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Application of SMA anchors to the seismic performance of tanks

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Keywords: liquid storage tank, SMA anchor bolts, uplift, incremental dynamic analysis (IDA), near-field earthquake records, forward directivity

Abstract. This paper is aimed at investigating the feasibility of using shape memory alloy (SMA) materials as anchor bolts in steel liquid storage tanks. The seismic performance of a case study liquid storage tank anchored with steel and SMA bolts is evaluated. For this purpose, a parametric study is performed to determine the optimum length and diameter of the anchor bolts which results in the minimum tank uplift. Furthermore, incremental dynamic analyses (IDAs) are performed to gain insights into the effects of the axial stiffness of the anchor bolts on the uplift of the tank. The uncertainties regarding the seismic input, i.e., the record-to-record variability and seismic intensity, are taken into account by selecting a set of near-field earthquake ground motion records with and without forward directivity. It should be noted that peak ground acceleration (PGA) is chosen as the intensity measure in IDAs. According to the results, using steel anchor bolts significantly reduces the uplift of the tank due to their high axial stiffness, which may result in a severe damage at the connection as a result of high axial forces in the bolts. Conversely, the self-centering feature of SMA anchor bolts allow the tank to undergo a limited uplift, which also leads to significant energy absorption. Furthermore, the Incremental dynamic analysis results show that tanks anchored with SMA bolts are less sensitive to the frequency content of the seismic input compared to the tanks anchored with steel bolts. Based on the findings of this research, it is possible to reduce the required diameter of the anchor bolts and eliminate the residual deformation of the anchorage system after a severe seismic event by using SMA anchor bolts.

1. Introduction

Seismic vulnerability assessment of buildings in urban areas is one of the priorities of crisis management institutions for planning to reduce risks in the future. On the other hand, storage facilities play a key role in modern production industries, as their functionality is essential for the proper operation of a wide range of petrochemical and processing operations. Therefore, health monitoring of the tanks and investigating possible damage under earthquakes is very important. Accordingly, much research has been done on the behavior of the tanks.

Liquid storage tanks are thin-walled structures utilized for storing a wide range of liquids such as water, oil, or even hazardous materials [1–3]. Because of the crucial function of these structures, their seismic performance is significantly important as seen in past earthquakes [4]. The damage due to such strong vibrations can lead to devastating consequences such as extensive fire due to the leakage of flammable substances such as oil as well as damage caused by wave turbulence [5]. Therefore, evaluation of the seismic vulnerability of such structures has attracted the attention of several researchers and

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practicing engineers during the recent decades [6]. The results of some of those researches and practical experiences have been implemented in design codes AWWA [7, 8].

The Seismic performance of cylindrical liquid storage tanks during the occurred seismic events has indicated the notable seismic vulnerability of these structures [9–16]. Most of the existing old steel storage tanks are un-anchored. Unanchored tanks are simply rested on their foundation without any clamps, and hence they are prone to uplift and consequently, a wide variety of failure mechanisms such as shell buckling and failure of their pipes during destructive earthquakes. On the other hand, anchored tanks are clamped to their foundations. Failure of anchor bolts and shell buckling are among the common failure modes of these tanks. In this regard, many studies were aimed at investigating the effect of design parameters on their potential failure modes [17]. The effect of height to diameter (H/D) ratio evaluated on the critical horizontal peak ground acceleration of anchored steel liquid storage tanks. It was shown that the critical acceleration was reduced with increasing H/D. In addition, was studied the effects of base flexibility on the seismic performance of liquid storage tanks. According to the results, base flexibility may increase the seismic vulnerability of tanks. Furthermore, the insufficient effective embedded length or cutting off anchor bolts may lead to partial or total pull-out of the anchor bolts, which imposes a great damage to the anchoring system. In some cases, inadequate material strength results in failure of the anchor bolts due to excessive strain [18]. In another study by Hamdan [19], reported a list of field observations for tanks suffering from anchor bolts damage due to uplift under seismic excitation. To overcome this limitation, some researchers evaluated the seismic vulnerability of liquid storage tanks isolated with different isolation systems [20–22]. However, implementing such systems can be economically inefficient due the costs associated with their installation and maintenance. An alternative method is to provide anchors to clamp the tank to its foundation. It has been shown that this technique can noticeably reduce the seismic vulnerability of tanks [23]. The main shortcoming of this method is that a considerable number of anchors should be provided in order to fully restrain the tank bottom. Another problem with steel anchor bolts is the residual uplift of the tank after a strong ground motion. This phenomenon, in many cases, results in a significant damage to the anchorage system, which necessitates its total replacement.

On the other hand, shape memory alloy (SMA) materials can recover their inelastic deformations after unloading. Such a special behavior leads to flag-shaped hysteresis loops, which can eliminate the residual drifts at a lower energy dissipation rate as compared to steel [24]. However, due to the lower modulus of elasticity of SMA bars, they undergo larger deformations under seismic forces. Previous studies investigated the behavior of SMA materials in different applications such as dampers [25], concrete reinforcements [26], and bolts in self-centering steel columns [27].

In this study, has been investigated the seismic behavior of liquid storage tanks anchored by using SMA anchor bolts for the first time and steel bolts. SMA anchors can reduce the damage to the tank through self-centering effect. Herein, the tank uplift under near-field earthquake ground motions with and without forward directivity is investigated through performing Incremental Dynamic Analysis(IDA) [28]. The tank has been modeled in three conditions: un-anchored, anchored with steel and SMA mechanical anchors. Finally, the results are compared with those of the anchored tanks with un-anchor tank.

2. Materials and Methods

2.1. Specifications of the studied tank

The liquid storage tank considered in the study is a tank which suffered uplift and shell buckling during the Silakhor earthquake in 2006 in west of Iran. The tank is supported by a reinforced concrete foundation and is used for storage of fuel oil with density of 920 kg/m^3. It should be noted that the tank was 90 % full during the seismic event. The properties of the steel used in the tank are tabulated in Table 1 and Fig. 1 shows the geometry of the tank [29].

