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INNOVATIVE DAMAGE-FREE ANCHORAGE SYSTEM FOR CYLINDRICAL STEEL STORAGE TANKS

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Abstract

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. The liquid storage systems are anchored to the ground with a limit number of connections and are taken into account as structures with minimum redundancy. Therefore, in such structures, the connection details are key design factors on the force and deflection demands imposed during an event. The conventional 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 because of uplift resulting in severe damage of the tank. However, a new approach is using a partially restrained connection to control both the deflection and force at the desired levels.

In this study, a new ductile anchorage system has been introduced by employing the recently developed Resilient Slip Friction Dampers (RSFDs) as self-centring hold-downs for liquid storage tanks. 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. The self-centring feature of this damper also allows to control and limit the rocking motion of the tank and restore it to its original position, crucial for tanks with large height to base aspect ratios. Therefore, this new system does not require post-event maintenance and is able to resist against the possible aftershocks. The issues with conventional ductile systems (Necked rod, buckling restrained anchorage system), are that they commonly have a sacrificial element which experiences damage which causes strength and stiffness degradation or even failure in a worst-case scenario. Buckling restrained systems proposed to solve this problem but caused another which is inducing resisting force in reverse cycle. Resisting in the return cycle create a high compression zone in the tank body and makes it vulnerable to buckling. In fact, in such systems buckling has been just transferred from connections to the tank’s barrel.

In this paper, first, an experimental component testing has been conducted to represent the RSFD performance. Then, according to the results, to introduce and also compare the effect of RSFD anchorage system to other ductile concepts (necked-rod and buckling-restrained system) a case study of steel cylindrical storage tanks has been investigated. For this purpose, incremental nonlinear dynamic analysis (IDA) has been done, and the results based on the average of a collection of seven ground motions have been represented. This damage-free, tension-only, self-centring mechanism due to the flexibility of design compared to other systems considerably decreases the transmitted force and its tension-only mechanism avoid buckling failure.

Keywords: RSFD, Resilient Slip Friction Damper, Self-centring, Tanks anchorage system, Energy dissipation

1. Introduction (Retrieved by NZSEE 2009 [3])

Above ground cylindrical steel liquid storage tanks are vastly used in the different industry ranging from the petrochemical industry for storage and processing liquid or liquid-like material including oil, liquefied natural gas and so on [1] to winery or dairy industry. Depend on the type of liquid and preserving condition, the type, shape and volume of storages are different.

The first study of tank behaviour return to Housner [2] works, and he was a pioneer in proposing a methodology for seismic action in storage tanks. In his early studies, the tank assumed to be rigid, and the hydrodynamic effect of liquid consider into two separate actions: Impulsive and Slushing motion. The methodology was the basis of the constitutes the basis American Petroleum Institute (2003,2007) Standard provisions and New Zealand standards (NZNSEE 1986 Red Book) and Seismic Design of Storage Tanks NZSEE 2009 [3]. Extensive damages 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, and hydrodynamic pressure was discovered to be significantly dependent on the flexible behaviour of tank walls (Veletsos and Yang 1977 [4]; Haroun and Housner 1981 [5]). Veletsos assumed the liquid tank as a cantilever beam under the force of a horizontal earthquake. They extended the Housner formulation but investigated the effect of barrel flexibility and decoupled the impulsive and convective part of a liquid motion through their frequency of movement. These two factors depend on the flexibility and height level of liquid could change the hydrodynamic pressure pattern along the storage wall and base plate.

These effects have been studied by Veletsos and Tang (1990) [6], and Malhotra (1995) [7]. Then with considering the finding a design approach, the seismic response of anchored and unanchored liquid storage tanks has been presented by Fischer and Rammerstorfer et al. (1979) [8] which the results were used in Part 4 of Eurocode 8, Annex A (European Committee for Standardization 2006b) for to be used by engineers to design cylindrical tanks. API 650 (American Petroleum Institute 2007) 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 reservoirs in petrochemical 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 Seismic Tank Design Recommendations (Priestley et al. 1986 [9]) is a document that, when published in 1986, contained pioneering recommendations for the seismic design of storage tanks, developed by a study group of the New Zealand National Society for Earthquake Engineering [3]. This study group intended to collate existing information, available in research papers and codes, and to 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, which the major changes in this revised document 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 relation of NZSEE 2009 has been employed for the primary design of the steel tank.

