Effect of wall-slab connection details in liquid containing structures under cyclic loading

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ABSTRACT

Concrete Liquid Containing Structures (CLCS) are primarily designed based on serviceability criteria to control cracking and leakage. These structures are designed not only to have functionality during their normal life cycle, but also to resist seismic loading without any extensive cracking that could result in unacceptable leakage. In a typical reinforced concrete wall-slab connection, a downturn shear key is provided. Mechanical water-stops are used at these joints to control leakage in or out of the tank. One of the major issues in such joints is that the waterstop can often conflict with reinforcement. Because the waterstop is typically the last item installed before the concrete is placed, the workers will either curl the waterstop so it lies above the steel, or cut notches in the waterstop so it clears the bars. Neither of these remedies is acceptable practice. The problem becomes more complicated when shear keys are provided in the slab. An alternative solution is to avoid the shear key at the joint by roughening the concrete surface at the slab to increase the shear resistance of concrete. In recent years, designers have developed and used different joint detailing to overcome the problems such as providing an upturn joint key. However, there are concerns on the use of upturn keys especially under cyclic loading. To determine the efficiency of different joint types, an experimental study was conducted on full scale wall-slab connections under liquid pressure. It was aimed to evaluate the performance of different wall-slab joints under hydrostatic and cyclic loading. This paper reports on the result of the experimental study of four full-scale wall-slab specimens, with four different construction joints subjected to monotonic and cyclic loading. Based on the performance of different types of wall-slab connections, it is concluded that conventional joints perform better than those with upturn keys.

KEYWORDS: leakage, wall-slab connection, rectangular container, liquid containing, experimental, cyclic load

INTRODUCTION

Liquid Containing Concrete Structures (LCCS) are used for the storage of water, oil, different types of gas, oxygen and even different types of hazardous chemicals. These structures are commonly known and referred to as storage tanks. Concrete tanks are commonly used in water treatment facilities and provide storage for water used for drinking, fire suppression, agriculture and many other important applications. Therefore these structures are designed based on serviceability criteria such as cracking and leakage. LCCS are designed not only to have functionality during their normal life cycle, but also to resist seismic loading without any extensive cracking that could result in leakage [1]. In LCCS, cracking which leads to leakage could be regarded as a possible mode of failure [1]. Therefore a thorough understanding of failure mechanisms caused by cracking and leakage, especially under seismic loading conditions, is important.

When it comes to the construction of the concrete tanks, the base slab or the foundation of the tank is cast first and the walls are cast later on. This causes the formation of a construction joint or a cold joint between the wall and the slab of the tank structure. As it is for all concrete structures, the cold joint could become the weakest part of the structure and it is more likely that cracking and leakage could begin at the location of the joint. Analytical studies have also shown that this region of the structure, at the middle of a long wall of a rectangular tank, in which the wall behaves as a cantilever member, is the most critical region with respect to leakage [1]. Therefore, design and construction of such a connection that is able to resist cracking under applied forces and prevent leakage becomes critically important. There are different types of joints that are being used in construction industry and while each type has its own benefits and flaws, when it comes to choose a type of joint for a specific project, unfortunately there are no code guidelines or standards to follow and most designers have to rely on their engineering judgment and experience.

The structural design criteria of environmental engineering structures (such as LCCS) are different from those of general building structures. While the design criteria for the latter is usually based on strength requirements, in the case of environmental engineering structures, the design is governed by serviceability requirements such as leakage, deflection and durability. For the LCCS, the leakage criterion usually governs the design [1].

One of the methods of leakage control is by controlling the width of cracks. There are different criteria concerning the width of cracks based on different design codes. For example according to ACI 224R-01 [2], the maximum allowable crack width in water retaining structures is 0.1mm, however, the type of crack is not specified in this design guideline [3]. For another example, ACI 350-06 [4] specifies that the width of flexural cracks in environmental engineering structures should be limited to approximately 0.25mm in normal environmental exposure conditions [1]. Numerous studies have been conducted in order to establish models that can be used to predict the crack widths in reinforced concrete structures. Formulas resulting from these studies are mostly based on simplifications and were subsequently implemented into national design codes.

Crack width prediction formulas are usually developed based on the stress calculations within the tension zone of the reinforced concrete members. Researchers have used different analytical and experimental procedures in order to determine the concrete tensile stress distributions, and while some of the analytical studies have used experimental works for verification, some other studies are solely based on experimental test results [3].

