CRC Final Report

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Project: Crack control and leakage criteria for concrete liquid containing structures

Other Supporting Organizations:
Cement Association of Canada, Toronto, Canada
Klein and Hoffman Inc, Chicago, IL
Dullerud Associates Limited, Toronto, Canada
Jorgensen & Close Associates Inc, Denver, CO
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OBJECTIVES:

The objective of the proposed research was to study the behaviour of concrete liquid containing structures (CLCS) with the aim to provide the necessary input for code decision making. The major issues in the study were: (i) the development of cracks in the vulnerable regions of CLCS due to hydrostatic loading and seismic shaking; and, (ii) the crack-leakage potential in CLCS. These issues were studied analytically, using non-linear finite element analysis and experimentally, measuring the leakage as a function of the crack conditions. In this investigation, several full-scale specimens representing segments from typical tank walls were subjected to load and leakage tests. The main objective of this study was to develop a rational design procedure for concrete tanks that assumes a safe leak resistant structure. It was also proposed to formulate explicit expressions for the response modification factor, R. This was done for both rectangular and circular above ground tanks considering the effect of the end fixity. The results of this research study is expected to provide some useful information and insights on the behaviour of CLCS and will be used towards the improvement of the current design practice for these types of structures.

PROGRESS MADE TOWARDS THE OBJECTIVES

In this study, both analytical and experimental studies were carried out to investigate the response of both rectangular and circular tanks under hydrostatic and dynamic loading. A description of the progress made towards each of these objectives during the period covered by this report is outlined here. The experimental program was based on testing specimens under hydrostatic loading which was extended to include specimens which were tested under cyclic loading. Also, analytical studies on both rectangular and circular tanks have been carried out under dynamic loading as will be described in this report.

Experimental Investigation:

1. Behaviour under hydrostatic loading- flexural loading

An experimental study was conducted on reinforced concrete specimens in which the concrete is subjected to pressurized water at a crack location. A variety of loading configurations was arranged to enable various combinations of flexural stresses with other types of stresses across the reinforced concrete section. The cracking behavior and water tightness of the specimen were closely monitored. A comparison was made between experimental results and several well-known crack prediction models, through which their advantages and disadvantages were revealed and discussed.

To evaluate the flexural cracking and the leakage behavior of reinforced concrete walls, experimental tests were performed on three identical U-shape specimens. These specimens represent a segment of a tank wall. Three different loading configurations were arranged to simulate various stress distributions in the section of the middle RC panel similar to those might exist in a section of a tank wall. In this manner, three different combinations of stresses are induced in specimens, namely, dominating flexural stresses and a lesser amount of direct tensile stresses (high eccentricity test), dominating direct tensile stresses and a lesser amount of flexural stresses (low eccentricity test), and a combination of major flexural stresses with minor tensile and shear stresses (high eccentricity with shear test). Cracks are expected to develop in specimens subjected to these stress conditions, and hence, the possible liquid leakage through cracks can be examined. A longitudinal reinforcement ratio of 1% was provided by 8 No.20 bars in two layers which were tied and held in place by 4 No.15 ties. The specimens were cast with rigid ends to ensure a proper transfer of the eccentric load to the middle RC panel. Specimens were also instrumented with concrete strain gauges at top and bottom surfaces of the RC panel. The concrete used in specimens was a normal mix concrete with compressive strength in the range of 30 MPa. As mentioned, the specimens were subjected to a combination of flexural, tensile and shear stresses through various tests, and the cracking behavior and the water tightness of the cracked specimen were closely monitored. The liquid tightness was measured using a fully contained chamber designed to create a constant water pressure over a specific region above a crack in concrete. The chamber was completely sealed to the concrete surface by using a layer of rubber gasket and water resistant silicon caulk between the concrete and the chamber.

It was found that the compression zone developed in the section as a result of flexural stresses can effectively prevent leakage through the crack regardless of the crack width. This means that flexural cracks are not of concern with regard to leakage, because the liquid passage through the depth of the section is obstructed by the presence of uncracked concrete in compression. Although experiments confirm that cracking is to some degree a random phenomenon, it would be valuable to predict a marginal maximum possible crack width for design purposes. Therefore, available crack prediction models were evaluated against the test observations, in which, some have shown a reasonable accuracy. It is also realized that the accuracy of flexural crack prediction models is reduced when the section stresses deviate from purely flexure to other stress combinations.