2. RSFD as an Anchorage System

Resilient Slip Friction Damper (RSFD) is a friction-based connection which has a self-centring feature to pull it back after full expansion phase. The following figure represents the constituents of this connection. This damper has been introduced and patented by Darani et al. (2018) [10]. RSFD have a flag-shaped hysteresis curve which stiffness, strength and the nonlinearity come from the disk springs align with a friction mechanism.

The friction is provided by stiffening the slotted cylinder to the inner shaft through the clamping bolts. The induced friction force dissipates the input energy and also satisfied part of the required slip force. The stiffness and self-centring feature of this connection rely on the disk spring, which is pre-stressed to conquer friction in reverse cycle and to provide resiliency of the 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.

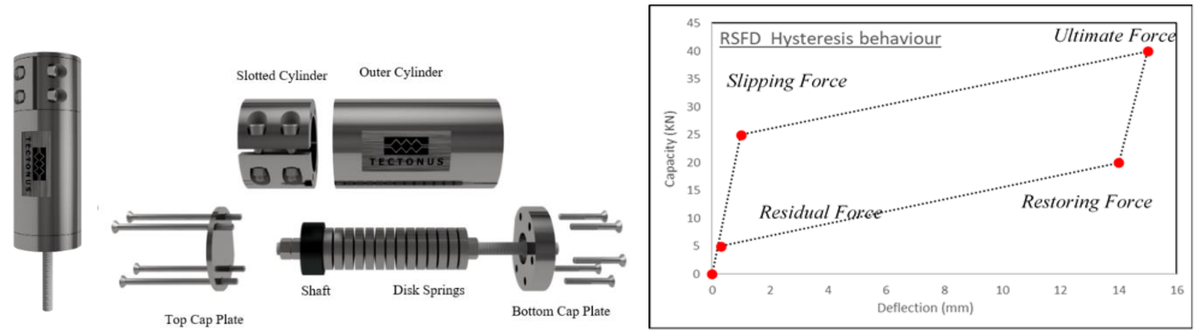


Fig. 1 –Assembly of RSFD Joint, RSFD hysteresis behaviour

To verify the performance of RSFD, a component joint with an ultimate capacity of 40 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 of the joint.

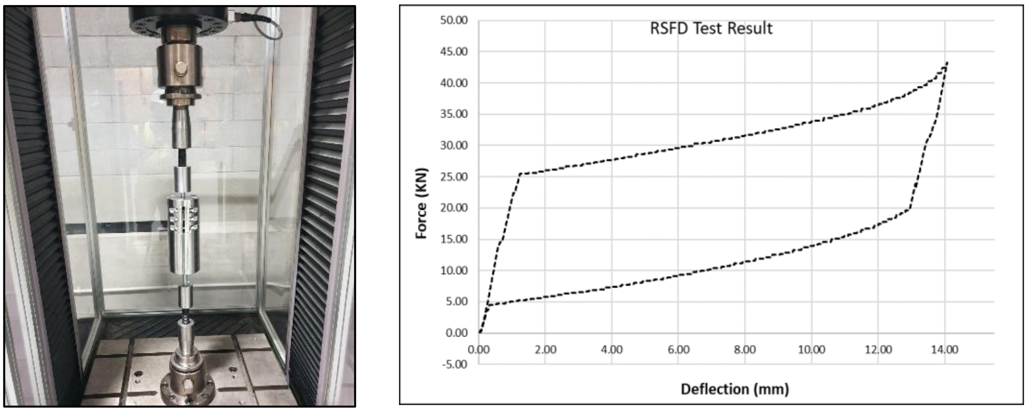
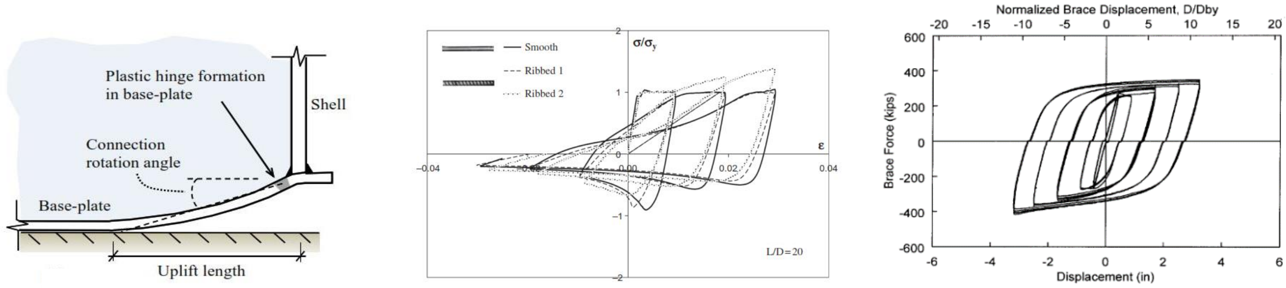


