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LEAK-TIGHTNESS DESIGN OF NUCLEAR SAFETY RELATED LIQUID-CONTAINING AND BURIED CONCRETE STRUCTURES

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ABSTRACT

Since cracking is inevitable in concrete structures, consequent leakage is often observed in both liquid-containing and underground concrete structures. In the former case, the leakage is primarily due to sustained water load inside the tank which is often readily apparent on the outside walls for above ground tanks. In the latter case, leakage results from ground water infiltration into the building. In both cases, as a minimum, such leakage can cause both serviceability and long-term durability concerns for these structures. In some cases, cracking may also result in serious issue of leakage of radioactive substances. Note that for both these cases, the current nuclear regulation and the industry standards do not specifically address the leak-tightness of these structures. The objective of this paper is to provide a proposal for design of leak-tight nuclear safety related liquid-containing and buried structures by meshing the appropriate provisions of design, leak-tightness and durability of the ACI 350 Code for Concrete Liquid-Containing Structures with those of the ACI 349 Code for Concrete Nuclear Structures.

INTRODUCTION

ACI 349-06, Code Requirements for Nuclear Safety-Related Concrete Structures and Commentary provides the requirements for design and construction of nuclear safety related structures other than containments. This Code currently has no guidance on leak tightness design of nuclear liquid-retaining or buried structures. Section **1.1.10** of this Code indicates that this Code (ACI 349) along with relevant sections of ACI 350 governs design and construction of tanks and reservoirs associated with safety related nuclear structures. Commentary **R1.1.10** further elaborates that ACI 349 Code provision should be applied to the spent fuel pool pit and refueling canal as well as other safety-related tanks. In addition, detailed recommendations given in *"Code Requirements for Environmental Engineering Concrete Structures and Commentary"* reported by ACI Committee 350 should be followed. Note that design of buried structures is not addressed at all.

Note that to prevent leakage and long-term durability concerns due to cracking, concrete liquid-containing structures are designed using ACI 350 Code Requirements for Environmental Engineering Concrete Structures and Commentary.

Partially or fully embedded concrete structures are also subject to leakage due to surrounding groundwater infiltration. There have been several instances of ground water infiltration into buried concrete structures in the United States including, more recently, at the Seabrook power station. The consequences of such leakage can be significant in terms of degradation of the concrete due to corrosion, sulphate attack and the alkali silica reaction (ASR).

NUCLEAR LIQUID-CONTAINING STRUCTURES

Nuclear-safety-related liquid containing concrete structures are extensively used in nuclear power plants. Examples include Spent Fuel Pool (SFP), Refueling Water Storage Tanks (RWST), Refueling Pools (RP) and other tanks / containers inside or outside of containments.

NUREG-0800 Standard Review Plan (SRP) provides guidance for the review of safety analysis reports for nuclear power plants. In practice, regulatory review of nuclear-safety-related liquid containing concrete structures follows NUREG-0800 Section 3.8.3 as “other interior structures” or NUREG-0800 Section 3.8.4 as “other seismic category I structures”, depending on whether the subject structure is located inside or outside of the containment. In both sections, design of concrete structures are acceptable if found to be in accordance with ACI 349 with additional guidance provided by RG 1.142. It is also required per Sections 3.8.3 and 3.8.4 that for structures subjected to hydrodynamic loads, fluid-structure interaction associated with these hydrodynamic loads should be taken into account as indicated in the appendix to NUREG-0800 Section 3.8.1. NUREG-0800 Section 9.1.2 and RG 1.13 also provide additional guidance regarding design new and spent fuel storage facilities. However, no specified guidance is provided in ACI 349 and aforementioned regulatory guides for seismic design of liquid containing concrete structures.