2. Behaviour under hydrostatic loading- tensile loading

A study was carried out to investigate the cracking characteristics and liquid tightness of a reinforced concrete element under direct tensile loads. Contrary to the current practice in some design codes, pure tension cracks are more detrimental to the serviceability of the structure and must be treated more cautiously than other types of cracks. This study targets this issue both experimentally and analytically. Accordingly, a reinforced concrete specimen representing an element of a tank wall was subjected to a monotonic increasing direct tensile load and its cracking behavior was closely monitored. The influence of direct tension cracks on water tightness of the specimen was examined by exposing a major crack to pressurized water and evaluating the water leakage. Additionally, the water leakage flow rate was monitored over a period of 30 hours to show any probable early self-healing capability of the cracked concrete. In the analytical phase, the load at cracking and the strain of the steel reinforcement are determined and compared with experimental test data. The accuracy of crack prediction models, namely, Broms and Lutz model, and a modified version of Gilbert model were assessed by comparing their results for crack spacing and the maximum crack width against those obtained from the experiment.

For this experiment, a particular design of the specimen was contemplated in a manner that would allow for purely tensile stresses to develop in the reinforced concrete section. The tested specimen was similar to those reported earlier under flexural loading. However, due to the nature of loading which was different from that under flexure loading, the specimen was cast with steel I beams cast in concrete as rigid ends to ensure a proper transfer of the load to the middle RC panel. As a result of the force applied to the I-beams, uniform direct tensile stresses develop along the RC panel. A longitudinal reinforcement ratio of approximately 1% was distributed in two layers with 4 No.20 reinforcing bars in each, which are held in place by 6 No.15 ties. Longitudinal reinforcements were completely tied to I-beams to provide a complete coherence and unity of the entire steel skeleton. Ten steel strain gauges were installed evenly on longitudinal bars. The use of strain gauges is essential in order to obtain stress/strain history of steel reinforcements which has proved to have a close link with the crack width. The specimen was also instrumented with concrete strain gauges. While carefully aligned in the longitudinal direction, a total number of six concrete PI-gauges were installed on top and bottom surfaces of the RC panel.

The primary intention of this experimental test was to observe the cracking and leakage behavior of the RC panel subjected to direct tension, and in particular, to inspect the relation between the crack width and leakage. The water leakage behavior was examined by exposing a major crack to pressurized water and monitoring water flow through the crack at different loading levels. The test conducted in this study can help to further clarify how and to what extent a direct tension crack can affect the water tightness of the structure.

It was observed that direct tension cracks are full depth cracks which can cause liquid leakage even at an extremely low range of crack widths. Therefore, to assure a proper liquid tightness the possible formation of tension cracks in the liquid containing structures must be avoided. It was also observed that a tension crack as wide as 0.25 mm can partially remediate itself through self-healing process when it is exposed to a flow of water through the crack, while the width of the crack is kept constant under a steady tensile load.

In the theoretical part of this study, the initial cracking load and the relation between the steel strain and the tensile load were calculated, which are consistent with the experimental results. These findings were utilized in two well-known crack prediction models to estimate the maximum crack width. Comparing the final results of these models with the experimental data it was found that a modified version of Gilbert model can be used successfully.

3. Behaviour of two-way elements under hydrostatic loading

The above two studies were extended to investigate the cracking characteristics and liquid tightness of a reinforced concrete elements under biaxial loading in the form of combined direct tension and bending. In this study, the extent of occurrence of longitudinal, transverse and inclined cracks were investigated.

An experiment program was specifically designed to simulate a segment of a tank wall under bi-axial loading conditions comparable to those of an actual tank wall. This study showed that the initial cracking load was much less than that calculated based on one-way action. This implies that for a proper prediction of the cracking load two-way stress condition should be considered. A considerable number of longitudinal and transverse cracks were initiated at locations coinciding with the reinforcement mesh. This could be due to both high stress concentration at reinforcement intersections and reduction in the effective section of concrete at the section where the reinforcement exists. This phenomenon must be considered in the crack prediction of two-way members. Also this may reduce the leakage through the cracks due to the presence of the reinforcement. The results also showed that the widths of direct tension cracks at the top of the specimen are wider when it is loaded in two-way as compared to one-way loading.