Fig. 2 – Manufactured RSFD connection for cyclic test

3. Advantage of Ductile, Tension Only Connections in Storage Tanks System

This flexibility of conventional anchorage systems (standard or necked rod) satisfied by the rod or even the base plate of tanks and could be subjected of damage (buckling) in reverse cycle which caused strength and stiffness degradation.



a b c

Fig. 3 – (a) Plastic hinge in the base plate during the uplift [11]; (b) Hysteresis performance of the necked rod [12]; (c) Bucking-restrained behaviour [13]

Stiffness and strength degradation in base connections means different path in each cycle, increment in displacement demand and eventually rupture in 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 address this issue, the idea of bucking-restrained mechanism (similar to BRB performance) has been proposed. 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 so there would be residual displacement in base connection.
- The returning force is at a higher level compared to resisting force, so could bring it back, but create a high compression zone in-tank body at the gripping end, which could lead to barrel buckling. So, the thickness of the barrel around the high-stress zone must increase to control the buckling mode. That means while the buckling of the anchorage has been controlled, buckling mode is transferred to the barrel.

Fig 4 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 (control bucking mechanism), tank body at the gripping point would be the fuse. Another issue with buckling-restrained connection is lack of enough rotational stiffness due to the sleeve part, which also causes additional induced stress in the tank body.

Fig. 4 – Reported damage in Kaikoura earthquake; (a, b) Barrel buckling; (c) Rod rupturing [14]

4. Case Study (Steel Cylindrical Storage Tank)

In this research, the performance of anchorage systems in three different cases, including necked rod, buckling-restrained and RSFD anchorage system have been investigated. Assumed seismic coefficients according to NZSEE (2009) for a steel cylindrical tank of twelve-meter height, four-meter diameter and average thickness of 3 mm are summarised in table 1:

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

Anchorage system contains 32 Ø20 grade of 8.8 necked rods attached with asymmetric arrangement to the skirt. Considering the ductility factor of two and overstrength factor 1.25, the base shear and overturning moment are calculated as 1330 KN and 7425 KN.m. Following the code design approach, considering the flexible and rigid part of the impulsive mode, the seismic mass has been distributed in their corresponded equivalent heights.

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

$C_h(T_i)$: 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 factor due to ductility the effect of damping. This parameter used to compare the effectiveness of the anchorage system performances. The necked-rod backbone for 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 Ø20.

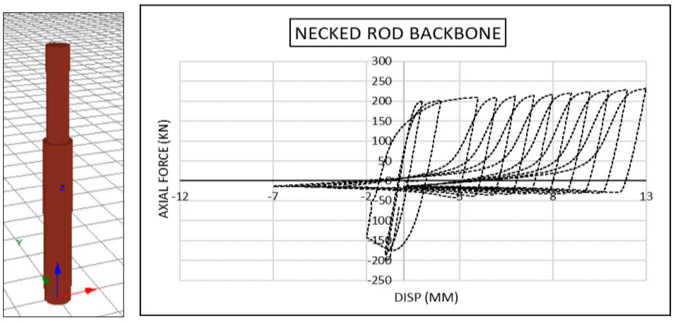


Fig. 5 – Backbone for rod M20 with a length of 100 mm

For buckling-restrained system the yielding point calculation would be the same as necked-rod case. For RSFD, as the disk spring provides the ductility (no damage even after slipping point), the only limitation for slip force is satisfying 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 tank for the three concepts are represented as below:

