RESPONSE MODIFICATION FACTORS FOR REINFORCED CONCRETE LIQUID CONTAINING STRUCUTRES

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ABSTRACT :
Reinforced concrete liquid storage tanks have been extensively used as a part of environmental engineering facilities. Since functionality of these structures after an earthquake is very important to meet the emergency state requirements, seismic damage of these structures is of main concern. One of the main parameters used in the seismic design of structures is the "Response Modification Factor" (R). The values of "R" for different structural systems and materials for buildings are well defined and included in the building Codes. For liquid containing structures (LCS), there has not been a justifiable guideline for determination of the "R" and the empirical values have been implemented in the design of such structures. While the seismic design criteria for the buildings are mainly based on life safety and prevention of collapse, the concrete storage tanks should be designed to meet the serviceability limits such as leakage. In this paper the mechanism of leakage in RC tanks is discussed. The response modification factor for LCS along with the corresponding experimental tests will also be discussed. It is concluded that the use of period independent R factor for the LCS may not be appropriate. The current values of R might need to be adjusted as no leakage was observed prior to the yielding of the wall reinforcement.

KEYWORDS: tank, liquid containing, response modification factor, reinforced concrete, seismic design

1. INTRODUCTION

Reinforced concrete liquid containing structures (LCS) have been extensively used as a part of environmental engineering facilities such as water reservoirs and sewage treatment tanks. These structures provide services necessary for the emergency response after an earthquake. LCS are an important part of lifeline system and any damage to these facilities might cause catastrophic consequences. Some of theses structures might contain liquids such as oil or petrol or even hazardous materials. Leakage of such materials if accompanied by a fire might cause damages many times greater than those of the earthquake itself. In RC tanks, leakage can be regarded as a possible mode of failure. Leakage of tanks might also contribute to further damage of the tank by washing the earth on which the tank is supported. The uneven settlement of the foundation can cause the leaking cracks to expand. While cylindrical shapes may be structurally suitable for tank construction, rectangular tanks are often preferred for water treatment process related purposes. Little attention has been drawn into the behaviour of RC rectangular tanks. The purpose of this study is to evaluate the seismic performance of rectangular LCS under pressurized water and cyclic loading and to determine the leakage criteria for the evaluation of R factors. It is believed that the current design loads in practice are very conservative. Considering the large number and size of concrete liquid storage tanks, any safe reduction in the thickness of the walls or amount of reinforcement can result in economical benefit.

2. THE LEAKAGE FAILURE MECHANISM

The leakage failure mechanism under earthquake loading is different from that under static loading. Under monotonic static loading, the leakage of concrete water tanks occur after the concrete crack initiation and may be primarily related to the strength and strain relationship as well as the compatibility of concrete and reinforcement. Cracking starts when the tensile stress in the concrete reaches the tensile strength of the concrete. At the crack, the entire force is carried by the reinforcement. Bond gradually builds up the stress in the concrete on either side of the crack until, with further loading; the stress reaches the tensile strength at some other section, which then cracks. With increasing load, this process continues until the distance between the cracks is not big enough for the tensile stress in the concrete to develop enough to cause more cracking. Once this stage is reached, the crack pattern has stabilized and further loading merely widens the existing cracks. The distance between stabilized cracks is mainly a function of the overall member thickness, the cover area, the efficiency of the bond. After a crack becomes sufficiently wide, reinforcement takes the entire tension force. The concrete crack width develops linearly until the tension bar yields due to the compatibility between the tension bar and concrete around the bar. The crack would propagate up to the neutral axis. At last, if the compression zone becomes small enough; the depth of the neutral axis will decrease and leakage might occur. At the cracks, the steel stress and strain are at a maximum. Under cyclic loading, the crack opening may start as the load is increased, but when the load direction is reversed the crack closes. This crack opening and closing would reduce the stiffness of the tank wall rapidly. The reinforcing bars at both sides would start to deform linearly until yielding during cyclic loading. When the cracks at both sides propagate up to the neutral axis and intersect each other, the leakage might start. No cyclic load test relating reinforcement and concrete stress level with leakage limit state has yet been performed. It has been experimentally observed that in an RC specimen under flexure, the compression zone significantly enhanced the water-tightness of the specimen that even after the tension zone of the member experienced tensile cracking with the crack width in excess of the minimum width permitted by the codes, the compression zone prevented the leakage. It is possible that the *R* factor specified in the codes may not represent the true behaviour of members under earthquake load effects. The reason might be that neither the leakage phenomenon under cyclic load reversals is fully understood, nor the effect of factors such as ductility and over-strength can be accurately incorporated in the value of response modification factor (R). Consequently, experimental tests are need to examine the leakage limit state due to reinforcement and concrete stress level, and to account for the stiffness degradation and softening under cycling loading.

