Earthquake-resilience of storage tanks: using an innovative anchorage system

K. Sahami & P. Zarnani
Auckland University of Technology, Auckland.

P. Quenneville
University of Auckland, Auckland.

ABSTRACT

In this study, a new anchorage system has been introduced by employing the recently developed Resilient Slip Friction Dampers (RSFDs) as ductile self-centring hold-downs for liquid storage tanks. This new anchorage mechanism significantly mitigates the transmitted earthquake force to storage tanks by providing more dynamic flexibility and dissipating the input energy through friction without experiencing any damage in the designed level, contrary to other common ductile yielding hold-downs. The conventional ductile systems such as necked rods include sacrificial elements which experience undesirable damage resulting in strength and stiffness degradation or even failure in severe scenarios. Recently, buckling restrained systems were adopted to control the pinching effect of the necked rods, however resulting is high stress zones in the tank body requiring thickening of wall, not to be cost efficient.

In this paper, a new tank seismic anchorage system has been introduced addressing the shortcomings of the current available solutions. Initially, an experimental component testing has been conducted to demonstrate the RSFD performance. Then, a case study of steel cylindrical storage tanks has been investigated comparing the effect of RSFD anchorage system with other ductile concepts (eg, necked-rod and buckling-restrained system). For this purpose, IDA time history analyses have been performed and the findings have been presented based on the average of a collection of seven ground motions.

Keywords: *RSFD, Resilient Slip Friction Damper, Self-centring, Storage tanks, Energy dissipation, Seismic hold-down*

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 back 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 [13]), 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 the 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 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. In particular, 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 New Zealand Tank Seismic Design Recommendations published in 1986 [7] is also a valuable document containing pioneering recommendations for seismic design of storage tanks, developed by Priestley and a study group from NZSEE. This study group intended to collate the existing information available in the research publications and codes, and ultimately produce uniform recommendations that would cover a wide range of tank configurations and contained materials. The NZSEE guidelines were updated in 2009 [3]. However, the same general performance criteria were maintained from the Red Book. The major updates in this revision are:

- The seismic load is derived from the current national standard for the derivation of seismic loads for buildings in New Zealand, NZS 1170.5.
- A procedure is presented to allow assessment of an appropriate return period factor, Ru.
- A correction factor based on the ductility and damping applicable to tank behaviour is applied.
- Some limited ductility is permitted in steel tanks on grade. This generally reduces the load demands from those given previously.
- The document is presented in a form that can be interfaced with other international design codes.

For this study, the provisions of NZSEE 2009 has been employed for the design of the prototype steel tank.

2 CONVENTIONAL TANK ANCHORAGE SYSTEMS

Conventional anchorage systems (such as standard or necked rods) experience buckling damage in reverse cycles 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. To control the buckling of the rod, the bucking-restrained mechanisms (through using extra sleeve surrounding the rod) have been introduced to the market.
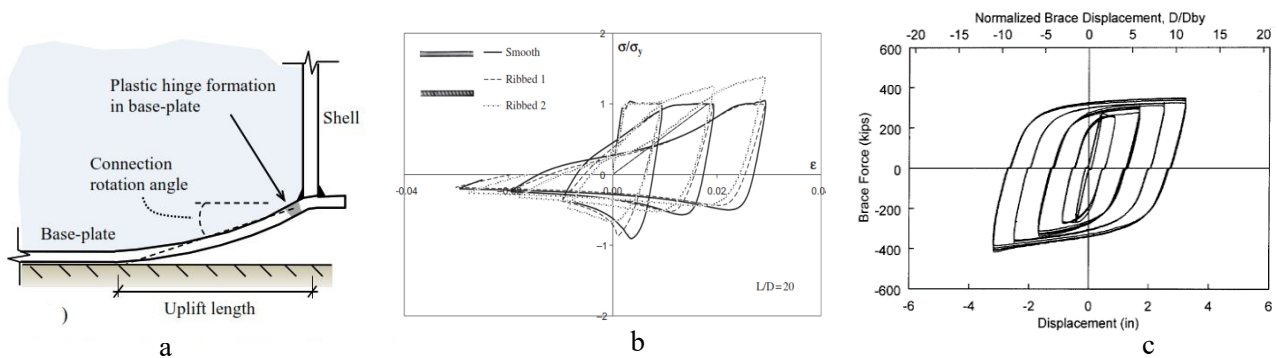

Figure 1: (a) Plastic hinge in the base plate during the uplift [9]; (b) Hysteresis performance of the necked rod [10]; (c) Bucking-restrained behaviour [11]

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.