4. Testing of specimens under cyclic loading subjected to pressurized water

Five full-scale wall-foundation specimens made of reinforced concrete were constructed and tested during the experimental program in this study. These specimens were subjected to cyclic loading with the aid of an actuator while the walls were subjected to pressurised water using a water pressure camber. The height of the walls in all specimens corresponded to a tank with a wall height of 4 m. Two different wall thickness values of 300 mm and 400 mm were considered. Also leakage performance for two different configurations of the shear key was evaluated. Both conventional and inverted shear keys at the joint between the foundation slab and the wall were used. The tests were aimed at providing information regarding the behavior of the RC rectangular tanks under cyclic loading including and mainly with respect to their leakage behavior. Following these tests, some of the damaged specimens were retrofitted with Glass Fibre Reinforcing Polymers (GFRP) and re-tested under similar conditions as the tested specimens. The purpose of these test were to determine the effectiveness of GFRP on leakage behavior of concrete tanks.

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

1- Cracking at both faces of the wall was necessary for leakage to occur. Specimen-1 was subject 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 cracking tensile stress/strain. This specimen was pushed in one direction and pulled back to its original neutral position under cyclic loading. Although the specimen was additionally subjected to more number of cycles at the near failure loading, 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. The steel stress/strain values were far beyond the current Code maximum permissible limits for environmental engineering structures.

2- For the specimen with inverted shear key configuration without a water-stop, leakage at the back side of the wall was observed at the initial stage of cyclic loading where the steel strain level was below 15% of yield value. The ensuing monotonic loading stage did not show any apparent increase in the rate of leakage indicating that the leakage was due to the effects of cyclic loading.

3- For Specimens-3, 4, and 5 the conventional shear key incorporated a water stop at the joint region. The loading condition was in a way that both faces of the wall experienced cracking during the cyclic loading stage. Although the base of the wall was the first region that experienced cracking and the crack width showed to be wider in this region, no leakage was observed at the back face of the wall. It is postulated that the water stop was effective in preventing the leakage at the base of the wall.

4- Retrofitting of the cracked wall with Glass Fiber Reinforcing Polymer (GFRP) sheet with respect to leakage was effective only under monotonic loading situation and also for very low level of cyclic loading. The cyclic straining of the GFRP and its matrix in tension and compression might be the cause for leakage of water past the GFRP layer(s). Although the GFRP layer is very effective in tension, its performance when subjected to compression is questionable with respect to leakage. In the test of the retrofitted Specimen-1, the cyclic load put the GFRP layer in repeated states of tension and neural stress (no compression stress). The GFRP was able to prevent the leakage below the load levels corresponding to about twice the hydrostatic force. However, the loading scheme for Specimen-3 subjected the GFRP layers to repeated cycles of tensile and compressive stress/strain, resulting in leakage at relatively low levels of cyclic loading.

5- It is believed that under cyclic loading, the crack opening may start as the load is increased; but when the load direction is reversed and part of section containing the crack experience compressive stress/strain, the crack closes and the compression block is able to prevent leakage. This crack opening and closing would 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 close the crack(s). If opening of the crack(s) at the other side (in contact with the liquid) happens before closing of the crack(s) at the other side, leakage may occur.

ANALYTICAL INVESTIGATION

1. Reinforced concrete tank walls under restrained shrinkage

In this study, the response of fixed base reinforced concrete walls subjected to shrinkage cracking which is a widespread problem in liquid containing structures was investigated. Restrained shrinkage causes tensile stress and cracking in concrete. In general, concrete standards and codes of practice recommend a minimum area of reinforcement for shrinkage and temperature effects. This reinforcement area is satisfactory where shrinkage and temperature strains are not fully restrained and partial movements are permitted to occur. However, in some cases large structural elements provide significant restraint to concrete members. For instance, in a tank, where the wall is anchored into the base slab at its base or is connected to the other walls at its ends, movements are significantly restrained to the extent that the specified minimum area of reinforcement needs to be increased. In this study the response of fixed base reinforced concrete walls with different length/height ratios due to shrinkage was examined considering linear and nonlinear finite element analysis. The variation of the degree of restraint in uncracked concrete walls was determined. In cracked concrete walls the strain caused by restraint was much greater than shrinkage strain of concrete at crack location. It was concluded that the degree of restraint cannot be expressed in the scale of 0 to 1 as is defined in uncracked concrete walls. Linear analysis indicated that the degree of restraint at the top of the walls is less than that at the base. However, from nonlinear analysis it was found that in the walls with length/height ratios of 5, 10, and 20 the restraint strain increases dramatically from the base to the top of the walls. As a result, the top of the walls should be reinforced properly to compensate such significant movements. In addition, by placing 0.5% reinforcement ratio, reinforcing bars almost yielded under shrinkage strain of 600x10-6 and hence the cracks are not well controlled. The tensile stress in reinforcing bars declines dramatically by increasing the reinforcement ratio.