3. EXPERIMENTAL PROGRAM

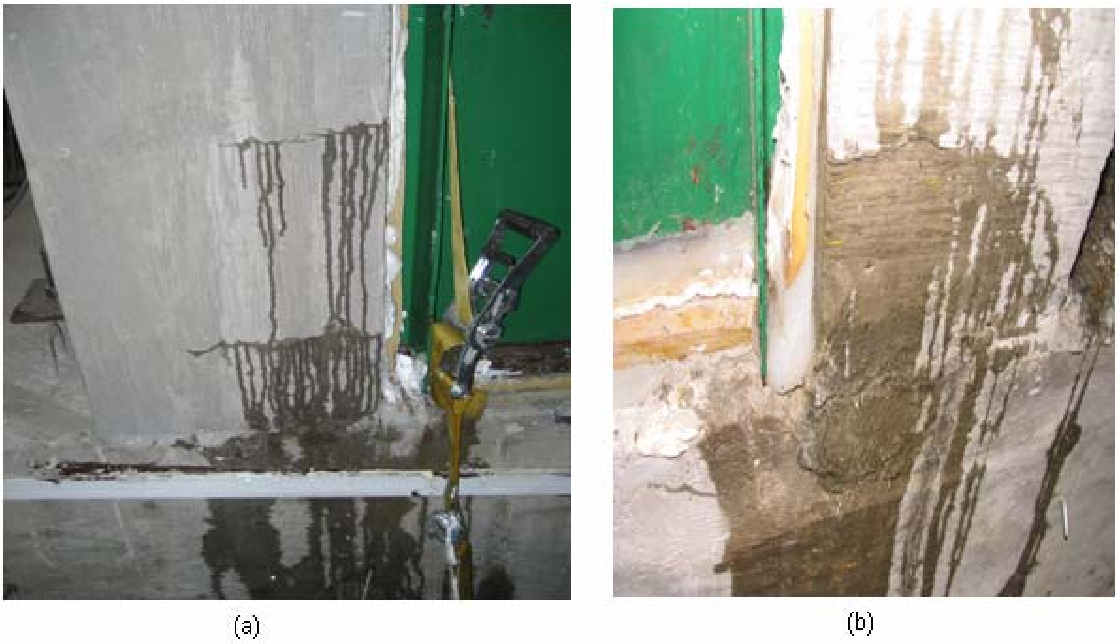
A series of experimental tests are being conducted on several specimens to investigate the leakage behaviour of the RC rectangular tank wall under the effect of seismic induced loading and to identify the important parameters with respect to leakage behaviour of RC tanks. Assuming that a specified crack width that would initiate leakage can be assumed to be a function of the steel reinforcement stress (or strain), then one of the most important objectives of the mentioned experimental program is to find the stress (or strain) in the steel at the onset of leakage. The analysis of a rectangular tank with fix base and free at the top of the tank wall shows that the moments and stresses are highest at the middle of the larger side of the tank walls near the connection of the wall and base slab. Because the larger side of the tank behaves like a one-way slab, the vertical strip at the middle of the large side of the tank can be considered to behave similar to a cantilever member. Experimental studies are conducted on several specimens that are representative of full scale base slab-wall connection portion of rectangular tanks at this middle strip. The sections were designed using the provisions of the American Concrete Institute [1]. A quasi-static imposed displacement loading is imposed on the tank wall to simulate the seismic effect. The specimen is subjected to hydrostatic pressure using a water pressure chamber. The pressure chamber is placed across the full width of the wall to capture all the leakage through the cracks as shown in Figure 1. Data are collected on the extent of damage, including the nature of the cracks, whether surface or through cracks, and acceptable through crack width related to leakage. Several strain gauges are installed in different parts of the specimens which allow data acquisition during the experimental tests. To follow the practice which is used in the industry, the concrete for the base slab and the wall, are poured separately by creating a construction joint where a water-stop is installed in the shear key region to inhibit the leakage through the shear key. The steel water pressure chamber is designed to accommodate pressurized water up to 10m head pressure. The pressure chamber is placed across the full width of the wall to capture all the leakage through the cracks. The pressure chamber is of sufficient height to ensure all the major cracks that may leak are covered. The wall-foundation specimen and the water pressure chamber are shown in Figure 1.The pressure chamber is flexibly connected to the wall to ensure that it does not contribute to the wall response during the cyclic loading which involves the back and forth movement of the wall. Also, the connection is made watertight to be able to resist the hydrostatic force generated inside the chamber. A 25mm thick gum rubber sheet is installed on the wall at the perimeter of region where the water pressure chamber is supposed to contact the concrete wall. The water pressure chamber sits on the rubber on the foundation to eliminate the leakage of water between the chamber and foundation. For elimination of the leakage of water between the chamber and the moving wall, the chamber should is forced into the rubber sheet installed on the wall. The force needed to push the chamber into the wall is provided by means of a large steel beam and a hydraulic jack installed as shown in Figure 1. Approximately 50 kN horizontal force was required to push the chamber into the gum rubber installed on the wall enough to prevent leakage from the wall-chamber interface as the wall moves forward and backward.