Figure 2 represents the two possible situations. 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.

Figure 2: Reported damage in Kaikoura earthquake; (a, b) Barrel buckling; (c) Rod rupturing [12]

Paper 67 – Earthquake-resilience of storage tanks: using an innovative damage-free anchorage system

3   RSFD AS A NEW ANCHORAGE SYSTEM

Resilient Slip Friction Damper (RSFD) is a friction-based connection which has a self-centring feature to restore it back after full expansion phase. Figure 3 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 the 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 rely 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 original version of RSFD [8], a component joint has been redesigned to be compatible with tanks anchorage system. The hysteresis performance of the system is shown in Figure 3.
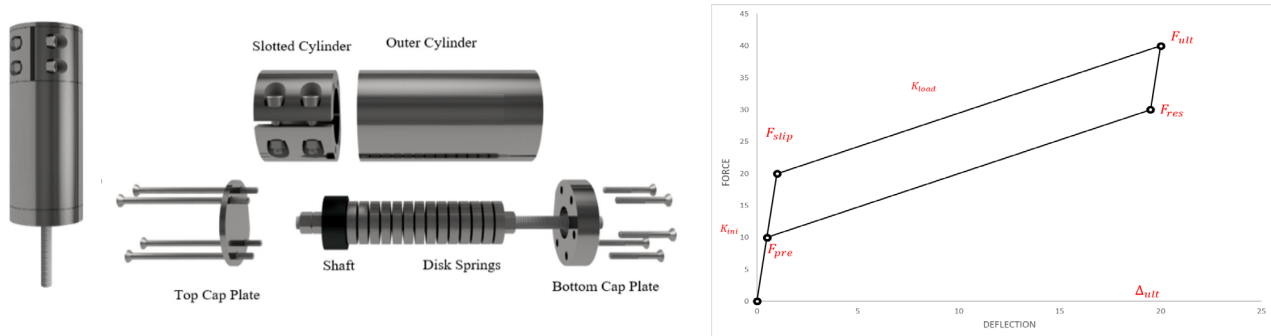

Figure 3: Assembly of RSFD Joint, RSFD hysteresis behaviour

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 Figure 4, the cyclic result represents the fully self-centring hysteresis response of the joint.
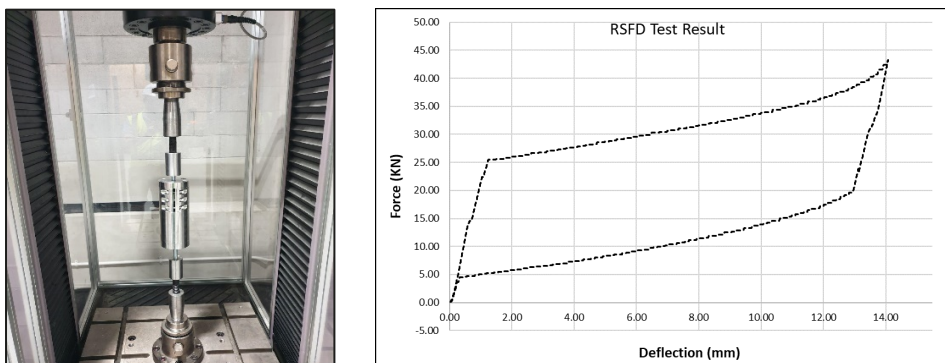

Figure 4: Manufactured RSFD connection for cyclic test

4   CASE STUDY ON A PROTOTYPE STORAGE TANK

In this study, the performance of anchorage systems in three different cases including necked rod, buckling-restrained and the new RSFD anchorage system have been investigated. Assumed seismic coefficients according to NZSEE (2009) for the prototype steel cylindrical tank of 12m in height, 4m in diameter and average thickness of 3mm are summarized in Table 1. Anchorage system contains 32*Ø20 G8.8 necked rods attached with a symmetric arrangement to the tank skirt. Considering a ductility factor of 2 and overstrength factor of 1.25, the base shear and overturning moment are calculated as 1330 kN and 7425 kNm. Following

the code design approach and considering the flexible and rigid parts of the impulsive mode, the seismic mass has been distributed in their corresponding equivalent heights.