Seismic analysis of liquid storage tanks requires consideration of the hydrodynamic forces exerted by the fluid on the tank wall, as a result of seismic excitation. This effect can be well represented by an equivalent mechanical model. Housner (1963) was the first to propose such a mechanical model for circular and rectangular rigid tanks, which was later improved by Wozniak and Mitchell (1978). Veletsos and Yang (1977) used a different approach to develop a similar type of mechanical model for circular rigid tanks. Subsequently, Haroun and Housner (1981) and Veletsos (1984) developed mechanical models for flexible tanks. The flexible tank model by Veletsos (1984) was further simplified by Malhotra et. al.(2000). Design parameters for cylindrical, spherical and ellipsoidal tanks can be found in various literatures done by Budiansky (1960), Dodge et. al. (1965), Kana (1966), Mccarty et. al. (1960), Mccarty and Stephens (1960), Rattaya (1965), Stofan and Armstead (1962) and Papaspyrou et. al. (2004).

Mechanical models described above are widely used by various design codes for liquid storage tank design. ACI 350.3 (2006) adopts mechanical model by Housner (1963) with modification of Wozniak and Mitchell (1978). The Guideline (Priestley, et. al., 1986) by New Zealand National Society for Earthquake Engineering (NZSEE) use mechanical model of Veletsos and Yang (1977) for rigid tanks and the one by Haroun and Housner (1981) for flexible tanks. Eurocode 8 (1998) suggests the models of Veletsos and Yang (1977) and Housner (1963) for rigid circular and rigid rectangular tanks, respectively. For flexible tanks, the models of Veletsos (1984) and Haroun and Housner (1981) are recommended by Eurocode 8 (1998) along with the procedure of Malhotra et. al. (2000).

As already stated above, seismic analysis of a liquid storage tank should include hydrodynamic forces generated by acceleration of the contained liquid. The pressure associated with these forces can be separated into impulsive and convective parts. The impulsive pressures are associated with inertia forces produced by accelerations of the walls of the container and are directly proportional to these accelerations. The convective pressures are those produced by the oscillations of the fluid. This phenomenal can be well represented by an equivalent mechanical model, in which impulsive part of the liquid is rigidly fastened to the tank walls while the convective part is connected to the tank wall either by springs or as a pendulum. The tank-liquid system using springs as adopted in ACI 350.3 is demonstrated in the figure below.

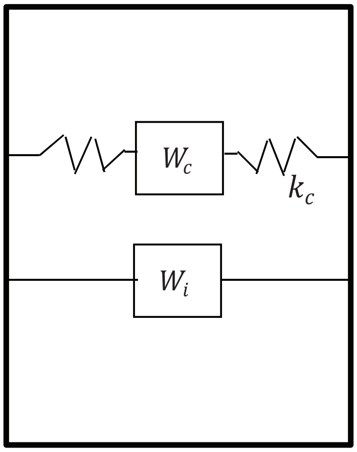

Figure 1. Tank-liquid system using springs

As shown in the figure, the convective fluid mass W_c is connected to the tank by the spring with stiffness k_c, and the impulsive fluid mass W_i is rigidly connected to the tank. W_c, W_i and k_c can be calculated using the suitable approach available in several design codes and literatures as discussed before. Note these parameters depend only on the tank shape, liquid properties and free surface elevation, but not the characters of excitation imposed on the tank. For evaluation of impulsive force, mass of tank wall is generally included along with impulsive mass W_i as a conservative approach. ACI 350.3 and Eurocode 8 suggest a reduction factor to suitably reduce the mass of tank wall.

In order to combine the impulsive and convective forces, Eurocode 8 (1998) recommend use of absolute summation rule while ACI 350.3 suggests SRSS rule.

Although methodology proposed by Housner (1963) has been extensively used in the past for seismic design of nuclear liquid-containing structures, the recent expectation and experience has been to do a detailed fluid-structure interactions using more sophisticated software packages like LS-DYNA. Note that whether it is the simplified Housner model or the detailed FEA, the analysis does not explicitly address expected cracking of concrete which may result from a variety of complex reasons including shrinkage that cannot be included in the analysis.