Table 1 Properties of the steel used in the tank [29].

Material	Density (kg/m^3)	Modulus of elasticity (GPa)	Tangent modulus (GPa)	Yield stress (MPa)	Poisson ratio
Steel	7850	210	4×103	240	0.3

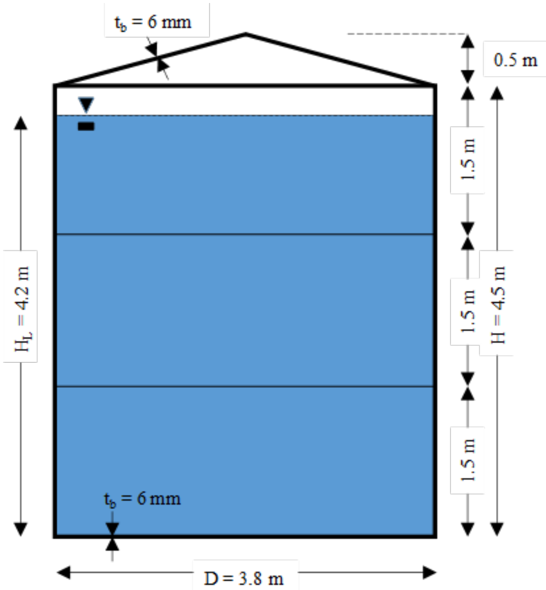


Figure 1. Geometry of the tank used in this study [29].

2.2. Analytical modeling

There is a wide variety of methods to characterize the dynamic behavior of tank-fluid systems. Commercial software usually provides Finite Element (FE) and Finite Volume (FV) techniques to model tank-fluid systems. However, these methods usually require a significant computational effort, which limits their application in practice. In this regard, other simplified models have been proposed to characterize the liquid motion at a lower computational cost without notably compromising the accuracy of the results [30, 31]. In this study, is employed to simulate the liquid motion inside the tank. This model uses an equivalent mass-spring system, which consists of an impulsive component with mass M_0 and a convective component with mass M_1. The convective component is attached to the tank walls by means of a spring with stiffness K_1, which enables it to oscillate during an excitation. The dynamic properties of the equivalent system are calculated as follows:

$$M_0 = M\frac{\tanh(1.7\,D/h)}{1.7\,D/h}, \tag{1}$$

$$M_1 = M\frac{0.83\tanh(1.6\,D/h)}{1.6\,D/h}, \tag{2}$$

$$K_1 = 3\frac{M_1^2}{M}\frac{gh}{D^2}, \tag{3}$$

where M is the total mass of the liquid, D and h represent the radius and height of the tank, respectively, and g is the gravitational acceleration. The natural period of vibration of the liquid inside the tank T is calculated as given below:

$$T = 2\pi\sqrt{\frac{M_1}{K_1}}. \tag{4}$$

The elevations of the impulsive and convective components are respectively denoted by h_0 and h_1, which are calculated by the expressions given below:

$$h_0 = \frac{3}{8}h\left\{1+\alpha\left[\frac{M}{M_1}\left(\frac{D}{h}\right)^2 - 1\right]\right\}, \tag{5}$$

$$h_1 = h\left[1-\frac{1}{3}\frac{M}{M_1}\left(\frac{D}{h}\right)^2 - 0.63\beta\frac{D}{h}\sqrt{0.28\left(\frac{M}{M_1}\frac{D}{h}\right)^2-1}\right], \quad (6)$$

where α = 1.33 and β = 2.0.

Herein the abovementioned model is implemented in OpenSEES platform [32]. To do so, zero Length element is used to model the convective component of the numerical model described above. The impulsive and convective components are located at elevations h_0 and h_1, respectively, to establish a more accurate numerical model of the tank. In addition, the numerical model built in OpenSEES software is observable in Fig. 2.

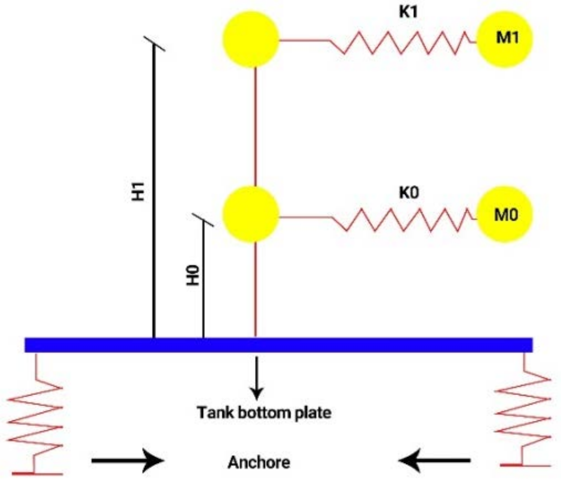
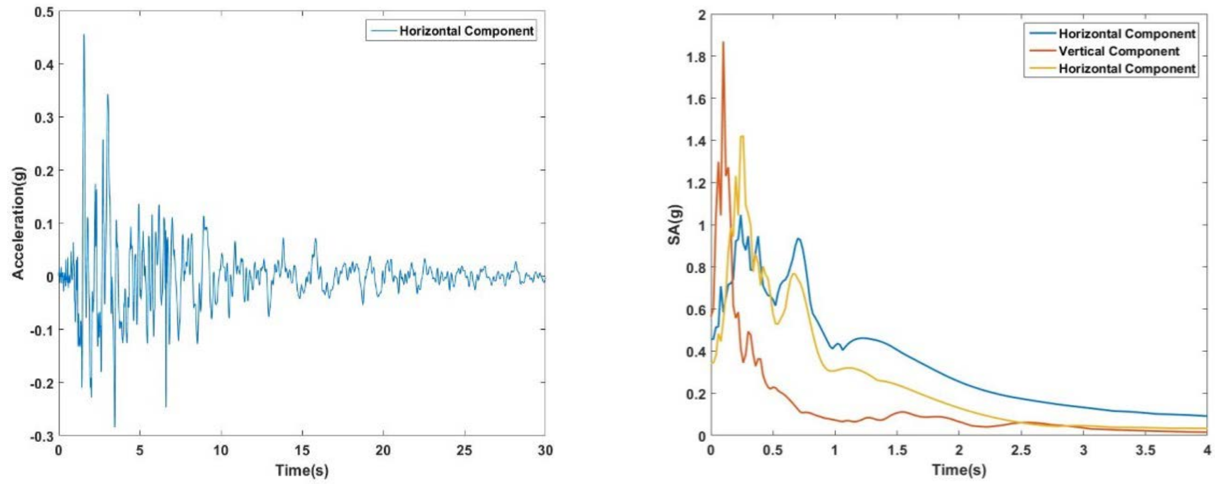


