Cracking and Leakage at Reinforced Concrete Pomona Reservoir 5C

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Introduction and Summary

- Concerns about integrity and serviceability
- Exponent inspections and analysis
- Design and construction errors led to inadequate performance
- Structural safety of the tank not significantly impacted
- Heightened repairs and maintenance required
Walls

- Wall concrete quality is good
- Excessive temperature and shrinkage cracking
- Design-reinforcement inadequate to control cracking
- Additional future cracking likely
- Defective construction led to wall patching and build-up
- Continued additional maintenance required:
  - Inspection for new cracks
  - Repair of cracks on interior face of exterior walls
  - Repair of wall patching
Roof

- Roof **concrete quality** is good
- Large cracks found
- Excessive temperature and **shrinkage** cracking
- Design-reinforcement inadequate to control cracking
- Additional future cracking likely
- Heightened inspection and maintenance required
**Floor**

- **Initial repairs complete**
  - Repairs require monitoring
  - Repair of new cracks required
- **Seepage from underdrain ~520 gal/day**
  - Loss rate is relatively low
  - More accurate test, if desired
Recommendations

- **Repair of roof and wall cracking:**
  - Use Exponent outlined approach (February 2007 report):
    - Estimated material cost for **walls** $\sim$312,000
    - Estimated material cost for **roof** $\sim$720,000
    - Prices DO NOT include design, planning, contracting, and supervision
  - Continue repairs with current method
    - Develop inspection and repair protocol
    - Heightened inspection and repair frequency
    - Repairs of concrete patch material

- **Repair of tank floor cracking:**
  - During periodic tank emptying perform tank floor inspection for crack repair failures and for new cracks
  - Repaired cracks with filler failure are to be re-patched
  - New cracks to be routed and repaired
Conclusions

- Defective design and construction:
  - Led to inadequate performance
  - Did not significantly impact structural safety
- Heightened repairs and vigilant maintenance required to maintain intended useful life of the tank
- Future repairs methodology based on existing scheme or based on Exponent’s outline
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End
Tank Description

- Approximately 10MG reinforced concrete reservoir
- Designed and constructed in 2002-2003
- 305 ft long x 207 ft wide
- Exterior walls 3 ft thick; interior walls 2 ft thick
- Roof slab 9 in thick
- Bottom slab 7 in thick
Concrete Design Specifications

- Water-cement ratio: 0.45
- Minimum 3500 psi compressive strength at 28 days
- Maximum slump 4 inch
Defects

Photos taken November 17, 2006
Defects

- Roof cracking

Photos taken November 17, 2006
Exponent Evaluation

- Wall and roof exterior inspection  
  November 17, 2006
- Coring of the exterior walls  
  December 5, 2006
- Laboratory and numerical studies
- Exponent report  
  February, 2007
- Interior and exterior roof inspection  
  November 8, 9, 2007
- Tank interior inspection  
  December 5, 2007
- Interior inspection and roof supplemental report  
  January, 2008
Exterior Wall Concrete Evaluation

- Petrographic analysis
  - Properly consolidated and cured
  - Excellent strength
  - Low water-cement ratio
  - Depth of carbonation minor to moderate
  - No deleterious reactions
  - Very few small shrinkage cracks along the exterior surface
Shrinkage, Temperature Analysis

Mechanism of stress development in the wall subject to temperature and shrinkage shortening

The as-designed wall was bound to develop excessively wide cracks to the height of several feet from the ground
Consequences of Excessive Cracking

- Ongoing leakage
- Corrosion of reinforcement
- Long-term integrity and serviceability affected
- Elevated inspection and maintenance needed
Exterior Wall Reinforcement

 foundation 19'-8" x 3'-3" BxH

wall 3'-0" x 23' TxH

reinforcement
#7 @ 12" each side
Exterior Wall Reinforcement Requirements

- Crack spacing and width control is accomplished through reinforcement ratio and control joints
- Wall control joints spaced at about 37 feet
- Wall horizontal reinforcement ratio of 0.28%
- Minimum horizontal reinforcement ratio of 0.4% per ACI 350R.01 Table 7.12.2.1
- Where crack tightness is critical ACI 224R-01 recommends reinforcement ratio of minimum 0.6%
- Restraint requires additional reinforcement (ACI 350-06)
Interior Wall Repairs

- Walls repaired in the interior through patch-material
- The patches are failing
- Restoration to original repair condition is needed
Roof Concrete Evaluation

- Petrographic analysis:
  - Concrete properly consolidated and cured
  - Excellent overall strength properties
  - Portland cement sufficiently hydrated
  - Depth of concrete carbonation:
    - exterior is moderate
    - interior is minor
    - Large crack contained some fractured aggregate

- Concrete compressive strength:
  6,210 psi and 6,590 psi (design 3,500 psi)
Roof Exterior