Several tests have been carried out on specimens with different wall thicknesses (see Figure 2). The cyclic load was incrementally increased (mostly in the direction of the applied water pressure) until the section reaches near its ultimate strength. The strain gauges show yielding of the reinforcement. As expected, most of the inelastic action in the tanks concentrates in the connection region. The experimental observation showed no leakage at the back side of the wall before yielding of the steel. The results of these experimental studies would be useful to provide meaningful recommendation for the response modification factor, R. In the following sections, the basis for the development of the R factor applicable to LCS is discussed.

4. RESPONSE MODIFICATION FACTOR (R)

In zones of relatively frequent seismic activity, intense earthquakes are rare events. Most buildings may not experience a design earthquake and, therefore, design to resist such events without damage would be economically impractical for most structures. In regions of strong ground shaking, it is sometimes impractical to design tanks for forces obtained from elastic (no damage) response analysis without considering the response modification factors. R factors are assumed to represent the ratio of the forces that would develop under a specified ground motion if the structure behaves entirely elastically to the ones prescribed as design forces at the strength state assumed equal to a significant yield level (Uang [2]), (Whittaker [3]). Therefore it is possible to design a RC structure for forces smaller than the elastic forces and safely survive the ground motion excitation. The actual response of the structure is also higher than stipulated by the design force level. This is mainly because of over-strength and redundancy factor which will be discussed later. When subjected to strong shaking, tanks therefore respond in a non-linear fashion and may experience some damage. In a LCS, however, the *R* factor needs to reflect serviceability limits including leakage, which makes it difficult to choose an appropriate *R* value. To ensure adequate serviceability (i.e., no leakage), LCS may not withstand as large dynamic forces as the general building structure. A typical force-displacement relationship for a RC member is shown in Figure 3. Line OE denotes the linear response of the RC member if it is stiff enough to remain linear elastic during the design earthquake loading. Considering the low probability of occurrence of the severe motion of the design earthquake and also nonlinear behaviour of the RC section it is possible to design the section based on design forces that are reduced from F_E by R factor. This design level force is denoted by F_Y in Figure 3. The extent, to which the curve passed point A, depends on several parameters such as ductility, overstrength, redundancy. A structure can display additional resistance if it is redundant and if yielding takes place in a sequence rather than all at once. In a redundant RC system or a system where capacity design philosophy governs the behavior, different members will yield sequentially as shown by points B and C until the ultimate capacity of the system FU is reached at point D. This increase in the strength of the system from FY to FU is due to the over-strength. ΔY denotes the displacement corresponding to the first yielding and ΔU denotes the maximum displacement of the system before failure. The ability of the system to deform beyond ΔY is called ductility and the ratio of ΔU to ΔY is called displacement ductility ratio. The Ductility based reduction factor, R_d, shows the ability of a system to deform beyond its initial yielding point and survive the failure. This parameter which is illustrated as R_d in Figure 3 denotes the reduction of the design strength from the linear elastic force level to the ultimate strength of the section. If the displacement ductility ratio is denoted by μ, then the strength of the section should be considered in a way to maintain μ less than or equal to the predetermined level of displacement ductility when subjected to the earthquake ground motion. This factor is dependent on the period of vibration and level of inelastic deformation and to a lesser degree on the damping and hysteretic behaviour of the system, soil condition, and the earthquake ground motion characteristics.