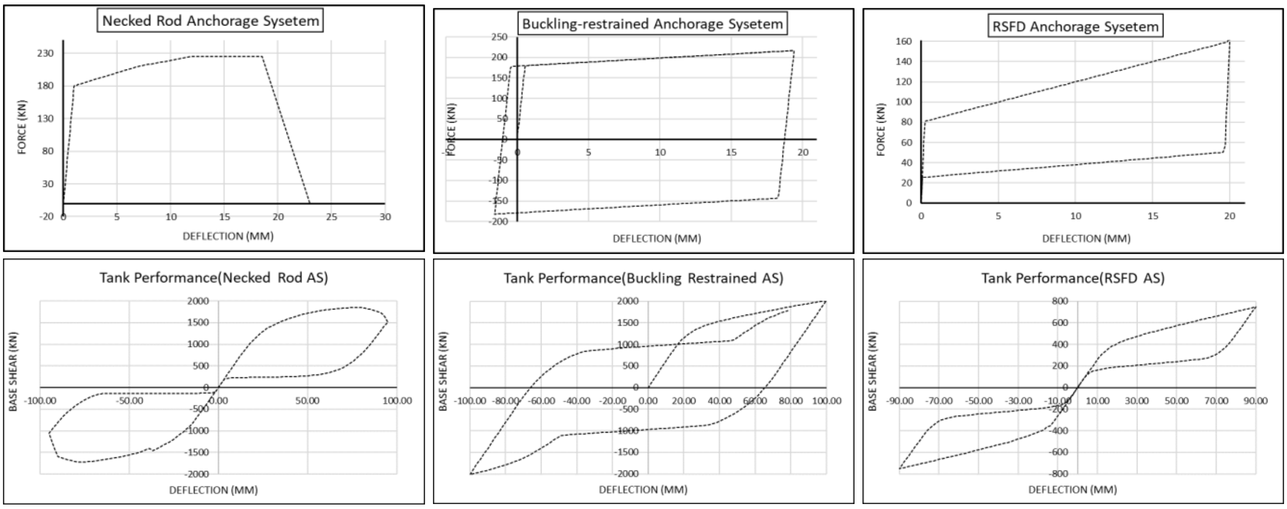


Fig. 6 – The hysteresis behaviour of joints and tanks in three introduced mechanism

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 Fig 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

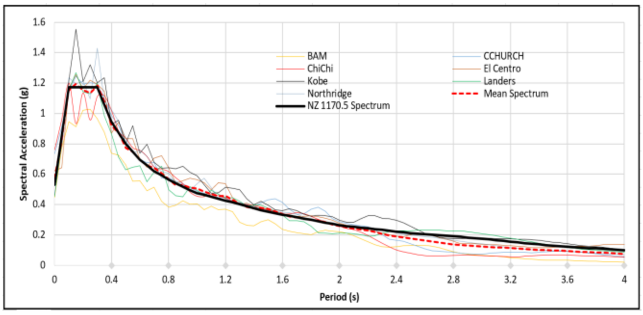


Fig. 7 – PGA and mean spectrum of selected ground motions

In this study, the increment factors for IDA 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 derives as below:

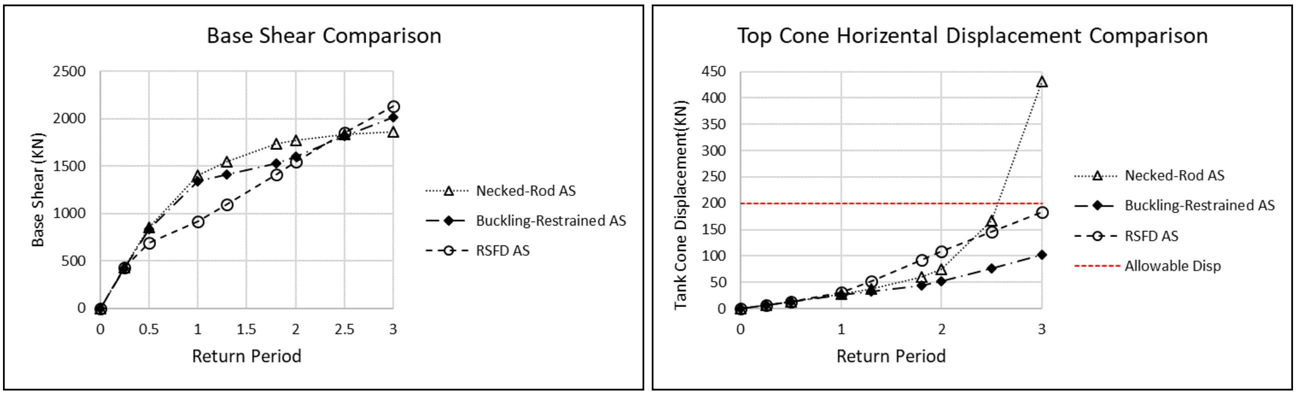
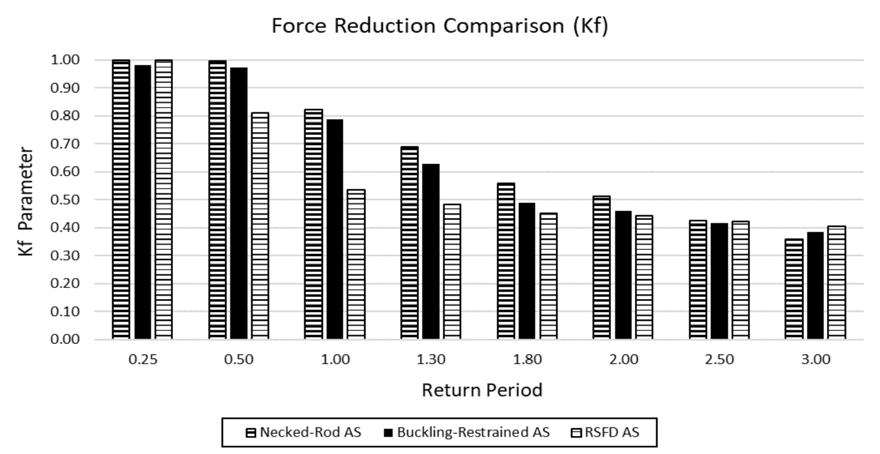


Fig. 8 – Base shears and top tank’s cone displacements subjected to seven selected records



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

Fig. 9: k_f values for different amounts of the return period

As reported in Fig 9, in 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) and the equivalent of ductility factor $\mu = 2$. While for RSFD, $k_f = 0.53$, which means around 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. Results are affected by effective stiffness and damping ratio so in case of top fields of scale factors (more than 2), the buckling-restrained system provides a higher rate of damping and results in a lower range of transmitted force. However, the higher level of damping supplied by the nonlinearity of material, means damage and residual displacement in the connections. For necked rod system, the higher scale factors could lead to rupture because of stiffness and strength degradation of the necked rod. The hysteresis performances of the tank subjected Kobe record under two scale factors of $R_\mu = 1\ \&\ 2.5$ are represented:

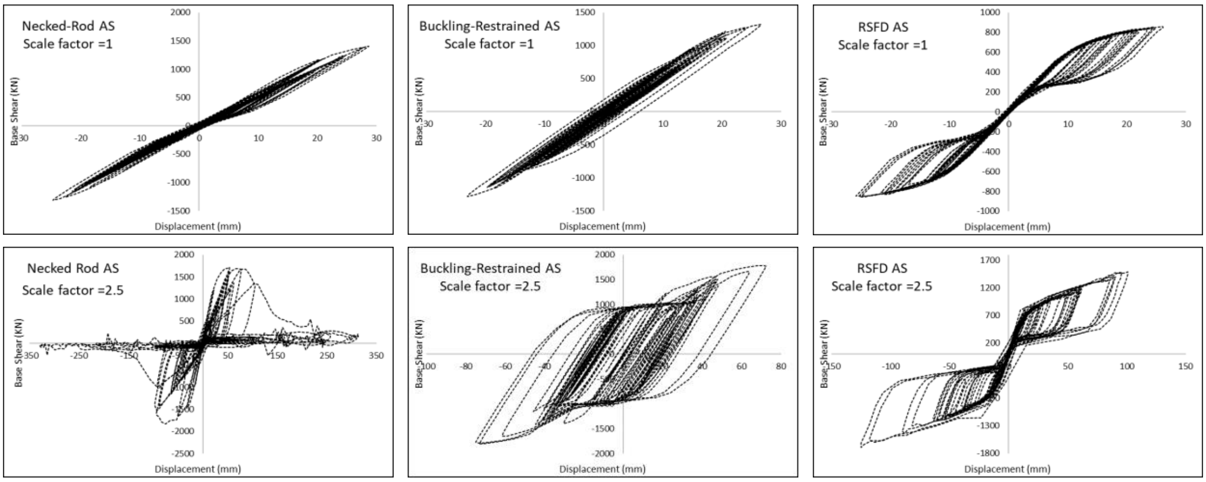


Fig. 10 – Tank hysteresis for the investigated anchorage systems subjected to Kobe record

Another critical parameter to controlled is tanks displacement, which should be considered for designing the tank's equipment like catwalks, pipelines and so on. The top cone displacements for all anchorage systems are represented in Fig 8. API recommendation for maximum horizontal displacement is 200 mm, which assume to be the upper allowable limit in this study. As the results show for $R_\mu = 1$ for all cases, almost the top cone displacements are at the same.

6. RSFD Design and Over-Strength Factor

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

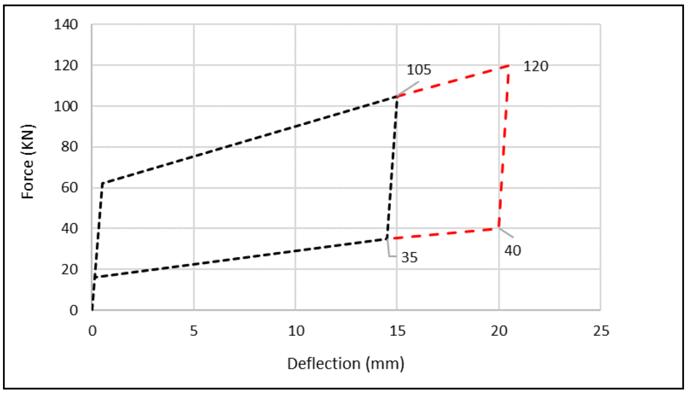
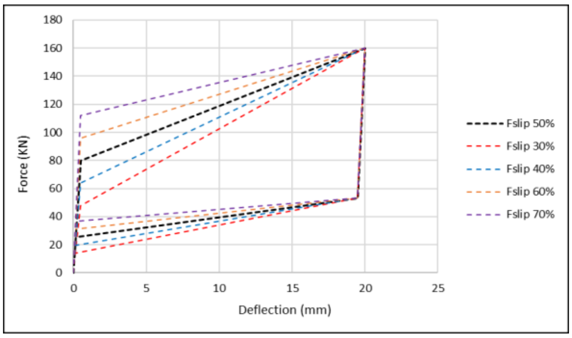


Fig. 11 – RSFD Re-designed force-displacement capacity

To have the deflection capacity for MCE level, considering scale factor of compare to the ULS level, the corresponding joint deflection capacity designed to be 20 mm so the over-strength factor would be 1.15 which is essential to design the tank’s barrel. This amount for the necked-rod and buckling-restrained mechanism normally are 1.25 and 1.4 respectively. There should be noted that all comparisons have been made lies on the accepting damage in sacrificial elements in 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 such structures with a lower degree of redundancy.

6.1 The effect of RSFD slip force

In the primary design of the RSFD system, the slip forces designed 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 revised as long as the system does not slip before SLS level. The less slip force provides less effective stiffness and more damping, which both decrease the transmitted effects but meanwhile increase the deflection level. To evaluate the effectiveness of this factor, a range of the slip forces have been defined and force and displacement results are as below:



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

Fig. 12 – RSFD hysteresis behaviour with a different slip forces and comparison of different varieties of F_{slip}

The trends are displayed in Fig 13. While increasing the slip force decreasing the force reduction in the system. However, for the higher level (more than 60%) the tank displacements are stranded at the same level.