Table 1 – Design Parameters

Hazard Factor	0.4
Soil Type	D
Importance Level	1
Design Life	50 Years
S_p	1
μ	2
$N(D, T)$	1
Return Period	1

$$V_i = C_h(T_i)\, N(T_i.D)\, m_i\, g\, S_p\, Z\, R_u\, k_f \tag{1}$$

$C_h(T_i)$: spectral shape factor for the site subsoil type and the relevant mode

$N(T_i.D)$: near-fault factor

m_i : the equivalent mass of tank and contents responding in particular mode of vibration considered.

Z: is seismic zone hazard factor,

R_u : return period factor for the ultimate limit state with a tank importance level

S_p: structural performance factor, to be taken as 1.0.

$k_f(\mu, \varepsilon)$: force reduction due to ductility and the effect of damping. This parameter is used to compare the effectiveness of different anchorage system performances.

For the necked-rod backbone, numerical modelling has been achieved from the result of FEM software (SeismoStruct 2020) based on Menegotto-Pinto steel model verified with [12] for 100 mm length of rod $\emptyset$20.
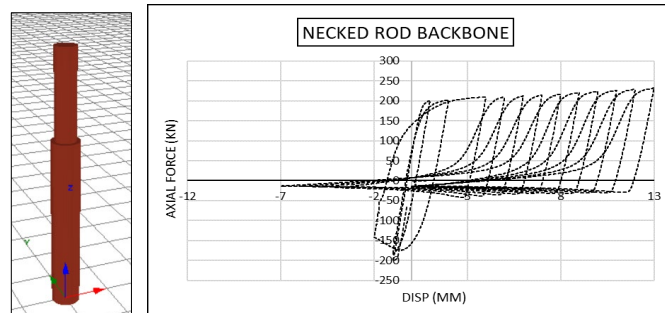

Figure 5: Backbone for rod M20 with a length of 100 mm

For the anchorage system (AS) using buckling-restrained rods, the yielding point calculation would be the same as necked rod case. For RSFD AS, as the disk springs provide the ductility (with no damage even after slipping point), the only limitation for slip force is satisfying the service limit state and wind action, which in this case considered to be half of the ultimate capacity. Push-Pull responses of a single joint and the whole tank sytem for the three concepts are presented in Figure 6.
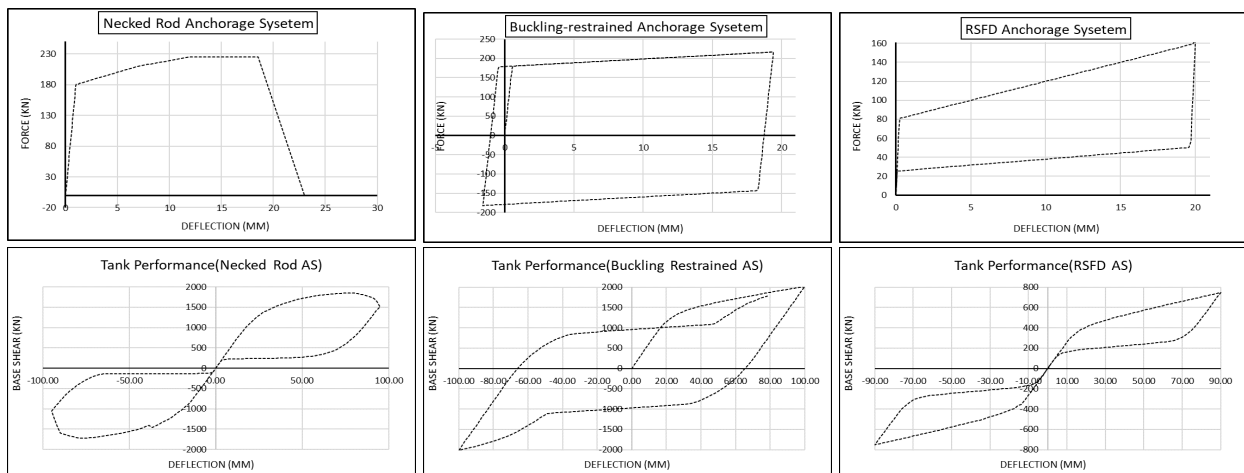

