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USING AN INNOVATIVE LOW DAMAGE ANCHORAGE SYSTEM FOR INDUSTRIAL TANKS AND VESSELS

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SUMMARY

In this paper, an innovative generation of anchorage system has been introduced by employing Resilient Slip Friction Damper (RSFD) as a ductile self-centring hold-down system 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, through the validated experimental results, a comparison of the effect of RSFD anchorage system to other ductile concepts (necked-rod and buckling-restrained system) considering a real case study of cylindrical steel storage tanks has been conducted.

Keywords: RSFD, Resilient Slip Friction Joint, Self-centring, Storage tanks and silos, Energy dissipation

1. INTRODUCTION

Above ground cylindrical steel liquid storage tanks are vastly used in different industries 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 returns 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 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.

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].

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

2. RSFD AS AN ANCHORAGE SYSTEM

Resilient Slip Friction Damper (RSFD) is a friction-based connection that has a self-centring feature to restore it back after the full expansion phase. The Figures 2-a represents the components of this type of connection. This damper has been introduced by Darani et al. [10] 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 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 the tanks anchorage storages system. The hysteresis performance of the system is shown in Figure 1.

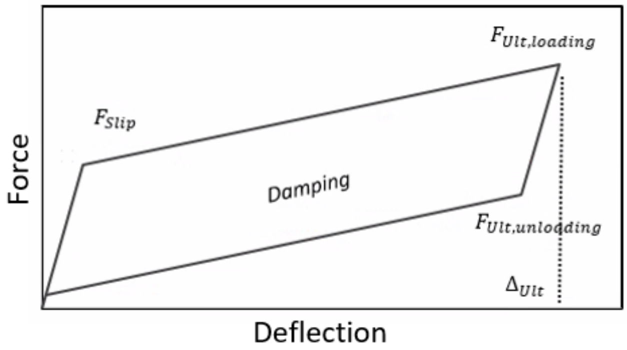


Figure. 1 – RSFD hysteresis performance

2.1 Component test

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

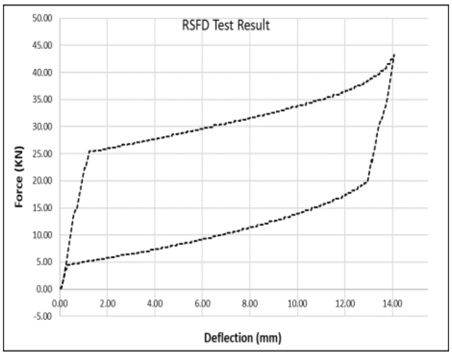
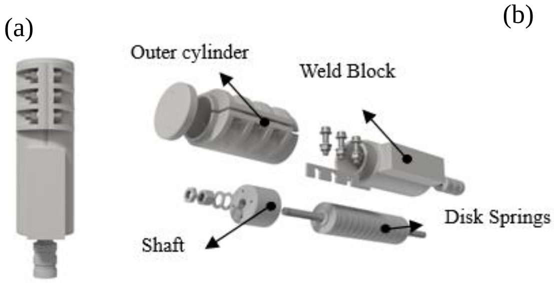



Figure. 2 – RSFD test setup and performance test result [11]

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. The enclosed area of the hysteresis loop represents the damping ratio provided by the RSFD. Added damping and flexibility of this system is tunable and can be efficiently designed according to the demand of the force and deflection. For tanks, vessels, and other exposed structures, RSFD components are made from stainless steel material to ensure the durability of the device is not affected over time.



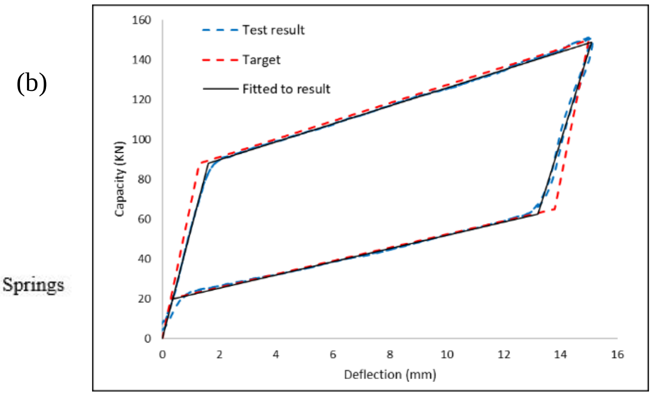


Figure. 3 – (a) RSFD components (Left); (b) Test result (Right)

3. ADVANTAGE OF DUCTILE, TENSION ONLY CONNECTION IN STORAGE TANK SYSTEMS

Conventional anchorage systems generally include a rod that 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 in which the buckling mode of the rod has been controlled.