Figure 2. Numerical model of the study tank.

2.3. Model verification

As previously mentioned, in this study, the seismic performance of cylindrical tank which was moderately damaged during the Silakhor earthquake of March 2006 in western Iran was evaluated. The actual seismic performance of the tank was evaluated in different numerical studies [33, 34]. In order to verify the results of numerical analysis, the studied tank was numerically analyzed under the acceleration time history of Silakhor earthquake recorded at Chalancholan station. Fig. 3(a) and Fig. 2(b) show the acceleration time history and pseudo acceleration response spectrum of Silakhor record, respectively. The model adopted for the bottom plate of the tank, which the uplift of the tank was calculated as the vertical displacement of a beam. The maximum estimated tank uplift is compared to that previously estimated by other researchers [32, 33].



(a) Acceleration time history **(b) Pseudo acceleration response spectrum**

Figure 3. Silakhor record.

The uplift of the tank subjected to the selected record calculated in different studies are compared in Table 2. As indicated in this table, the model adopted in this study, satisfactorily simulates the dynamic behavior of the case study tank.

Table 2. The tank uplift in different studies.

Model	This study	Eshghi and Razzaghi[33]	Miladi and Razzaghi[29]
Tank uplift (mm)	36	36.8	40

On the other hand, in this study, a Nickel-Titanium (Ni-Ti)-based SMA is employed for anchor bolts, which is among the most widely used SMAs in practice. The properties of the SMA material used in the present work are tabulated in Table 3.

Table 3. Properties of SMA.

Modulus of elasticity (GPa)	Austenite-to-martensite start stress (GPa)	Austenite-to-martensite finish stress (GPa)	Martensite-to-austenite start stress (GPa)	Martensite-to-austenite finish stress (GPa)
42	0.35	0.45	0.1	0.01

To verify the SMA element used, the cyclic behavior of SMA wires studied by DesRoches et al. [35] was investigated. To this end, the cyclic behavior of an SMA bar with diameter of 25.4 mm subjected to the standard cyclic loading protocol was determined using OpenSEES in order to verify the model adopted in this study. Fig. 4 shows the cyclic stress-strain diagram of the numerical model along with that obtained through experiment. As illustrated in this figure, the numerical cyclic behavior is in good agreement with that of the experiment.