Figure 6: The hysteresis behaviour of joints and tanks for three compared mechanism

5   SEISMIC PERFORMANCE OF DIFFERENT ANCHORAGE SYSTEMS

For non-linear dynamic time-history analyses, a suite of seven ground motions have been scaled to match NZS.1170.5 spectrum with the return period of $R_\mu = 1$, soil type D and $Z = 0.4$. The records details are presented in Figure 7.

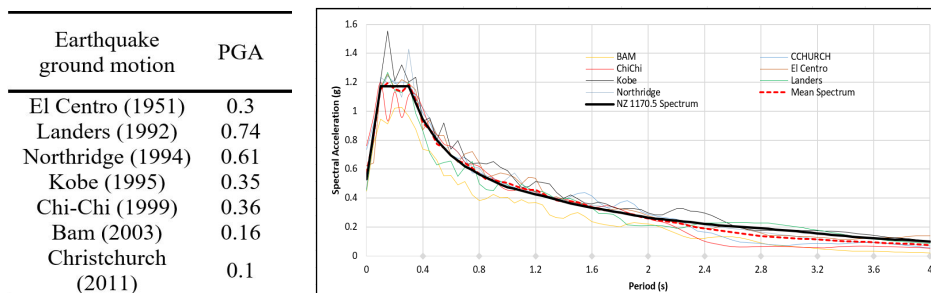| Earthquake ground motion	PGA
El Centro (1951)	0.3
Landers (1992)	0.74
Northridge (1994)	0.61
Kobe (1995)	0.35
Chi-Chi (1999)	0.36
Bam (2003)	0.16
Christchurch (2011)	0.1

