Rocking concrete shear walls with self-centring friction dampers for seismic protection of building structuress

Farhad Mohammadi Darani [1], Kaveh Sahami[1], Pouyan Zarnani[1], Sajad Veismoradi[1], Hamed Bagheri[2], Pierre Quenneville[2], Enrico Haemmerle[1]

1 Auckland University of Technology (AUT), Auckland , New Zealand

2 The University of Auckland, Auckland, New Zealand

Contact e-mail: farhad.darani@aut.ac.nz

ABSTRACT: Ductile concrete shear walls are suitable for protecting buildings from collapse. However, a high level of damage is expected after moderate to severe earthquakes. Low damage design concepts can be considered as an efficient alternative to traditional high damage design to minimize damage so that buildings could be reoccupied quickly with minimal business interruption and repair costs. Rocking wall structures absorb and dissipate seismic input energy during their rocking motion. However, this rocking motion should be controlled by a set of additional systems in which high initial stiffness, damping, and self-centering are provided. Resilient Slip-Friction Joint (RSFJ) is a technology in which seismic damage avoidant characteristics are provided. Damage free energy dissipation and self-centring capability have made this connection a suitable alternative for current ductile and low-damage solutions. In this paper, the seismic performance of rocking concrete shear walls is assessed analytically and experimentally using RSFJs. Firstly, analytical, experimental and numerical studies are carried out in order to verify the performance of the connections. Secondly, a simple structural configuration is introduced to apply these connections.

1 INTRODUCTION

Ductile concrete shear walls have widely been used in earthquake resisting systems. High stiffness and high strength, as well as acceptable ductility levels, can be named as positive points of such lateral load-resisting walls (Paulay and Priestley, 1992). Following 2010 and 2011 Canterbury earthquakes and the resulting economic and social impacts, researchers and engineers got more inclined to move from ductile design concepts to low damage ones given the advantages involved. The low damage design concept is based on the fact that the earthquake energy should be dissipated in certain structural elements as sacrificial fuses which can be easily repaired or replaced after moderate to severe earthquakes.

The concept of rocking structures as a resisting system against lateral forces was initially introduced by Housner (1963). Aslam (1978) proposed adding a post-tensioning mechanism in order to provide a self-centring capability for rocking systems. Later, Priestley (1995) with the aim of elimination of residual drift, conducted a series of non-linear dynamic time history analyses for moment resisting structures equipped by pre-stressing tendons. Through further research, Stone et al. (1995) introduced a hybrid system, which incorporated mild steel reinforcement for dissipating energy along with self-centring mechanism provided by unbonded post-tensioned tendons.

High initial stiffness, controlled rocking motion and repetitive hysteresis cycles can be named as the positive aspects of unbonded post-tensioned walls. On the other hand, higher acceleration and displacement demands compared to ductile structures, when an additional energy dissipating system is not used, and cost and complexity of post-tensioning during the construction phase are some of the negative points of these systems.

Zarnani and Quenneville (2015) introduced a new generation of friction damper which provides restoring force and energy dissipation combined in one compact joint. Such resilient slip friction joint (RFSJ) was initially studied in a rocking timber wall application as a hold-down (Hashemi et al. 2017). Darani et al. (2018) extended this concept to rocking concrete shear walls as a damage-avoidance solution. By adopting the RSFJs as shear links between reinforced concrete shear walls and their boundary columns, the resisting force will be distributed along the wall resulting in a reduction of bending moment demand. The use of shear links not only avoids high-stress concentration at the conventional hold-down connections but also reduces the wall size significantly.

In this paper, the application of RSFJs in rocking shear walls is assessed via analytical and numerical modelling.

