Seismic Response of Pre-cast Concrete Shear Walls with Controlled Rocking Motion using Self-Centring Friction Devices

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Abstract

Friction dampers have been used as passive energy dissipation devices for seismic protection of different types of structures. These dampers have shown repetitive cyclic performance when properly designed. This repetitive performance means that the device can resist many severe earthquake events when the input cycles are within its design slip displacement. However, residual displacement is expected after moderate and severe earthquakes. The use of pre-cast concrete improves the construction process with decreasing the required time and labour and provides higher quality compared to conventional cast-in-situ concrete. Besides, pre-cast concrete members can form low-damage structures when connected with properly designed low-damage connections. This potential makes pre-cast concrete a suitable choice for modular construction in countries such as New Zealand where development in seismic-prone areas is of high priority. Amongst low damage systems, rocking concrete shear walls have been considered as an efficient system when their inherent self-centring capability is combined with an additional system to control the rocking motion and to add energy dissipation. Rocking walls with unbonded post-tensioning and additional yielding dampers are one of the examples of such systems. In this paper, the performance of a pre-cast rocking concrete shear wall equipped with re-centring dampers is assessed experimentally. The input action is designed for the ultimate limit state demand defined in New Zealand code. The results have shown that the system is able to withstand the seismic input energy with a repetitive manner while self-centring is achieved at the same time.

1. Introduction

To minimise the earthquake damage in addition to satisfying the life-safety of the occupants, researchers and engineers' focus has been on the development of low damage concepts for concrete structures where they could still have the benefits of concrete shear walls. The initial solution introduced was the rocking wall systems in which the rocking motion is controlled using post-tensioned cables (Priestleyet al., 1999). In earthquake resistant rocking systems, the earthquake input energy will be balanced by the required energy to swing the structure (Housner, 1963). Even though such systems have shown acceptable seismic performance in comparison to the traditional high damage design, the lack of damping leads to high acceleration and ductility demands. This lack of damping makes the design for deformation compatibility, occupants comfort, and non-structural components more challenging (Sritharan et al., 2015). Adding supplemental damping devices is proposed by researchers to improve the seismic response of the rocking wall systems. Yielding, friction and viscous damping are proposed, tested and used in rocking shear walls (Sritharan et al., 2015).

While these rocking walls with additional damping have become more reliable given the improved performance, there are still some challenges with these systems. For example, yielding elements providing energy dissipation should be replaced after each intense event which is costly and causes operational problems for the building. In addition, as the residual capacity of these sacrificial elements will not be sufficient to resist against severe aftershocks, the structure will still be vulnerable until getting fully repaired by replacing the damaged fuses. Furthermore, the creep in post-tensioning steel strand cables and their supporting members, has always been an issue requiring regular checks and adjustments of the pre-tensioning force in the cables. Therefore, there is still a remaining step to achieve an ideal maintenance free rocking wall system which provides the desired level of performance during the earthquake and aftershocks.

2. Self-centring devices

2.1 Resilient Slip-Friction Joint

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):

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

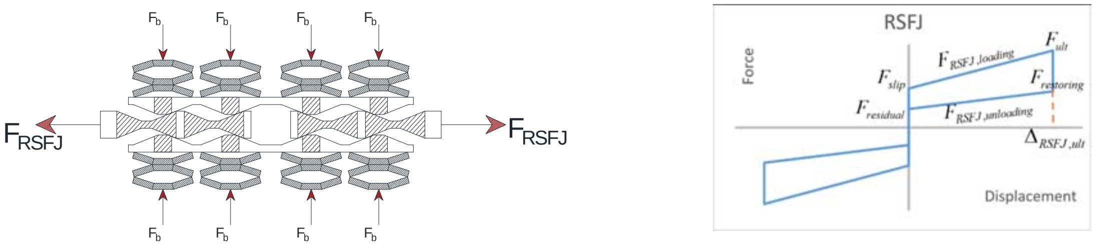
$$F_{RSFJ,res} = 2n_b F_{b,pr}\left(\frac{\sin\theta - \mu_k \cos\theta}{\cos\theta + \mu_k \sin\theta}\right) \tag{2}$$

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 $\mu_k=0.85\mu_s$ (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.

