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Using a self-centring friction damper as anchorage system for industrial tanks and vessels

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ABSTRACT

The conventional tank's connections make the tanks to be either fully restrained or free for rocking motion, which generally creates a high level of force due to lack of ductility or large displacement demand due to uplift resulting in damage of the tank. However, a more efficient approach is using a partially restrained connection to control both the deflection and force at the desired levels.

An innovative generation of anchorage system has been introduced by employing Resilient Slip Friction Dampers (RSFDs) as ductile self-centring hold-downs for industrial tanks and silos. This new tension-only damage-free anchorage mechanism mitigates the transmitted earthquake force to storage tanks by dissipating the input energy through friction without experiencing any damage, contrary to other common ductile yielding hold-downs.

In this study, based on the validated experimental results, a comparison of the effect of RSFD anchorage system to other ductile concepts (necked-rod and buckling-restrained system) considering three case studies of cylindrical steel storage tanks has been conducted. The proposed damage-free self-centring damper mechanism is capable to considerably decreases the transmitted force to the whole system which leads to less demand for designing a tank's barrel and foundation.

1 INTRODUCTION

Aboveground cylindrical steel liquid storage tanks are vastly used in different industries ranging from the petrochemical industry for storage and processing of liquid or liquid-like material (eg, oil, liquefied natural gas) [1] to winery, dairy, food and beverage industries. Depending on the type of liquid and preserving condition, the type, shape and volume of tanks are different.

The first study of tank behaviour returns to Housner's work [2]. He was the pioneer in proposing a methodology for identifying the seismic actions in storage tanks. In his early studies, the tank was assumed to be rigid, and the hydrodynamic effect of liquid was considered through two separate actions: Impulsive and Slushing motion. The methodology was the basis of several standards such as the provisions of American Petroleum Institute (API), New Zealand Society for Earthquake Engineering (NZSEE) Red Book and NZSEE Guideline for Seismic Design of Storage Tanks [3]. Extensive damage on liquid storage tanks from Chile earthquake in 1960, Alaska earthquake in 1964 and Parkfield earthquake in 1966 inspired researchers to investigate the cause thoroughly. It was found that the hydrodynamic pressure is significantly dependent on the flexibility of tanks wall [4]. Veletsos and Yu [4] considered the liquid tank as a cantilever beam under the horizontal force of an earthquake. They extended the Housner's formulation through investigating the effect of barrel flexibility. They decoupled the impulsive and convective part of a liquid motion through their frequency of movement. These two factors depend on tank flexibility. Also, the height of liquid level could change the hydrodynamic pressure pattern along the storage wall and base plate.

These effects have been studied by Veletsos and Tang [5]. By considering the findings, a design approach for seismic response of anchored and unanchored liquid storage tanks has been presented by Fischer et al. in 1979 [6]. The results were used in Part 4 of Eurocode 8, Annex A (European Committee for Standardization) for the design of cylindrical tanks. API 650 is also a standard dedicated to the general design of liquid storage tanks, developed by the American Petroleum Institute and widely used by the petrochemical industry for the design and construction of petrochemical reservoirs and facilities. Appendix E of API 650 refers exclusively to seismic design and contains provisions for both determining seismic actions on containers and calculating the strength of the tank.

The response modification factors in API 650 appendix and ASCE7, just have been specified for self-anchorage and mechanically anchorage system. Enhancement of the seismic performance of liquid containers, especially strategic tanks or those with valuable contents used in the winery, dairy or petrochemical industry, has been in the center of attention during recent years given the damages and economic loss experienced after severe events. Seismic Design of Storage Tanks NZSEE 2009 [3] has narrowed down the mechanically anchored system according to the ductility and damping. For example, for necked-rod allows engineers to decrease the seismic demand with a lower reduction factor. This approach concentrating damage in a sacrificial element and protect the other elements.

In-field post-earthquake damage assessment of wineries located in Marlborough, New Zealand was conducted following the 2013 Seddon earthquake (Mw 6.5), the 2013 Lake Grassmere earthquake and (Mw 6.6) and the 2016 Kaikoura earthquake (Mw 7.8). According to the gathered information, in 2013, tank base shell (39%) and anchor (47%) parts of the flat-based wine tanks sustained the largest proportion of damage. In the 2016 earthquake, damage to the barrel (54%) and cone (43%) parts of flat-based wine tanks were identified as being most significant [7]. A proper detailing and reliable performance of the anchorage system is a key factor of protecting steel storage tank and their content. Otherwise, the seismic force concentrates in the tank body or in the connections which causes an undesirable performance.