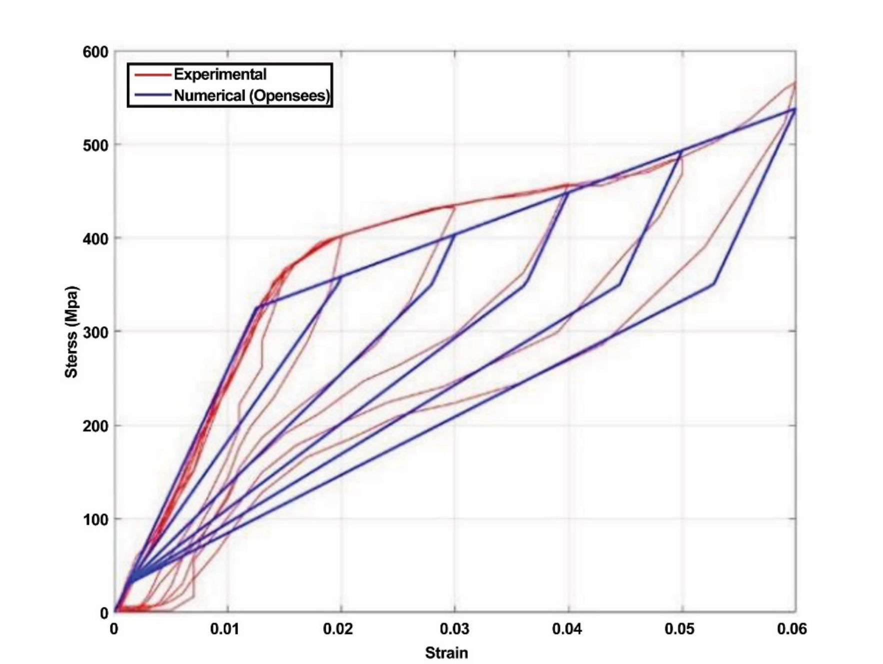


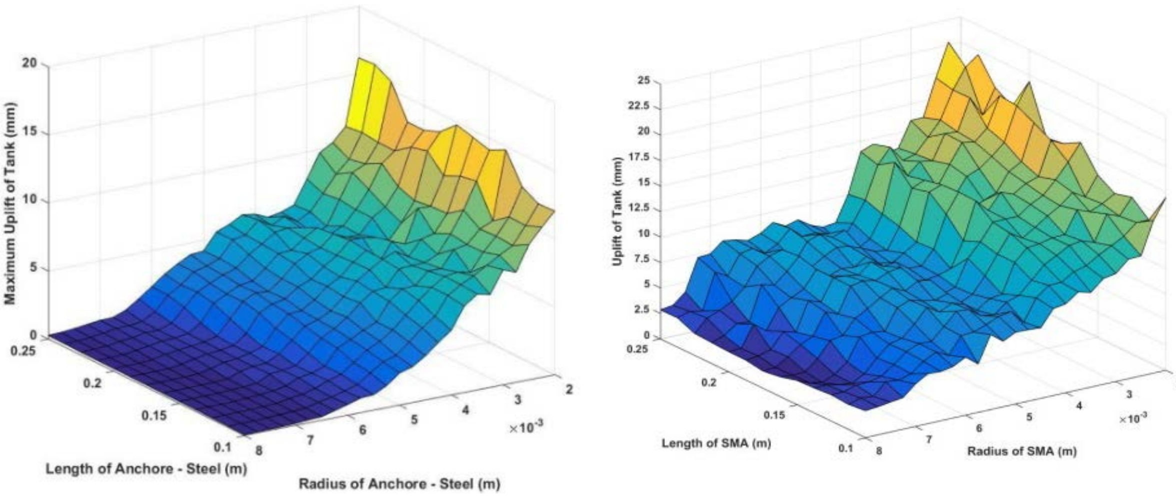
Figure 4. Numerical versus experimental cyclic behavior of SMA bar with diameter of 25.4 mm.

3. Results and Discussion

3.1. Numerical analysis

3.1.1. Preliminary analyses

In order to investigate the effect of mechanical anchors as retrofit tools for the studied tanks, seismic analyses are conducted. To this end, two types of mechanical anchors are considered: regular structural steel and SMA anchor bolt. A parametric study is conducted on the studied tanks in terms of the diameter and the length of anchor bolts. Note that the anchor bolts diameter is varied between 2 and 14 mm and their lengths are varied within the range of 100-250 mm. Nonlinear response history analyses are preformed utilizing the acceleration time history of Silakhor earthquake. The results are illustrated in Fig. 5(a) and 5(b) for regular and SMA anchor bolts, respectively.



(a) Steel anchor bolts **(b) SMA anchor bolts**

Figure 5. Effect of length and diameter of anchor bolts on the uplift of liquid storage tanks.

As it can be observed and in other research [18, 37, 38], the uplift of the storage tank reduces with increasing stiffness of anchor bolts. According to the properties and capability of SMA in energy dissipation, the large deformations experienced by the tank are reduced acceptably, without causing permanent deformation in SMA. This characteristic of SMA reduces the total force transmitted from the base to the tank, which is beneficial to its protection against potential damage due to strong ground motions. It should be noted that based on the analysis results, for SMA anchor bolts, a diameter of 10 mm and length of 12 cm, results in the minimum uplift. On the other hand, for steel anchor bolts, a diameter of 14 mm and length 12 cm, yielded the best results regarding the uplift of the tank. The maximum axial force developed in the anchor bolts with the aforementioned dimensions is 27 tons, which is remarkably smaller than the critical buckling load 1640 kN.

3.2. Complementary analysis

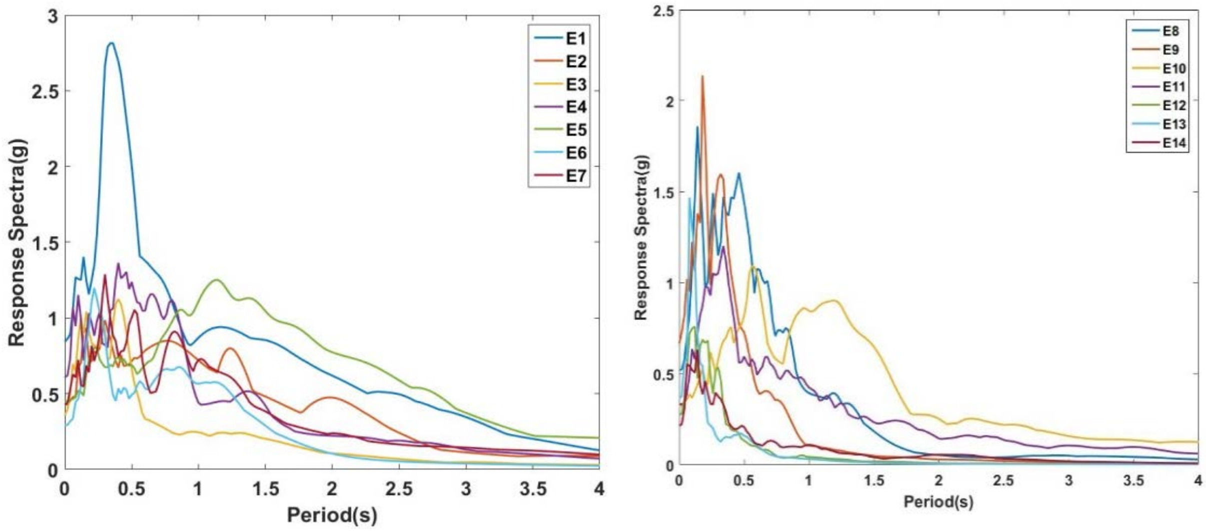
In order to obtain a comprehensive understanding of the effect of regular steel and SMA anchors on seismic performance of tanks, complementary analyses are conducted. To this end, incremental dynamic analyses are performed using acceleration time histories of 14 natural earthquake ground motion records. Selecting appropriate strong ground motions is an important step in every response history analysis. The specification of suitable strong ground motion depends on the characteristics of the seismic source and site such as fault mechanism, level of seismicity, and probabilistic distribution of the earthquake intensity [36]. In this study, 14 near-field earthquake ground motions including 7 ground motions with forward directivity and 7 ground motions without forward directivity, hereinafter referred to as records set 1 and set 2, respectively, are selected. All of the selected records show a distinct pulse in their time histories and possess a shear wave velocity of 375 m/s and higher, which are consistent with the characteristics of relatively stiff sites. Table 3 presents the properties of records with and without forward directivity.