Figure 7: PGA and mean spectrum of selected ground motions

In this study, the increment factors for IDA analysis are chosen based on the return period recommended in NZS.1170.5, which could be representative for different case scenarios of importance factor and annual probability of exceedance. Also, all the results are presented by the average of above-mentioned records. The average of base shear for scale factors ranged from 0.25 for SLS level to three times of ULS level, are derived as below:
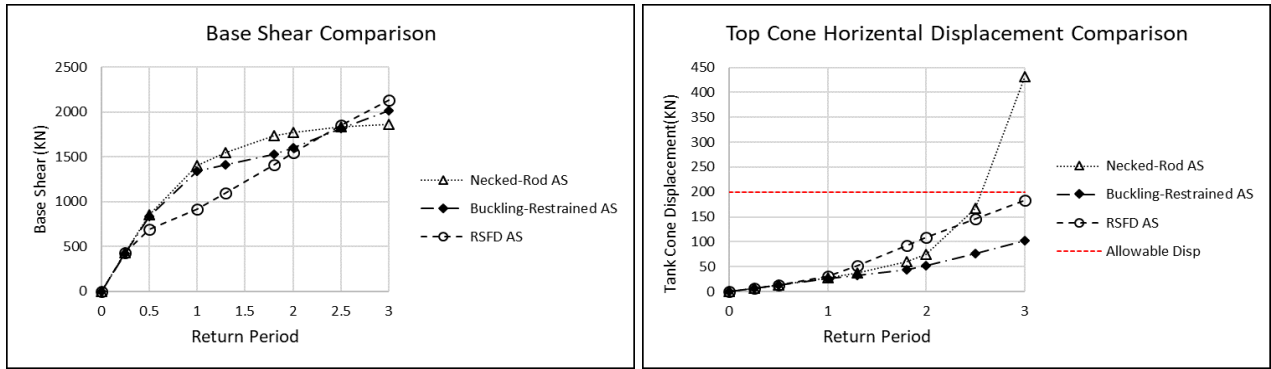
Figure 8: Base shears and top tank's cone displacements subjected to seven selected records
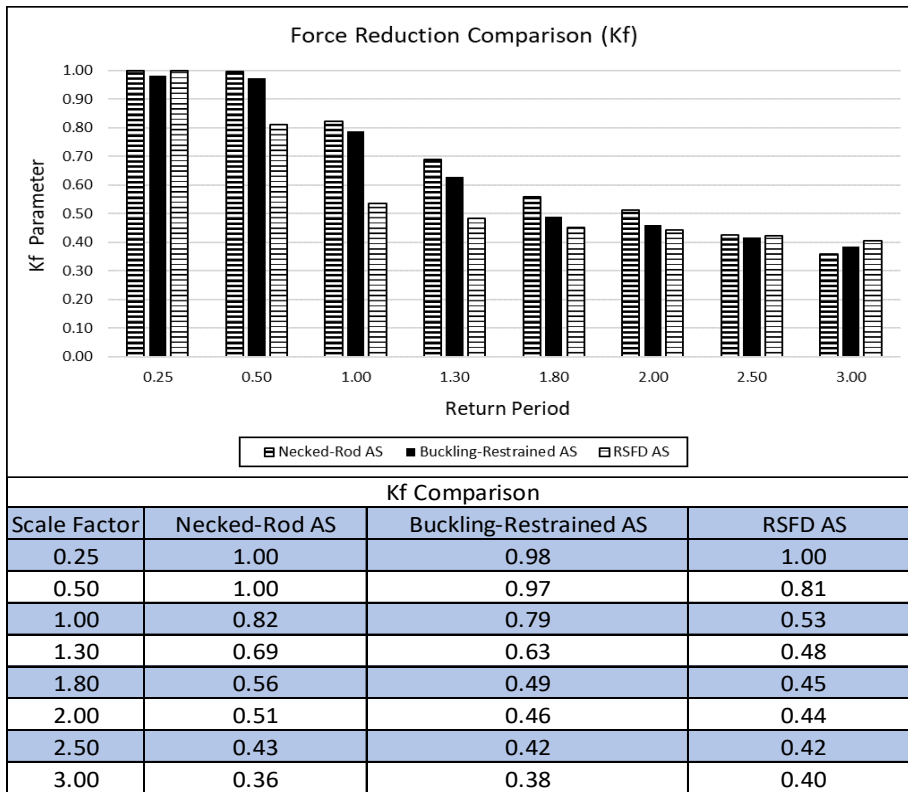

Kf Comparison			
Scale Factor	Necked-Rod AS	Buckling-Restrained AS	RSFD AS
0.25	1.00	0.98	1.00
0.50	1.00	0.97	0.81
1.00	0.82	0.79	0.53
1.30	0.69	0.63	0.48
1.80	0.56	0.49	0.45
2.00	0.51	0.46	0.44
2.50	0.43	0.42	0.42
3.00	0.36	0.38	0.40

Figure 9: k_f values for a different amount of return period

As reported in Figure 9, in case of design level (scale factor =1) for necked-rod and buckling-restrained system $k_f = 0.8$, which is equal to the value recommended by the NZSEE (2009), corresponding to the equivalent of ductility factor $\mu = 2$. While for RSFD, $k_f = 0.53$, which results in about 33% more force reduction compared to the other two mechanisms. Considering the SLS level ($R_\mu = 0.25$), the force level is below the slippage point, so the considered slip force is sufficient. The, results are affected by effective stiffness and damping ratio. So, in case of higher range of scale factors (more than 2), the buckling-restrained system provides a higher rate of damping which results in a lower range of transmitted force. However, the higher level of damping provided by the nonlinearity of material means damage and residual displacement in the connections. For the necked rod system, the higher scale factors could lead to rupture because of stiffness and strength degradation of the necked rod. Another critical parameter to control is the tank displacement, which should be considered for designing the tank equipment such as catwalks and pipelines. The top cone

displacement for all anchorage systems are presented in Figure 8. API recommendation for maximum horizontal displacement is 200 mm, which is assumed to be the upper allowable limit in this study. As the results show for $R_\mu = 1$ for all the cases, almost the top cone displacement are the same.