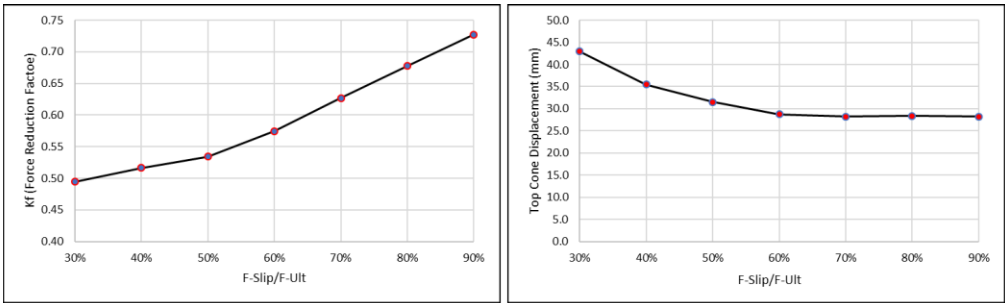


Fig. 13 – k_f and displacement of the tank for different F_{slip} ratio

6.2 RSFD Capability of Dissipation Energy

As discussed, the dissipation energy capability has a significant impact on force reduction factor and also deflection demand. Fig 14 contains the graphs displaying the accumulative energy dissipated by RSFD during the earthquake. As represented almost half of the impute energy come to the structure dissipated by connections through a safe friction mechanism (no damages in anchorage connectors). To compare this amount with the other systems accumulative dissipated energy by the connections to the total input energy shown in Fig 15. These results are based on the average of the selected records. The results reveal that for scale factor less than 1.5, as the RSFD has a lower slipping point could provide a higher damping rate while for the higher scales factors buckling-restrained systems could dissipate a higher rate of absorbed energy.

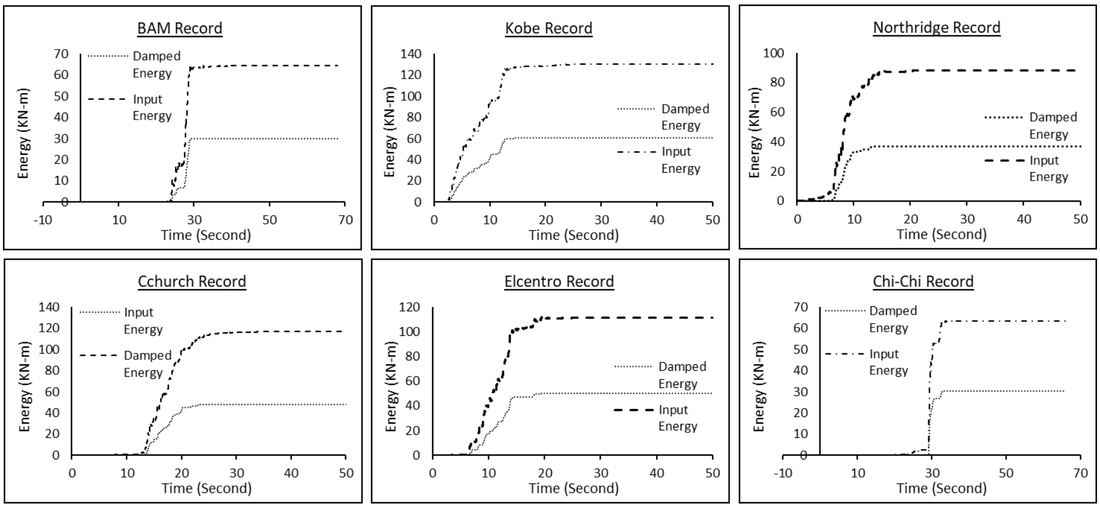


Fig. 14 – Comparison of accumulative dissipated energy by the connections to the total input energy

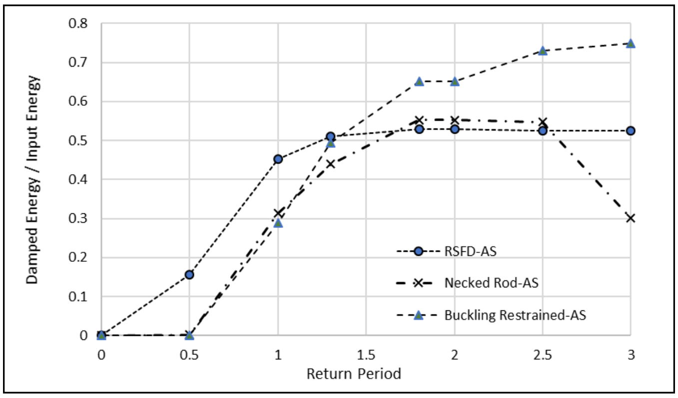


Fig. 15 – Comparison of dissipated energy to total input energy in different anchorage systems