Table 3. Properties of ground motions with forward directivity.

Name	Earthquake name	Station name	Magnitude	Rrup (km)	PGA (g)	PGV/PGA (s)
E1	Northridge-01	Sylmar – Olive View Med FF	6.69	5.3	0.8634	0.1534
E2	Northridge-01	LA Dam	6.69	5.92	0.426	0.1755
E3	Loma Prieta	Gilroy – Gavilan Coll	6.93	9.96	0.358	0.0867
E4	Loma Prieta	LGPC	6.93	3.88	0.607	0.0848
E5	Chi-Chi_Taiwan	TCU052	7.62	0.66	0.428	0.3850
E6	Morgan Hill	Gilroy Array #6	6.19	9.87	0.292	0.1248
E7	Chi-Chi_Taiwan	TCU076	7.62	2.74	0.446	0.1390

Name	Earthquake name	Station name	Magnitude	Rrup (km)	PGA (g)	PGV/PGA (s)
E8	Loma Prieta	BRAN	6.93	10.72	0.525	0.0717
E9	Northridge-01	Simi Valley – Katherine Rd	6.69	13.42	0.653	0.0419
E10	Chi-Chi_Taiwan	CHY006	7.62	9.76	0.371	0.1602
E11	Chi-Chi_Taiwan	TCU089	7.62	9	0.337	0.0934
E12	Landers	Joshua Tree	7.28	11.03	0.275	0.0254
E13	San Fernando	Lake Hughes #12	6.61	19.3	0.376	0.0210
E14	N. Palm Springs	Cabazon	6.06	7.92	0.213	0.0352

Furthermore, Figs (a) and (b) show the pseudo acceleration response spectra of set 1 and set 2 records, respectively. The selected records exhibit a good variability in terms of frequency content and can excite both of the impulsive and convective modes of the liquid storage tank and in some cases, the natural frequency of the tank is very close to the dominant frequency of the records.



(a) records with forward directivity **(b) records without forward directivity**

Figure 6. Pseudo acceleration response spectrum.

3.2.1. Comparison of the hysteretic behavior of steel and SMA anchor bolts

In this section, a comparison is made between the behaviors of tanks anchored with the optimal SMA and steel anchor bolts. Fig. 7 (a)-(d) illustrate the tank uplift with respect to the axial force of the bolt for E1, E2, E8, and E9 earthquake ground motions. With reference to these figures, SMA bolts demonstrate a significant energy dissipation through stable hysteresis loops except for the E1 record, which is not strong enough to cause nonlinear behavior. The self-centering characteristic of SMA anchor bolts is evident in these figures, which favors the seismic performance of the tank through facilitating proper energy dissipation with limited uplift. Furthermore, the hysteretic behavior of SMA anchor bolts is more uniform under near-field ground motions without forward directivity, i.e., E8 and E9 records. However, abrupt changes are observed in the hysteresis loops under near-field ground motion with forward directivity E2 due to its pulse-type characteristic.