2 ANALYTICAL MODELS FOR RSFJ AND R-RSFJ

In RSFJs, the restoring force comes from a specific steel grooved plates which are tied through high strength bolts and disk springs. By slipping of grooved plates, the input energy is dissipated through frictional resistance. Based on the free body diagrams presented in Fig. 1, the design procedure is developed for the prediction of the performance of the RSF joint (Zarnani et al. 2016). The slip force (F_{slip}) and residual force (F_{res}) can be determined by Eq. (1) and Eq. (2):

$$F_{RSFJ,slip} = 2n_b F_{b,pr}\left(\frac{\sin\theta + \mu_s \cos\theta}{\cos\theta - \mu_s \sin\theta}\right) \tag{1}$$

$$F_{RSFJ,res} = 2n_b F_{b,pr}\left(\frac{\sin\theta - \mu_k \cos\theta}{\cos\theta + \mu_k \sin\theta}\right) \tag{2}$$

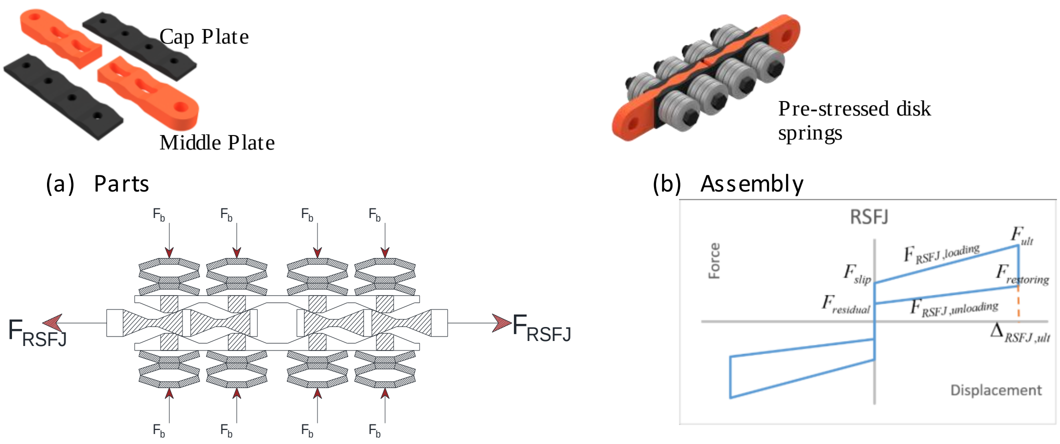
Where n_b=number of bolts on each splice, θ=groove angle, $F_{b.pr}$ is clamping force of pre-stressing and the μ_s and μ_k are the static and kinetic coefficient of friction respectively, while considered μ_k=0.85μ_s (Hashemi, et al. 2017). The general hysteresis behaviour of RSFJ is illustrated in Fig. 1(d). $F_{ult,\ loading}$ and $F_{ult,\ unloading}$ are the system forces at the maximum disk springs displacement and bolts force.

$$F_{b,u} = F_{b,pr} + K_s \Delta_s \tag{3}$$

$F_{ult,\ loading}$ and $F_{ult,\ unloading}$ are derived by replacing the bolt forces in Eq. 1 and Eq. 2 by Eq. 3, and μ_s, μ_k with μ_k, μ_s.

3 EXPERIMENTAL VERIFICATION

In this section, the experimentally achieved load-displacement response of a RSFJ is compared to the analytical models. The properties and parameters of the tested RSFJ are summarised in Table 1.



(a) Parts (b) Assembly

(c) Free body diagram (d) flag-shaped response of RSFJ

Figure 1: Resilient Slip Friction Joint

Table 1. The properties of the tested RSFJ

Parameter	Value
θ	25°
μ	0.18
n_j	2
Number of bolts per joint (n_b)	6
Number of discs in one stack	7
Discs ultimate capacity	110 kN
Bolts Pre-stressing force ($F_{b,pr}$)	30 kN
Discs internal height	1.55mm

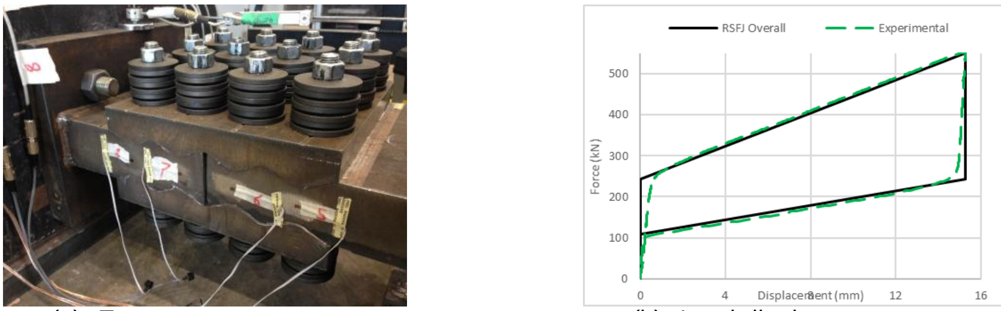
The test setup is shown in Figure 2a. The experimental load-displacement response is compared to the analytical predictions in Figure 2b. As it can be seen from the graphs, the response is well predicted using the analytical model. Considering the flag shape response of the connection, the input energy is dissipated by friction and the joint is finally self-centred by the partially pre-stressed disc springs.

