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EXPERIMENTAL STUDY ON THE SEISMIC BEHAVIOR OF SHELL-BASE CONNECTIONS IN LARGE STORAGE TANKS

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Abstract. *When an unanchored tank is subjected to strong motion, the impulsive mass of the contained liquid generates a moment which if strong enough could cause partial uplift of the tank's base plate. As the tank undergoes uplifting, the shell-base welded connection is subjected to cycles of rotation which could lead to its failure. To address this issue, the Eurocode and the New Zealand's recommendations limit the rotation amplitude that the shell-base connection of a tank may undergo to 0.2 radians. This limit is obtained from the following two assumptions: (1) a plastic hinge with a length equal to twice the thickness of the base plate forms at the base plate, next to the connecting weld, and (2) the maximum strain that can be sustained by the base plate is 5%. While these two assumptions are reasonable and have been the state of practice for many years, no research work is believed to exist backing these two assumptions and therefore the 0.2 radians limit. For this reason, an experimental research was conducted to determine the real rotational capacity of shell-base welded connections found in tanks. A total of 24 shell-base connections were tested considering the bending and membrane stresses that develop at the base plate when uplift occurs. Constant amplitude tests were carried at different amplitudes of rotation in order to create curves of rotation versus number of cycles to failure. The main finding from this investigation is that the current limit of 0.2 radians is very conservative and that a limit of 0.4 radians would be more realistic.*

1 INTRODUCTION

Unanchored steel tanks are widely used to store water, gasoline and other petroleum-derived liquids. As these tanks are not anchored to the ground, they may be subjected to sliding or rocking motion. Rocking of the tank implies that the wall (shell) uplifts from the ground, causing a rotation at the junction of the shell-base connection. Design codes allow tanks to be unanchored [1, 2], however, they set a limit in the rotation amplitude that the connection may undergo. The Eurocode [1] and the New Zealand's recommendations [2] set the limit to 0.2 radians. This limit is based on two assumptions: (1) a plastic hinge with a length of twice the thickness of the base plate forms at the base plate, next to the shell-base joint, and (2) that the maximum strain at the plastic hinge is 5%. The allowed plastic rotation in the connection, θ_p, is then computed from these two assumptions, by means of equation 1.

$$\theta_p = \int_0^{2t} k \cdot dx = \left(\frac{\varepsilon}{t_{base}/2}\right) \cdot 2 \cdot t_{base} = \left(\frac{0.05}{t_{base}/2}\right) \cdot 2 \cdot t_{base} = 0.2rad \quad (1)$$

where dx is the length of the plastic hinge ($2t_{base}$), k is the curvature of the section ($\varepsilon/(t_{base}/2)$), ε is the maximum strain (5%) and t_{base} is the thickness of the base plate. A typical shell-base connection of a steel tank showing the assumed plastic hinge length and strain distribution is shown in Figure 1.

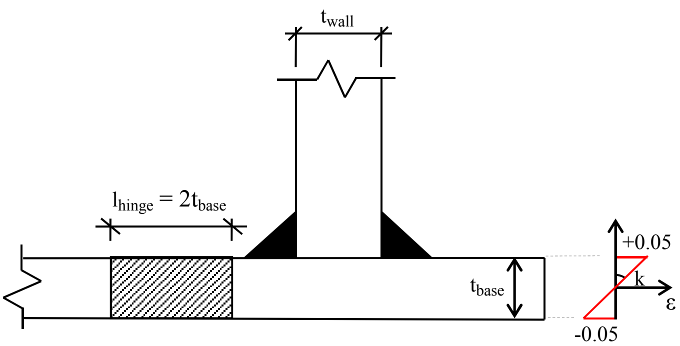

Figure 1: Shell-base connection.

The New Zealand's recommendations state that the assumptions that lead to a 0.2 radians limit should be conservative for a base plate adjacent to a well prepared weld. While the assumptions are conservative and seem reasonable, no experimental work was done to verify these limits. For that reason, an experimental work was conducted to determine the rotational capacity of the shell-base connection.

This paper summarizes the findings from the experimental work conducted on the shell-base connections. An introduction explaining the development of the current 0.2 radians limit is presented in Section 1. Section 2 presents the specimens used for testing. The loading protocol and the tests matrix are presented in Section 3. The test setup is presented in Section 4. Section 5 presents the results. Section 6 applies the findings from the experiments to estimate the rotational capacity of the connection. The conclusions are presented in Section 7.