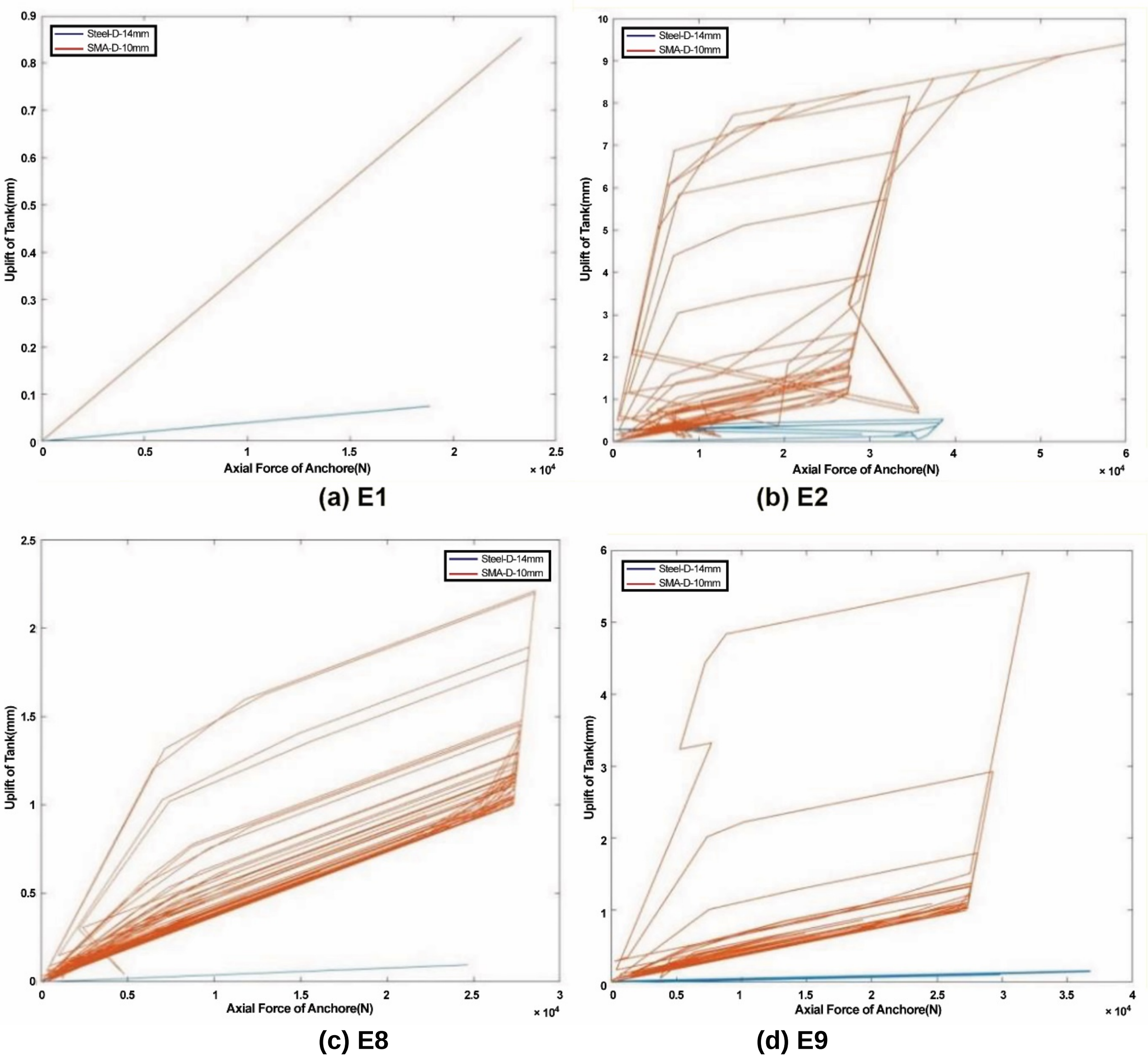


Figure 7. Comparison between hysteretic behavior of steel and SMA anchor bolts under different earthquake records.

3.2.2. Incremental Dynamic Analysis (IDA)

Incremental dynamic analyses (IDAs) are performed on tanks anchored with steel and SMA bolts with different axial stiffness to gain insights into their seismic performance under a wide range of earthquake severities. It should be noted that the tank uplift is selected as the engineering demand parameter (EDP) in IDAs. Furthermore, the uncertainties associated with seismic input including uncertainties in seismic intensity and record-to-record variability are taken into account. The uncertainties associated with the intensity of the seismic event are addressed by defining an Intensity Measure (IM). In the present work, peak ground acceleration (PGA) is selected as IM, which is varied in the range of 0.1–1.0 g. On the other hand, the uncertainties for a fixed intensity are taken into account by employing a set of near-field ground motion records with and without forward directivity as given in Table 4, which are scaled to a common value of IM.

3.2.2.1. IDAs of tanks anchored with steel bolts

Fig. 8(a)-(d) show the IDA results of tanks anchored with steel bolts subjected to E1, E2, E8, and E9 earthquake records.

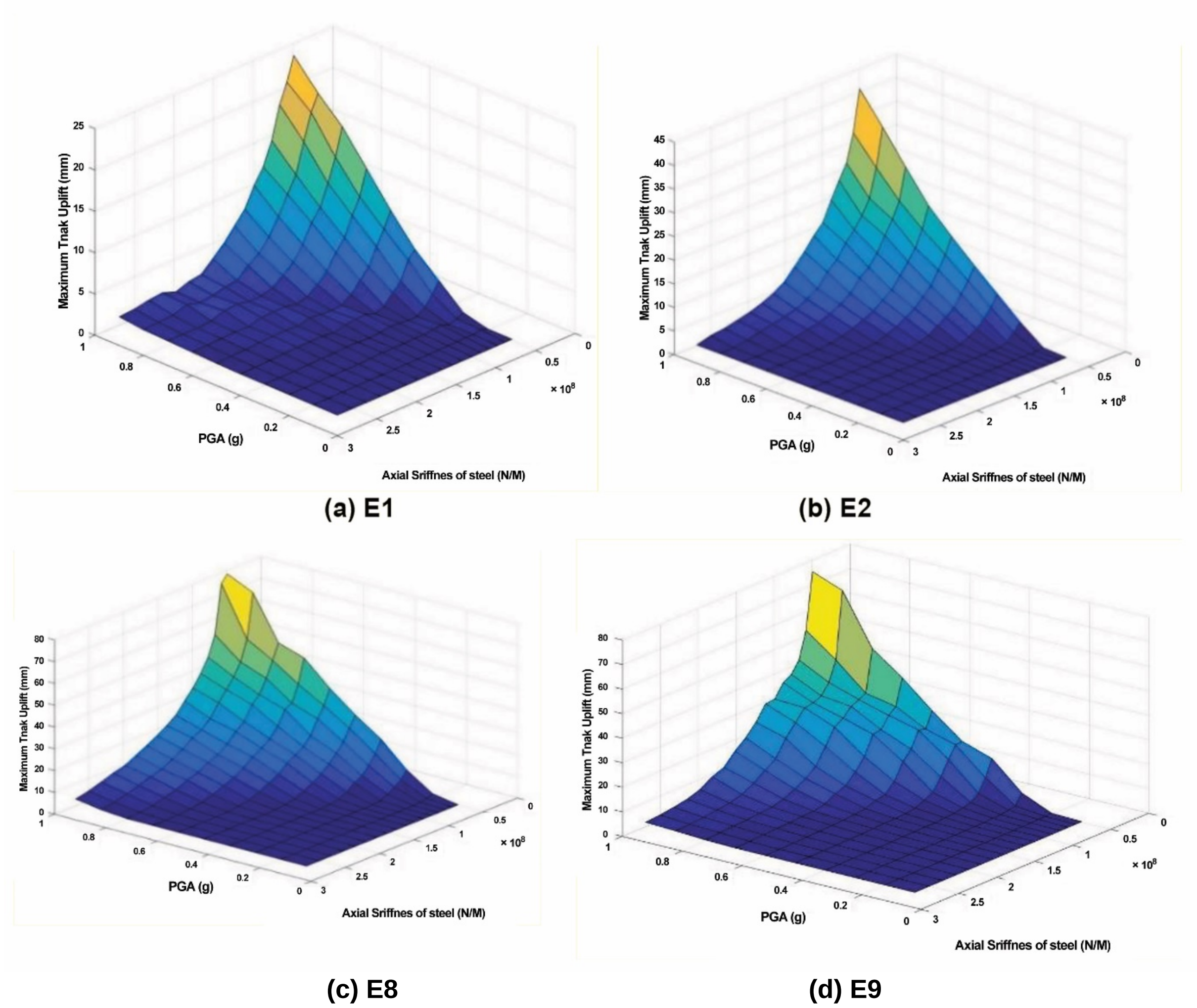
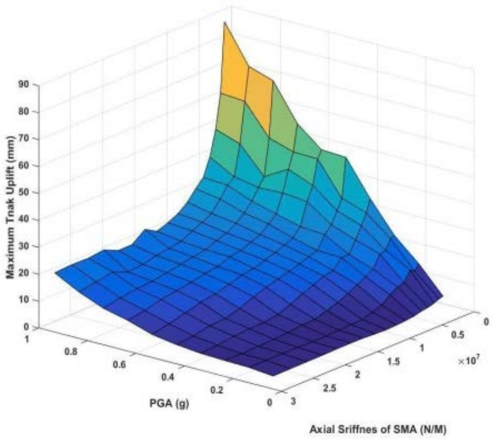