DESIGN OF LIQUID-CONTAINING CONCRETE STRUCTURES USING ACI 350 CODE

Environmental engineering structures are designed for strength but crack control to prevent leakage and other long-term durability problems remain important serviceability requirements. To accomplish this, this Code has specific requirements for materials (Chapter 3), loading and serviceability (Chapters 9 and 10), durability (Chapter 4) and detailing (Chapter 7) for crack control and leak tightness of liquid-containing structures.

The service design requirement is accomplished by using the environmental durability factor (EDF) on top of the applicable load factors to limit the stresses/strains in reinforcement at the service load level. The use of EDF increases the factor of safety and reduces the strain in tension steel at nominal strength. This is not consistent with the concept of Strength Design Approach (SDA) of concrete. The SDA requires that for flexural tension controlled sections, strain in the tension reinforcement should reach at least 0.005 at nominal strength.

Thus EDF works like a patch in the strength design approach that helps limit the stress levels in the steel for control of cracking, leakage and corrosion. It is worth noting that although a flexural section cannot theoretically develop a full depth crack to cause leakage, limiting of crack width is used as an indirect way of preventing corrosion and ensuring long-term durability. Shrinkage cracks are more dangerous from leakage point of view because they typically run through the thickness. Accordingly, a more stringent crack control criterion is appropriate in this case (Fig. 2).

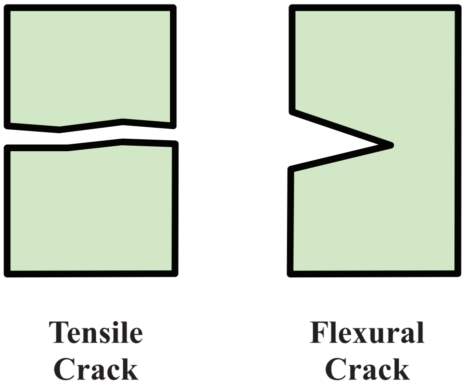

Figure 2. Tensile and Flexural Cracks

The current ACI 350 (Section 9.2.6) indicates that for tension controlled sections, environmental durability factor (Sd > 1) for flexure is to be applied in strength level load combinations. The code indicates that the EDF need not be applied to compression controlled members and load combinations involving seismic loading.

BURIED OR UNDERGROUND CONCRETE STRUCTURES

Partially or fully embedded concrete structures are also subject to leakage due to surrounding groundwater infiltration. The structure is to be designed for the pressures exerted by the soil and groundwater against the embedded walls which can result in out-of-plane flexural cracking which can result in long-term durability issues. Also, even minor shrinkage cracking under high ground water pressures, can cause potential infiltration of groundwater through the walls, into important safety related structures disrupting operations and causing long-term maintenance issue. Although a multi-tiered approach involving well-proportioned concrete mix, adequate reinforcement, adequate spacing and detailing of joints and impervious protective coatings or barriers can be used to help minimize the potential for infiltration, use of several portions of ACI 350 Code should be included in the design to minimize the cracking to begin with and to develop a defense-in-depth against potential infiltration consequences for important safety related structures.

To ensure leak tightness, appropriate design and detailing provisions of ACI 350-06 Code can be used for crack control of embedded concrete walls. The stresses in the reinforcement at service level or operating conditions should be limited to no more than 60% of the yield to keep the cracks tight. In addition, applicable requirements for durability, design and construction of movement joints and minimum reinforcement for shrinkage and temperature control from ACI 350-06 Code should be implemented, where appropriate. Since ACI 350 is an independent stand-alone Code, various sections related to the above-mentioned provisions from Chapters 4 (durability), 7 (details of reinforcement) and 9 and 10 (strength and serviceability) of this Code will be compared to those of ACI 349-06 Code and more stringent of the two applied, as appropriate.

CONSIDERATIONS FOR LEAK TIGHTNESS

The leak tightness of both liquid-containing as well as buried concrete structures can be improved by supplementing/enhancing the design and detailing provisions of ACI 349 with appropriate and relevant provisions of ACI 350 Code that have proven to be successful. The following provides a discussion of these items.