2 SPECIMENS

Specimens were fabricated from one old tank built in 1961 and located in the city of Konolfingen, Switzerland. In addition, new specimens were fabricated in order to allow for more parameters (e.g., thickness, condition of specimen) to be tested. The new specimens were fabricated by a steel fabricator well acquainted with the fabrication process of steel tanks. Figure 2 shows two different specimens being tested. Note that the specimens are rotated 90 degrees, thus, the base is vertical and the wall is horizontal. This is explained in Section 4. 24 specimens were tested; these were divided in four types, depending on the shell-base thickness and the condition of the specimen (old vs. new). Table 1 summarizes the specimens used, their base and wall (shell) thickness, the weld size, and their condition.

Figure 2: Specimens being tested; left, view from “inside” of tank; right, view from “below” the tank’s base plate.

Type	No. of specimens	Base thickness, t_{base} [mm]	Wall thickness, t_{wall} [mm]	Weld size [mm]	Condition
1	8	6	10	4	New
2	6	8	12	6	New
3	4	10	15	7	New
4	6	7	8	7	Old

Table 1: Specimens used for experiments.

3 LOADING PROTOCOL AND TEST MATRIX

3.1 Loading protocol

When a tank undergoes uplifting of its base, the rotation induced at the shell-base connection is first resisted by bending at the base, in the region next to the weld. However, if the rotation is sufficiently large and causes yielding, the subsequent uplifting is resisted by membrane action of the base plate. The stress developed by the membrane action is normally less than 10% of the material’s yield strength, for rotations less than 0.5 radians. In addition to bending and membrane loading, circumferential compressive stresses are also developed in the base plate. These stresses may be significant for large deformations, however, that is not the case during tank uplift. In order to have a realistic scenario, both bending and tensile (membrane) loading were considered for all tests.

Experiments were loaded using two levels of membrane loading, either 10% or 50% of the specimen's base plate yield strength. While the real behavior is expected to be less than 10% of the yield strength, 50% was also studied to observe the behavior of the connection under such conservative scenario. The tests were performed at three different levels of rotation: 0.2, 0.3 or 0.4 radians. All three series were subjected to initial cycles at 0.02, 0.03, 0.05, 0.07 and 0.1 radians as shown in Figure 3. The first series continued with three cycles at 0.2 radians followed by cycles at 0.3 radians until failure. The second series continued with cycles at 0.2 radians until failure. Finally, the third series continued with three cycles at 0.2 radians, 3 cycles at 0.3 radians, and cycles at 0.4 radians until the specimen failed. Failure was achieved when total rupture of the specimen occurred.

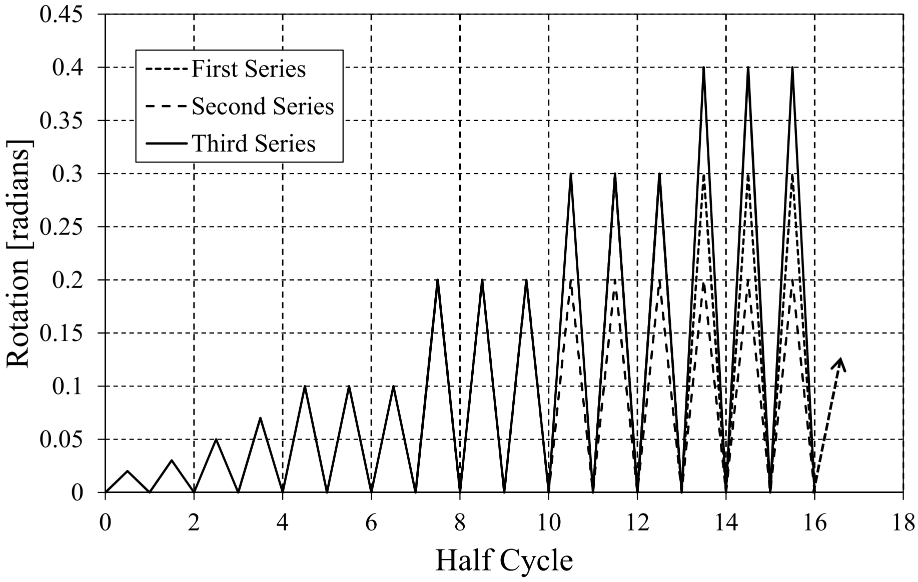

Figure 3: Loading protocol.

3.2 Test matrix

Different parameters of interest were studied in the experimental program. Specimens with different thicknesses were used to study how the thickness of the base plate affected the maximum number of cycles resisted by the specimen. The axial load applied to the bottom of the tank (membrane load) was either 10% or 50% of the nominal yield strength. Also, specimens were either newly fabricated or from an old tank. Finally, the amplitude of rotation applied was 0.2, 0.3 or 0.4 radians. The test matrix is shown in Table 2.