Figure 8*.* IDA results of tanks anchored with steel bolts.

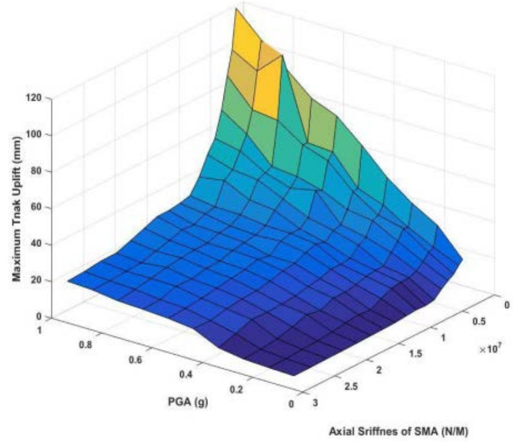
As it can be observed, the maximum tank uplift under each of these earthquake ground motions decreases with increasing axial stiffness of the steel anchor bolt: at very high axial stiffness of steel anchor bolt, the uplift of the tank approaches zero and the bolt rigidly moves with tank. Conversely, the tank uplift escalates with decreasing stiffness of the bolt, which can result in instability of the system. In order to control the displacement in the tank, the stiffness of the restraints must be defined, because if the stiffness is high, it may cause serious damage to the tank, and if it is low, energy dissipation may not be done by the anchor. Note that the range of stiffness defined in this study was based on engineering judgment and trial and error. Furthermore, it is observed that the frequency content of the seismic input has a profound influence on the uplifting behavior of liquid storage tanks. Given a constant stiffness of the anchor bolt, the tank subjected to a near-field earthquake ground motion record with forward directivity exhibits a notably larger uplift than the same tank subjected to a record without forward directivity. For the sake of illustration, for a fixed axial stiffness of 0.5×107 N/m and PGA of 1.0 g, the uplift of the tank subjected to the record E9 is approximately 78 % larger than that of the tank subjected to the record E2. This can be attributable to the pulse-type nature of near-field ground motions with forward directivity, which exerts a very large amount of input energy on the structure in a very short period of time.

3.2.2.2. IDAs of tanks anchored with SMA bolts

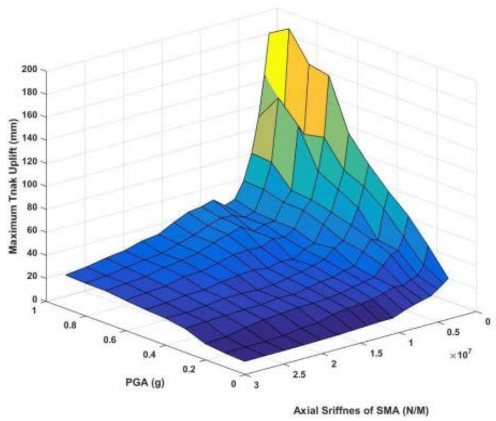
Figs. (a)-(d) demonstrate the IDA results of tanks anchored with SMA bolts subjected to E1, E2, E8, and E9 earthquake records. Similar to the tanks anchored with steel bolts, the maximum tank uplift reduces with increasing values of the bolt's stiffness. Unlike steel bolts, SMA bolts exhibit nonlinear behavior when PGA exceeds a certain value. This is beneficiary to the seismic performance of the tank, since the SMA bolt dissipates energy through nonlinear deformation. Furthermore, the uplift of the tank anchored with SMA bolts is considerably larger than that of the tank anchored with steel bolts. As a case in point, for an equal axial stiffness of 0.5×10^7 N/m and PGA of 1.0 g, the maximum uplift of the tank anchored with SMA bolts is approximately 300 % larger compared to that of the tank anchored with steel bolts under E2 earthquake record. In fact, the self-centering feature of SMA materials enables the tank to undergo a limited uplift which in turn enhances the seismic performance of the tank through energy dissipation and reducing the force transmitted to the tank. Moreover, comparing the uplifting behavior of the tanks anchored with SMA bolts under near-field ground motions with and without forward directivity indicates that they are less sensitive to the frequency content of the seismic input. The tank's uplift under the record E9 is about 17 % larger than that obtained under the record E2 for axial stiffness of 0.5 × 107 N/m and PGA of 1.0 g, whereas the corresponding value for the tank anchored with steel bolts is 78 %. Therefore, it can be concluded that SMA anchor bolts show a satisfactory performance under both near-field earthquake ground motions with and without forward directivity.