Chi & Kirstein [5] analyzed cylindrical uniaxial tension members to determine the concrete tensile stresses within concrete beams. The resulting average crack width was calculated as the extension of steel bar between the two ends of the beam while disregarding the concrete extension. Broms [6] used a different approach in order to determine the concrete tensile stress distributions based on bond forces. Results of elastic analysis have shown that high tensile stresses in concrete are developed within a circle inscribed between two adjacent flexural cracks. Thus, Broms hypothesized that a new crack will form at midway between the two cracks, provided that the crack spacing is larger than twice the concrete cover measured from the center of the steel bar. Only concrete members reinforced with a single bar were investigated in this study however.

Broms and Lutz [7] performed uniaxial tensile tests on multiple concrete specimens reinforced with multiple rebars which were symmetrically placed within the cross section. The test results showed that the formulas derived for members with single bars were also applicable for members with multiple bars with a slight modification in measurement of concrete cover.

A theoretical study of the flexural cracking of reinforced concrete members was conducted by Beeby [8] and Beeby [9]. The results of this study were adopted by BS 8110 [10] Part 1 for the calculation of crack width in flexural members. Gergely and Lutz [11] derived a crack width prediction relation through statistical analysis of a large number of test results obtained from various sources. The result of this study were adopted by ACI 318 [12] in distribution of tension reinforcement for controlling the crack width.

Frosch [13]proposed a method for prediction of a crack width based on a physical model in which the width of the crack at the reinforcement level can be calculated based on crack spacing and cover distance. Crack control in ACI 318 [14] is based on the results of this study. It has been shown that the use of different methods to estimate the crack widths developed in the same reinforced concrete member could result in widely different values [15]. Similarly, an investigation of different crack width prediction models was performed in a study conducted by Ziari & Kianoush [16] using full-scale reinforced concrete specimens subjected to monotonic loadings. It was observed that not only large discrepancies exist between the results of different crack prediction models, but also commonly used flexural crack prediction models may not accurately predict the width of the cracks caused by combination of tensile and flexural stresses. However, there is an agreement between different sources that major factor affecting the crack width and spacing of flexural cracks, is the average strain in reinforcement relative to that in the adjacent concrete[17]. In addition to the problems stated above, it should be mentioned that the crack width might not be a good variable for prediction of leakage because it does not consider some important factors such as the effect of compression zone and the condition of the reinforced concrete member under cyclic loading.

This paper reports the result of an experimental study of four full-scale wall-slab specimens, with four different construction joints under monotonic and cyclic loading which is focused on comparison of the performance of different types of wall-slab connections in LCCS, subjected to monotonic and cyclic loading conditions, with regards to cracking and leakage.

EXPERIMENTAL STUDY

A full scale specimen of a concrete tank was built, with each one of its four walls having a different type of connection to the base slab. All of the walls were subjected to the same type of tests and testing conditions in order to provide a basis for the analysis and comparison on the performance of four different construction joints with regards to load capacity and leakage.

Test Specimen

In this study a single base slab was constructed to support four walls. The base slab was designed as a rectangular footing of 2070 mm long, 1990 mm wide and with a thickness of 400mm. The reinforcement of the slab was designed as two layers of rebars extending in both directions located both at the top and the bottom of the slab. Each layer of reinforcement consisted of 20M rebars placed at 150mm intervals. The walls were designed with a thickness of 300mm, width of 1000mm and a height of 2000mm. The walls were reinforced with a layer of rebars on each side, each containing four 20M bars placed at 300mm intervals. Each of these rebars would be tied to a 15M dowel bar pre-installed in the base slab. The concrete had a 28-day specified strength of 30 MPa, a water-cement ratio of 0.4, no air entrainment and a maximum aggregate size of 20 mm. For the steel reinforcement, the modulus of elasticity of the steel is taken as 200000 MPa and the corresponding stress at yield point is taken as 400 MPa.

To follow the common construction practice, the slab and the walls were cast at two separate stages. The slab was cast first and then all of the walls were cast together at a later date. Most of the design features such as the thickness of the walls and the slab, size and arrangement of rebars and the mix design of concrete were all designed very similar to those common in the industry based on the CSA A23.3-14 [18].