No. tests	Specimen condition	Base thickness t_{base} [mm]	Wall thickness t_{wall} [mm]	Tension [$\%P_y$]	θ_p [rad]
2	Old	7	8	10	0.3
2	Old	7	8	50	0.3
2	New	6	10	10	0.3
2	New	6	10	50	0.3
2	New	8	12	10	0.3
2	New	8	12	50	0.3
2	New	10	15	10	0.3
2	New	10	15	50	0.3
2	New	6	10	10	0.2
2	New	8	12	50	0.2
2	New	6	10	10	0.4
2	Old	7	8	10	0.4

Table 2: Test matrix.

4 TEST SETUP

In order to introduce the membrane loading and the uplifting of the shell-base connection at once, a complex setup involving two actuators and a four pin frame (leveling frame) were introduced. Figure 4 shows the test setup in its displaced position. Note that the specimen was rotated 90 degrees counter clockwise, therefore, the membrane load was applied by the vertical actuator and the uplift was applied by the horizontal actuator. The leveling frame's function was to keep the specimen horizontal under all levels of uplift.

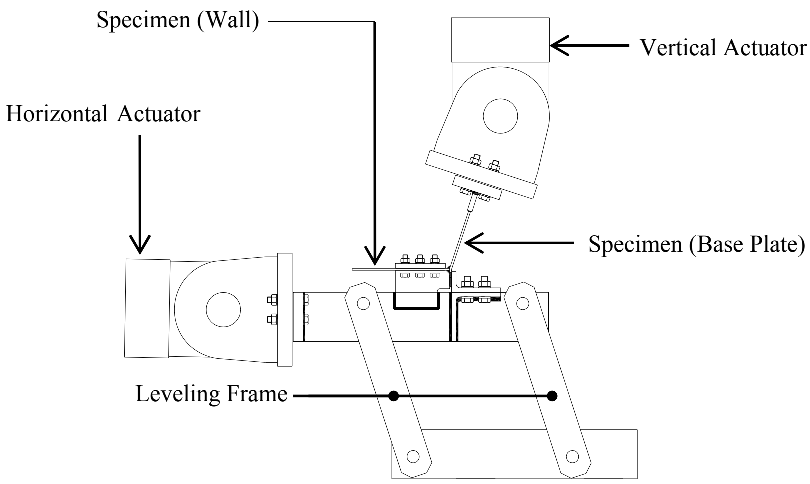

Figure 4: Test setup.

5 RESULTS

The parameter which clearly had the most influence in the number of cycles resisted by the specimens was the membrane load applied. Specimens with 50% membrane load endured between 2.5 and 9 cycles, while specimens with 10% membrane load endured between 84 and 200 cycles. In average, specimens with 10% membrane load endured 19 times more cycles than specimens with a 50% membrane load.

The thickness of the base plate was also found to influence the number of cycles resisted by a connection. For tests carried out with a membrane load of 50% of P_y, specimens with a thickness of 10mm endured about 50% more cycles than specimens 8mm thick and 183% more cycles than specimens 6mm thick. For tests carried out with a 10% of P_y membrane load, specimens with a thickness of 10mm endured 36% more cycles than 8mm thick specimens and 41% compared to 6mm thick specimens.

With the number of cycles to failure, N_f, recorded for each test (see [3] for a comprehensive discussion), plots of rotation amplitude vs. number of cycles to failure were created. Figure 5 shows the data points, the 50% confidence level (linear regression) and the 95% confidence level line for all tests carried out at a 10% of P_y membrane load. Note that the initial smaller cycles applied were considered by converting them into equivalent cycles (see [4]). From Figure 5 it can be seen that for the rotation limit of 0.2 radians, the number of cycles that may be resisted is about 342 cycles (using the 95% confidence level). It can also be seen that the connections underwent 64 cycles at 0.3 radians and about 20 cycles at 0.4 radians. Having established the relationship between rotation and number of cycles to failure, only the number of cycles that the tank is likely to undergo (for a given location) is needed to estimate the maximum rotation that the connection will undergo. Figure 5 is used in the next section to estimate a rotation limit.

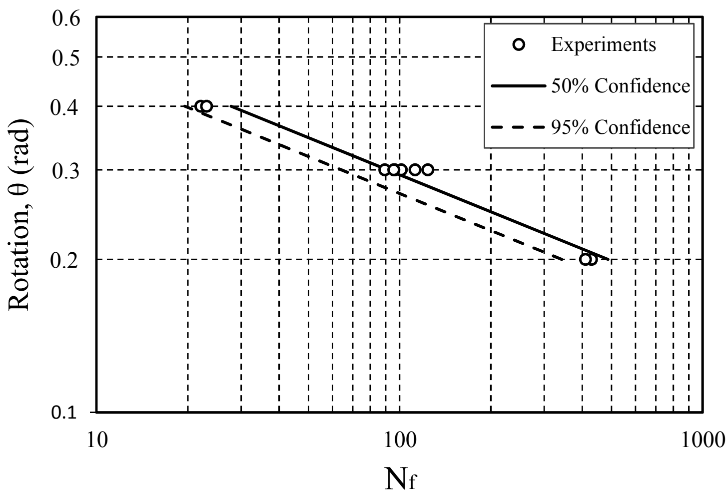

Figure 5: RN curve for shell-base connections.