Concrete Mix Design

A dense and durable concrete mix with very low permeability should be the primary focus to keep the groundwater intrusion under control. Low-permeability concrete is obtained by using a lowest possible water-cement ratio that can still result in satisfactory workability and allow good consolidation. The maximum water-cement ratio for embedded walls and the basemat should be limited to 0.4, consistent with ACI 350 Code and applications where concrete is immersed in water. To cover potential water intrusion, adequate considerations should be given to provide protection against ASR (alkali-silica reaction) by selecting appropriate aggregate sources and using appropriate amounts of fly ash, silica fume and/or slag per latest industry recommendations.

Reinforcement Design Methodology

In addition to requirements in ACI-349, the reinforcement design of nuclear safety related liquid-containing and buried concrete structures should include requirements described in ACI-350 (Ref. 1). For information, a comparison of ACI 349 and ACI 350 design philosophy is also demonstrated in Fig. 3.

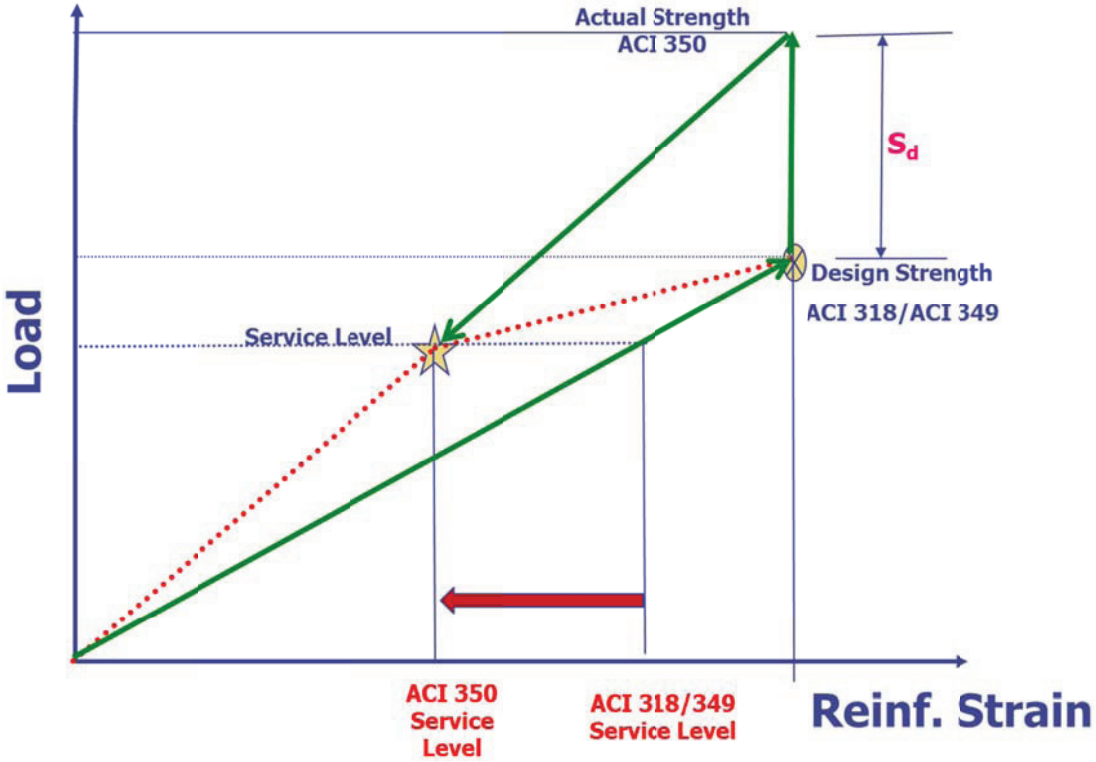

Figure 3. Comparison of ACI 349 and ACI 350 Design Philosophy.

The following provides a discussion of these requirements and applicability to embedded walls.

