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FATIGUE LIFE ESTIMATION OF SHELL-BOTTOM PLATE CONNECTIONS IN STAINLESS STEEL LIQUID STORAGE TANKS

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Abstract

When ground-supported liquid-storage tanks are subjected to lateral loads due to earthquake-induced hydrodynamic pressures, a portion of the bottom plate tends to uplift locally. This partial base uplifting may provoke large inelastic rotation on the shell-bottom plate connection and possible low-cycle fatigue failure. The failure of the shell-bottom plate connection can cause losses of the contained liquid which imply significant economic and environmental consequences. In order to avoid this failure, current code provisions limit the rotation at this connection to 0.2 rad. However, recent studies have shown that this limit is unrealistic and overly conservative for shell-bottom plate connections made of carbon steel and thicknesses of the bottom plate between 6 mm and 10 mm. No investigation about the fatigue life of the shell-bottom plate connection in stainless steel liquid storage tanks has been found in the technical literature. Therefore, this paper presents a numerical analysis for the estimation of the low-cycle fatigue life of the shell-bottom plate connection in stainless steel liquid storage tanks. A typical base plate thickness of 2 mm was considered for the stainless steel connection. A finite element model was subjected to a non-linear quasi-static analysis and life estimation based on the strain-life method. More precisely, finite element modelling in conjunction with the Coffin-Manson model was used to estimate the fatigue life of the shell-bottom plate connection. The Coffin-Manson model was based on experimental data for stainless steel (304L). The herein obtained results are presented as a plot of the maximum rotation vs. number of cycles to failure (i.e., RN curves). These results showed that a stainless steel tank connection having 2 mm base-plate thickness could be expected to achieve about 300 cycles at 0.2 rad which may represent rotation capacities larger than current code limits.

Keywords: Unanchored tanks; low-cycle fatigue; base uplift.

1. Introduction

Ground-supported stainless steel tanks are widely used in food and chemical industry for the storage and treatment of liquids such as water, oils, wine, and fertilizer among others. The use of this material, i.e. stainless steel, over other material for storage tanks is due to its: (i) ease cleaning; (ii) noble chemical inertness; (iii) better control of the chemical processes; and (iv) aesthetically attractive appearance. However, several earthquakes have affected many of these tanks. For instance, many reports of damage provide evidence of failure and extensive damage in wine storage tanks such as during the 1977 Caucete earthquake in Argentina [1], the 1980 Livermore earthquake [2], the 1983 Coalinga earthquake[3], the 1989 Loma Prieta earthquake [4] and the 2003 San Simeon earthquake [5] (all in California, USA), the 2007 Pisco earthquake in Peru [6], the 2010 Maule earthquake in Chile [6], the 2014 South Napa earthquake again in California, USA [7], and the 2016 Kaikōura earthquake in New Zealand [8]. Therefore, the seismic vulnerability of these structures is evident.

The most common types of damage observed in ground-supported liquid storage tanks are: damage to the piping connections caused by large base uplifts, damage to the roof caused by the sloshing of the free liquid surface, buckling of the tank walls caused by the high compressive stress, failure of the anchorage system caused by the high overturning moment transmitted to the base, penetration of the tank wall with anchor bolts caused by the previous failure of the anchorage system and damage to the shell-to-base connection caused by the plastic rotation of the base plate. Among these causes, the failures that are responsible for a large or total loss of the liquids contained in storage tanks are rupture of the shell-bottom connection and the penetration of the tank wall with anchor bolts. For instance, in the past 2010 earthquake in Chile the losses reached approximately 125 million litres of wine (250 million U.S. dollars) representing 12.5% of production in 2009 [6]. The earthquake struck a week before the start of the harvest, when only 50% of storage capacity was in use. This indicates that more than 25% of tanks with wine lost all or part of their content. Among these different modes of failure, our main interest in this paper is the shell-to-base connection failure.

During strong ground motion, both anchored and unanchored ground-supported tanks develop a large overturning moment caused by the hydrodynamic pressure on the walls. As a consequence of this large overturning moment, the tanks may experience a partial uplift of the base. This partial base uplifting may provoke large inelastic rotation demands at the shell-to-base connections and possible low-cycle fatigue failure (see Figure 1). In order to avoid this shell-bottom connection failure current tank design guidelines (e.g., EC8 [9] and NZSEE [10]) limit the rotation at this connection to 0.2 rad; however, this limit is based on an assumed allowable base-plate strain of 5% for an unspecified number of base uplift cycles. There is no study to support this rotation limit assumption of 0.2 rad.