4 ROCKING CONCRETE SHEAR WALLS WITH RSF JOINTS

4.1 System configuration

In this section, the concept of post tensioned pre-cast concrete walls with RSFJs as hold-downs is introduced. Since the RSFJ will be used as hold downs, bending in the wall due to lateral loading will produce axial compression and tension stresses in the concrete. Considering the weakness of concrete in tension, tension cracks will be formed in the first phases of loading which significantly reduces the initial stiffness of the system before the joint initial slip stage. An efficient way to compensate this is applying pre-stressing forces on the wall.

In order to eliminate the tension cracks, a pre-stressing concept is developed. In this concept, the pre-cast concrete panel is connected to the foundation using RSFJ hold-downs. This precast concrete panel is post-tensioned using unbonded cables or rods. There is no need for additional connections to the foundation such as post-tensioning tendons (Figure 3a). After manufacturing



(a) Test setup (b) Load-displacement responses

Figure 2: experimental testing on a RSFJ

and considering proper timing for the concrete curing, the pre-cast concrete panel will be compressed using the unbonded tensioning elements. It should be noted that the post-tensioning force should be higher than the joint slip force in order to prevent the cables from elongating before slipping of the joint. Post-tensioning can be done either at the factory or the construction site when the wall is laid-down on the floor. This decreases the construction time and cost in comparison to the current post-tensioning concepts. In current post-tensioning systems, post tensioning is done when the walls are mounted vertically, which requires more labour and time consuming in comparison to the proposed method.

The wall can then be mounted vertically and get connected to the foundation using the RSFJs and end pins. In addition to providing a resilient damage avoidance solution, this concept makes the construction process of the earthquake resisting structures with pre-cast concrete elements easier and more efficient when it is compared to current approaches.

Another advantage of this system in comparison with the current post-tensioned rocking walls is that there is no need to design the post-tensioning elements for high displacement demands as the flexibility of the system comes from the RSFJs. The RSFJ end connections at the foundation side can be used as the shear load transferring mechanism (shear key) of the system, in order not to allow the wall to slide laterally.

4.2 Lateral loading performance

Considering Figure (3b), by taking the moments about the centre of rotation, which is the wall's toe, the horizontal force applied at the top ($F_{top,slip}$) can be determined by Eq. (4), (Hashemi et al. 2017). In this equation, H is the height of the wall, W is the vertical loads, L_W is the horizontal distance from the vertical load to the centre of rotation, and $F_{RSFJ,slip}$ is the slip force of the RSFJ. It is assumed that the employed RSFJs are identical.

$$F_{top,slip} = \frac{1}{H}\left[WL_W + F_{RSFJ,slip}(L_1 + L_2)\right] \tag{4}$$

After the slip stage, the force within the RSFJ corresponds to the deflection within them. Therefore, the lateral strength of the wall can be specified by Eq. (5), where $F_{RSFJ,1}$ and $F_{RSFJ,2}$ are the forces within the tensioned and compressed RSFJ, respectively. The relationship between $F_{RSFJ,1}$ and $F_{RSFJ,2}$ can be determined by Eq. (6) during the loading of the wall. By employing Eqs. (5) and (6), the overall load-deformation behavior of the wall can be determined.

$$F_{top} = \frac{1}{H}\left[WL_W + F_{RSFJ,1}L_1 + F_{RSFJ,2}L_2\right] \tag{5}$$

$$F_{RSFJ,2} = \frac{L_2}{L_1}\left(F_{RSFJ,1} - F_{RSFJ,slip}\right) + F_{RSFJ,slip} \tag{6}$$

A numerical modelling has been done using SAP2000 software and the results are compared to the analytical model (Figure 3c). Modeling parameters are summarised in table 2. As it can be seen from Figure (3c), the analytical and numerical results are in agreement.