Loading – The loading and the load combinations in ACI 350 are generally similar to and enveloped by the load combinations of ACI 349. Note that ACI 350 Code was adapted from ACI 318 and has, therefore, all the same loading criteria as in ACI 318. ACI 318 also serves as the base code for ACI 349. Section 9.2.1 of ACI 350 does not carry any loading condition above and beyond ACI 318 or ACI 349 that is aimed at crack control. Therefore, it can be concluded that specific load combinations 9.2.1 of ACI 350 need not be considered in design of nuclear structures as these are deemed to be already included in ACI

349 Code. On the other hand, ACI 349 Code provides a complete set of load combinations that are pertinent to nuclear structures and being a stand-alone Code, must be followed in its entirety to meet the intent of the Code.

Serviceability – Section 9.2.6 of ACI 350 requires that structures that need to be leak-tight be designed for strength larger than that indicated in Section 9.2.1 by a factor of Sd (Eq. 9-8) to ensure that at service load, stresses and strains in steel reinforcement are within limits to control crack widths to prevent leakage and ensure long-term durability. Therefore, Sd factor serves as an overstrength factor that is applied to the required strengths. Note that per Section 21.2.1.8 of ACI 350 Code, this Sd factor is not to be applied to the load combinations involving seismic load effects. Since the design of deeply embedded walls is expected to be controlled by out-of-plane flexure and associated shear due to the height of the retained soil and the water, it is prudent to evaluate them for cracking that may impact long-term durability. Section 10.6.4 of ACI 350 Code requires that stress in flexural steel should be less than values predicted by Eqs. 10-4 and 10-5 but not more than 36 ksi (0.6fy) for Gr. 60 steel at service level to keep the cracks tight. Figures R10.6.4 (a) and (b) show the allowable maximum stresses for normal exposure and thickness of section (less than, or more than 18 in) as a function of reinforcement spacing, with an upper-bound limit of 36 ksi. For embedded walls, with No. 11 bars spaced at 6 in and beta = 1.2 for thickness larger than 18 in, Eq. 10-4 gives maximum allowable stress is 33 ksi for normal exposure condition which is similar to what Fig. R10.6.4 suggests. For this situation Sd factor is approximately 1.0 (per Eq. 9-8) assuming fy of 60 ksi, phi of 0.9, gamma of 1.6 and fs of 33-36 ksi which indicates that no overstrength (additional reinforcement) is required to meet the crack width criteria of ACI 350 Code.

Note that normal environmental exposure is assumed given the fact that walls will be fully embedded with no availability of free oxygen and that these walls may also be protected from outside by a water-proofing liner/barrier. Also, it is possible that design of embedded walls may be controlled by static load combination involving earthpressure and ground water (Load Combination 9-2, ACI 349 and ACI 350) and not necessarily the safe shutdown earthquake (SSE). Note that this load combination 9-2 uses a load factor of 1.6 for earth and water pressure compared to load factor of 1 used for SSE. If that is the case, then by inspection the maximum stresses in reinforcement at service load (for a load factor of 1.0 for H) is expected to be 60/1.6 = 37.5 ksi, if it is assumed that reinforcement will fully yield (60 ksi) at the design load (load combination involving 1.6H). But it is expected that actual demands will be less than the capacity as the demand to capacity (D/C) ratios of less than 1 are generally targeted as part of the design process and strategy for nuclear structures. Therefore, for a maximum D/C of 0.9, the service load stress in reinforcement is expected to be 0.9x60/1.6 = 33.8 ksi which is less than the maximum allowable stress at service load for crack control. Therefore, in this situation the embedded walls are expected to meet the ACI 350 serviceability criteria for flexure. However, the maximum stress in the reinforcement should be checked for critical section of the embedded walls as part of the detailed design process.

The basemats of nuclear structures are generally much thicker (12 – 24 ft thick) and less likely to leak. Besides other load combinations involving seismic effects, the basemat will also be designed for load combination 9-2 with load factor of 1.6H for buoyancy effects, where water table is high enough. Therefore, even if seismic controls the design at ultimate, the basemat will have a strength based on 9-2 under service loads resulting in a factor of at least 1.6 for ratio between the actual strength to service load stress of the reinforcement, as in case of embedded walls. The actual strength will be higher if seismic controls the design which will reduce the stresses/strains at service level load for gravity plus buoyancy effects. Therefore, the allowable stresses for crack control per ACI 350 for basemat would be similar to that for the walls and the corresponding stresses/strains are expected to be less than these limits, as in case of the embedded walls.