(a) Parts (b) Assembly



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

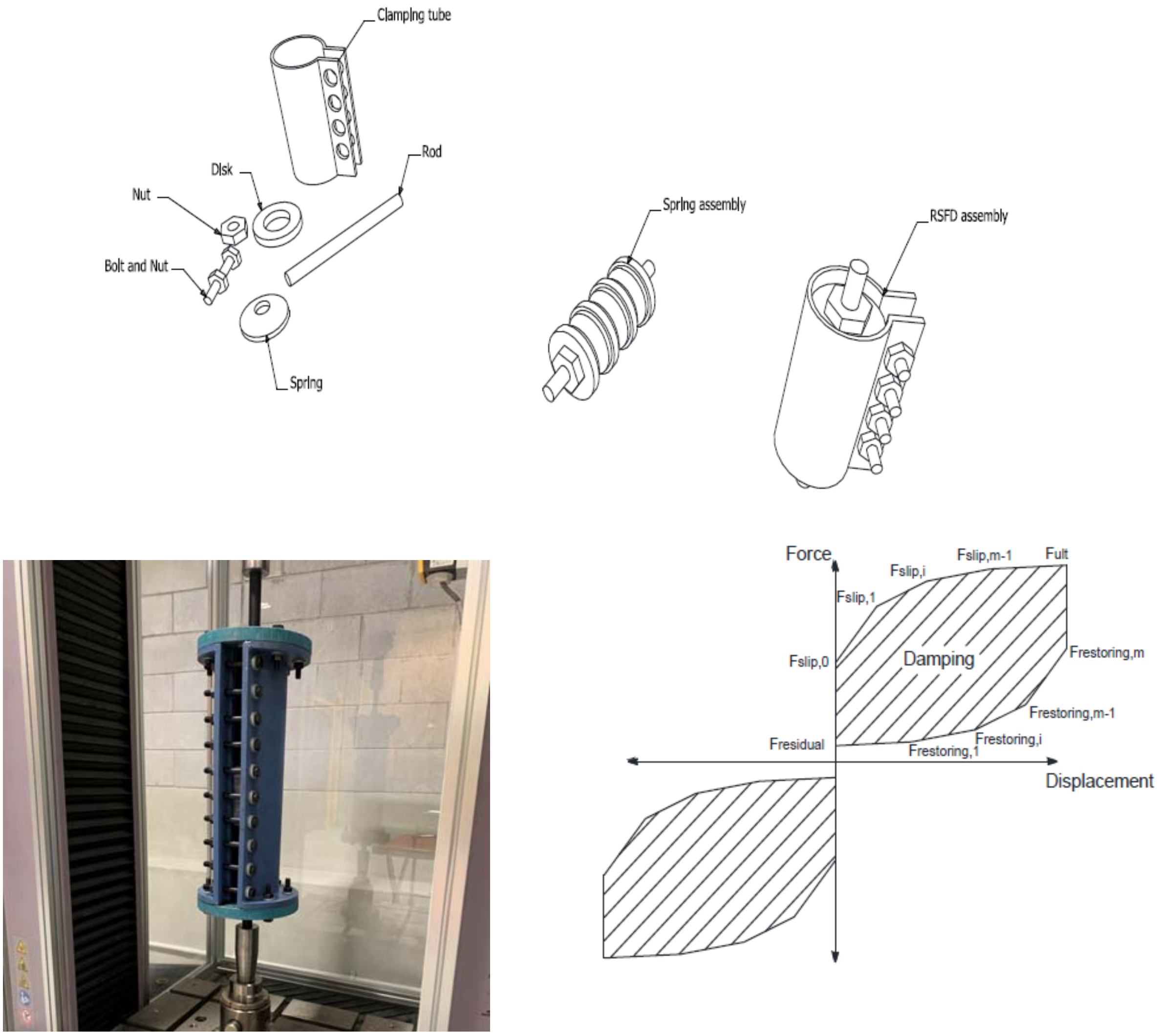
Fig. 1 - Resilient Slip Friction Joint.

2.2 Resilient Slip-Friction Damper

Resilient Slip-Friction Damper consists of a tube and an assembly of disk-springs and friction elements inside the tube (Darani et al 2018). The assembly, should be pre-stressed before being inserted inside the tube. The amount of pre-stressing force, $F_{pr,rod}$, is designed based on self-centring criteria for this damper. After inserting the assembly, the tube will be clamped by tightening the bolts on its external tabs. This will produce a normal pressure on the friction elements. The amount of this pressure, can be calculated using classic mechanics of materials. The axial force required to overcome the friction between the tube and the assembly, $F_{friction}$, can be calculated by multiplying the coefficient of friction, μ, and the normal force acting on the friction element.

$$F_{friction} = 2\pi\mu F_{clamp,bolt} n_{bolt}$$

Where, $F_{clamp,bolt}$ is the tightening force in each bolt and n is number of the bolts. Figure 2 shows the damper and the characteristics of the hysteresis curve.