The hysteresis performances of the tank subjected to Kobe earthquake record under two scale factors of $R_\mu = 1$ & 2.5 are shown in Figure 10.
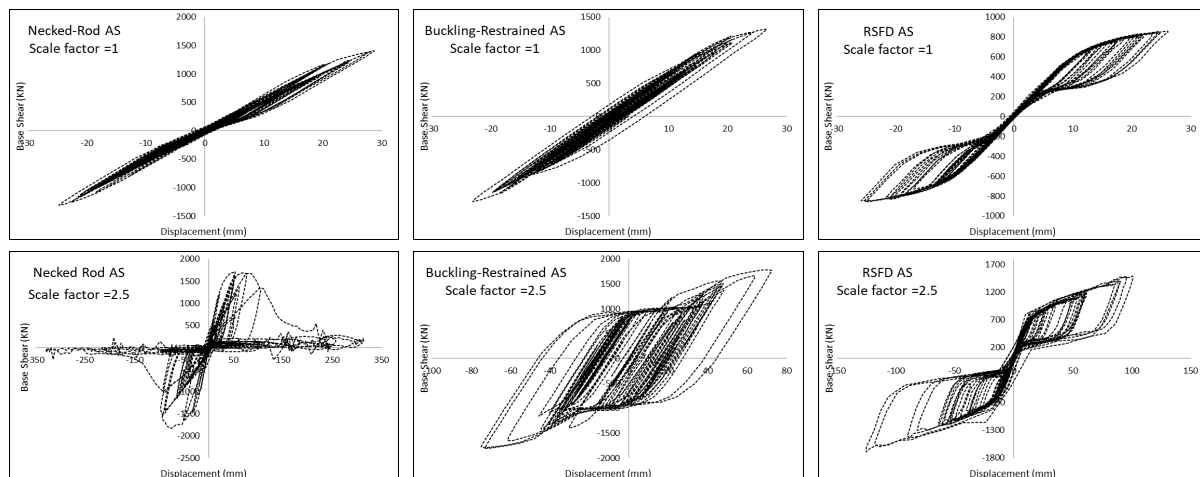

Figure 10: Tank hysteresis for the investigated anchorage systems subjected to Kobe earthquake record

6   RSFD DESIGN AND OVER-STRENGTH FACTOR

Considering the result of the time history analysis in the case of $R_\mu = 1$ which is common for dairy and winery storage tanks, the RSFD specifications for $k_f = 0.53$ (instead of 0.8) is achieved based on Figure 11.
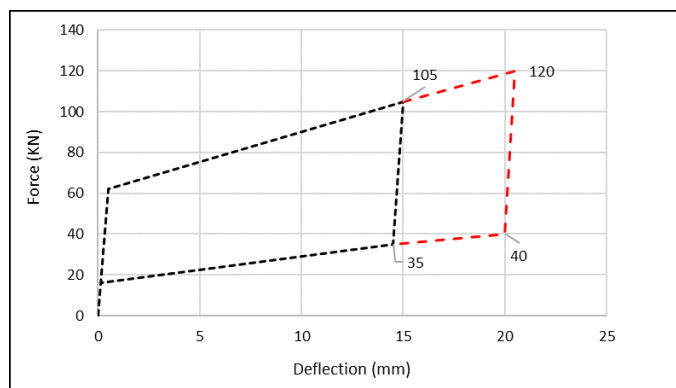