Table 2. The properties of the modeled rocking wall

Parameter	Value
H (mm)	4000
W (kg)	3300
B (mm)	1700
L_1 (mm)	1250
L_2 (mm)	150
L_W (mm)	550
$F_{RSFJ,slip}$ (kN)	140 kN
$F_{RSFJ,ult}$ (kN)	250 kN

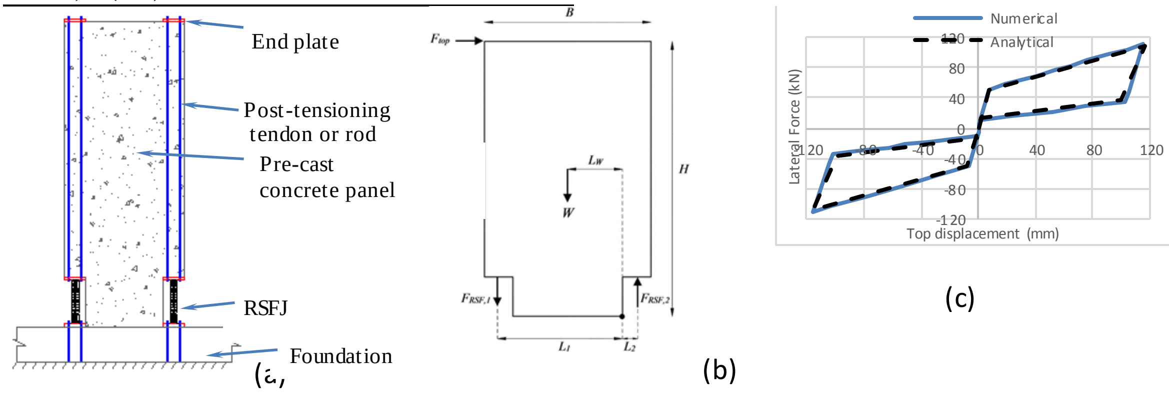


Figure 3: (a) different components of the proposed rocking pre-cast concrete wall system (b) Analytical parameters (c) Comparison of numerical results and analytical predictions

5 SINGLE ROCKING SHEAR WALL EQUIPPED WITH RSFJ AS SHEAR KEYS

The proposed configuration for a single rocking wall with RSFJs as shear keys with end columns is shown in Fig. 4a. Wall and columns in this configuration are pinned to the floor and bracket beams are used to connect shear links to wall and end columns. The damage to the columns is controlled by making a proper pin connection at the column base. Columns are axial members which should be designed for localized shear and bending at the connections to the joints. Additional pre-stressing is not required in this system as there is not major bending stresses in this concept. The rocking moment can be found by taking the moment about the rocking base:

$$M_{rock} = M_{weight} + M_{damper} = W\frac{l}{2} + n_d\left[F_{DL_i}(l+d) + F_{DR_i}(d)\right] \qquad (7)$$

where $n_d$is the number of dampers in each side of the wall, F_{DL_i}, $F_{DR_i}$are the force of dampers in left and right sides of the rocking toe. Assuming that the bracket beams, columns and wall are all rigid compared to RSFJs, the deflection in dampers in right side (δ_{DR}) and left side (δ_{LR}) of the wall is determined.

$$\delta_{DR} = (L+d)\sin(\theta) \qquad (8)$$

$$\delta_{DL} = d\sin(\theta) \qquad (9)$$

While the wall rotates with the angle of θ, the deflection of the joint in each side of the wall are the same, so their forces would be the same. The general push-pull response of the system is shown in Fig. 4b. Before the slipping point ($M \leq M_{slip}$), stiffness of each link connected to other element can be determined by:

$$k_{ini} = \left(\frac{1}{k_{col,axial}} + \frac{1}{k_{bb,bending}} + \frac{1}{k_{wall,axail}} + \frac{1}{k_{RSFJ,initial}}\right)^{-1} \tag{10}$$

$k_{col,axial}$: axial stiffness of column with the height equal to the level of corresponding damper, ($\frac{EA}{h_i}$), $k_{bb,bending}$: bending stiffness of bracket beam, ($\frac{b_{bb}h_{bb}^3}{12}$), $k_{wall,axial}$: axial stiffness of wall with the height equal to the level of corresponding damper and with length of around 10% of wall total length ($\frac{EA_W}{h_i}$).