2. Finite element modeling of reinforced concrete walls

Predicting the formation of cracks in RC liquid containing structures under service loads is essential to ensure the structure meets the serviceability requirements. Earlier investigations have shown that the precision of crack prediction models relies extremely on the accurate determination of the stress in the steel reinforcement after cracking. Realizing that theoretical calculations based on the concrete crack theory may become quite tedious for complex structures and loadings, and are not practical unless several simplifications could be made, specific attention was given to the non-linear finite element (FE) analysis of the reinforced concrete. Previously, the tensile cracking behaviour of RC panel specimens has been investigated through a number of experimental tests as reported above. In this study, the efficiency of several reinforced concrete FE models in capturing the nonlinear behaviour of RC panels was examined with the aid of ABAQUS/6.5 (a FE computer program). Various types of elements were used to simulate RC specimens. FE models were analyzed under different tensile and flexural load combinations. The output results were compared to the collected experimental data, through which, FE models showed to be capable of providing quite accurate results for the strain of the steel reinforcement.

3. Dynamic analysis of rectangular tanks

A structural model using the generalized single degree of freedom (SDF) system has been proposed for seismic design of concrete rectangular liquid containing structures (LCS). The proposed model considers the effect of flexibility of tank wall on hydrodynamic pressures and uses the consistent mass approach. The results of analysis obtained from proposed model was compared with the results obtained using the current practice as well as the finite element method. It was concluded that the current approach in design codes and standards does not truly represent the behavior of LCS. The proposed model using the generalized SDF system can be simply used in seismic design of LCS.

4. Development of a simplified method based on generalized single degree of freedom (SDOF) system for seismic analysis of rectangular tanks

A simplified method using the generalized single degree of freedom (SDOF) system for seismic analysis and design of concrete rectangular liquid storage tanks was proposed. In most of the current design codes and standards for concrete liquid storage tanks, the response of liquid and tank structure is determined using rigid tank wall and the lumped mass approach. However, it has been shown that the flexibility of tank wall increases the hydrodynamic pressures as compared to the rigid wall assumption. On the other hand, the consistent mass approach reduces the response of liquid containing structure as compared to the lumped mass approach. In the proposed method, the consistent mass approach and the effect of flexibility of tank wall on hydrodynamic pressures was considered. Five prescribed vibration shape functions representing the first mode shape for the cantilever wall boundary condition were studied. The application of the proposed shape functions and their validity were examined using two different case studies including a tall and a shallow tank. The results were then compared with those using the finite element method from previous investigation. The results showed that the proposed method is fairly accurate which can be used in the structural design of liquid containing structures.

In this study the results of parametric studies on seismic response of concrete rectangular liquid storage tanks using the generalized SDOF) system were evaluated. The effects of height of liquid and width of tank on dynamic response of liquid storage tanks were investigated. The liquid level varied from empty condition to full tank. Also, instead of the commonly used ratio of width of tank to the liquid height, L_x/H_L, the ratio of width of tank to the full height of tank wall, L_x/H_W was used as a characteristic parameter of tank to study the effect of tank size on the dynamic response. The trends of added mass of liquid, effective height and the natural frequencies for different sizes of tanks were established. The values of the added mass of liquid due to impulsive hydrodynamic pressure and the effective height in relationship with the ratios of L_x/H_W and H_L/H_W were determined which can be used in the seismic design of liquid storage tanks. Since the natural frequencies of liquid containing structures were within a band of natural frequencies between the full level of liquid and empty tank, it was recommended to use the frequency which may cause the maximum dynamic response in the design of tank wall.

5. Seismic behavior of concrete rectangular liquid storage tanks under horizontal and vertical ground motions

In this study, the finite element method was used to investigate the seismic behavior of rectangular liquid tanks in two-dimensional space. This method is capable of considering both impulsive and convective responses of liquid-tank system. Two different finite element models corresponding with shallow and tall tank configurations were studied under the effects of both horizontal and vertical ground motions using the scaled earthquake components of the 1940 El-Centro earthquake record. The containers were assumed fixed to the rigid ground. Fluid-structure interaction effects on the dynamic response of fluid containers were taken into account incorporating wall flexibility. Several boundary conditions including rigid side walls, walls with uncracked and cracked section properties which include uniform and non-uniform distribution of cracked section properties over the height of the tank wall were considered. The results showed that the wall flexibility has a major effect on seismic behavior of liquid tanks and should be considered in design criteria of tanks. The effect of vertical acceleration on the dynamic response of the liquid tanks was found to be less significant when horizontal and vertical ground motions were considered together.

