Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 1769

RESPONSE MODIFICATION FACTOR FOR REINFORCED CONCRETE (RC) LIQUID CONTAINING STRUCTURES

R. Sadjadi[1] and M. R. Kianoush[2]

ABSTRACT

Reinforced concrete liquid storage tanks have been extensively used as a part of environmental engineering facilities. The continual functioning of Liquid Containing Structures "LCS" is necessary for the well being of a society especially during and after an earthquake. 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. One of the main parameters used in the seismic design of structures is the "Response Modification Factor" (R). For LCS, there has not been a justifiable guideline for determination of R factor and the empirical values have been implemented in the design of such structures.

In this paper the experimental study of leakage in RC rectangular tanks under the effect of cyclic loading due to pressurized water will be discussed.

This study is aimed at providing information on the cyclic behaviour of RC tanks with respect to leakage. The information may be used to facilitate the process of derivation of R values for the rectangular reinforced concrete LCS considering the leakage as the limit state. This study is limited to rectangular tanks in which the wall dimensions promote a one-way behaviour.

Introduction

Reinforced concrete liquid containing structures (LCS) are considered as essential facilities that require careful design and detailing. These structures may provide services necessary for the emergency response after an earthquake. 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. 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. Also, no code existed in North America until 2001 to address the seismic design of concrete tanks. The current R values included in the ACI Code (ACI 350.3/350.3R 2006) are empirical and without justification, and therefore, questionable by designers.

The purpose of this study is to evaluate the seismic performance of RC rectangular LCS walls

[1]Graduate Research Assistant, Dept. of Civil Engineering, Ryerson University, Toronto, Canada
[2] Professor, Dept. of Civil Engineering, Ryerson University, Toronto, Canada

under pressurized water and cyclic loading and to determine the leakage criteria for the evaluation of R factors. It is aimed at evaluation of the leakage behaviour of ground supported open top rectangular RC rectangular tanks in which the wall dimensions promote a one-way behaviour.

Response Modification factor (R)

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. In regions of strong ground shaking, it may be impractical to design tanks for forces obtained from elastic response analysis without considering the nonlinear behaviour of the structural system. Therefore, it is possible to design an RC structure for forces smaller than the elastic forces and safely survive the ground motion excitation with an accepted level of damage. The values of "R" for different structural systems and materials for buildings are well defined and included in the building Codes. As an example the 2005 edition of the National Building Code of Canada has clear guidelines and justifications for the new values of the "R". For the 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. When subjected to strong shaking, tanks are expected to respond in a non-linear fashion and experience some damage. In an 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), reinforced concrete LCS can not withstand as large dynamic forces as the general building structure.

Several researches have been performed for determination of the R factors for different structural systems (Uang and Bertero 1986), (Whittaker et al. 1987), (ATC 1995). Most of these researchers have described R as the product of several factors such as reserve strength, ductility, redundancy, and viscous damping.

A typical force-displacement relationship for an RC member is shown in Fig. 1. 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 most severe motion of the design earthquake and also the nonlinear behaviour of the RC section, it is possible to design the member based on the design forces that are reduced from F_E by R factor. This design level force is denoted by F_Y corresponding to point A in Fig. 1. The extent, to which the response passes 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 different members will yield sequentially as shown by points B and C until the ultimate capacity of the system F_U is reached at point D. This increase in the strength of the system from F_Y to F_U is due to the over-strength. Δ_Y denotes the displacement corresponding to the first yielding and Δ_U denotes the maximum displacement of the system before failure.