Figure 1 Test set-up for a wall-foundation specimen



(a)

(b)

Figure 2. Experimental leakage test on wall- foundation specimens
(a) wall thickness= 400mm (b) wall thickness= 300mm

The relationships between R_d and the displacement ductility and period of vibration for different soil condition have been investigated by many researchers. The reader is referred to (Miranda and Bertero [4]) (Miranda and Ruiz Garcia 2002) for a detailed discussion of the relevant research in this field. Most of these researches have pointed out the important effect of the period of vibration of the system; however, some have not considered other parameters such as damping, hysteresis model, or soil condition as influential. Figure 4 illustrates the relationships proposed by Newmark and Hall [5], Nassar and Krawinkler [6], and Vidic, Fajfar and Fischinger [7]. The normal trend, pointed out in most of the mentioned researches, for the strength reduction factor variation with respect to the period of the system shows an increase from a value of Rd=1 for period of vibration equal or near zero, to a value approximately equal to the target displacement ductility ratio at periods of vibration as defined in each research work, after which it remains almost constant and equal to the target displacement ductility ratio. It is important to mention that the current value for response modification factor for LCS in North America is independent of the period of vibration.

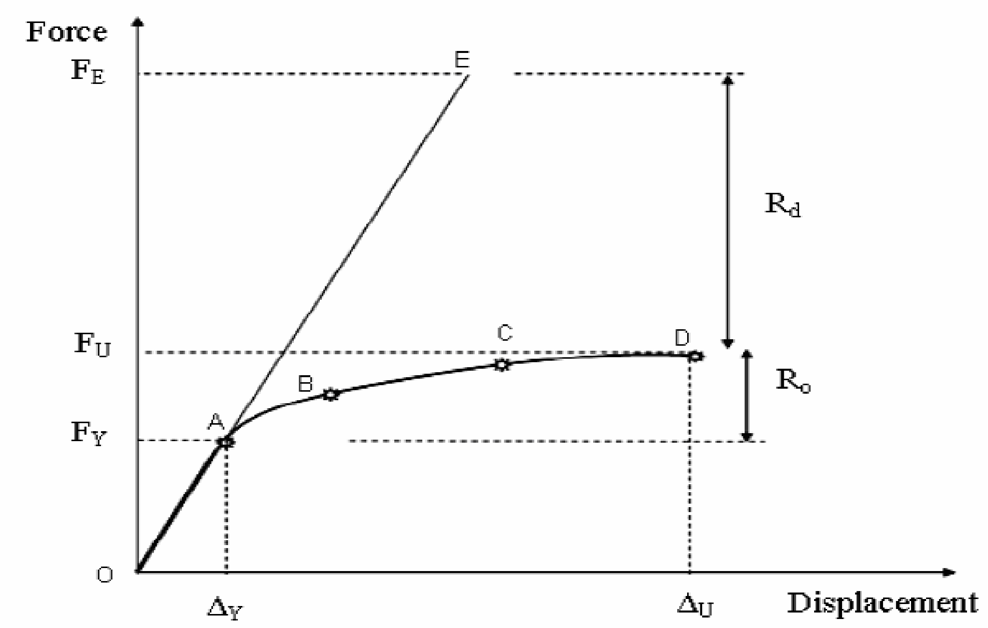


Figure 3. Force-displacement relationship for an RC system

Over-strength factor, shown by parameter Ro in Figure 3, denotes the ratio of the ultimate force the system can resist to the first yield force level by which the section has been designed. In a reinforced concrete member the over-strength factor can stem from the fact that the member will end up having more strength than what originally was postulated. Sometimes this over-strength is the result of parameters other than strength criterion such as parameters for satisfaction of the drift limits or code prescribed details. As an example, columns in a ductile RC moment resisting frame are required to have higher flexural stiffness than the intersecting beams and also have to meet special detailing of stirrups in the plastic hinge zone in excess of those required for strength criterion of the columns. Also the fact that RC walls might be designed with reinforcement for both faces can produce some un-intentional over-strength and ductility as the wall can perform as a doubly reinforcement section with both tension and compression reinforcement.

RC tanks do not have the redundancy as is expected to exist in building structures. In RC tanks the initiation of major leakage in any region is assumed as failure condition, therefore no redundancy factor seems relevant. Also the ductility factor is not a significant issue in a RC tank as the wall does not posses a ductile nonlinear behaviour and also the short period range associated with the period of vibration of the impulsive component restricts the ductility factor between unity and the displacement ductility which is relatively small such as μ=2. The wall sections do not have a well confinement detailing (closed stirrups) in the plastic hinge regions rendering the force-deformation relationship (hysteretic loops) pinched (not wide and open), indicating low energy dissipation and ductility. However, it is necessary to evaluate this factor for RC tanks using experimental and analytical studies incorporating appropriate material models. An important assumption for seismic design of RC tanks is that the seismic induced leakage starts at yielding of steel. Provided that the stress at leakage is in excess of the yielding stress, then the effect of ductility and strain hardening will become pronounced. If analytical studies verified by experimental results indicate a higher stress in the reinforcement than the yield stress for initiation of leakage, it will be possible to safely increase the R value. The other important factor is the effect of the compression zone on prevention of leakage which has been experimentally observed. It was observed by the authors that in an RC slab specimen under flexure, the compression zone significantly enhanced the water-tightness of the specimen that even after the tension zone of the concrete slab experienced tensile cracking with the crack width in excess of the minimum width permitted by the previous edition of the ACI-350 Code [8], the compression zone prevented the leakage.