6. Response modification factor (R) for circular tanks

There are concerns by the designers on the use of appropriate values of the response modification factor “R” in tanks design. The “R” factor has a significant effect on the seismic forces considered in design and can affect the required cross sectional dimensions and the amount of reinforcement. This study was focused on the nonlinear behaviour of circular reinforced concrete tanks under the effect of seismic loads in order to evaluate the response modification factors included in current practice. Also, this study investigated the limit of inelastic deformation “maximum tolerable displacement ductility demand” based on the crack width to prevent the leakage of the stored liquid. Several tank configurations with different dimensions and base conditions were used in this study to arrive at appropriate R values.

The non-linear finite element analysis was carried out to investigate the behaviour of fixed and hinged based circular tanks under seismic loading. Three different tanks having liquid heights of 3m, 6m, and 9m were investigated. This study showed that fixed based tanks developed the first yield of reinforcement at higher load levels as compared to hinged base tanks. It was concluded that higher response modification factors could be applied to fixed based tanks. Also, shallower concrete tanks can be assigned higher response modification factors.

7. Effect of earthquake frequency content on seismic behavior of rectangular tanks incorporating soil-structure interaction

In this study, a finite element method was introduced that can be used for the analysis of dynamic behavior of partially filled rectangular fluid container under horizontal and vertical ground excitations in three-dimensional space. The liquid sloshing was modeled using an appropriate boundary condition and the damping effects due to impulsive and convective components of the stored liquid are modeled using the Rayleigh method. The soil foundation was modeled as an elastic homogeneous medium with viscous boundary condition applied on the truncated zone to simulate the wave energy absorption. Two different configurations including shallow and tall tank models were considered to investigate the effect of geometry on the response of the liquid-structure system in time-domain. Effect of wall flexibility on the dynamic response of system was taken into account. Four different ground motions with the same peak ground acceleration were applied to investigate the effect of earthquake frequency content on the seismic behavior of liquid-tank system.

Effect of foundation deformability on the overall dynamic response of system was investigated by comparing the results among six different soil types.

The results were presented in terms of the maximum structural base shear and base moment obtained from time history analysis of the considered system as well as pressure distribution and surface sloshing heights for different seismic excitations. Assuming a rigid foundation, the high-frequency earthquakes resulted in the highest impulsive response in shallow tank model, whereas the intermediate-frequency earthquakes highly amplified the tall tank response. Due to significant difference between impulsive and convective fundamental frequencies, a different trend was observed for the convective response under the same earthquakes. It should be noticed that because of the high magnitude of impulsive response and a significant time lag between peak impulsive and convective response, the overall seismic behavior of tank was governed by impulsive component.

In this study the FE results were compared with those obtained by spectral analysis based on design earthquake response spectra. Although the spectral values were higher than FE results, the same trend due to earthquake frequency content was seen for both methods.

Considering the effect of SSI, the results show that the maximum impulsive base shear and base moment obtained from time history analysis of the considered system may increase or decrease as the soil stiffness changes which was a result of dynamic pressure variation in the middle of the wall due to the rocking motion of the foundation. This phenomenon was highly dependent on earthquake frequency-content and tank configuration.

A unique trend was seen under low frequency-content earthquake for both shallow and tall tank configurations. In this case, the structural responses increased as the soil stiffness increased.

In addition, the convective response was almost independent of variations of flexibility of the foundation and seems to be related to geometric configurations of tank, earthquake characteristics and liquid properties.

The dynamic behavior of liquid concrete tanks depended on a wide range of parameters such as seismic properties of earthquake, tank dimensions and fluid-structure interaction which should be considered in current codes of practice. This study shows that the proposed FE method can be used in the time history analysis of rectangular liquid tanks.

This study was done based on 3D analysis of rectangular tanks in time-domain using four different earthquake records and six different soil types. Although the liquid tank design procedure were based on simplified frequency-based methods, the FE time-history results which were more realistic can be used to verify these methods in future works.

Dissemination of Research Results

Papers in Refereed Journals

J1. Sadjadi, R., Ziari, A. and Kianoush, M.R. *Experimental study of RC rectangular liquid containing structures retrofitted with GFRP composites*, Journal of Applied Composite Materials, Springer Science, Volume 17, Issue 2, Page 195, 2010.