The four types of joints investigated in this study are as follows:

a) **Conventional Flat Joint (CF):** for this connection, the surface of the slab beneath the wall is roughened to increase the friction between the top of the slab and the bottom surface of the wall. Waterstops are typically used in wall-slab connections to provide water tightens to the structure and prevent leakage through the joint. Since half the height of waterstop (about 3inch) will be place in the slab and also a clear space (12 mm) is required between the bottom of the waterstop and the top layer of reinforcements, the rebars beneath this region should be bent or pushed down, which is somewhat problematic with regards to ease of construction.

b) **Conventional Joint with Shear Key (CS):** a shear key is considered in the middle of the section to provide an interlocking mechanism between the base slab and the wall. The surface of the slab beneath the wall is roughened as well. The width of the shear key is equal to a third of the wall thickness (100 mm) and 25 mm in depth. Due to the depth of the shear key, the issue with the placement of waterstops becomes even more problematic for this type of connection.

c) **Upturn Flat Joint (UF):** for the upturn connection, about 150mm (6inch) of the wall is cast at the same time when the concrete of the base slab is poured. The remainder of the wall is cast when the base slab has gained sufficient strength. The top surface of the upturn is roughened as well. In the upturn connections, the issue with the waterstop installment is no longer present since there is sufficient space between the waterstop and the rebars due to the height of the upturn part. However, the additional formwork required for the construction of the upturn part increases the construction time and cost.

d) **Upturn Joint with Shear Key (US):** this type of connection is very similar to the UF joint with the difference of a shear key that is considered in the middle of the section for interlocking. The dimensions of the shear key are the same as those mentioned in the details of CS connection.

The dimension and reinforcing details of the slab and walls and the detailing of all the four types of connection are presented in the Figure 1.

To obtain the response of each wall separately, it was necessary to build the specimen in such a way that the walls would not contribute to lateral stiffness of one another. Therefore each wall was built on each side of the slab and disconnected from other walls by leaving a 10mm gap placed between the inside corners of the walls. A neoprene membrane was placed at the wall corners to confine the water inside the tank.

Test Setup

A hydraulic actuator was used to apply controlled displacements (or force, depending on the test) on top of the wall. For this purpose, the actuator was installed on the strong wall of the laboratory while being supported by a steel bracket and connected to the front of the test wall through a reinforced I-beam. Having a beam on each side of the wall was necessary since a cyclic test was to be performed on the wall and it was necessary to ensure that during the push and pull actions of the actuator, the walls would not disconnect from it. Figure 2 shows the fully constructed specimen and the setup of the experiments.

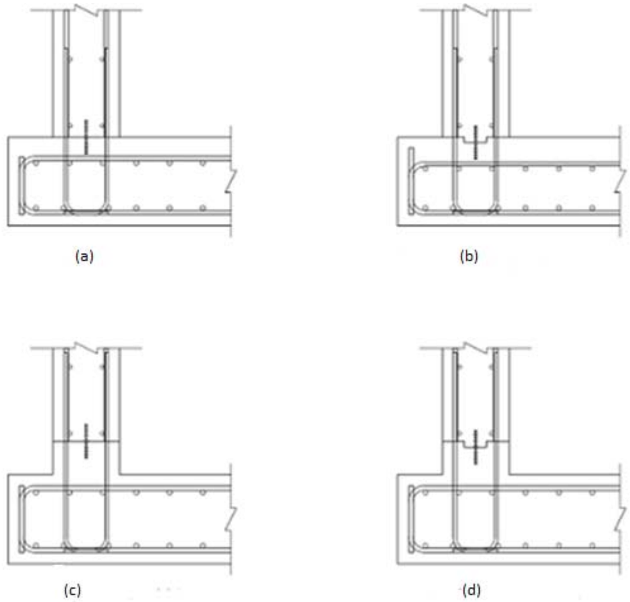

Figure 1- Details of construction joint (a) Conventional Flat Joint (CF), (b) Conventional Joint with Shear Key (CS), (c) Upturn Flat Joint (UF), (d) Upturn Joint with Shear Key (US)

Figure 2- The specimen and test setup (a) the fully constructed specimen, (b) Setup of the experiments

Once a wall was connected to the actuator and prepared for testing, the wires of strain gauges were connected to a data acquisition system so that a time history of strain values could be recorded during the period of each test. The values of the force, displacement and time were also collected and recorded by the software associated with the actuator. These recordings provided sufficient information to plot the force-displacement, force-time, displacement-time and stain-time diagrams for each test.