The aim of this study is introducing an innovative ductile hold-down system which decreases the tank's seismic demand by adding flexibility and damping meanwhile remain operational after a seismic event. This system relies on a friction mechanism to dampening the input energy which makes it damage-free at the design level. Since API 650 is still considered as a reference standard specially for designing industrial tanks and vessels, in this study API approach has been followed.

2 RESILIENT SLIP FRICTION DAMPER (RSFD)

Resilient Slip Friction Damper (RSFD) is a friction-based connection which has a self-centring feature to restore it back after full expansion phase. The following figure represents the components of this type of connection. This damper has been introduced and patented by Darani et al. [8] providing a flag-shaped hysteresis response. This new damper addresses the shortcomings of conventional solutions with no post-event maintenance. The input energy is being dissipated through friction which is provided by clamping of the slotted cylinder to the inner shaft using prestressing bolts. The slip force in the damper is set by the prestressing force in the clamping bolts. The self-centring feature of this connection relies on the disk springs, which are pre-stressed to conquer the friction in reverse cycles, providing a resilient system.

In this study based on the patented version of RSFD, a component joint has been redesigned to be compatible with tanks anchorage storages system. The hysteresis performance of the system is shown in Fig 1.

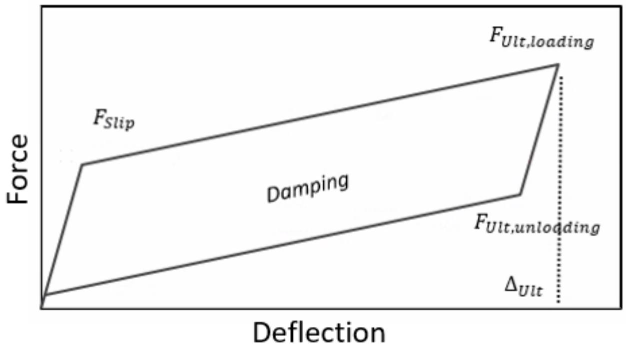


Figure 1: RSFD hysteresis performance

2.1 Component testing

To verify the performance of RSFD, a component joint with an ultimate capacity of about 45 KN and 15 mm deflection has been manufactured and successfully tested. As can be seen in Fig 2, the cyclic result represents the fully self-centring hysteresis response of the joint.

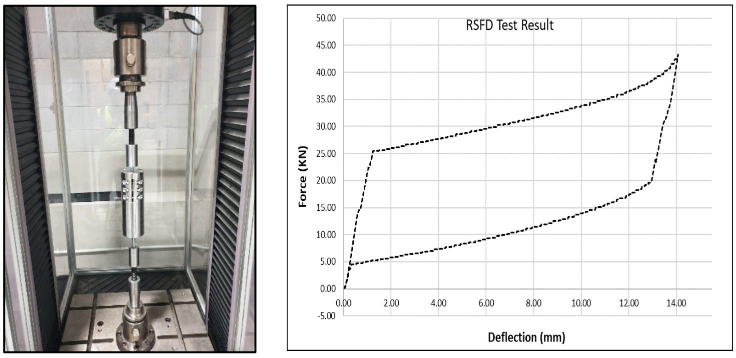


Figure 2: RSFD test setup and performance test result [9]

In the following figure shows the recent version of RSFD with 150KN which have been used for some practical wine projects. In this version, a block has been added to be able to weld the joint directly to a tank.