3.1 Necked-rod anchorage system

Figure 4-a represents the hysteresis performance of two ribbed and smooth rods with the same length over the diameter of 20 [12]. Standard rod or necked rod buckles in reverse cycle causing strength and stiffness degradation known as pinching (Figure 4-a). This stiffness and strength degradation leads to a different performance path in each cycle, increment in displacement demand and eventually rupture of the rod due to low cycle fatigue. Ductility in such systems comes from material nonlinearity, therefore, the hold-downs must be inspected and replaced if required when an earthquake strikes.

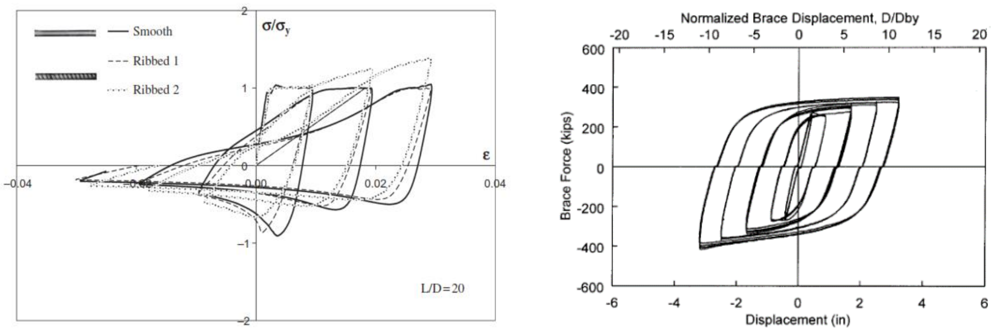


Figure. 4 – (a) Hysteresis performance of the necked rod [12] (Left); (b)Bucking-restrained behaviour [13] (Right)

3.2 Buckling-restrained system

To control the buckling of the rod, bucking-restrained mechanisms have been introduced. Typically, this can be achieved through a sleeve surrounding the rod. Such details avoid performance degradation while the connection has load-carrying capacity in both tension and compression. However, such a performance in the 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 with the buckling force of the rod, therefore, there would be residual displacement in the 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.

Figure 5 represents the two possible situations. When there is just a rod, the 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 the lack of enough rotational stiffness due to the sleeve part, which also causes additional induced stress in the tank body.

Figure. 5 – Reported damage in Kaikoura earthquake; (a, b) Barrel buckling; (c) Rod rupturing [14]

4. CASE STUDY – CYLINDRICAL STEEL 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 cylindrical steel tank of twelve-meter height, four-meter diameter and average thickness of 3 mm are summarised in table 1. Anchorage system contains $32\emptyset20$ grade of 8.8 necked rods attached with a symmetric arrangement to the skirt. Considering the ductility factor of two and the 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.

Table 1 – Design Parameters

Hazard Factor	0.4
Soil Type	D
Importance Level	1
Design Life	50 Years
$\mathbf{S_p}$	1
$\boldsymbol{\mu}$	2
$\mathbf{N(D,T)}$	1
Return Period	1

$$V_i = C_h(T_i)\,N(T_i.D)\,m_i\,g\;\;S_p\,Z\,R_u\,k_f \qquad (1)$$

$C_h(T_i)$: 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
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
$k_f(\mu,\varepsilon)$: The force reduction 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 $\emptyset20$.

For the buckling-restrained system, the yielding point calculation would be the same as the 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:

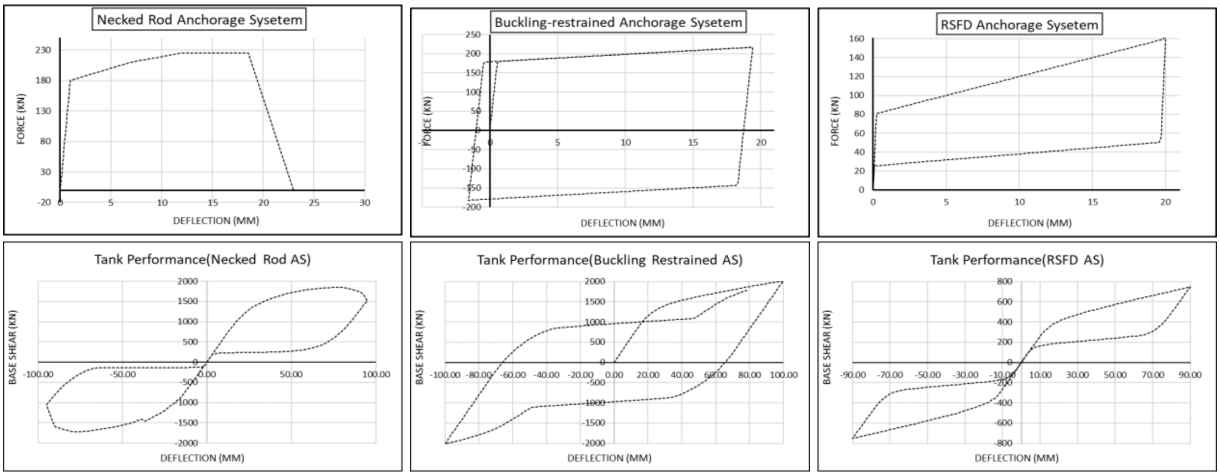


Figure. 6 – The hysteresis behaviour of joints and tanks for three introduced mechanism

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 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

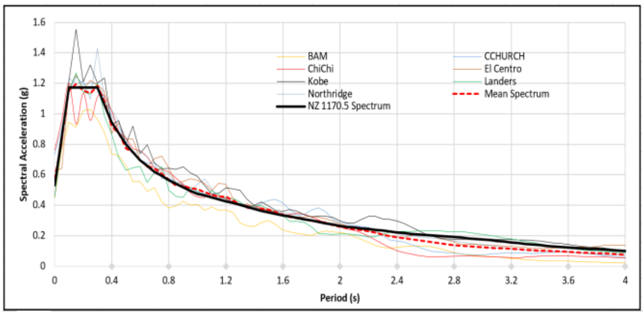


Figure. 7 – PGA and mean spectrum of selected ground motions

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 (figure 8).
As reported in Figure 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 higher 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 the necked rod

system, the higher scale factors could lead to rupture because of stiffness and strength degradation of the necked rod.

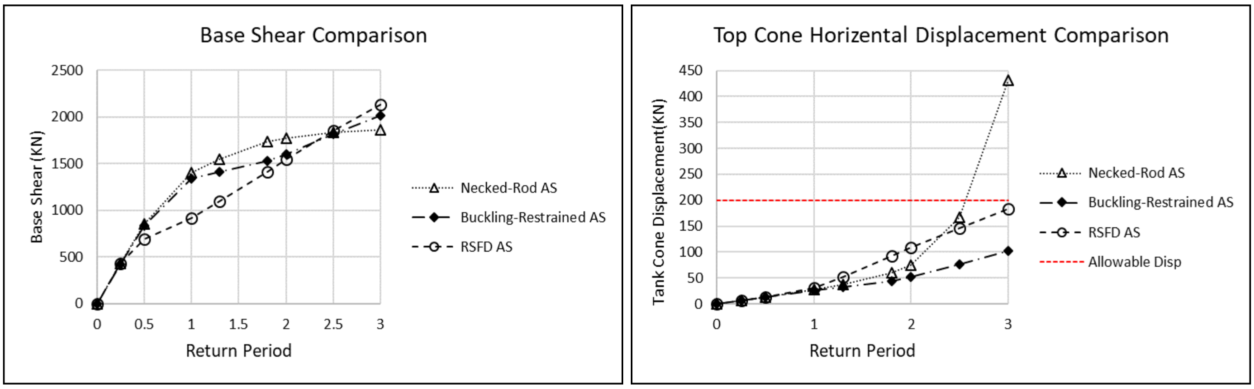
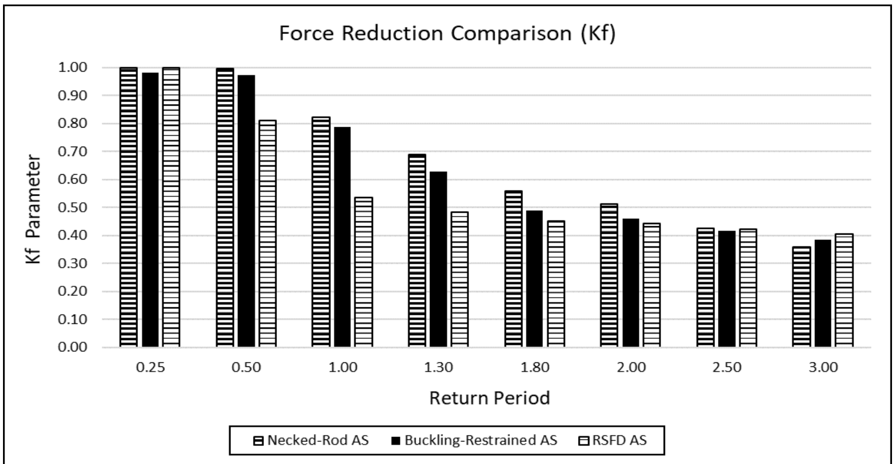