J2. Chen, J.Z. and Kianoush, M.R. *Generalized SDF system for dynamic analysis of concrete rectangular liquid storage tanks: Effect of tank parameters on response.* Canadian J. of Civil Engineering, 37:262-272, 2010.

J3. Ghaemmaghami, A. and Kianoush, M.R. *Effect of wall flexibility on dynamic response of concrete rectangular liquid storage tanks under horizontal and vertical ground motions.* American Society of Civil Eng. (ASCE), Structural Journal, Vol. 136, No. 4, pp. 441-451, 2010.

J4. Ziari, A. and Kianoush, M.R. *Investigation of flexural cracking and leakage in RC elements*, Journal of Engineering Structures, Volume 31, Issue 1, pages 1056-1067, 2009.

J5. Ziari, A. and Kianoush, M.R. *Investigation of direct tension cracking and leakage in RC elements*, Engineering Structures, Volume 31, Issue 2, Pages 466-474, 2009.

J6. Chen, J.Z. and Kianoush, M.R. *Generalized SDOF system for analysis of concrete rectangular liquid storage tanks, Journal of Engineering Structures,* Elsevier, Vol. 31, Issue 10, pp 2426_2435, 2009.

J7. Acarcan, M., Kianoush, M.R. and Ziari, A. "*Behavior of base restrained reinforced concrete walls under volumetric change*" Journal of Engineering Structures, vol 30, issue 6, 2008.

Papers Submitted to Referred Journals

J8. Ghaemmaghami, A. and Kianoush, M.R. *A comparison between two and three dimensional behavior of concrete rectangular tanks under seismic loading.* Canadian Journal of Civil Engineering, 2010.

J9. Kianoush, M.R and Ghaemmaghami, A. *Effect of earthquake frequency content on seismic behavior of concrete rectangular liquid tanks using the finite element method incorporating soil-structure interaction effects.* Journal of Engineering structures, Elsevier, Accepted for publication.

Conference Papers

P1. Sadjadi, R. and Kianoush, M.R., *Response modification factor for reinforced concrete (RC) liquid containing structures,* Proceedings of the 9th U.S. and 10th Canadian Conference on Earthquake Engineering, Toronto, Canada, July 2010.

P2. Chen, J.Z. and Kianoush, M.R., Effect *of tank parameters on dynamic response of concrete rectangular liquid storage tanks,* Proceedings of the 9th U.S. and 10th Canadian Conference on Earthquake Engineering, Toronto, Canada, July 2010.

P3. Ghaemmagahmi, A.R., Moslemi, M., and Kianoush, M.R. , *Dynamic behaviour of concrete liquid tanks under horizontal and vertical ground motions using finite element method,* Proceedings of the 9th U.S. and 10th Canadian Conference on Earthquake Engineering, Toronto, Canada, July 2010.

P4. Hafez, A., Kianoush, M.R. and Abrishami, H, *Response modification factor (R) for circular reinforced concrete tanks,* Proceedings of the Canadian Society for Civil Engineering, Conference, Winnipeg, Manitoba, 2010.

P5. Chen, J.Z, Ghaemmaghami,A. and Kianoush, M.R. *Dynamic analysis of concrete rectangular liquid storage tanks*. Proceedings of the 14th World Conference on Earthquake Engineering, Beijing, China, Oct. 2008.

P6. Sadjadi, R. and Kianoush, M.R., *Response modification factors for reinforced concrete liquid containing structures.* Proceedings of the 14th World Conference on Earthquake Engineering, Beijing, China, Oct. 2008.

P7. Sadjjadi, R. and Kianoush, M.R. *Earthquake Response Modification Factor for Reinforced Concrete (RC) Liquid Containing Structures (LCS),* Proceedings of the Canadian Society for Civil Engineering, Conference, Quebec City, 2008.

P8. Ziari, A. and Kianoush, M.R.,*Non-linear FE Modeling of RC Panels with Emphasis on Tensile Cracking Mode of Failure,* Proceedings of the Canadian Society for Civil Engineering Conference, Quebec City, 2008.

P9. Ziaolhagh, N. , Abrishami, H. and Kianoush, M.R. *Behavior of Reinforced Concrete Walls due to Restrained Shrinkage,* Proceedings of the Canadian Society for Civil Engineering Conference, Quebec City, 2008.