While h_i is the link level, b_{bb}, h_{bb} are thickness and height of bracket beam. After slipping point, as the stiffness of RSFJs decreases considerably ($k_{rock} \ll k_{ini}$), the stiffness of the links is considerably smaller in comparison to other elements, so rocking stiffness could be directly derived by:

$$k_{rock} = n_d k_{d,ini} \left[(L+d)^2 + (d)^2 \right] \tag{11}$$

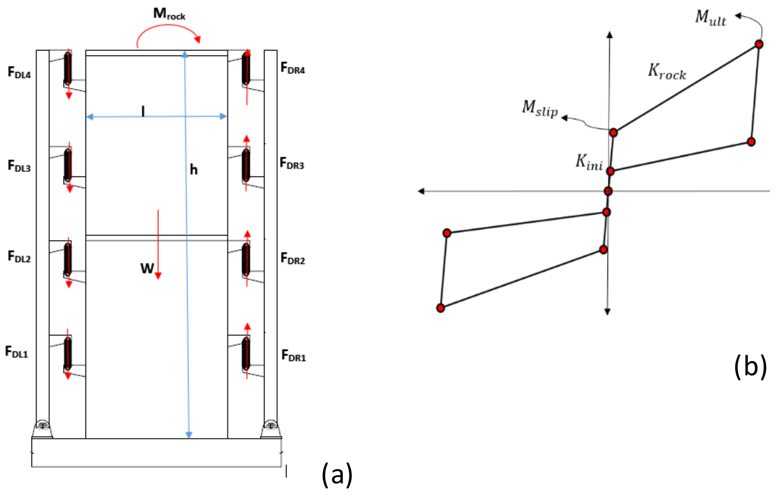


Figure 4: (a) Schematic of single wall system (b) general push-pull of rocking wall with RSFJ

6 SUMMARY AND CONCOLUSION

This paper presents a new low-damage seismic resisting system in which Resilient Slip Friction Joints (RSFJs) have been adopted for rocking concrete shear walls. This system provides self-centring as well as energy dissipation through incorporating damage-avoidance connections. The results of the preliminary study have shown that this new rocking pre-cast concrete shear wall can be considered as an efficient alternative to traditionally ductile designed walls to minimise damage so that buildings could be reoccupied quickly with minimal business interruption and repair costs. The lateral loading performance of the proposed system was derived analytically and compared to the numerical results. Large scale experimental studies will be carried out in order to further study the performance of the proposed systems.

References

Aslam, M. (1978). "Earthquake rocking response of rigid bodies."

Darani, F. M. Zarnani, P. Haemmerle,E . Hashemi, A. Quenneville, P (2018). "Application of new resilient slip friction joint for seismic damage avoidance design of rocking concrete shear walls." New Zealand Society for Earthquake Engineering (NZSEE) Conference.

Hashemi, A., Zarnani, P. Masoudnia, R. and Quenneville, P. (2017). "Experimental Testing of Rocking Cross-Laminated Timber Walls with Resilient Slip Friction Joints." Journal of Structural Engineering 144(1): 04017180.

Housner, G. W (1963). "The behavior of inverted pendulum structures during earthquakes." Bulletin of the seismological society of America" 53(2): 403-417.

Paulay, T. and Priestley, M. N. (1992). "Seismic design of reinforced concrete and masonry buildings." John Wiley & Sons

Priestley, M. (1995). "Myths and Fallacies in Earthquake Engineering--Conflicts Between Design and Reality." 157: 231-254.

Stone, W. Cheok, G. Stanton, J. (1995). "Performance of hybrid moment-resisting precast beam-column concrete connections subjected to cyclic loading." 92(2): 229-249

Zarnani, P., Valadbeigi, A. and Quenneville, P. (2016). "Resilient slip friction (RSF) joint: A novel connection system for seismic damage avoidance design of timber structures " World Conf. on Timber Engineering WCTE2016, Vienna Univ. of Technology, Vienna, Austria.

Zarnani, P. Quenneville, P (2015). "A resilient slip friction joint, Patent No. WO2016185432A1, NZ IP. Office."