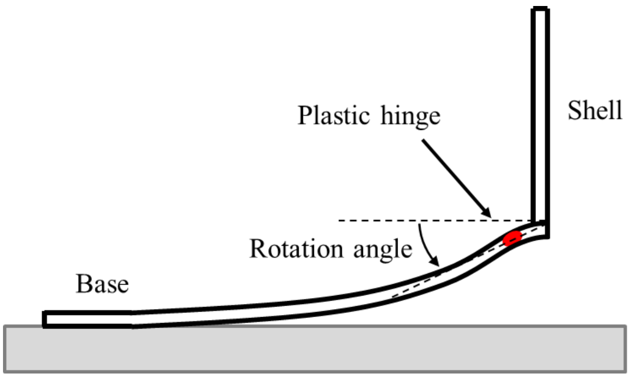

Fig. 1 – Partial base uplifting of liquid storage tanks

Some recent studies have been carried out in order to understand the rotation capacity of shell-bottom connections in carbon steel liquid storage tanks [11–13]. Cortés et al. [11] performed an experimental campaign and the results indicated that the EC8 and NZSEE 0.2 rad rotation limit is overly conservative and suggested a rotation limit of 0.4 rad. Similarly, Prinz and Nussbaumer [12] carried out a numerical investigation using finite element models in order to estimate the connection capacities under multi-axial loads. Finally, Prinz and Nussbaumer [13] developed an experimental study to evaluate the effects of the base-plate ductility on the connection rotation capacity. All these studies were carried out for shell-bottom connections made of carbon steel and thicknesses of the base plate between 6 mm and 10 mm.

Nevertheless, to the best of the authors' knowledge, none investigation about the rotation capacities of the shell-bottom connection in stainless steel liquid storage tanks has been reported in the technical literature. Besides of this material differentiation, the shell-bottom connections in stainless steel storage tanks have other two main differences: (i) typical plate thickness of 2 mm; and (ii) a curve butt welded shell-to-base connection (see Figure 2) [6]. Therefore, in this paper, a numerical study is carried out in order to determine the rotation capacity of shell-bottom connections in stainless steel storage tanks. A typical stainless steel connection with a thickness of 2 mm is evaluated. Results from this study are presented as plots of maximum rotation vs. number of cycles to failure (i.e., RN curves). These results showed that a stainless steel tank connection could be expected to achieve about 300 cycles at 0.2 rad which may represent rotation capacities larger than current code limits.

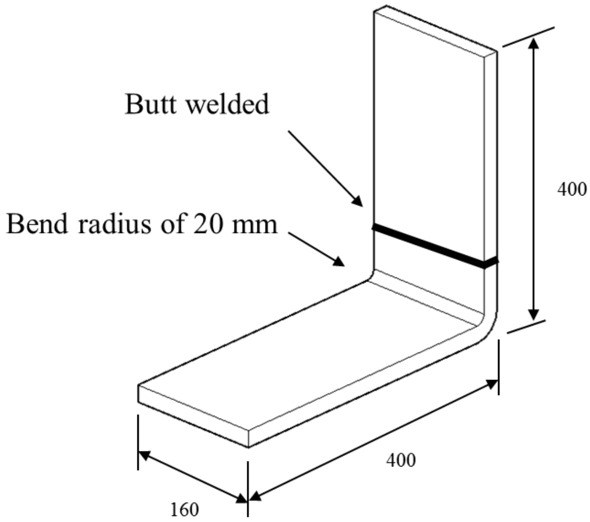

Fig. 2 – Typical shell-bottom connection in stainless steel tanks

2. Fatigue life simulation

In order to estimate the rotational capacity of a typical shell-bottom connection in stainless steel (304L) storage tanks, finite element models were developed using ANSYS software. The finite element models herein developed were capable of providing a local elastic-plastic analysis with considering non-linear material properties. More specifically, finite element simulations in conjunction with the local strain-life method were used for the low-cycle fatigue life estimation considering crack initiation. Similar approaches have been previously presented in the technical literature for the fatigue life estimation of metal specimens (see e.g. [14–16]).

The stress-strain relationship of stainless steel 304L used in the model was obtained from the tensile test results published by González et al. [6]. Additionally, a kinematic hardening model was used. Figure 3 shows the material model behaviour. Because crack initiation is expected to originate in the base material above the weld toe [11,12], the same material properties were assigned to the shell-plate, base-plate and welds. Large displacement and deformation effects, such as large deflection, large rotation and large strain, were accounted for by using the non-linear geometry option in ANSYS.