- Large cracks (~1/32 inch) observed on roof
- Cracks are thru-thickness

Cracking pattern observed for roof exterior -northwest corner of tank-
Roof Exterior

Core #4
Roof Interior

- Minor hairline cracking in locations of large positive bending
- Corrosion product visible in some locations
Roof Interior
Slab on Ground

- Typical cracking running north-to-south
- Locations of previously repaired cracks
- Un-repaired cracks are also visible
- Cracking at surface extends through depth of slab

Typical cracking pattern observed for tank floor - northeast corner of tank-
Tank Floor

- Previous repairs
Tank Floor

- Unfinished repairs
Tank Floor

Through thickness crack

Core F1

Tank floor crack – no repairs initiated
Roof Reinforcement

Continuous reinforcement at **contraction joints**

Longitudinal reinforcement ratio provided: 0.0036
Roof Deck Reinforcement Requirements

- Crack spacing and width control is accomplished through reinforcement ratio and control joints
- Roof control joints spaced at about 30 feet
- Roof transverse reinforcement ratio of 0.36%
- Minimum horizontal reinforcement ratio of 0.5% per ACI 350R.01 Table 7.12.2.1
- Restraint requires additional reinforcement (ACI 350-06)
Seepage

- Seepage measured from underdrain (more precise testing recommended)
- ~98 gallons measured in 4.5 hours = 520 gallons/day
- For 10MG tank = 0.005% loss/day
- ACI/AWWA: 0.1% loss/day generally acceptable

ACI 350R indicated that a 0.1 percent leakage rate in any 24-hr period (after absorption and stabilization) would be generally acceptable for a water reservoir. Visible leakage or dampness should not be considered acceptable. The report also indicated that “acceptable leakage volume will vary depending on the specific application.”
Contraction Joints

- Also known as control joint, and classified as a subset of movement joints

6.5.3 — Contraction joints, when used, shall be permitted to be partial or full, depending on the reinforcing detail, and shall include a groove or recess at the surface for the placement of joint sealant.

R6.5.3 — Full contraction joints have all reinforcement stopped at the joint. Partial contraction joints have a portion of the normal reinforcement passing through the joint up to a maximum of 50 percent.

Source: ACI 350-06
ACI 350-06 – Reinforcement With Constraint

- Additional shrinkage constraints require increased reinforcement

7.12.1.2 — Where shrinkage and temperature movements are significantly restrained, the requirements of 8.2.4 and 9.2.3 shall be considered.

R7.12.1.2 — The area of shrinkage and temperature reinforcement required by 7.12 has been satisfactory where shrinkage and temperature movements are permitted to occur. For cases where structural walls or large columns provide significant restraints to shrinkage and temperature movements, it may be necessary to increase the amount of reinforcement normal to the flexural reinforcement in 7.12.1.2 (see __________). Top and bottom reinforcement are both effective in controlling cracks. Control strips during the construction period, which permit initial shrinkage to occur without causing an increase in stresses, are also effective in reducing cracks caused by restraints.

Source: ACI 350-06
Shrinkage Cracking in Fully Restrained Concrete Members

by R. Ian Gilbert

This paper considers the problem of cracking in fully restrained members subjected to direct tension caused by shrinkage. The mechanism of direct tension cracking is discussed, and some popular misconceptions concerning the behavior of restrained members are explored. Paper presents a rational approach for the determination of the number and spacing of cracks and the overall crack width in a member, which is fully restrained and subjected only to a direct tensile force caused by shrinkage. The approach is based on the principles of mechanics and is illustrated by worked examples. Provisions appear well with observed cracking in restrained members. The procedure is said to calculate the quantity of steel required for crack control in a number of practical situations. Given, the results of the investigation are compared with the provisions for shrinkage and temperature requirements in the ACI Building Code (ACI 318-95) and AS 3600 1990.

To connect cracking, shrinkage, crack width and spacing, group deflection, combined concrete, temperature, shrinkage, time, ACI structural members.

In reinforced and partially prestressed concrete structures, cracking is to be expected at service loads. Cracks may be caused by the external loads, or by restraint to shrinkage and temperature variations, or by a variety of other causes. If uncontrolled, cracking may spoil the appearance of a structure or otherwise adversely affect its performance.

Excessive wide cracks in floor systems and walls may often be avoided by the inclusion of strategically placed contraction (or control) joints, thereby removing some of the restraint to shrinkage and temperature movements and reducing the internal tension. When cracking does occur, it is important that crack widths remain acceptable to the client.

400 MPa = 58 ksi

Where the ends of a slab are restrained and the slab is not free to expand or contract, the minimum ratio of reinforcement to gross concrete area in the restrained direction, when the slab is located in a severe exposure condition, is

\[ \rho_{min} = \frac{2.5}{f_p} \]  

Where this crack may be reasonable provided visible cracking can be tolerated.