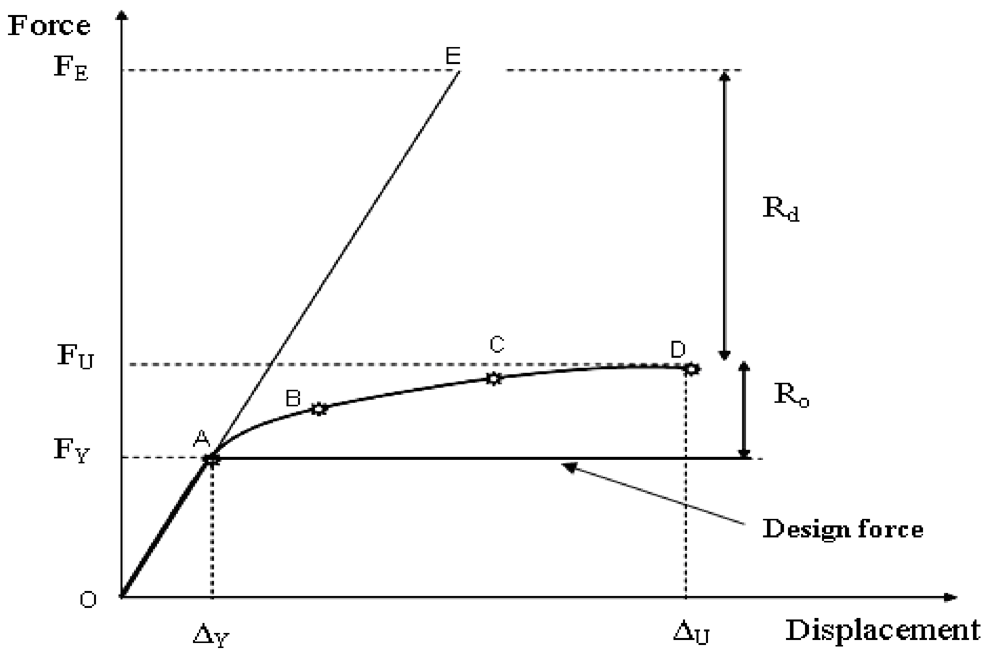

Figure 1: Force-displacement relationship for an RC system.

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 Fig. 1 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. The ductility related reduction factor (R_d) denotes the ability of the system to deform beyond yielding and is calculated as the base shear for elastic response divided by the maximum induced base shear force. As a result of ductility, the structure has a capacity to dissipate hysteretic energy. Because of this energy dissipation capacity, the elastic design force can be reduced to a yield strength level by the factor R_d.

The relationships between R_d and the displacement ductility and period of vibration for different soil condition have been investigated by many researchers (Miranda and Bertero 1994) (Miranda and Ruiz Garcia 2002). 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 very influential. The normal trend, pointed out in most of the conducted researches shows an increase from a value of R_d=1 for period of vibration equal or near zero, to a value near the target displacement ductility ratio at short periods of vibration as defined in each research work, after which it remains almost constant and equal to the target displacement ductility ratio. Fig. 2 illustrates the relationship proposed by Vidic et al. (1992).

Over-strength factor, shown by parameter Ro in Fig. 1, 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 results 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 members might be designed with reinforcement for both faces which can produce some un-intentional over-strength and ductility as the wall can perform as a section with both tension and compression reinforcement.

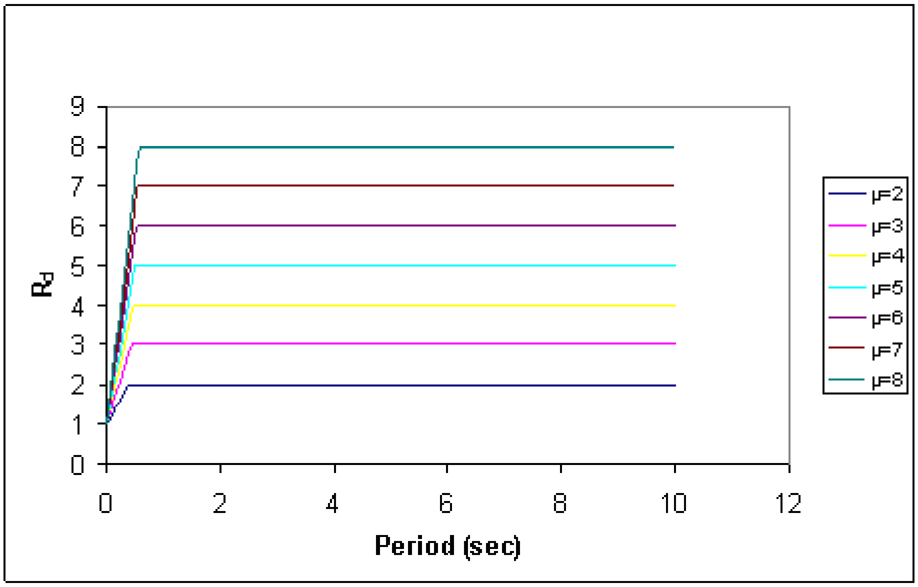

Figure 2: Leakage Strength reduction factors proposed by Vidic et al. (1992)