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

Fig. 2 - Resilient Slip Friction Damper.

The parameters of the flag shaped load-displacement performance of RSFD can be calculated using following equations. Figure 3 mentions the test results of the damper. Self-centring condition:

$$F_{prerod} > F_{friction}$$

Hysteresis loop equations:

$$F_{slip} = F_{prerod} + f_{friction}$$

$$F_{ult} = F_{slip} + k * \Delta_{max}$$

$$F_{restoring} = F_{ult} - f_{friction}$$

$$F_{restoring} = F_{prerod} - f_{friction}$$

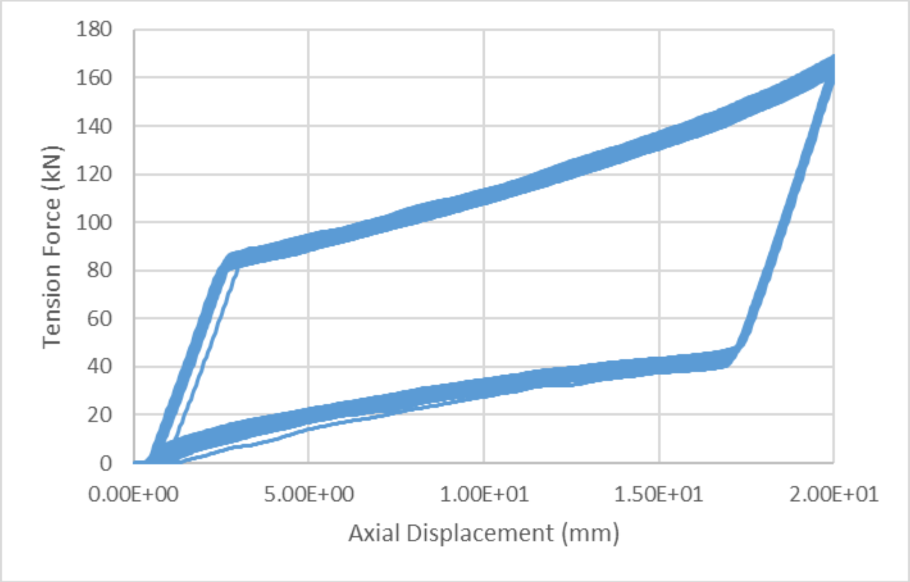


Fig. 3 – Experimental verification of Tension-only RSFD.

3. Rocking concrete shear walls with self-centring hold-downs

3.1 System Configuration and Performance Characteristics

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 4a). After manufacturing

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.

Considering Figure (4b), 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.

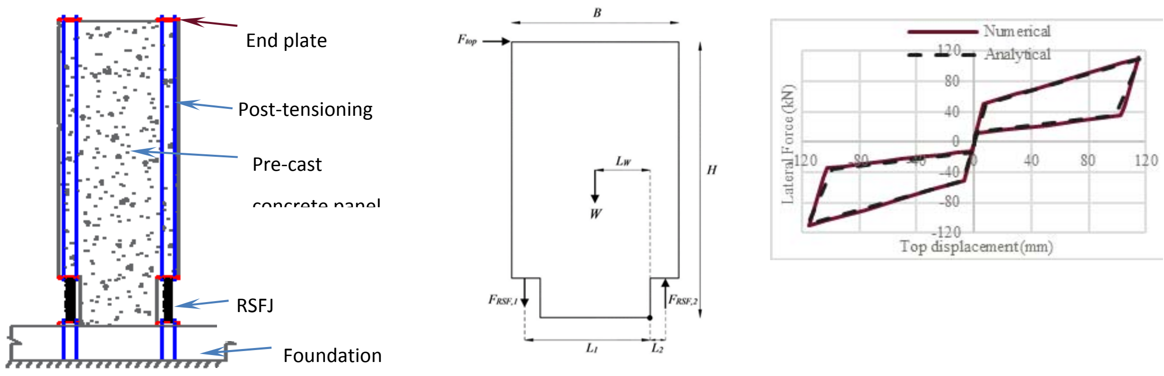
$$F_{top} = \frac{1}{H}\left[WL_W + F_{RSFJ,1}L_1 + F_{RSFJ,2}L_2)\right] \tag{5}$$

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

A numerical modelling has been done using SAP2000 software and the results are compared to the analytical model (Figure 4c). Modeling parameters are summarised in table 2. As it can be seen from Figure (4c), the analytical and numerical results are in agreement.