Test Description

An actuator was used to apply static and cyclic loadings on the top of each wall. The investigation of leakage for each connection type was of interest in this study. Therefore it was necessary to provide sufficient water pressure at the location of construction joint to cause leakage through the cracks caused under cyclic loading.

Testing of the specimens were carried out in two steps. The first test performed on each wall was the first cracking test. This test was performed as a deflection controlled static test. For consistency, this test was continued for each wall until the strain in the dowel reinforcements reached forty percent of the yield value (800 microstrains), which corresponds to the state of stress-strain associated with service loads for these types of structures. After the first cracking test was completed (and the load was removed), the tank was filled with water up to a height of 1.7m. Once the tank was filled to the prescribed water level, the second test, which was a leakage test, was performed on each wall. For this test, a force controlled cyclic excitation on top of the wall was applied, until the leakage of water through the cracks forming at the location of wall-slab connection, on the front side of the wall was observed. Since the tank specimen had to be rotated every time a new wall was to be placed in front of the actuator for testing, it was decided to do the first cracking and the leakage tests on the same wall before rotating the tank for testing another wall, to minimize the number of required rotations. Therefore, once the first two tests were performed on a wall, the tank was emptied of water, disconnected from the strong floor and the actuator, and then rotated until the next wall would be placed in the testing position. The same procedure was applied four times, until all of the four walls were subjected to the first cracking and leakage tests.

First cracking test

The first cracking test was the first test performed on each wall. It consisted of applying a controlled displacement at the top of the wall with a displacement rate of 0.1mm/min. Such a low rate of displacement was chosen in order to comply with the static loading conditions. Moreover a slow rate of displacement would allow for the detection of any cracks forming in the walls. As the value of displacement at the top of the wall was increasing linearly with time, the value of force that was being applied by the actuator was recorded during the period of the test. The values of strains developed in the reinforcements were also recorded by the data acquisition system at the same time. Both devices were set to perform ten readings of the values of force, displacement, time and strain in every second. The displacement was applied on the walls in an outward direction, thus pulling the walls away from the center of the specimen. The test was stopped when the maximum strain value of the rebars in tension reached 800 microns. The reason behind this criteria is that the value of 800 microstrains corresponds to the state of stress-strain associated with the application of service loads as mentioned previously. The main objective of this test was to find the magnitude of the force required to cause initial cracking in each type of wall-slab connection.

Leakage test

The leakage test was the second test performed on each wall. The test was performed in a force controlled fashion by applying push and pull actions on top of the walls. The actuator was set to apply cyclic forces of ±5kN magnitude with a period of 10 seconds (or frequency of 0.1Hz). The magnitude of the force was set to increase by 5kN after each three cycles. All the readings of force, displacement, time and strain were performed in the same way as the first cracking test. The cyclic test was stopped as soon as leakage through the cracks in wall-slab connection region was observed. The main objective of this test was to compare the performance of each type of connection with regards to leakage and to find the time and force required for each connection to initiate leakage through the cracks. It should also be mentioned that usually after leakage was observed, it took about 10 seconds to stop the test and the recording devices.

TEST RESULTS

As it was described previously, the four types of wall-slab connections that are investigated in this study were subjected to two different types of tests. The strain gauges of the dowel reinforcements are located about 75mm above the surface of the slab and are named J1 to J4, from left to right on the front side of the wall (the side facing the actuator) and J5 to J8, from left to right on the back of the wall. These strain gauges have usually recorded the maximum values of the strains during the tests, which is due to the stress concentrations at these locations.

First Cracking Test

The first cracking test was performed by applying a monotonic, controlled displacement on top of the walls. The displacement was applied in a way that walls were pulled towards the actuator. The objective of this test was to obtain the magnitude of the lateral force which is required to cause first cracking in the walls. For this reason, during the test, the values of force, displacement, strain and time were recorded by the data acquisition system used in the experiments. These data were then used to plot the force-displacement diagrams of each test. From the force-displacement diagrams, the occurrence of first cracking could be detected by observing the drops and the changes in the slope of the force-displacement curve.

The force-displacement graphs of the first cracking tests of all four joints are plotted together in Figure 3. For the case of US joint, only a part of the diagram up to the occurrence of first cracking is included. As it can be seen, all graphs follow the same linear path at the beginning of the test, up to the values of force between 8.5kN to 10kN.