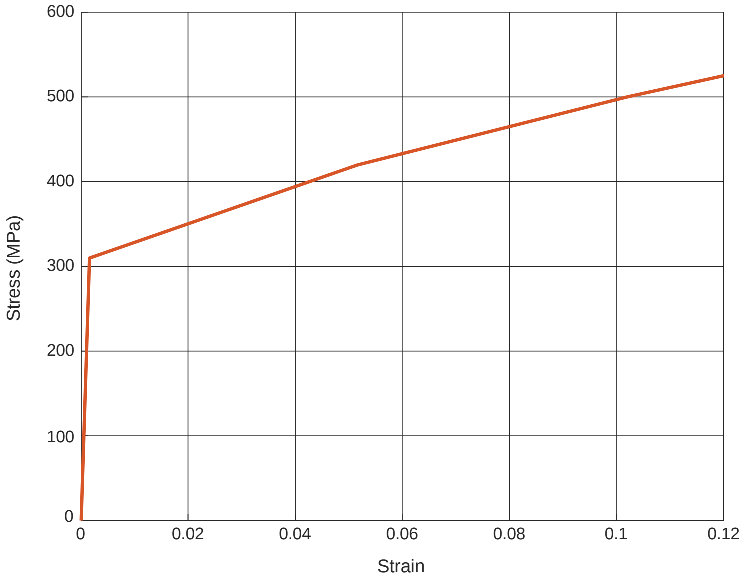

Fig. 3 – Stress-strain relationship for the material model

The shell-bottom connection was discretized using a 20-node solid element (SOLID186) (see Figure 4). This element has three degrees of freedom per node (i.e. translation in the x, y and z directions), which is suitable to perform a non-linear analysis with a detailed determination of stress and strain through the base-plate thickness. In order to increase the strain accuracy near the shell-to-base connection, element sizes were reduced providing at least four elements through the base-plate thickness.

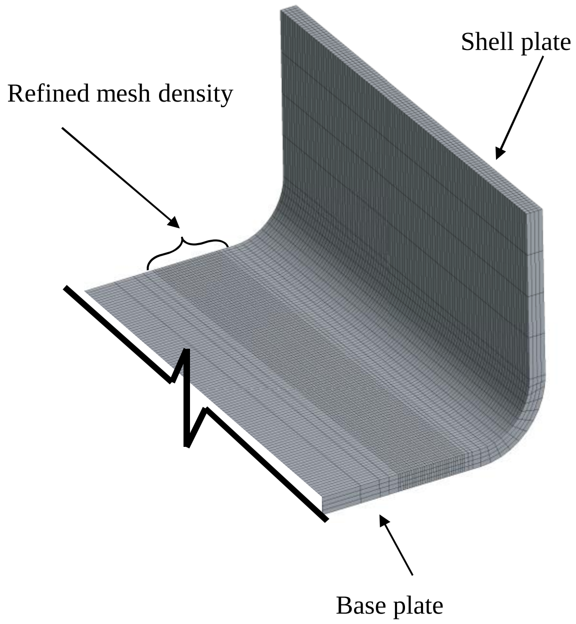

Fig. 4 – Finite element model of the stainless steel connection

In order to simulate the surrounding conditions of the connection, boundary constrains and applied stresses were imposed in the finite element models. Roller constrains located along the tank shell were used to prevent global rotations and to keep the shell in the plane. Roller constrains at the end of the base-plate were also used to avoid out-of-plane displacements. Vertical displacements were applied to the shell in order to simulate the tank base uplifting. Similarly, an applied stress at the end of the base-plate simulated the membrane load developed in the base-plate. This membrane load can reach up to 5 % of the material's yield strength for maximum rotation of 0.5 rad [11,17]. For this reason, as a conservative approach, the specimen was subjected to a base-plate tensile load equal to 10% of the nominal yield strength. Finally, the life prediction was assessed for 0.2, 0.3 and 0.4 rad of base rotation. In other words, the fatigue life of the connection was evaluated in terms of the number of base uplift cycles to failure for a base rotation of 0.2, 0.3 and 0.4 rad. The model constrains are shown in Figure 5. These boundary conditions were also imposed on the shell-bottom connections in the experimental campaign developed by Cortés et al. [11].