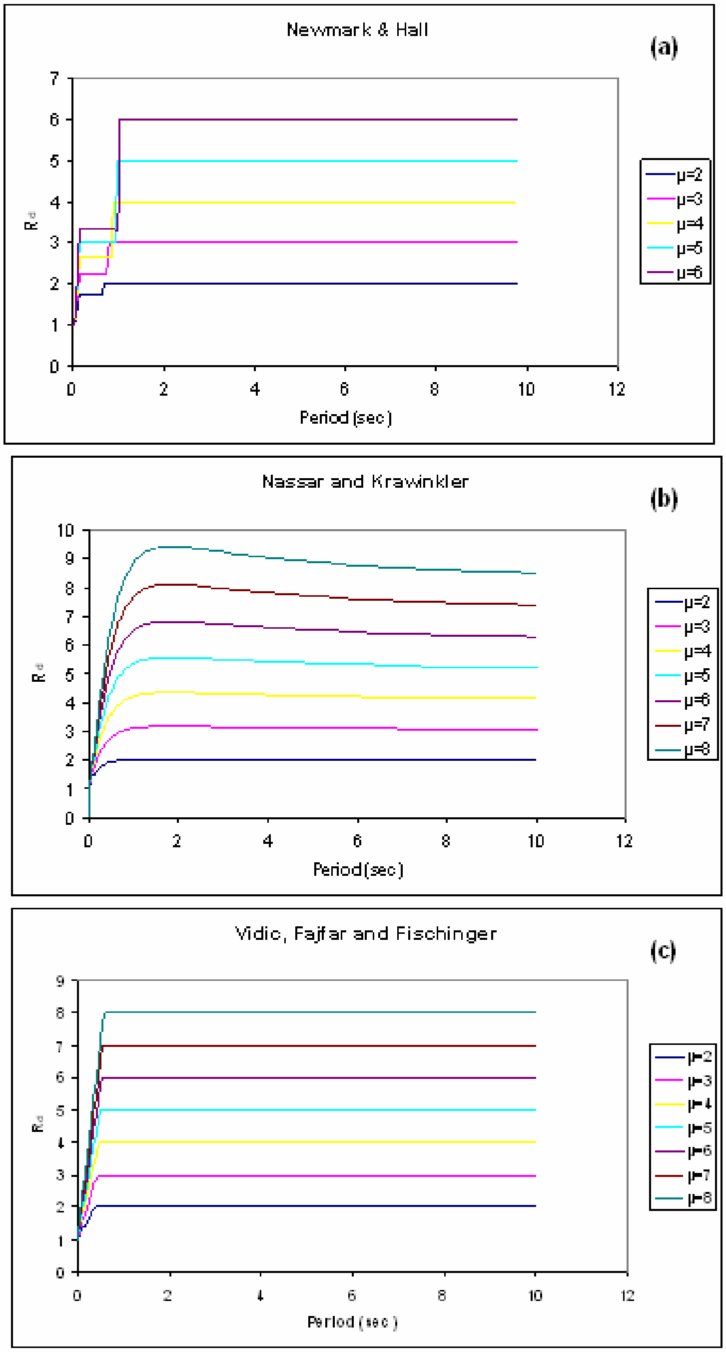


Figure 4. Reduction factors proposed by (a) Newmark and Hall [5] (b) Nassar and Krawinkler [6] (c) Vidic, Fajfar and Fischinger [7].

5. CONCLUSIONS

Liquid containing structures should be capable of surviving an earthquake event. These structures should meet the serviceability limit states such as leakage. In this paper, the mechanism of leakage in RC tanks is discussed. The rationale for introducing the R factor based on its constituents such as ductility and over-strength factors was also introduced. The current period independent value for R factor in North America might not be accurate as the period of vibration was observed to have a significant influence of the ductility based reduction factor. The experimental results showed that the connection of the wall and foundation is the most critical region causing the deepest cracks and damage. Also no leakage was obvserved prior to yielding of the steel reinforcement. The results of a comprehensive analytical and experimental research might lead to more accurate values for response modification factors for LCS.

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