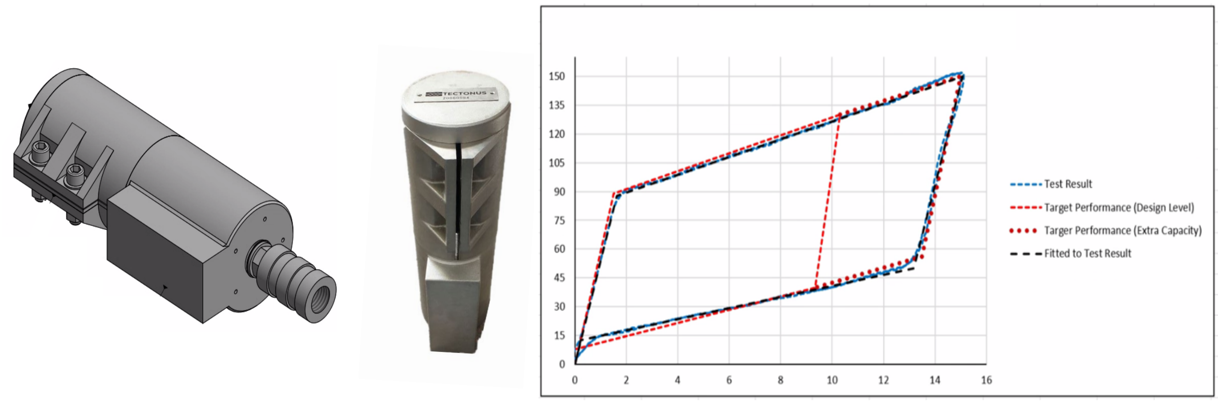


Figure 3: Test result of 150 KN RSFD

The enclosed area of the hysteresis loop represents the damping ratio provided by the RSFD. Added damping and flexibility of this system is tenable and can be efficiently designed according to the demand of the force and deflection.

3 CONVENTIONAL DUCTILE HOLD-DOWNS

Conventional anchorage systems generally include a rod which is anchored to the foundation and acts as a weak point of the hierarchy chain of failure to avoid propagating damage to the other sections. The buckling-restrained anchorage systems are developed as a new generation of such systems which the buckling mode of the rod has been controlled.

3.1 Necked-rod anchorage system

Standard rod or necked rod experience buckling in reverse cycle causing strength and stiffness degradation known as pinching. This stiffness and strength degradation in base connections leads to a different performance path in each cycle, increment in displacement demand and eventually rupture in the worst-case scenarios. Ductility in such systems comes from material nonlinearity so every component must be checked and then replaced if required when an earthquake strike.

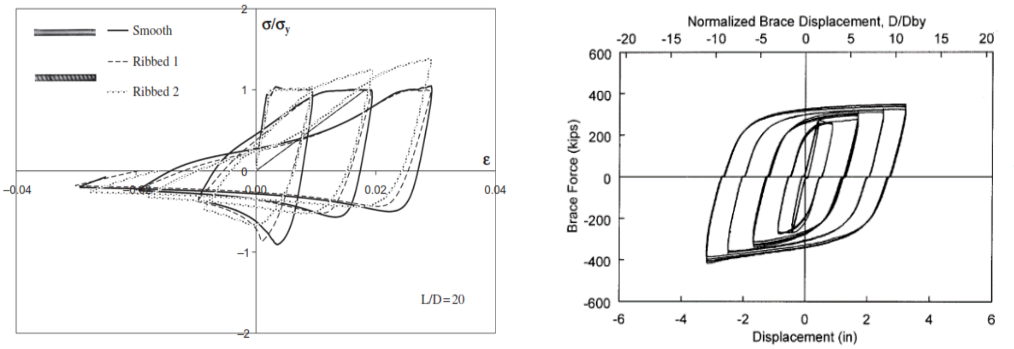


Figure 4: Hysteresis performance of the necked rod [10] (Left); Buckling-restrained behaviour [11] (Right)

3.2 Buckling-restrained system

To control the buckling of the rod, the bucking-restrained mechanisms (through using extra sleeve surrounding the rod) have been introduced. However, such a performance in tanks anchorage system means the possibility of residual displacement and a need for an external force to bring the tank back when weight resisting moment is not enough. In this situation, two possible scenarios could happen:

- The reverse cycle cannot concur buckling force of the rod so there would be residual displacement in the base connection. The more the residual drift, the higher the repairing costs.
- The returning force is at a higher level compared to resisting force, so could bring it back, but creates a high-stress zone on tank body at the gripping end, which could lead to barrel damage. So, the thickness of the barrel around the high-stress zone must increase to prevent such failure.

When there is just a rod, buckling mode of the anchorage system dominates as a weak chain of the system. In rod with sleeve (controlled bucking mechanism), tank body at the gripping point becomes vulnerable. Another issue with buckling-restrained connections is their high rotational stiffness due to the sleeve part, which also causes additional induced stresses in the tank body.

4 CASE STUDIES

In this research, the performance of anchorage systems including necked-rod, buckling-restrained and RSFD anchorage system have been investigated through three case studies as per specs of table 1:

Table 1: Summary of the significant test properties.