7. Residual Displacement of Different Anchorage Systems

In the case of the RSFD anchorage system, the system does not have any residual displacement as connection are fully self-centered. For the necked-rod system, also as long as the tank during the motion does not experience rupture and collapse, the system would come back to its original position by its weight as the unloading stiffness is negligible. The residual displacement is a case of matter for the buckling-restrain system as required sufficient restoring force to bring the structure back. Table 2 shows the maximum, minimum, average and ratio of residual to the maximum displacement of the buckling-restrained joints. As the results illustrate, at least 30% of maximum displacement averagely remain in connections as residual displacement which required an external force to bring the storage tanks back to its 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 a seismic event.

Table 2 — The displacement demand of buckling-restrained joints

Ru	Links Max Displacement (mm)	Links Min Displacement (mm)	Links Average Displacement (mm)	Links Ratio of Residual Displacement to Displacement
1	1.98	0.69	1.44	0.31
1.3	3.61	1.46	2.62	0.39
1.5	4.79	1.98	3.55	0.40
1.8	7.07	2.89	5.35	0.35
2	8.82	3.66	6.75	0.33

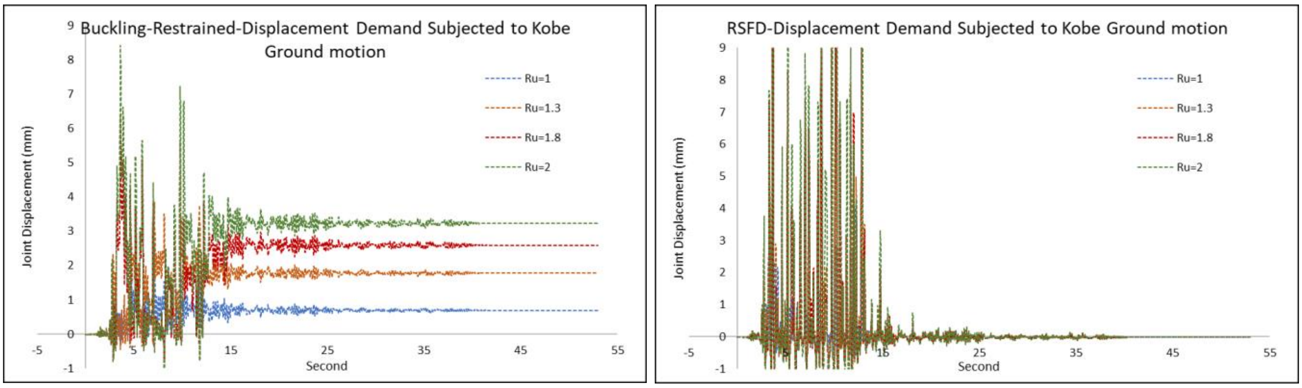


Fig. 16 – Time history of buckling-restrained and RSFD joint subjected to Kobe record

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 tank. In this regard, based on the RSFD patent, a component joint has been re-design and successfully tested and its performance analytically and numerically verified. To investigate the performance of this mechanism as anchorage system of storage tanks a case study of a cylindrical tank with the aspect ratio of three has been employed and the result compared with the two other conventional ductile anchorage system including necked-rod and buckling-restrained anchorage system.

As discussed, the anchorage system should have a tension only performance to not create a compression zone at the gripping point on the tank body, which caused buckling issue for the barrel plate. RSFD (for $R_\mu = 1$) reduce overturning moment ($k_f = 0.53$) 33% more than the two other systems while has almost the same displacement demand. The overstrength factor in RSFD system for 200 mm displacement demand is 1.15 compared to 1.25 of the necked rods and 1.4 for buckling-restrained connection. Also, analysing RSFD slip forces shows that increasing slip point lead to a higher rate of k_f factor while for slip forces more than 60% displacement almost stands at the same level.

Compare to all other anchorage systems, 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.

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