It is reasonable that, similar to the method employed for *R* factors in buildings, the *R* factors for LCS be considered as a product of several components including strength, ductility, damping, and redundancy factors. For LCS such as water tanks, the redundancy component seems irrelevant because as soon as the leakage starts at the most critical part, the structure can be assumed to have lost its functionality. In a force-based procedure similar to the current practice for computing the design forces, the damping factor can be assumed as unity and its effect on the response modification factor is through its effect on the ductility factor component. In this study it is assumed that the value of R is the product of only two components, namely the strength related reduction factor (R_o), and the ductility related reduction factor (R_d). The overstrength factor (R_o) is decomposed into several components as suggested by Mitchell et al. (2003).

$$R_o = R_{size} \times R_{\phi} \times R_{yield} \times R_{sh} \times R_{mech} \tag{1}$$

R_{size} is the overstrength arising from restricted choices for sizes of members and elements and rounding of sizes and dimensions. R_{Φ} is a factor accounting for the difference between nominal and factored resistances, equal to $1/\Phi$, where Φ is the material strength reduction factor. R_{yield} is the ratio of "actual" yield strength to minimum specified yield strength; R_{sh} is the overstrength due to the development of strain hardening; and R_{mech} is the overstrength arising from mobilizing the full capacity of the structure such that a collapse mechanism is formed.

Assessment of the above factors is not possible before experimental tests are conducted on the leakage behaviour of the tanks under cyclic loading. For instance, if the leakage happens long beyond yielding of the reinforcement, then finding the appropriate values for the ductility related factor (R_d), and the strain hardening factor (R_{sh}) becomes very important. However, if leakage happens before or immediately after yielding of the reinforcement it might be reasonable to assume the ductility related factor (R_d), and the strain hardening factor equal to unity.

Experimental Program

The magnitude of vertical flexural moment is the highest in the middle of the larger side of a tank and at the bottom of the wall and the contained liquid also has the highest pressure near the base of the tank, leading to possible leakage after cracking. Therefore, any experimental research on the leakage behavior of RC rectangular tanks should focus on this critical region. If the length of the tank wall is relatively large compared to the wall height, its behavior approaches that of a one-way slab and the vertical middle strip at the middle of the tank wall behaves similar to a cantilever member. To focus on the leakage behavior of the most critical part, the middle portion of the wall at the larger side of the tank was selected and 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. 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 sections are designed using the provisions of the American Concrete Institute (ACI 350-06). 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 specimens to be tested are subjected to hydrostatic pressure using a water pressure chamber. The pressure chamber is of sufficient height to ensure all the major cracks that may leak are covered and is placed across the full width of the wall to capture all the leakage through the cracks. Fig. 3 illustrates the complete test set up for the experimental test in which the water chamber is installed at the base of the wall using a hydraulic jack and a special setup. A quasi-static imposed cyclic loading is imposed on the specimen wall by the actuator to simulate the seismic effect. Full-scale wall-foundation specimens are constructed and tested during the experimental program in the current study. The height of the walls in all specimens corresponds to a tank with a wall height of 4 m. Two different wall thicknesses of 300 mm and 400 mm are considered. In the following, the results of the test are summarized and discussed. Based on the conclusions reached from the experimental program, an attempt is made to determine the appropriate values for response modification factor for RC rectangular tanks. More detailed information can be found in Sadjadi (2009).

Specimen-1

This specimen has a wall thickness of 400 mm. The wall is reinforced with eight No.20@200 mm and seven No.20@230 mm at the front and back faces, respectively. Throughout the entire tests for Specimen-1, the loading scheme is in a way to push the specimen forward and then pull it back to its neutral position. Therefore, the back face of the wall does not experience any tensile stress/strain, and the front face of the wall does not experience any compressive stress/strain. The specimen (without the water chamber) is first subjected to a monotonic stage of loading when a first visible cracking is observed at the wall-foundation interface. The observation shows that the back face of the wall does not experience any visible cracking. After the water chamber is installed, the leakage test is conducted. During this test, due to the loading scheme, the back side of the wall does not experience cracking. At the last stages of the test, the leakage penetrates deep into the wall as is observed from the side faces of the wall; and also the reinforcement strain at the front side of the wall exceeds far beyond the yield level. After conclusion of the test, the observed crack widths at the front face of the wall are rather excessive. However, no leakage at the back side of the wall is observed. Fig. 4 illustrates the condition of the cracks at the sides near the base after conclusion of the test.

Figure 3: The complete setup including the water pressure chamber.

Figure 4: Cracking of the side faces of the wall after the test.