Case Study	Capacity (m^3)	H (m)	D (m)	H/D
Case 1	395	5	10	0.5
Case 2	295	15	5	3
Case 3	490	25	5	5

The tanks assume to be in a zone with site class of D, $S_s = 2.31, S_1 = 0.73$, and the seismic use group of I=1. For each scenario, the hold-downs are designed to satisfy the demanded overturning moment (API 650):

$$A_i = S_{DS}\left(\frac{I}{R_{wi}}\right) \quad (1)$$

$$A_c = KS_{D1}\left(\frac{I}{R_{wc}}\right) \quad (2)$$

$$M_{rw} = \sqrt{[A_i(W_iX_i + W_sX_s + W_rX_r)]^2 + [A_c(W_cX_c)]^2} \quad (3)$$

A_i,A_c:Impulsive and convective design response spectrum acceleration coefficient, %g

S_{DS}:The design, 5% damped, spectral response acceleration parameter at short periods (T = 0.2 seconds)

I:Importance factor

R_{wi},R_{wc}:Force reduction factor for the impulsive and convective mode

K:Coefficient to adjust the spectral acceleration from 5 % to 0.5 % damping

S_{D1}:he design, 5 % damped, spectral response acceleration parameter at one second

W_i,W_s,W_r,W_c: Impulsive portion of the liquid weight, weight of tank shell, fixed tank roof, convective portion of the liquid weight

X_i,X_c:Effective Impulsive, convective height

X_s,X_r:Height from the bottom of the tank shell to the roof, shell center of gravity

In the following step, the performance of a system has been studied through a nonlinear time history analysis. To perform NTHA, spring-mass analogy according to the API 650 equations have been used (impulsive and convective mass as well as correspondent height). In this regard, a suite of seven ground motions has been scaled to match ASCE 7 spectrum in line with the assume seismic factor. In this study tanks' wall have been designed to remain elastic and ductility is provided just through the hold-down system.

The response modification factor (R) constitutes of three terms of ductility, damping and over-strength factor [3]:

$$R = R_\mu R_\beta R_\Omega \quad (4)$$

The performance of the hold-down system is reflected in R factor, so in this study, the transmitted forces of each system are compared based on the resulted R factor. The over-strength factor is deducted from R to ensure that the connections, tank body and foundation are design to the maximum force of the hold-down system. The over-strength factor according to ASCE 7 for mechanically anchor system is 2. The comparison in the following section has been done based on the average of the selected ground motions.

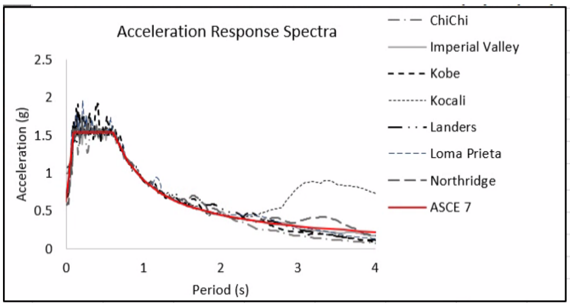


Figure 6: Scaled selected ground motions

4.1 Necked-rod anchorage system

The hold-down's necked-rod diameter and grade for each tank are achieved as below:

Table 2: Necked-rod hold-down specifications

Case	Num of hold-downs	Fy (Mpa)	Necked-rod diameter (mm)
Case study 1	20	300	22
Case study 2	28	300	40
Case study 2	46	500	40

The backbone of the necked-rod has been achieved from the result of FEM software (SeismoStruct 2020) verified with [4] for 100 mm length of the rod. For example, for M22 rod the hysteresis graph and backbone are as below:

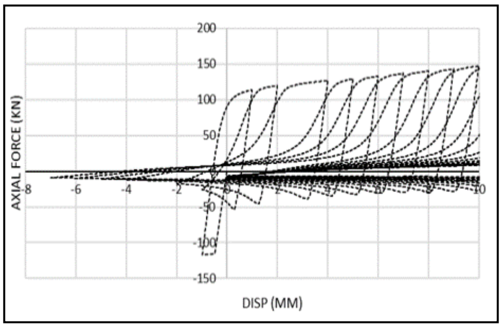


Figure 7: The hysteresis performance of a M22 (G300) derived from FEM model

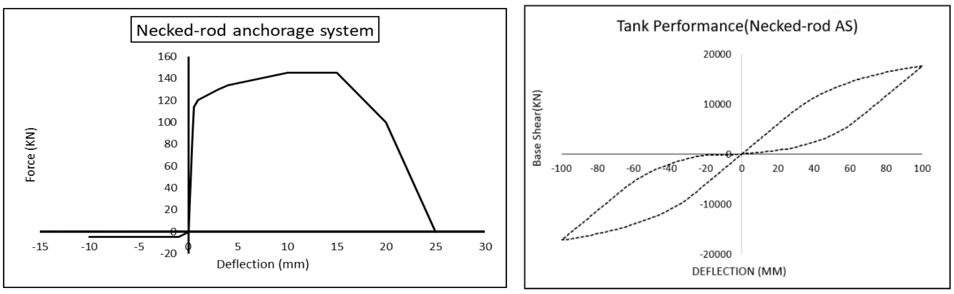


Figure 8: The backbone extract from the hysteresis curve (M22 G300)(left); the hysteresis behaviour of tanks (Case study 2) with 28 M40 necked-rod (Right)

The $R_\mu R_\zeta$ factor is deriving of from the ratio of the force demand of the elastic system over the ductile system and R_Ω is based on the force demand to the design force level. To determine the R_Ω, Since there could be a difference between numerical results to the code's values, the records have been scaled to get the same overturning moment in case of the fully elastic hold-down system.

Table 3: Necked-rod response modification factor

	R (design)	$R_\mu R_\zeta$	R_Ω	$R = R_\mu R_\zeta R_\Omega$
Case 1	4	1.26	3	3.8
Case 2	4	1.54	2.61	4.0
Case 3	4	1.56	2.46	3.9

As can be seen, the R_Ω result of this system is more than 2 which is proposed in ASCE 7, which means a higher level of the force are transferred to the tank body, connection, and foundation.

4.2 Buckling restrained anchorage system

For the anchorage system using buckling-restrained rods, the yielding point calculation would be the same as necked rod case. In this study, this system has been designed for a range of R factor from 4 to 6:

Table 4: buckling-restrained hold-down specifications

Case	R factor	Num of hold-downs	Design capacity (KN)
Case study 1	4	16	118
Case study 1	5	14	118
Case study 1	6	10	118
Case study 2	4	28	295
Case study 2	5	22	295
Case study 2	6	18	295
Case study 3	4	76	295
Case study 3	5	62	295
Case study 3	6	50	295

In the following figures the backbone of the 295KL tank with 22 of 295 KN capacity of the buckling-restrained link have been depicted:

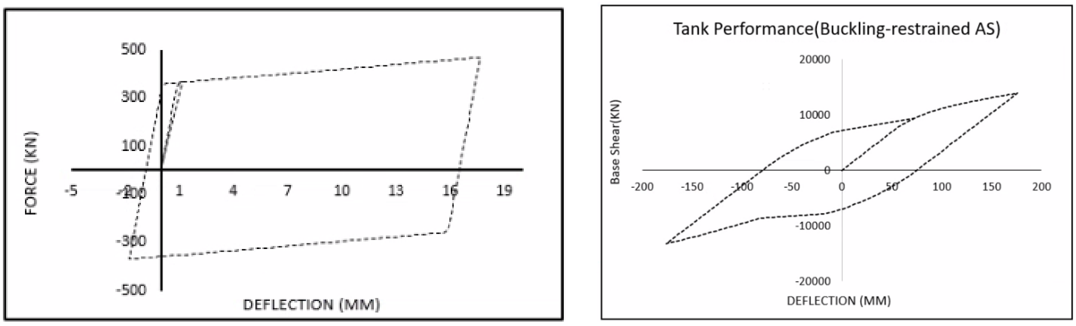


Figure 9: The hysteresis behaviour of Buckling-restrained used in the Case study of 2 and 3 (Left); The hysteresis behaviour of tanks (case study 2) with 28 M40 necked-rod (Right)

The derived $R_\mu R_\zeta$ and R_Ω factor for this concept are illustrated in table 5. The contribution of the over-strength factor in final R factor is more the assumed value (R_Ω=2). In this case, if the over-strength factor supposed to be limited to a maximum value of 2, R factor must be decreased.