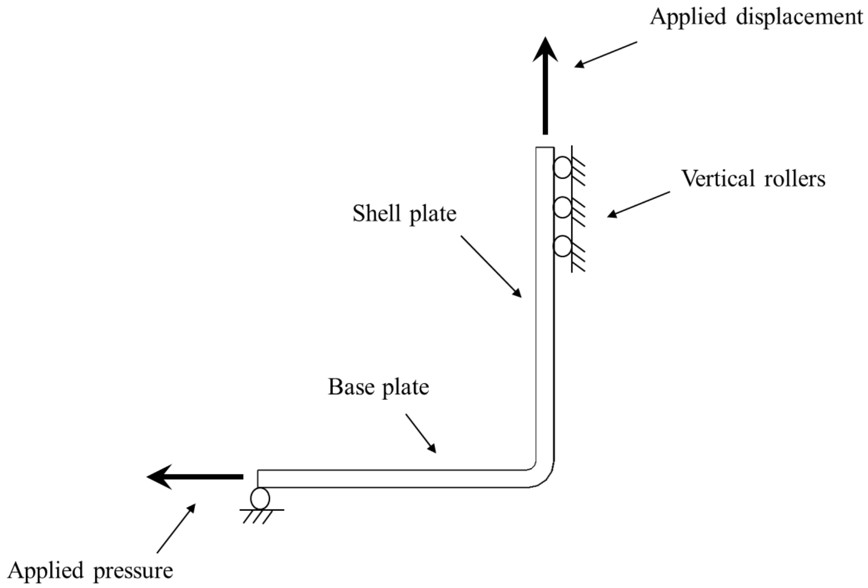

Fig. 5 – Constrain and boundary conditions on the shell-bottom connection

2.1 Local strain-life method

The local strain-life method in conjunction with the finite element simulation was used to estimate the fatigue crack initiation at the shell-to-base connection for the model. This approach has been addressed in the technical literature as finite element (FE)-based life prediction method, which is based on strain-life fatigue data of the base material [16]. In this approach, the localized plastic strain is calculated from a non-linear quasi-static analysis carried out using finite element models. Additionally, with this localized plastic strain, the fatigue damage or fatigue life is predicted using a strain-life model (e.g. [19–22]). One of the most commonly used strain-life models is the Coffin-Manson model [19,20] which has been capable of estimating the fatigue life with reasonable accuracy for metals such as carbon steel and stainless steel [23].

The Coffin-Manson model indicates that,

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon'_f \left(2N_f\right)^c \tag{1}$$

where $\frac{\Delta\varepsilon_p}{2}$ is the plastic strain amplitude, ε'_f is the fatigue ductility coefficient, c is the fatigue ductility exponent, $2N_f$ is the number of reversals to failure and N_f is the number of cycles to failure (1 reversal is equal to ½ cycle) [19,20]. The considered parameters for this study were obtained from the experimental results published by Nip et al. [23] for bending fatigue tests on stainless steel (304L) specimens. These parameters are $\varepsilon'_f = 0.4352$ and $c = -0.6766$.

Therefore, in this study the finite element model of the shell-to-base connection and the Coffin-Manson model based on the experimental data for stainless steel (304L) were used to estimate the fatigue life of the connection. It is important to mention that since the deformation of the shell-to-base connection is only considered for base uplifting (i.e., no penetration into the soil is considered), one base uplift cycle corresponds to one half-cycle of the fatigue test, which is directly one reversal on the fatigue test.

3. Analysis of results

For seismic analysis and design of ground-supported liquid storage tanks, it is essential to relate the shell-to-base connection rotation to the number of cycles to failure. This relationship can be carried out by means of the Coffin-Manson power law [11–13],

$$N_u = \left(\frac{1}{C_u \cdot \theta^{c_u}}\right) \tag{2}$$

where N_u is the number of base uplift cycles to failure, θ is the rotation at the shell-to-base connection, and C_u and c_u are the intercept and slope of the R–N curve, respectively. This relationship is usually plotted in a log-log scale in order to show this power relationship as a linear one. In this study, the R-N curve was developed for rotation magnitudes between 0.2 and 0.4 rad.