Specimen-2

This specimen has a wall thickness of 300 mm. The wall is reinforced with ten

No.20@155 mm at the front and back sides. The cyclic loading scheme includes same magnitudes of load in the push and pull directions. Therefore, the front and back faces of the wall experience compressive and tensile stress/strain. The leakage test on the specimen is conducted and it is observed that leakage at the back side of the wall occurred only after the reinforcement layers at front side of the wall experience yielding as shown in Fig. 5. It is necessary to mention that cracking is observed at front and back faces of the wall at the initial stages of test as detected on the side and back faces of the wall.

Figure 5: Leakage at the back face of the wall after yielding of the front side vertical reinforcement.

Specimen-3

This specimen has a wall thickness of 300 mm. The wall is reinforced with ten No.20@155 mm at the front and back sides. The cyclic loading scheme is similar to that of Specimen-2. Therefore, the front and back faces of the wall experience compressive and tensile stress/strain. The specimen (without the water chamber) is first subjected to a monotonic stage of loading when a first visible cracking is observed at the wall-foundation interface at the lateral. The pretest continues with the application of cyclic loading with same magnitudes of load in the push and pull directions, and therefore cracking is observed at the front as well as the back face of the wall. The pretest continues until the strain in the reinforcement approached the yield value. Fig. 6 illustrates the cracking at the side faces of the wall at the end of this stage. After the water chamber is installed, the leakage test is conducted. It is observed that leakage at the back side of the wall occurred only after the reinforcement layers at front and back sides of the wall experience yielding as shown in Fig. 7.

Specimen-4

This specimen has a wall thickness of 400 mm. The wall is reinforced with six No.20@280 mm at the front and back sides. The cyclic loading scheme is similar to that of Specimens-2 and 3. The specimen (without the water chamber) is first subjected to a cyclic stage of loading when the first visible cracking is observed at the wall-foundation interface. The pretest is continued until the reinforcement strain approaches very close to the yield value. After the water chamber is installed, the leakage test is conducted. As soon as the test starts, slight leakage is observed at the back of the wall as shown in Fig. 8, which increases due to the increase in the magnitude of loading.

From the observation during the experimental program conducted on five wall-foundation specimens the following observations are made.

Figure 6: Cracking at the side faces of the wall.

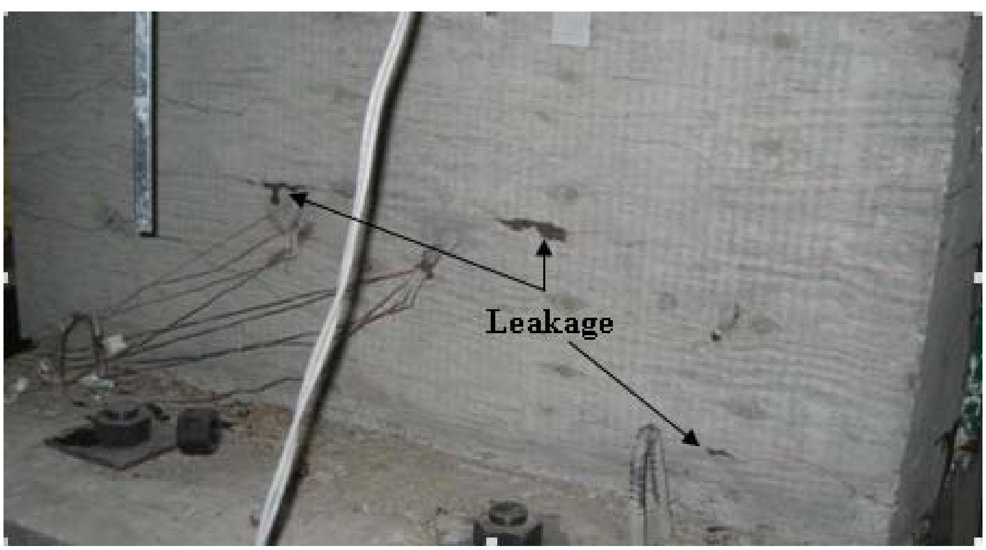

Figure 7: Leakage at back side of the wall immediately after yielding of the wall reinforcement.

Specimen-1 was subjected to a cyclic loading condition in which the front face experienced severe cracking, while the back face did not experience any cracking. This was due to the fact that the concrete at back face of the wall did not experience significant tensile stress/strain. Although the specimen was subjected to loading cycles at the near failure condition, no leakage was observed at the back of the wall. It is postulated that the compression block at the back side of the wall was able to prevent the leakage and also cracking at both faces of the wall is necessary for leakage to occur.