Figure 11: RSFD Re-designed force-displacement capacity

To provide the required performance at MCE level, the joint maximum deflection capacity was designed to be 20 mm after considering a higher scale factor of 1.3 (coming from time history results) compared to the ULS level. Therefore, the over-strength factor would be 1.15 for capacity design of the tank barrel as well as the foundation. This over-strength factor for the necked-rod and buckling-restrained mechanism normally are 1.25 and 1.4, respectively. It should be noted that all the comparisons have been lain on accepting the damage in sacrificial elements in the necked-rod or buckling-restrained system. Recent consecutive strong ground motions such as in Kaikoura, New Zealand (2016) and California, US (2019) once again revealed the importance of minimising the time and cost required for rehabilitation of structures, which is even a more sensitive issue for storage tanks with a lower degree of redundancy. It should be mentioned this k_f is

calculated for this example and for design purposes in each case the k_f the factor must be evaluated base on the tank's specifications.

6.1 Effect of RSFD slip force

In the initial design of the RSFD system, the slip forces were considered to be half of the ultimate capacity at ULS level. However, as this anchorage connection is a self-centring system, the slip force could be adjusted as long as the system does not slip before SLS level force demand. On one hand, the reduction of slip force provides less effective stiffness which decreases the transmitted effects. On the other hand, this would lead to decreasing of the damping rate as well as increasing the tank drift. To evaluate the effectiveness of this factor, a range of slip forces have been defined and the impacts have been studied. The force and displacement results are shown in the following table. While increasing the slip force decrease the force reduction in the system, for the higher Fslip/Fult ratios (more than 60%), the tank displacements are placed at the same level.
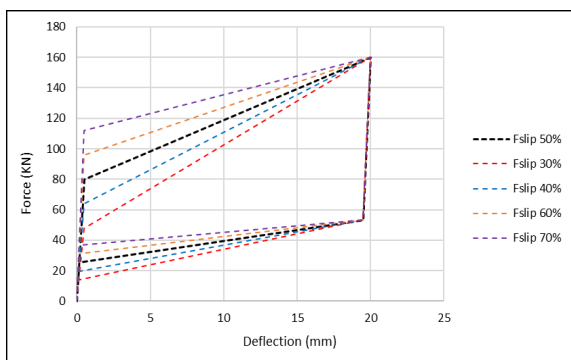
Flip/Fult	Kf	Base Shear (KN)	Top Cone Disp (mm)
30%	0.49	855	43.0
40%	0.52	888	35.4
50%	0.53	918	31.5
60%	0.57	983	28.8
70%	0.63	1071	28.2
80%	0.68	1158	28.4
90%	0.73	1242	28.2

Figure 12: RSFD hysteresis behaviour with different slip force and comparison of different varieties of F_{slip}