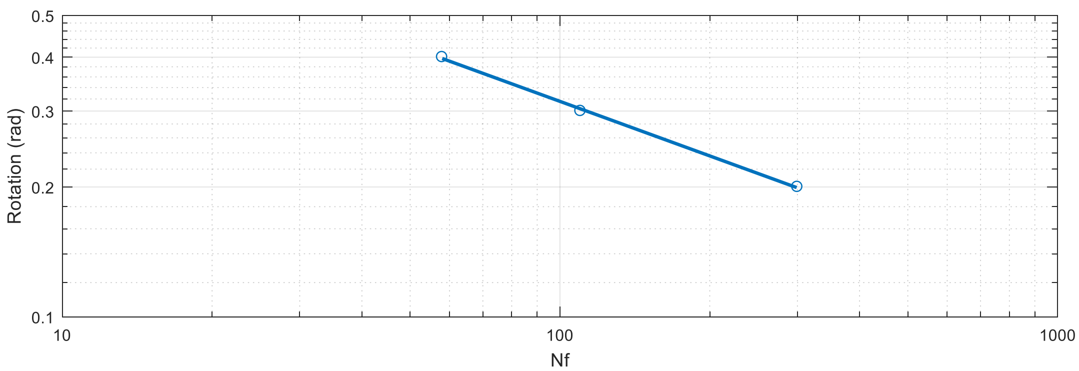

Fig. 6 – R-N curve for the stainless steel connection

Figure 6 shows the R-N curves for the 2 mm thick base-plate stainless steel specimens with 10% of the nominal yield strength. From this figure, a stainless steel tank connection could be expected to resist around 300 cycles at 0.2 rad with a base-plate tensile load equal to 10% of the nominal yield strength. Considering that the maximum number of equivalent cycles expected for a tank during an earthquake is about 6 [11,24], these results also confirm the conclusion of Cortés et al. [11] for carbon steel shell-to-base tank connections, that the 0.2 rad limit imposed by the EC8 and NZSEE is overly conservative. Furthermore, Figure 6 shows that a stainless steel tank connection could be expected to resist around 50 cycles at 0.4 rad with a base-plate tensile load equal to 10% of the nominal yield strength. The values of the resulting coefficients for the Coffin-Manson relationship (Eq. (2)) are $C_u = 0.18$ and $c_u = 2.38$.

Finally, Figure 7 shows the accumulation of plastic strain in the tank connection at 0.3 rad of rotation. As can be seen, the highest concentration of plastic strain occurred on the base-plate upper face, outside the weld geometry region. Additionally, this plastic strain concentration was developed in the base plate near the center of connection, which has also been reported as the location where the fracture initiation occurs for carbon steel connections [11,12].

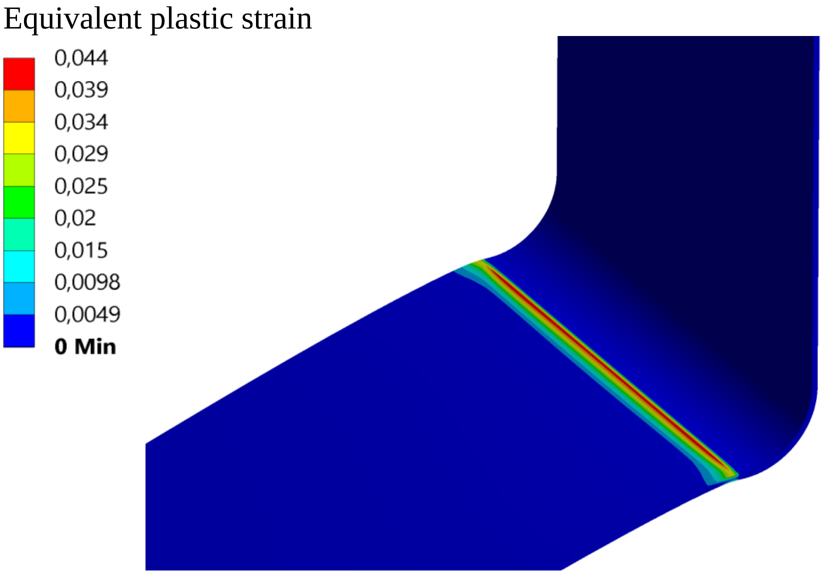

Fig. 7 – Plastic strain in the tank connection

4. Conclusions

Ground-supported stainless steel tanks are especially prone to seismic uplift issues because of the overturning moment caused by the hydrodynamic pressures. This paper presents a nonlinear finite element analysis used for the estimation of the low-cycle fatigue capacity of shell-to-base connections in stainless steel liquid storage tanks. A typical stainless steel connection with a thickness of 2 mm is evaluated. The number of cycles to failure was estimated for connection rotations of 0.2, 0.3 and 0.4 rad. Results from this study were presented as plots of maximum rotation vs. number of cycles to failure (i.e., R-N curves).

The following conclusions are based on the results presented in this work:

- The estimation of the low-cycle fatigue capacity of shell-to-base connections in stainless steel liquid storage tanks is presented by means of the R-N curves. This R-N curve is obtained for a typical connection stainless steel connection subjected to a base-plate tensile load equal to 10% of the nominal yield strength.

- Stainless steel connection capacities are higher than the capacity specified in current tank design codes which limit the maximum rotation capacity at 0.2 rad for an unknown number of cycles. Stainless steel connections, having a base-plate tensile load equal to 10% of the nominal yield strength, achieved about 50 cycles at 0.4 rad of base rotation.

- The relationship between the tank connection rotation and the number of cycles to failure (i.e., R-N curves) is of paramount importance for seismic analysis and design of ground-supported liquid storage tanks.

5. Acknowledgements

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