL LLP + WEBCOR CONCRETE
CAMBER DESIGN
SHORING CONSIDERATIONS
SHORING SYSTEM
METHOD OF GRADING

STEPS REQUIRED TO OBTAIN SOFFIT PROFILE

Measure deflection of lowest reshored level during placement
Measure shortening of formwork system during placement
Interpolate values based upon shore location relative to supports
Add deflection + formwork shortening to specified camber values
As-build deck soffit formwork elevations prior to placement
PLACE AND FINISH STRATEGY

- Strike-off was perpendicular to primary camber direction on long runs
- 10-ft increments to minimize effect of corded profile
- Verify screed elevations after deck is loaded / before strike-off
- No pans used for finishing
TOLERANCES
TIGHT CONTROL

Tolerance Requirements:

Deviation from elevation
ACI 117-10       +/- 3/4"
350 Mission       +1/4", -1/8"

Deviation of Cross Thickness
ACI 117-10       - 1/4", no + limit
350 Mission       -1/8 in., +1/2 in.
Hand set Pro-Shore
Day 3 – Tendons stressed and shores installed for next floor
Day 30 – Reshores out, mechanical equipment staging
Day 60 – Curtain wall staging
Day 90 – Mostly free of staging
PLACEMENT TOLERANCES AND DEFLECTION PERFORMANCE
AS-BUILT SURVEY
Survey Program
1. Formwork survey prior to pouring (-1 day)
2. Prior stressing of tendons (0-1 day)
3. After removal of all shore (≈28 days)
4. After 60 days (4 floors)
5. After 90 days (4 floors)

All floor surveyed at intervals 1, 2 & 3. First 4 floors poured received 60 & 90 day surveys.

Purpose of survey was to verify placement and monitor slab deflections for potential impacts on finish installation.
Survey immediately after casting

No. Cambered Pt Surveys: 8 pts x 22 floors = 176
No. Non-Cambered Pt Surveys: 24 pts x 22 floors = 528
Total = 704
### Survey Program

#### Placement Accuracy

**Non-Cambered Locations**

<table>
<thead>
<tr>
<th></th>
<th>If Placed High (in)</th>
<th>If Placed Low (in)</th>
<th>All Conditions (abs, in)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Avg</strong></td>
<td>0.27</td>
<td>-0.09</td>
<td>0.23</td>
</tr>
<tr>
<td><strong>Std Dev</strong></td>
<td>0.15</td>
<td>0.12</td>
<td>0.16</td>
</tr>
<tr>
<td><strong>Max</strong></td>
<td>1.12</td>
<td>-0.96</td>
<td>1.12</td>
</tr>
</tbody>
</table>

**1” and 1.5” Cambered Locations**

<table>
<thead>
<tr>
<th></th>
<th>If Placed High (in)</th>
<th>If Placed Low (in)</th>
<th>All Conditions (abs, in)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Avg</strong></td>
<td>0.22</td>
<td>-0.21</td>
<td>0.22</td>
</tr>
<tr>
<td><strong>Std Dev</strong></td>
<td>0.18</td>
<td>0.17</td>
<td>0.18</td>
</tr>
<tr>
<td><strong>Max</strong></td>
<td>1.06</td>
<td>-0.80</td>
<td>1.06</td>
</tr>
</tbody>
</table>

Survey immediately after casting

No. Cambered Pt Surveys: 8 pts x 22 floors = 176
No. Non-Cambered Pt Surveys: 24 pts x 22 floors = 528
Total = 704
### SURVEY PROGRAM

#### DEFLECTION FROM PLACEMENT

**Non-Cambered Locations**

<table>
<thead>
<tr>
<th></th>
<th>28 Days (in)</th>
<th>60 Days (in)</th>
<th>90 Days (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg</td>
<td>0.14</td>
<td>0.2</td>
<td>0.16</td>
</tr>
<tr>
<td>Std Dev</td>
<td>0.14</td>
<td>0.13</td>
<td>0.09</td>
</tr>
<tr>
<td>Max</td>
<td>1.2</td>
<td>0.6</td>
<td>0.36</td>
</tr>
</tbody>
</table>

**1” Cambered Locations**

<table>
<thead>
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<th>60 Days (in)</th>
<th>90 Days (in)</th>
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<tbody>
<tr>
<td>Avg</td>
<td>0.53</td>
<td>0.64</td>
<td>0.45</td>
</tr>
<tr>
<td>Std Dev</td>
<td>0.27</td>
<td>0.33</td>
<td>0.15</td>
</tr>
<tr>
<td>Max</td>
<td>1.68</td>
<td>1.44</td>
<td>0.72</td>
</tr>
</tbody>
</table>