Table 5: Buckling-restrained hold-down response modification factor

Case	R (design)	$R_\mu R_\zeta$	R_Ω	$R = R_\mu R_\zeta R_\Omega$
Case 1	4	1.25	3.16	4.0
Case 1	5	1.29	3.7	4.8
Case 1	6	1.33	4.2	5.6
Case 2	4	1.8	2.1	3.8
Case 2	5	2.05	2.4	4.9
Case 2	6	2.34	2.53	5.9
Case 3	4	1.95	2.05	4.0
Case 3	5	2.06	2.38	4.9
Case 3	6	2.33	2.53	5.9

4.3 RSFD anchorage system

The RSFD hold-downs in this study designed for the ultimate force capacity. RSFD performance is tunable so the efficient arrangement including the slip force, number and capacity for each case study have been determined through the numerical analysis results. RSFD connections have been designed for ultimate strength design per following details:

Table 6: RSFD hold-down specifications

Case	Num of hold-downs	Maximum capacity (KN)
Case study 1	14	200
Case study 2	22	300
Case study 3	44	360

As an example, responses of a single joint and the whole tank system of the case study of number two are presented in the following figures.

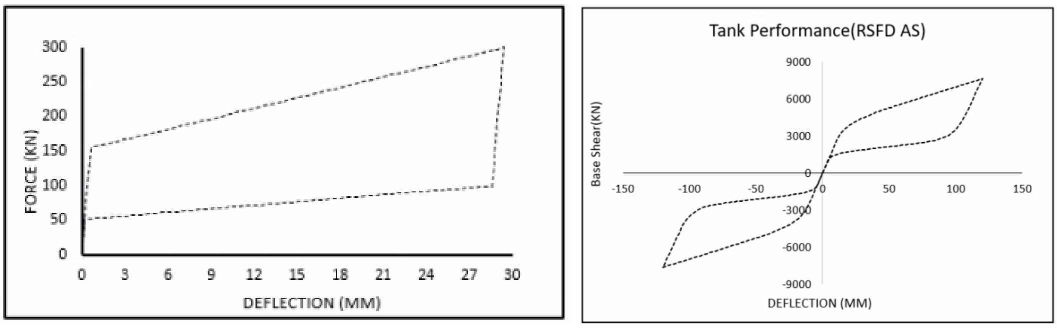


Figure 10: The hysteresis behaviour of RSFD used in the case study of 2 (Left); The hysteresis behaviour of RSFD used in the case study of 2 (Right)

Accordingly, the R factors for RSFD anchorage system are reported in table 7:

Table 7: Buckling-restrained hold-down response modification factor

Case	$R_\mu R_\zeta$	$1.4R_\mu R_\zeta$	R_Ω	$R = 1.4\, R_\mu R_\zeta R_\Omega$
Case 1	1.35	1.89	2	3.8
Case 2	2.41	3.37	2	6.7
Case 3	2.75	3.85	2	7.7

4.4 Residual displacement

RSFD anchorage system is a resilient system which brings back a tank to its original position. The necked-rod anchorage system in the reversing cycle would buckle and the weight of tank and liquid can overcome the resisting force and pull back the tank. The residual displacement is a case for the buckling-restrain system. As the results show, averagely 32% of maximum displacement remain in the connection as residual drifts which required an external force after the seismic event to bring back the storage tanks to their original position. Moreover, the results reveal that the damage is not just subjected to a limit number of joint at both corner rocking motions and a considerable number of the connections required to be replaced after the seismic event.

4.5 Low damage anchorage system: Importance of post-event immediate recovery

Steel aboveground tank's resisting system is considered as structures with minimum redundancy, anchored to the ground with a limit number of connections. Therefore, in such structures, the connection details are key design factors on the force and deflection demands imposed during an event. As rod-based anchorage systems are expected to experience yielding as design level to provide ductility, after a seismic event the structure must be immediately recovered. During the retrofitting time tanks are unarmed, so highly vulnerable to the next sequence of earthquake or aftershocks.

Following the Kaikōura earthquake (New Zealand, 2016) a range of winery facilities in the Marlborough region were instrumented with tri-axial accelerometers to capture seismic excitations during aftershocks [12].