Figure. 8 – Base shears and top tank's cone displacements subjected to seven selected records



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 different amounts of the return period

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

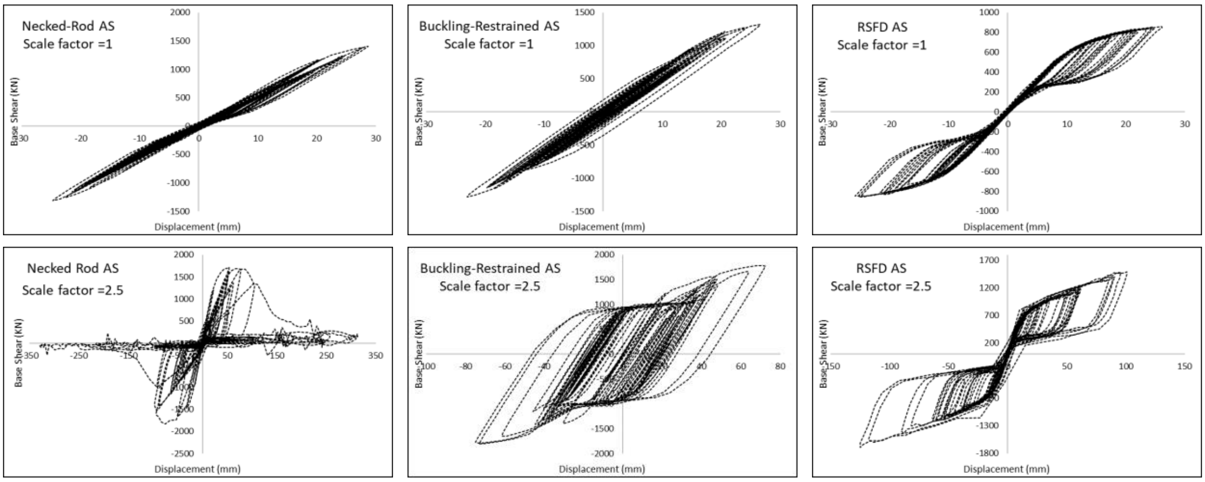


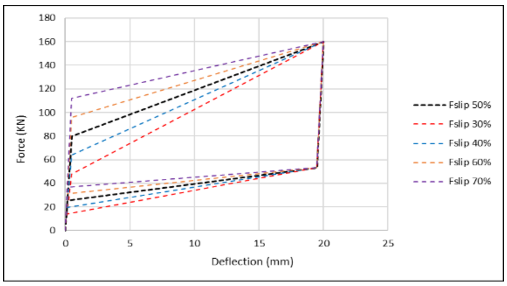
Figure. 10 – Tank hysteresis for the investigated anchorage systems subjected to Kobe record

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. To have the extra deflection capacity, considering scale factor 1.5 compared to the ULS level, the corresponding joint deflection capacity designed to be 22.5 mm so the over-strength factor would be 1.2 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.

7. EFFECT OF RSFD SLIP FORCE

In the initial design of the RSFD system, the slip forces were half of the ultimate capacity at the ULS level. However, as this anchorage connection is a self-centring system, the slip force could be adjusted if 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 in 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 $\mathrm{F_{slip}}$

8. CONCLUSION

In this paper, a new generation of self-centring friction damper (RSFD) has been introduced as an anchorage system for cylindrical steel 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, a cylindrical steel tank with an aspect ratio of three has been studied and the result compared with the two other conventional ductile anchorage system including necked-rod and buckling-restrained anchorage system.

The results show the transmitted seismic force for RSFD ($R_{\mu} = 1$) is around 33% less than the two other systems while almost has the same displacement demand. The overstrength factor in the RSFD system for 200 mm displacement demand is 1.2 compared to 1.25 of the necked rods and 1.4 for buckling-restrained connection which means the barrel and foundation can be designed for lower seismic demand.

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