Survey at 28, 60 & 90 days after casting

No. 28-day Pt Surveys: 24 pts x 22 floors = 528
No. 60-day Pt Surveys: 24 pts x 4 floors = 96
No. 90-day Pt Surveys: 24 pts x 4 floors = 96
Total = 720
SURVEY PROGRAM
DEFLECTION FROM PLACEMENT

- Non-Cambered Locations

<table>
<thead>
<tr>
<th></th>
<th>28 Days</th>
<th>60 Days</th>
<th>90 Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>(in)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avg</td>
<td>0.14</td>
<td>0.2</td>
<td>0.16</td>
</tr>
<tr>
<td>Std Dev</td>
<td>0.14</td>
<td>0.13</td>
<td>0.09</td>
</tr>
<tr>
<td>Max</td>
<td>1.2</td>
<td>0.6</td>
<td>0.36</td>
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- 1” Cambered Locations

<table>
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<th>90 Days</th>
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<tr>
<td>Std Dev</td>
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<td>0.33</td>
<td>0.15</td>
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<tr>
<td>Max</td>
<td>1.68</td>
<td>1.44</td>
<td>0.72</td>
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Survey at 28, 60 & 90 days after casting
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No. 60-day Pt Surveys: 24 pts x 4 floors  = 96
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Total           = 720
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No. 90-day Pt Surveys: 24 pts x 4 floors = 96
Total = 720
**SURVEY PROGRAM**

**DIFFERENCE FROM TARGET**

### Non-Cambered Locations

<table>
<thead>
<tr>
<th></th>
<th>As-Cast</th>
<th>28 Days</th>
<th>60 Days</th>
<th>90 Days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(in)</td>
<td>(in)</td>
<td>(in)</td>
<td>(in)</td>
</tr>
<tr>
<td><strong>Avg</strong></td>
<td>0.23</td>
<td>0.25</td>
<td>0.28</td>
<td>0.34</td>
</tr>
<tr>
<td><strong>Std Dev</strong></td>
<td>0.16</td>
<td>0.18</td>
<td>0.21</td>
<td>0.23</td>
</tr>
<tr>
<td><strong>Max</strong></td>
<td>1.12</td>
<td>1.04</td>
<td>1.2</td>
<td>0.96</td>
</tr>
</tbody>
</table>

### 1" Cambered Locations

<table>
<thead>
<tr>
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<th>As-Cast</th>
<th>28 Days</th>
<th>60 Days</th>
<th>90 Days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(in)</td>
<td>(in)</td>
<td>(in)</td>
<td>(in)</td>
</tr>
<tr>
<td><strong>Avg</strong></td>
<td>0.91</td>
<td>0.41</td>
<td>0.24</td>
<td>0.30</td>
</tr>
<tr>
<td><strong>Std Dev</strong></td>
<td>0.28</td>
<td>0.29</td>
<td>0.19</td>
<td>0.20</td>
</tr>
<tr>
<td><strong>Max</strong></td>
<td>1.56</td>
<td>1.20</td>
<td>0.84</td>
<td>0.72</td>
</tr>
</tbody>
</table>

Survey at 28, 60 & 90 days after casting

- No. 28-day Pt Surveys: 24 pts x 22 floors = 528
- No. 60-day Pt Surveys: 24 pts x 4 floors = 96
- No. 90-day Pt Surveys: 24 pts x 4 floors = 96

Total = 720
**SURVEY PROGRAM**

**DIFFERENCE FROM TARGET**

#### 1.5” Cambered Locations

<table>
<thead>
<tr>
<th></th>
<th>As-Cast</th>
<th>28 Days</th>
<th>60 Days</th>
<th>90 Days</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Avg</strong></td>
<td>1.44</td>
<td>0.39</td>
<td>0.48</td>
<td>0.49</td>
</tr>
<tr>
<td><strong>Std Dev</strong></td>
<td>0.24</td>
<td>0.31</td>
<td>0.35</td>
<td>0.31</td>
</tr>
<tr>
<td><strong>Max</strong></td>
<td>1.80</td>
<td>0.88</td>
<td>0.80</td>
<td>0.84</td>
</tr>
</tbody>
</table>

Survey at 28, 60 & 90 days after casting

No. 28-day Pt Surveys: 24 pts x 22 floors = 528
No. 60-day Pt Surveys: 24 pts x 4 floors = 96
No. 90-day Pt Surveys: 24 pts x 4 floors = 96
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