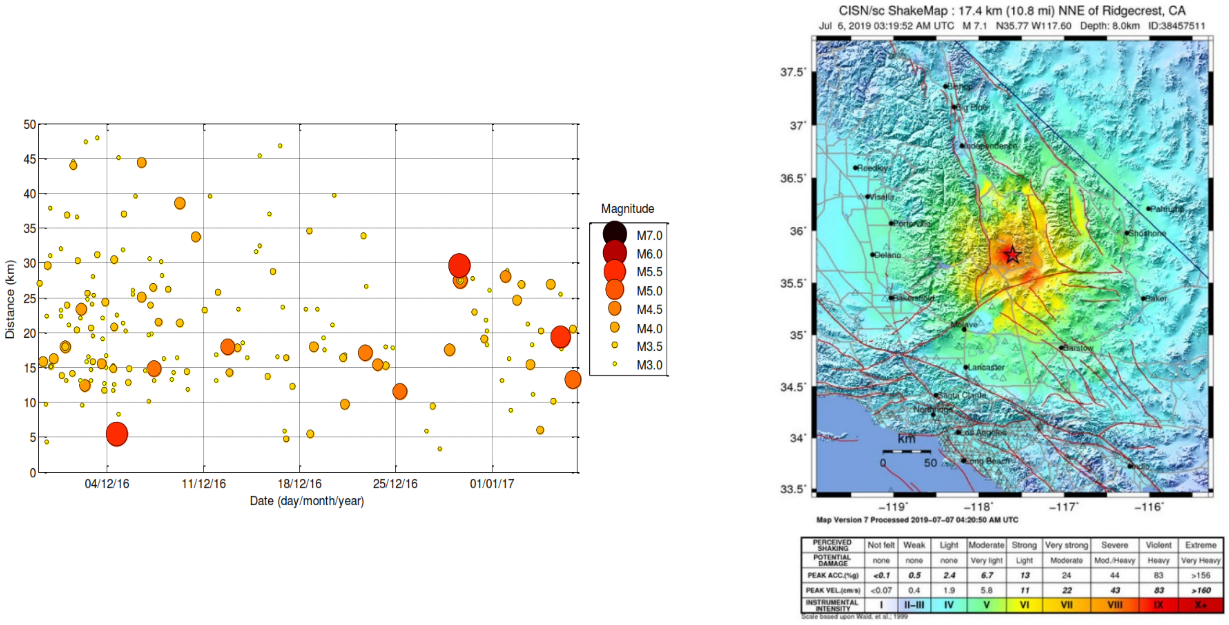


Figure 11: Aftershocks recorded from 28 November 2016 to 7 January 2017 Magnitude of aftershocks within 50 km of Seddon [12] (Left); ShakeMap for the M7.1 July 5, 2019 Earthquake near Ridgecrest [13] (Right)

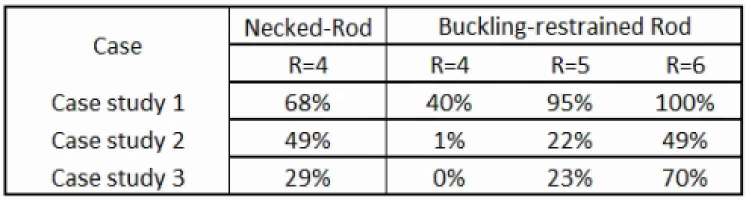
The accelerometers recorded at least 40 aftershock events that resulted in medium to significant levels of observed shaking to various winery structures. The largest recorded excitation was during a MW5.49 earthquake on 4 December 2016, which was located less than 10 km from many instrumented storage tanks. During this MW5.49 event, the recorded accelerations revealed significant amplification in acceleration response up the height of many storage tanks[12].

The recent consecutive earthquakes, the July 5, 2019 magnitude 7.1 earthquake near eastern California's Searles Valley happened which this event occurred about 34 hours after and about 7 miles northwest of a magnitude 6.4 foreshock on July 4, 2019 [13].

In the tanks studied in this paper, almost all hold-downs yield at the design level. Table 8 and 9 report the percentage of the hold-down reaching 10 mm and 20 mm deflection. 10 mm deflection can be assuming almost 50% of deflection of rupture point. According to the results, particularly in the broad tanks and the tanks designed for R factor more than 5, a considerable number of rod-based anchors at a design level will be lost which makes them vulnerable for the next possible events.   Considering the possibility of lack of sufficient resisting system, an immediate inspection and retrofitting operation after an event in a shortest possible time is crucial.

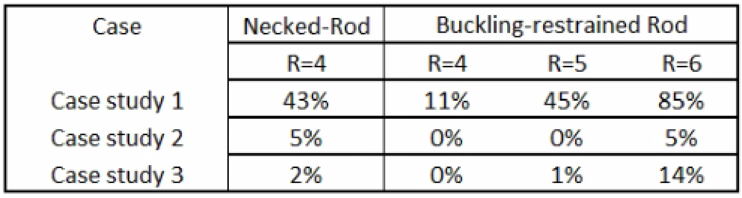
Having a damage-free self-centring connection for such a structure with a minimum degree of redundancy highly improve the reliability of the resisting system and will minimize the post-event maintenance.