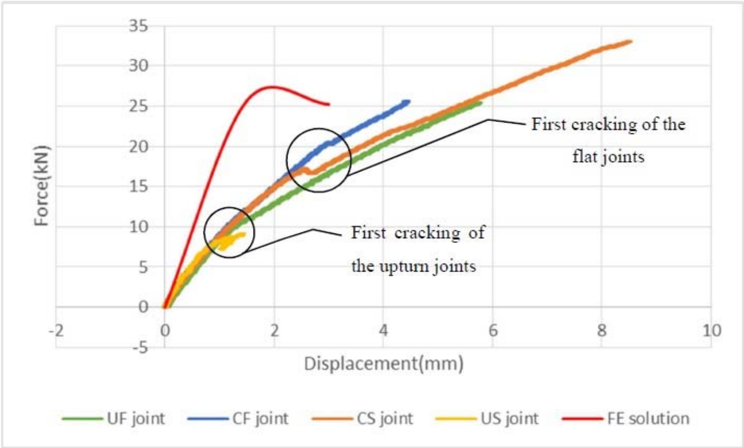

Figure 3. Force-Displacement graphs of the first cracking test of all four joints

However, for the upturn joints (shown by the yellow and the green lines), the initial change in slope occured at a smaller force compared to the flat joints (shown by the blue and brown lines). This is most likely because, the cold joint between the upturn part and the wall, acts as a weak plane of separation compared to the connection between the wall and the slab and as a result, the initial cracking requires a smaller lateral force to occur. In other words, the behavior of flat joint is closer to a monolithic connection than the upturn joint.

The graph of first cracking test of the CF joint (shown by a blue line) remains higher than all of the other types of joints, meaning that for the same values of displacement, this graph has higher values of force. Therefore, it seems that in terms of rigidity and stiffness, the CF joint has the highest value followed by the CS, UF and US.

Prior to the experiments, a non-linear finite element (FE) analysis was performed on the walls which is described by Atashi [19]. The force-displacement curve from this study is also shown in Figure 3. The slopes of all the force-displacement curves, are less steep than that of the FE solution. This is due to the fact that the finite element solution was obtained for a specimen with a monolithic wall-slab connection which will yield a higher stiffness compared to actual data from the tests.

All four tests were carried out until the maximum tensile strain in the dowel reinforcements reached 800 micro-strains. Since this value of strain corresponds to the state of stress strain at service load level (40 percent of yield strain), this criteria was chosen so that the walls would be loaded up to the service load condition prior to a seismic event. It was assumed that the first cracking would most likely happen before reaching the service load condition, and as it can be seen from the results, this assumption was correct for all cases.

Leakage Test

The leakage test was performed by applying force-controlled, cyclic excitations on top of the walls, pulling them towards and pushing them away from the actuator to simulate the seismic behavior. The test was run while the tank was filled with water to allow for the detection of leakage. During the test, the values of force, displacement, strain and time were recorded by the data acquisition system, and were used to plot the results of the test. The test was continued until leakage of water was observed through the cracks which occured at the location of the joints and was stopped upon observation of leakage. The objective of this test was to compare the performances of different types of wall-slab connections with regards to time and the maximum force required to cause leakage through the joints.

In Figure 4, the maximum force applied to each wall during the leakage test is plotted against the total time of the test (period of time that the wall was subjected to cyclic excitation until leakage was observed). From Figure 4, It can be seen that the US and CF joints, sustain higher values of force and were able to prevent the leakage of water for longer periods of time, when compared to other cases. However, a significant difference in the values of maximum strain was observed between the US and CF joints. For the US joint, leakage occurred once the strain in dowel reinforcements reached the yield value, yet for the CF joint, the value of maximum strain was significantly higher (up to three times the yield value). This could be due to local cracking at the corners of the wall caused by the stress concentrations at those locations. This can be confirmed by referring to the strain-time diagram of the leakage test of the CF joint, plotted in Figure 5. From this figure, it can be seen that except for the strain gauges located at the corners of the wall (J5 and J8), which show large values of strain, the strain gauges on the rest of the dowel reinforcement have reach the yield values at the occurrence of leakage.

However, it should be mentioned, that occurrence of leakage does not solely depend on the stiffness of the wall and the yielding of the dowel reinforcements. Several factors such as the existence of the shear keys, the effect of the waterstops, depth and width of the cracks, etc. play important roles on the performance of wall-slab connections with regards to leakage. For example, for the cases of UF and CS joints, the occurrence of leakage was observed while the dowel reinforcements were not even yielded. This observation is not consistent with the results of the test for the US and CF joints, which points out that other factors must have affected the outcome of the test.