6 APPLICATION

The RN curve shown in Figure 5 relates the rotation amplitude to the number of cycles (with same amplitude) that will cause failure at this rotation amplitude. It shows that at the current code limit of 0.2 radians the connection would be able to undergo about 340 cycles of equivalent amplitude. This number of cycles is clearly much greater than the expected number of cycles to which the shell-base connection of a tank would be subjected to during an earthquake. The rotation capacity of this connection can be directly obtained by entering Figure 5 with the number of equivalent cycles that it is likely to undergo for a specific site hazard.

The maximum number of cycles at the shell-base connection was estimated for the highest hazard in Switzerland [5]. To estimate the number of cycles, 2 tanks were modeled in ABAQUS and subjected to 8 ground motions. The number of cycles at the shell-base connection and their magnitude were then obtained for each ground motion. From this analysis, it was estimated that the number of cycles expected at the shell-base connection would be 4 cycles. Entering Figure 5 with this number of cycles is not possible as the range of number of cycles is between about 20 and 400 cycles. It is however clear that at a rotation of 0.4 radians (maximum tested) the tank would be able to undergo about 20 cycles which is much greater than the estimate of 4 cycles. This is a clear indication that the shell-base connection can resist at least 0.4 radians without failure.

As an alternative method for determining the equivalent number of cycles, the cyclic-demand spectrum developed in [4] could be used. The cyclic-spectrum is similar to a response spectrum, but instead of providing the acceleration for a given period of vibration, it provides the number of cycles that the structure will experience, as a function of the fundamental period of the structure. In order to apply the cyclic-demand spectrum, it was assumed that each cycle of displacement of the tank causes a cycle of rotation at the connection. This is a reasonable assumption since cycles in the shell-base connection are directly related to displacement of the tank. For full details on how to develop the cyclic-demand spectrum see [4].

The cyclic-demand spectrum was developed for the city of Sion, Switzerland, for a 2500-year return period and for 2% of critical damping. The equivalent numbers of cycles in the acceleration, velocity and displacement controlled regions (i.e., N_A, N_V and N_D) are 1.7, 1.4 and 1.1 respectively. From this analysis, the expected number of equivalent cycles was found to be about 4 cycles.

Both the time history analysis of tanks [5] and the cyclic-demand spectrum [4] estimated the number of cycles to be around 4 cycles. As mentioned before, 4 cycles is clearly much less than the 20 cycles that the connection is capable of resisting at 0.4 radians. Thus, it becomes clear that the 0.2 radians rotation limit established by the Eurocode and the New Zealand's recommendations is very conservative.

7 CONCLUSIONS

Current Eurocode and New Zealand's recommendations allow a tank to rest on ground, without anchorage, as long as uplift is limited. The uplift limit, given in terms of rotation of the shell-base connection, is set to 0.2 radians. This limit was derived from the assumptions that a plastic hinge with a length equal to twice the thickness of the base plate forms at the base plate, next to the shell, and that the maximum strain allowed in the plastic hinge zone is 5%. While both assumptions seem reasonable and have been the state of the practice for many years, to the knowledge of the authors no experimental work representing the behavior of these connections had been done to back these assumptions. With that in mind, an experimental research was performed to study the rotational capacity of shell-base connections in unanchored steel storage tanks. The experimental work included studies of connections with different shell-base thicknesses, with different amounts of membrane load and cycles at different amplitudes of rotation. In addition, new and corroded specimens were tested. The main conclusions from this experimental study are listed below:

- In average, specimens with a 10% of P_y membrane load endured 19 times more cycles than specimens with a 50% of P_y membrane load.
- The thickness of the base plate was found to influence the number of cycles resisted by a connection. Specimens with a thicker base plate endured more cycles than those with a thinner base plate.
- The main result from the experimental program was the creation of curves of rotation vs. number of cycles, called RN curves.

- The RN curves indicated that the wall-to-base connection of a tank would endure 342 cycles at the rotation limit of 0.2 radians given in the Eurocode and the New Zealand's recommendations (with 95% confidence).
- The number of cycles to which the shell-base connection of a tank will be subjected to was estimated to be about 4 cycles.
- Results from this research suggest that a limit of 0.4 radians, which was the maximum rotation angle tested, would be more realistic than the 0.2 radians limit.

Results from this research suggest that a limit of 0.4 radians would be more realistic, however, it should be noted that the results presented in this paper were drawn from a limited number of tests and therefore should be used with caution.

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