Table 8: Percentage of hold-down reach to 10 mm deflection



Case	Necked-Rod	Buckling-restrained Rod		
	R=4	R=4	R=5	R=6
Case study 1	68%	40%	95%	100%
Case study 2	49%	1%	22%	49%
Case study 3	29%	0%	23%	70%

Table 9: Percentage of hold-down reach to 20 mm deflection



Case	Necked-Rod	Buckling-restrained Rod		
	R=4	R=4	R=5	R=6
Case study 1	43%	11%	45%	85%
Case study 2	5%	0%	0%	5%
Case study 3	2%	0%	1%	14%

5 CONCLUSION

In this paper, a new generation of self-centring friction damper (RSFD) has been introduced as an anchorage system for steel cylindrical storage tank. In this regard, based on the RSFD patent, a component joint has been re-design and experimentally tested and its performance analytically and numerically investigated. To investigate the performance of this mechanism three case studies of a cylindrical tank with the aspect ratio of 0.5, 3 and 5 have been employed and the results compared with the two other conventional ductile anchorage system including necked-rod and buckling-restrained anchorage system.

According to the results, R factor of the broad tank is lower than the slender tanks which means these tanks can provide less ductility. $R_\mu R_\zeta$ is the part of R factor which represents the seismic demand for designing the tanks, connections and foundation. Comparing the results shows that tank equipped with RSFD system can be designed at least for 30% less overturning moment. This percentage for a slender tank with necked-rod reach to almost 50%. In this paper also discussed the importance of the immediate recovery after a seismic event especially for necked-rod system and bucking-restrained system with R-value of 6.

RSFD is the only damage-free mechanism and has no stiffness/strength degradation. As long as the force demand is less than the design level, the whole system is in the safe margin, and the tank is equipped for the possible aftershocks or next seismic event. In this regard, RSFD is unique, the only self-centring anchorage system and means saving cost in long term vision.

6 REFERENCES

Maria Vathi, Spyros A. Karamanos. Liquid Storage Tanks: Seismic Analysis. Encyclopedia of Earthquake Engineering.

Housner, George W. "Dynamic pressures on accelerated fluid containers." Bulletin of the seismological society of America 47.1 (1957): 15-35.

NZSEE: Seismic Design of Storage Tanks: 2009

Veletsos, Anestis S., and Yu Tang. "EARTHQUAKE RESPONSE OF LIQUID-STORAGE TANKS." (1977).

Veletsos, A. S., and Yu Tang. "Soil-structure interaction effects for laterally excited liquid storage tanks." Earthquake engineering & structural dynamics 19.4 (1990): 473-496.

Fischer, D. "Dynamic fluid effects in liquid-filled flexible cylindrical tanks." Earthquake Engineering & Structural Dynamics 7.6 (1979): 587-601.

Yazdanian, M., Ingham, J. M., Kahanek, C., & Dizhur, D. (2020). Damage to flat-based wine storage tanks in the 2013 and 2016 New Zealand earthquakes. Journal of Constructional Steel Research, 168, 105983.

A STRUCTURAL CONNECTOR, NZ Patent Office, Patent Number 744156; 2017.

Sahami, Kaveh, Pouyan Zarnani, and Pierre Quenneville. "Earthquake-resilience of storage tanks: using an innovative anchorage system." (2020).

G. S. Prinz, A. Nussbaumer, G. Cortes. Fatigue Analysis of Unanchored Steel Liquid Storage Tank Shell-to-Base Connections during Earthquake Induced Uplift. 15th World Conference on Earthquake Engineering 2012 (15WCEE)

Cyclic Behavior of Smooth Steel Reinforcing Bars: Experimental Analysis and Modeling Issues, A Prota, F De Cicco, E Cosenza - Journal of Earthquake Engineering, 13:4, 500-519

PERFORMANCE OF WINERY FACILITIES DURING THE 14 NOVEMBER 2016 KAIKOURA EARTHQUAKE, Giuseppe Loporcaro, Dmytro Dizhur, Gye Simkin, Marta Garrettson, Alessandro Palermo and Jason Ingham, Bulletin of the New Zealand Society for Earthquake Engineering, Vol. 50, No. 2, June 2017

https://www.usgs.gov/