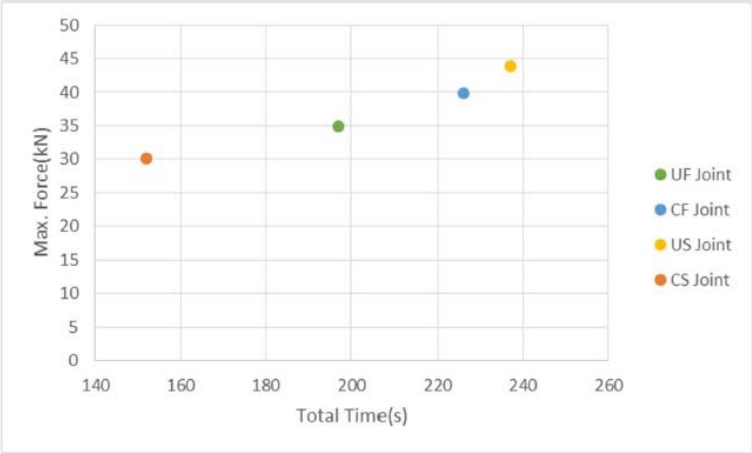

Figure 4. Combined results of all the leakage tests

One other important factor in the results of these tests, is the fact that the initial condition of all the specimens may not have been identical. As previously mentioned, all of these specimens were initially subjected to the first cracking test. Therefore, it is difficult to draw a conclusion solely based on the results of this test. However, if it can be assumed that after the first cracking test, the initial conditions of the specimens (with regards to damage caused by initial cracking), are roughly the same, then it can be concluded that based solely on the maximum force and the time required for the occurrence of leakage, the US and the CF joints have better performances in terms of leakage, when compared to the other cases.

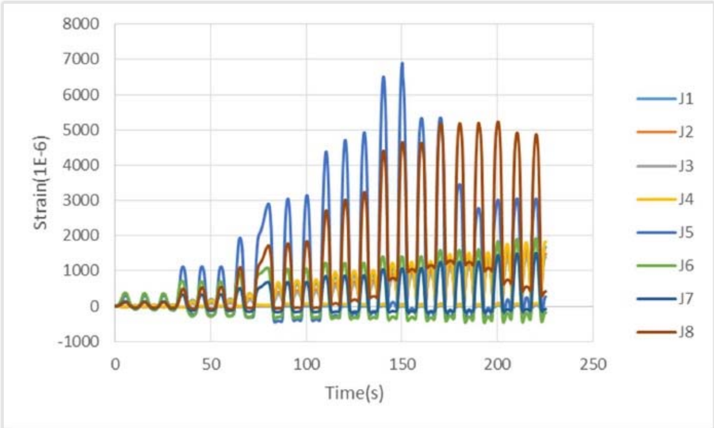

Figure 5. Strain-Time diagram of the leakage test of the CF joint

CONCLUSIONS

In the present article, four different experimental tests were conducted on four full-scale cantilever wall specimens. These specimens are full-scale representatives of wall-slab connection portion of rectangular concrete tanks and each specimen, consists of a different type of wall-slab connection. Based on the results of this experimental investigation, the following conclusions are made.

1- The conventional joints reach higher values of first cracking load, compared to the upturn joints. For the upturn joints, it appears that the wall, forms a weak connection with upturn part of the slab which creates a weak plane of separation at the joint. Therefore, a lesser magnitude of lateral force is required to form a crack at the location of the joint, causing a separation between the two parts. The CF joint has the highest value of the first cracking force among all others and exhibits higher stiffness in this regard.

2- The CF and the US joints, displayed better performances with regards to leakage under cyclic loading, in comparison with other joints. During the leakage test, these two joints were subjected to higher values of maximum force and prevented the leakage of water for a longer period of time. The maximum force applied to the US joint is roughly 10 percent larger than that of the CF joint. This difference is increased to 26 percent and 47 percent, for the UF and CS joints respectively.

3- The results of the experiments have shown that the conventional flat joint, generally exhibits higher stiffness and behaves more rigidly compared to other types of joints and its behavior is more similar to that of a monolithic wall-slab connection.

ACKNOWLEDGEMENT

This project was sponsored by ACI 350 Committee, Environmental Engineering Concrete Structures. Financial support received by Natural Sciences and Engineering council of Canada under the Engage program and also by ACI Foundation, Concrete Research Council.

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