6.2 RSFD Dissipation Input Energy

As discussed, the energy dissipation capacity has a significant impact on kf force reduction factor and also deflection demand. Figure 12 contains the graphs displaying the accumulative energy dissipated by RSFD during different earthquakes simulated. As represented, almost half of the input energy channelled to the structure gets dissipated by connections through a reliable friction mechanism (no damages in anchorage connectors in design level). To compare this rate within the other systems, the accumulative dissipated energy by the connections versus the total input energy are shown in Figure 13. These results are based on the average of the selected records. The results reveal that for the scale factor less than 1.5, the RSFD could provide a higher damping rate given having a lower slipping point while for the higher scale factors, the buckling-restrained system could dissipate a higher rate of absorbed energy.
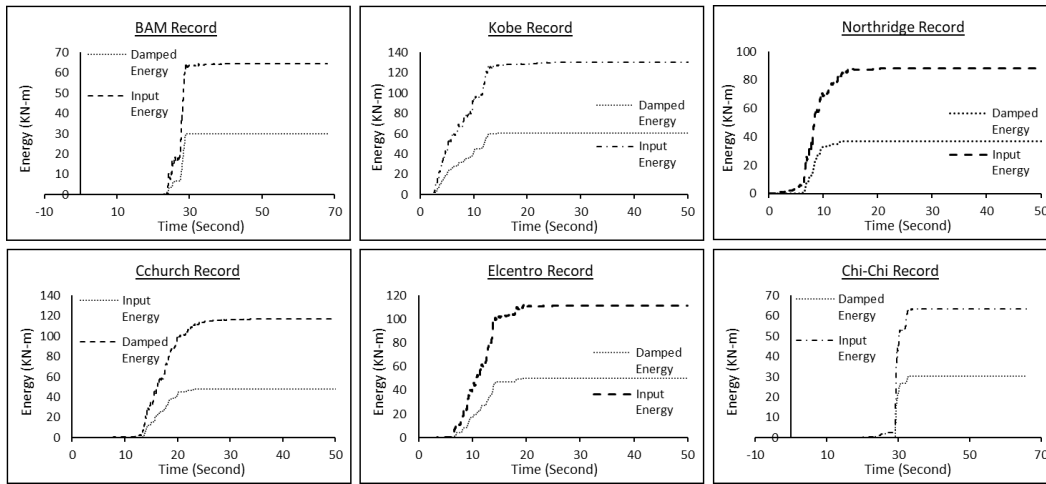
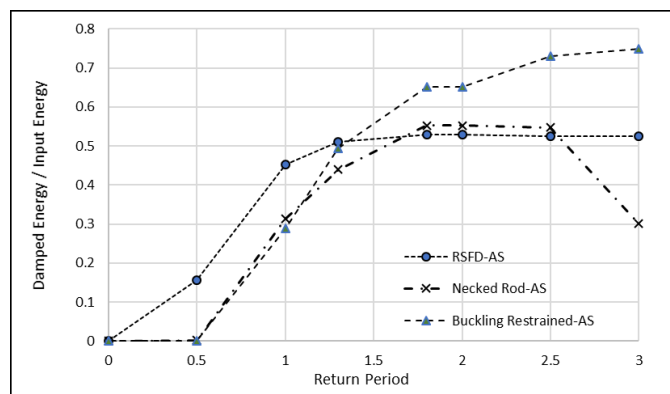*Figure 13: Comparison of accumulative dissipated energy by the connections to the total input energy systems*

Figure 14: Comparison of dissipated energy to total input energy in different anchorage systems

7   CONCLUSION

In this paper, a new generation of self-centring friction damper (RSFD) has been introduced as an anchorage system for steel cylindrical storage tanks. A component joint has been designed and successfully tested, verifying the performance already determined analytically and numerically. To investigate the performance of this mechanism as an anchorage system for storage tanks, a case study of a cylindrical tank with the aspect ratio of three has been employed and the results were compared with the two other conventional ductile anchorage systems including the necked-rod and buckling-restrained anchorage system. This new system prevents the high stress zones to be established in the tank body which would require thickening of it wall to control the buckling, not to be cost efficient with the current solutions.

For the case of $R_\mu = 1$, the RSFD could reduce the tank overturning moment ($with \; k_f = 0.53$) by 33% more than the two other systems while it was providing almost the same displacement demand. The overstrength factor in RSFD system for 20 mm displacement demand is 1.15 compared to 1.25 of the necked rods and 1.4 of buckling-restrained connections. Also, analysing the RSFD slip force effect shows that increasing the slip point leads to a higher rate of k_f factor while for slip forces more than 60%, the

Paper 67 – Earthquake-resilience of storage tanks: using an innovative damage-free anchorage system

displacement almost stands at the same level. Compare to the other anchorage systems, RSFD is the only hold-down mechanism with no stiffness and strength degradation. By incorporating the RSFD, there would be less force demand as well as the tank is well equipped for the possible aftershocks or next seismic event.

REFERENCES

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

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

[3] NZSEE: Seismic Design of Storage Tanks: 2009

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

[5] 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.

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

[7] New Zealand National Society for Earthquake Engineering, and Michael John Nigel Priestley. Seismic Design of Storage Tanks*: Recommendations of a Study Group of the New Zealand National Society for Earthquake Engineering. The Society, 1986.*

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

[9] 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)*

[10] 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*

[11] Analytical and Large-Scale Experimental Studies of Earthquake-Resistant Buckling-Restrained Braced Frame Systems, Larry A. Fahnestock, Lehigh University.

[12] 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*

[13] API 650: Welded Steel Tanks for Oil Storage, American Petroleum Institute 2007.