Concluding Remarks

A rational procedure is presented for the determination of the number and spacing of cracks in fully restrained members subject to direct tension caused by shrinkage. The approach is based on the principles of mechanics and is illustrated by worked examples. Provisions appear well with observed cracking in restrained members. The procedure is said to calculate the quantity of steel required for crack control in a number of practical situations. Given, the results of the investigation are compared with the provisions for shrinkage and temperature requirements in the ACI Building Code (ACI 318-95) and AS 3600 1990.

For a 5-m long and 150-mm thick unrestrained concrete slab with similar material properties to that analyzed in the numerical examples and with \( \rho = 0.0082 (d_0 = 12 \text{ mm}) \), the analysis described in this paper gives the following results immediately after first cracking:

- \( f_{cy} = 400 \text{ MPa} \)
- \( f_c = 25 \text{ MPa} \)
- \( f_{y} = 55 \text{ MPa} \)
- \( A_s = 0.0082 \) (for a 5-m long and 150-mm thick slab)

In a sheltered environment, this size crack may be reasonable provided visible cracking can be tolerated. Where the ends of a slab are restrained and the slab is free to expand or contract, the minimum reinforcement ratio is

\[ \rho_{min} = \frac{0.7 f_y}{f_{cy}} \]
ACI 350-06 – Reinforcement With Constraint

- Additional shrinkage constraints require increased reinforcement

7.12.1.2 — Where shrinkage and temperature movements are significantly restrained, the requirements of 8.2.4 and 9.2.3 shall be considered.

R7.12.1.2 — The area of shrinkage and temperature reinforcement required by 7.12 has been satisfactory where shrinkage and temperature movements are permitted to occur. For cases where structural walls or large columns provide significant restraints to shrinkage and temperature movements, it may be necessary to increase the amount of reinforcement normal to the flexural reinforcement in 7.12.1.2 (see top and bottom reinforcement are both effective in controlling cracks. Control strips during the construction period, which permit initial shrinkage to occur without causing an increase in stresses, are also effective in reducing cracks caused by restraints.

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In reinforced and partially prestressed concrete structures, cracking is to be expected at service loads. Cracks may be caused by the external loads, or by restraint to shrinkage and temperature variations, or by a variety of other causes. If uncontrolled, cracking may spoil the appearance of a structure or otherwise adversely affect its performance.

Extensively wide cracks in floor systems and walls may often be avoided by the inclusion of strategically placed contraction (or control) joints, thereby removing some of the restraint to shrinkage and temperature movements and reducing the internal tension. When cracking does occur, to assure that crack widths remain acceptable, a reduction in the design loads and in the reinforcement ratio may be required in the affected area.

400 MPa = 58 ksi

Where the ends of a slab are restrained and the slab is not free to expand or contract, the minimum ratio of reinforcement to gross concrete area in the restrained direction, when the slab is located in a severe exposure condition, is

\[
\rho_{min} = \frac{2.5}{f_p} \quad (36)
\]

In a sheltered environment, this size crack may be reasonable provided visible cracking can be tolerated.

Where the ends of a slab are unrestrained and the slab is free to expand or contract, the minimum reinforcement ratio is

\[
\rho_{min} = \frac{0.7 f_s}{f_p} \quad (37)
\]

This slab area is recommended for example, in slabs-on-ground with control joints at regular centers and is similar to the minimum provisions in ACI 318M-89.

CONCLUDING REMARKS

A tentative procedure is proposed for the determination of shrinkage stresses in both the concrete and reinforcement in a restrained member.
Shrinkage of Concrete

- Concrete is subject to shrinkage
- Caused by loss of moisture
- Decrease in volume
- Restraints inhibit movement inducing tensile stresses in concrete
- Cracking when concrete tensile capacity is exceeded
- Cracking is controlled with proper amount of reinforcement

Roof slab cracking

Floor slab cracking
## ACI 350-06 – Minimum Reinforcement

### TABLE 7.12.2.1—MINIMUM SHRINKAGE AND TEMPERATURE REINFORCEMENT

<table>
<thead>
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<th>Length between movement joints, ft</th>
<th>Minimum shrinkage and temperature reinforcement ratio</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Grade 40</td>
</tr>
<tr>
<td>Less than 20</td>
<td>0.0030</td>
</tr>
<tr>
<td>20 to less than 30</td>
<td>0.0040</td>
</tr>
<tr>
<td>30 to less than 40</td>
<td>0.0050</td>
</tr>
<tr>
<td>*</td>
<td>0.0060*</td>
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</tbody>
</table>

*Maximum shrinkage and temperature reinforcement where movement joints are not provided.

Note: This table applies to spacing between expansion joints and full contraction joints. When used with partial contraction joints, the minimum reinforcement ratio shall be determined by multiplying the actual length between partial contraction joints by 1.5.
The minimum-reinforcement percentage, which is between 0.18 and 0.20%, does not normally control cracks to within generally acceptable design limits. To control cracks to a more acceptable level, the percentage requirement needs to exceed about 0.60%.