If shear reinforcement is required for embedded walls or the basemat per analysis for the load combination involving 1.6H, corresponding Sd factor will be 1.17 assuming the phi factor of 0.75 for shear, fy of 60 ksi, gamma of 1.6 and fs of 24 ksi per Eq. 9-8. This would require approximately 20% more shear reinforcement to keep cracks tight per ACI 350 Code.

Durability – Chapter 4 of ACI 350 Code has either additional or more stringent requirements over and above ACI 318 and ACI 349 Codes which should be included in design and construction of embedded walls and basemat to improve durability.

Table 4.1.2 of ACI 350 has requirements for minimum cementitous content as a function of aggregate size not contained in ACI 349 or ACI 318 Codes. Nuclear plants should adopt this provision of the ACI 350 Code to improve durability of embedded walls and the basemat.

It is recommended that a water-cementitous ratio of 0.4 or less and a compressive strength of 5000 psi per Table 4.2.2 of ACI 350 and ACI 349 be used to reduce permeability of concrete and to protect against potential corrosion assuming the most severe exposure.

To achieve durability consistent with ACI 350 structures supplemental cementitous content requirement given in Table 4.2.3 of ACI 350 which are the same as in ACI 349 Code should be used.

For sulphate resistance, a water-cemetitous ratio of 0.4 and the compressive strength of 5000 psi given in Table 4.3.1 of ACI 350 Code should be used assuming the most severe sulphate exposure condition which is more stringent than ACI 349 Code.

To prevent corrosion, the limit on the chlorides should be per Table 4.4.1 of the ACI 350 Code.

Detailing - To protect the reinforcement, nuclear safety related structures should use the more stringent requirements of the minimum cover requirements of ACI 350 and ACI 349 Codes based on exposure and bar diameter. Based on this, the outer cover for embedded walls and basemat (exposed to soil) should be 3 in while as the cover on inside reinforcement can be 2 in for the main reinforcement. Furthermore, as indicated in the discussion for serviceability, spacing of reinforcement should be kept preferably to 6 in or less to keep the cracks tight. In order to control shrinkage cracks, minimum reinforcement will also be checked per Table 7.12.2.1 of ACI 350 Code based on joint spacing. The minimum reinforcement of 0.5% for joint spacing of 40 ft or more based on 12 in thickness for members larger than 24 in thickness.

CONCLUDING REMARKS

The load combinations of ACI 350 need not be specifically used as these are enveloped by those in ACI 349 Code. Per ACI 350 Code, the maximum allowable stresses at service load for deeply embedded walls and basemat is approximately 36 ksi for leak-tighness and durability. By inspection of the load condition controlling the flexural design of deply embedded walls and the expected demand to capacity ratio (less than 0.9), the maximum stress in the reinforcement under service load is expected to be less than this limit which meets the intent of ACI 350 serviceability requirements. It should also be noted that flexural cracks are not through-thickness cracks as part of the section is in compression. Therefore, leakage is not an issue under flexural loads. If shear reinforcement in required in deeply embedded walls, it should be increased by a factor of 1.2 (or 20% more) to keep the cracks tight. To achieve the durability consistent with ACI 350 Code, provisions of Tables 4.1.2, 4.2.2, 4.2.3, 4.3.1 and 4.4.1 of this Code should be followed to limit the maximum water- cementitous ratio (to 0.4), concrete strength (5000 psi), maximum chloride limit and minimum cementitous content. To achieve reinforcement protection, minimum cover requirements of Section 7.7 of ACI 350 should be used for embedded walls and basemat (3 in on outside and 2 in on inside). The amount and spacing of reinforcement should also meet the minimum shrinkage and temperature reinforcement requirements and crack control of Section 7.12 of ACI 350 Code (0.5% minimum).

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