For Specimens-2, 3, and 4, the level of steel strain was beyond the yield value (except for Specimen-4 where the strain level was slightly below the yield value) when leakage at the back face of the wall was observed. It is possible that the reinforcement for Specimen-4 had experienced yielding but the strain gauges showed a lower value. This can be due to the misalignment of strain gauge on the rebar or the rebar in the wall. Therefore, it may be appropriate to assume that leakage occurs soon after the yielding of the reinforcement.

Figure 8: Leakage at the back side of the wall at the initial stage of the leakage test.

Conclusions

Reinforced Concrete (RC) Liquid containing structures (LCS) are designed not only to have functionality during the normal life cycle, but also to withstand the earthquake loading without any extensive cracking that causes leakage. It is possible to design a RC tank for forces smaller than the elastic forces and safely survive the ground motion excitation. In RC tanks, cracking which leads to leakage can be regarded as a possible mode of failure. Therefore a thorough understanding of the cracking and possible leakage phenomena in concrete tanks, especially during the earthquake loading, is of main importance. An important aspect of the design of RC tanks for the earthquake loading is the response modification factor (*R* factor).

This study shows that the portion of a cantilever wall near the base is the most critical region with respect to leakage. In the current study the cracking and possible leakage behavior of such critical region under different loading conditions are studied.

Full scale RC specimens representing the critical region of a rectangular tank are constructed and tested. All specimens are designed based on ACI Code. The specimens are subjected to reverse cyclic loading using an actuator while a water pressure chamber is installed in the critical region to simulate the effect of the pressurized water at the bottom portion of a tank wall. It is postulated that, under cyclic loading, the crack opening starts as the load is increased beyond the tensile strength of the concrete. When the load direction is reversed and part of the section containing the crack, experience compressive stress/strain, the crack closes and the compression block is able to prevent the leakage. This crack opening and closing will continue until the reinforcement is in the linear elastic range and retrieves its initial condition when the load is removed. The reinforcing bars at both sides would start to deform linearly until yielding during cyclic loading. After the reinforcement experiences plastic deformation as a result of yielding in tension, it requires more compressive force to retrieve its original condition and to close the crack(s). If opening of the crack(s) at the side which is not in contact with the liquid, happens before complete closing of the crack(s) at the other side (in contact with the liquid), leakage may occur.

The results of this experimental study show that the value of the response modification factor specified in ACI 350.3 seems appropriate for rectangular fixed base tanks.

References

ACI Committee 350.3, 2006. Design of liquid-containing concrete structures (ACI 350.3-06) and Commentary (350.3R-06).

ACI Committee 350, 2006. Code requirements for environmental engineering concrete structures (ACI 350-06) and Commentary (ACI 350R-06).

ATC, 1995. A Critical Review of Current Approaches to Earthquake Resistant Design, *ATC-34 Report*, Applied Technology Council, Redwood City, California.

Miranda, E., and Bertero, V. V., 1994. Evaluation of strength reduction factors for earthquake resistant design, *EERI*, paper published in Earthquake Spectra, 10 (2).

Miranda, E. and Ruiz-Garcia, J., 2002. Influence of Stiffness Degradation on Strength Demands of Structures Built on Soft Soil Site, Engineering Structures, 24, 1271-1281.

Mitchell, D., Tremblay, R., Karacabeyli, E., Paultre, P., Saatcioglu, M., and Anderson, D. L., 2003. Seismic force modification factors for the proposed 2005 edition of the National Building Code of Canada, Canadian Journal of Civil Engineering, 30: 308–327.

NBCC., 1995. *National Building Code of Canada*. Institute for Research in Construction, National Research Council of Canada, Ottawa, Ont.

Sadjadi, R., 2009. Response of rectangular liquid containing structures under cyclic loading, *Ph.D. Thesis*, Ryerson University, Toronto.

Uang, C. M., 1991. Establishing R (or R_w) and C_d factors for building seismic provisions, Journal of Structural Engineering 117 1, pp. 19–28.

Vidic, T., Fajfar, P., and Fischinger, M., 1992. A procedure for determining consistent inelastic design spectra, *Proceeding of Workshop on nonlinear seismic analysis of RC structures*, Slovenia.

Whittaker, A. S., C. Rojahn, and G. C. Hart., 1999. Seismic response modification factors, Journal of Structural Engineering, Vol. 125, No. 4, ASCE, Washington, D.C.