Control of Concrete Cracking for Liquid-Tight Environmental Structures

Q. *Knowing that reinforced concrete will crack, how do I attain reasonable assurance that the walls of my environmental structure will be essentially liquid-tight?*

A. The current ACI 350-06[1] code provides minimum requirements for structural design, material selection, and construction of environmental engineering concrete structures. It is generally presumed that tank structures designed and constructed in accordance with ACI 350 will be liquid-tight. However, even in code-compliant structures, it is not uncommon for wider-than-expected vertical wall cracks to occur as a result of restrained concrete shrinkage and temperature (S&T) volume change. If these cracks leak, contractors are often expected to accept responsibility for repairing them.

The introduction to ACI 350-06 states that "…liquid-tightness of a structure will be reasonably assured if:
(a) The concrete mixture is well proportioned, well consolidated without segregation, and properly cured.
(b) Crack widths and depths are minimized.
(c) Joints are properly spaced, sized, designed, water-stopped, and constructed.
(d) Adequate reinforcing steel is provided, properly detailed, fabricated, and placed.
(e) Impervious protective coatings or barriers are used where required."

The ACI 350 Code provides minimum S&T reinforcement requirements based on joint spacing in walls of tanks (Table 1). However, no other specific provisions or guidance are provided in ACI 350 for mitigating the effects of expected volume change movements. The specified minimum reinforcement ratio (that is, ratio of steel area to gross concrete section area) is expressed as a function of distance between movement joints (expansion joints or full contraction joints). According to ACI 350 Commentary Section R7.12.1.2, the specified minimum S&T reinforcement quantities have been shown to be satisfactory where S&T movements are permitted to occur (that is, movements are not significantly restrained). However, many designers fail to recognize that walls of reinforced concrete liquid-containing structures include features that impose significant restraint to in-plane S&T movements.

ACI 350 Commentary Section R7.12.1.2 also alerts designers that the amount of S&T reinforcement might need to be increased above minimum quantities in situations where movements are significantly restrained. However, "significant restraint" is not defined. Furthermore, a footnote to Table 7.12.2.1 (refer to the note at the bottom of Table 1) indicates that the minimum reinforcement required for walls with movement joint spacing of 40 ft (12 m) and greater (0.6 and 0.5%, respectively, for Grade 40 and Grade 60 reinforcement) will also suffice for the condition where no movement joints are provided. This stipulation, combined with other statements contained in the Commentary, has led many designers to conclude that if 0.6 or 0.5% reinforcement is provided, no

Table 1:
Minimum shrinkage and temperature (S&T) reinforcement ratios per ACI 350-06, Table 7.12.2.1[1]

Length between movement joints, ft	Minimum S&T reinforcement ratio	
	Grade 40	Grade 60
Less than 20	0.0030	0.0030
20 to less than 30	0.0040	0.0030
30 to less than 40	0.0050	0.0040
40 and greater	0.0060*	0.0050*

*Maximum S&T reinforcement where movement joints are not provided.
Note: 1 ft = 0.3 m

further evaluation of movement restraint is required.

It is also noteworthy that some authors have concluded that the minimum S&T reinforcement provisions cited in ACI 350-06 and earlier editions of ACI 350 may not be adequate to achieve a leak-tight structure.[2-4] According to Hanskat,[2] when designing liquid-containing structure without movement joints, much higher reinforcement ratios (0.7 to 0.8% or more) may be required, depending on concrete shrinkage properties, structure geometry, and external restraint conditions. Kianoush et al.[3,4] determined that a reinforcement ratio of about 0.7 to 0.8% would be required to keep crack widths within acceptable limits in base-restrained walls with movement joint spacing of 40 ft or greater.

Although increasing the amount of horizontal S&T reinforcement may seem like the most direct and logical approach to achieving crack control, there could be a point of diminishing returns when using this tactic, as increasing the amount of horizontal S&T reinforcement could lead to the use of larger-diameter bars. For example, a reinforcement ratio of 0.8% in a 24 in. (610 mm) thick wall translates to a required steel area of 2.3 in.^{2}/ft (4868 mm^2/m). This required steel area equates to either No. 4 bars at 2 in. (51 mm), No. 5 bars at 3 in. (76 mm), No. 6 bars at 4 in. (102 mm), or No. 7 bars at 6 in. (152 mm) near each wall face. Some designers may be compelled to specify larger bars to minimize labor costs and reduce the potential for honeycombing due to congestion.

It is noteworthy that ACI 350-06 does not impose a limit on bar size used for S&T reinforcement, although reports previously published by ACI Committee 350 (for example, ACI 350R-89[5]) have recommended the use of small bar sizes to keep crack widths small. This has long been an accepted practice. As shown by Vetter,[6] for example, crack widths are kept small by making the distance between cracks small. Because crack spacing is inversely related to the bond between the concrete and steel, crack control generally improves as the ratio of bar perimeter to bar area increases. Smaller bars will provide a greater perimeter-to-bar area ratio than larger bars for any given total steel area requirement. Use of smaller bars for wall S&T reinforcement also offers the benefit of allowing the layers of horizontal S&T steel to be positioned closest to the surface without significantly compromising the effective depth of the vertical bars needed for flexural capacity.

Through-wall cracks in liquid-containing structures that exceed a width of about 0.004 in. (0.10 mm) will generally leak.[2,3] Fine concrete cracks have the unique ability to close through autogenous healing in the constant presence of moisture.[7] However, the likelihood and rate of healing depends on several factors, including the concrete characteristics, age of crack opening, initial effective crack width, chemical composition of the water, and water pressure. Unfortunately, contractors tasked with building liquid-tight environmental engineering structures will rarely have enough float in their schedules to attempt to resolve tank leakage issues through reliance on crack healing.

In summary, it is important to recognize that simply complying with the minimum requirements of ACI 350 will not necessarily result in a liquid-tight environmental structure. In some cases, it may be necessary to use a multi-faceted approach that includes:

- Consideration of quantity, placement, bar size, and distribution of S&T reinforcement;
- Consideration of construction sequencing and jointing practices; and
- Use of concrete mixtures with low shrinkage potential.

Owners should make their expectations related to leak-tightness known to the licensed design professional. Engineers need to develop contract documents that address both code compliance and serviceability expectations. Engineers also need to recognize that they are in the best position to determine what is necessary to achieve a leak-tight structure, and so they must work closely with contractors to achieve that goal. Where the leak-tightness integrity of a design is uncertain, it may be necessary to specify an impervious coating or barrier.

References

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