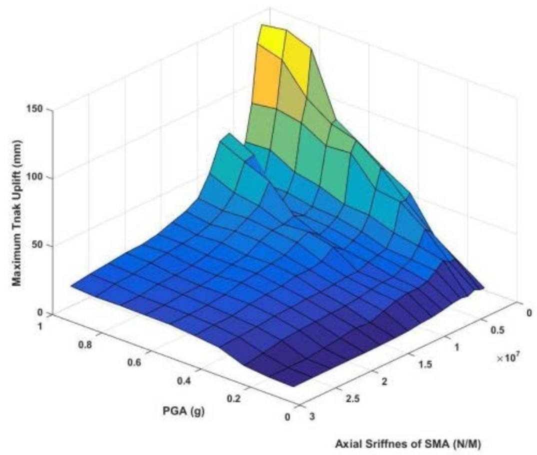
(a) E1



(b) E2



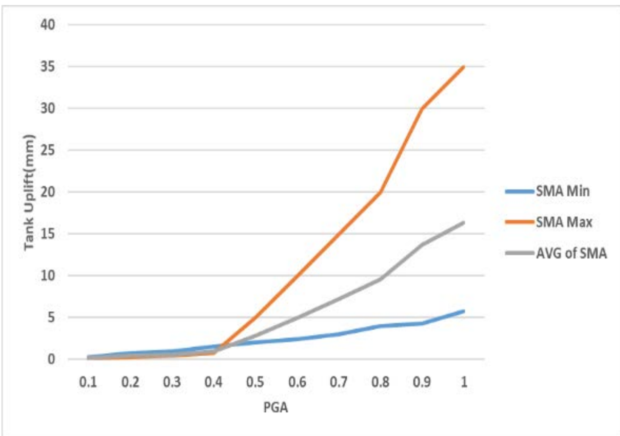
(c) E8



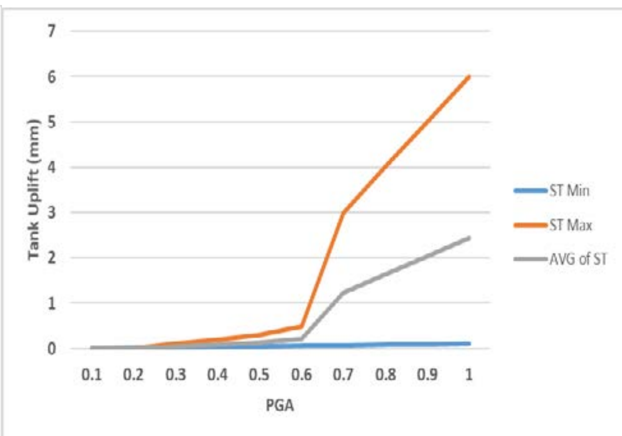
(d) E9

Figure 9. IDA results of tanks anchored with SMA bolts.

In Fig. 10, maximum, minimum and average uplift values of SMA anchor are compared with steel anchor in different PGAs.



(a) SMA anchor



(b) Steel anchor

Figure 10. Maximum, minimum and average uplift of tank.

As shown in Fig. 10, the average uplift in tank with SMA is 15 times that of the tank with steel anchor. Therefore, the SMA is allowed limited and controlled lifting.

4. Conclusions

Since most of the anchors used so far in the research and construction of tanks are made of steel, they usually suffer from multiple damages after the earthquake. The use of the SMAs results in the return of deformations and the absence of residual deformation in the anchors, which provides service after the earthquake.

This study investigates the viability of using SMA materials as anchor bolts in liquid storage tanks subjected to seismic excitation, which has not been studied yet. For this purpose, the seismic response of an existing steel liquid storage tank anchored with steel and SMA anchor bolts is evaluated in order to compare the performance of SMA bolts with steel bolts. First, a parametric study is carried out to determine the relatively optimum diameter and length of the anchor bolts based on the tank's uplift. Thereafter, IDAs are performed to gain insights into the seismic response of steel liquid storage tanks anchored with steel and SMA bolts with varying axial stiffness. In the analyses, the record-to-record variability and uncertainties in seismic intensity are taken into account. A set of near-field earthquake ground motion records with and without forward directivity is selected as the seismic input for the nonlinear time history analysis of the tank. Based on the analysis, the following results are obtained:

1. Implementing an anchorage system significantly reduces the residual uplift of the tank, which in turn reduces the damage induced by the strong ground motion. Furthermore, high axial stiffness of steel anchor bolts does not allow the tank to undergo a limited uplift, and thus the risk of experiencing a severe damage at the connection caused by high axial forces escalates.

2. The unique characteristics of SMA anchor bolts facilitates a limited uplift, according to the stability equations proposed by codes [8] to reduce the uplift of tanks, which is accompanied by high energy absorption by these anchor bolts under seismic excitations. In addition, using SMA anchor bolts instead of regular steel bolts, reduces the required diameter of anchor bolts. Although SMA anchor bolts undergo a larger deformation than steel anchor bolts during earthquake excitation, their residual deformation is close to zero, and therefore there is no need to replace them after a severe earthquake.

3. The residual deformation in steel anchor bolts under severe ground excitation can be so large that makes performs and necessitates the replacement of the anchorage system, which imposes a great cost. Based on the uplifting behavior of tanks anchored with steel and SMA bolts, it can be concluded that SMA bolts are less sensitive to the frequency content of the seismic input and perform satisfactorily under both near-field earthquake ground motions with and without forward directivity.

4. Due to the performance of SMAs, the allowable uplift to the tank anchored with SMA is, on average, about 15 times the uplift in the tanks anchored with steel, because the tank with steel anchors has high axial stiffness than the SMA. In case of uplift in the tank with steel anchors, the anchors and the body of the tank are damaged and must be replaced after the earthquake.

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