Table 1. 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

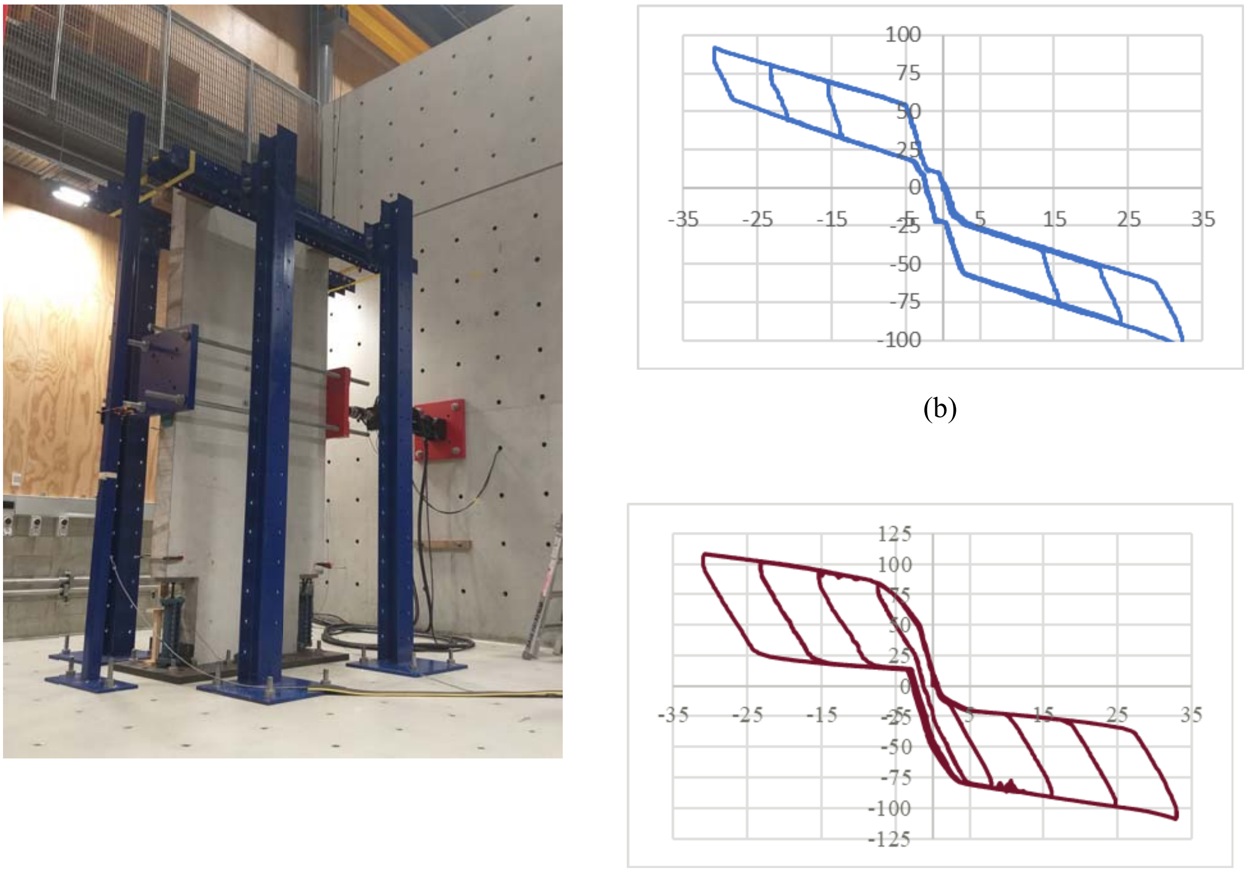


(a) (b) (c)

Fig.4 - (a) different components of the proposed rocking pre-cast concrete wall system (b) Analytical parameters (c) Comparison of numerical results and analytical predictions.

4. Experimental verification

An experimental study was done in order to assess the performance of the proposed system. The test setup is mentioned in Figure 5. As can be seen from the graphs. The desired self-centring performance is achieved by the proposed system.



(b)

(a)

(c)

Fig.5 – (a) RSFD Shear wall test setup, (b) RSFD shear Wall test result, (c) RSFJ shear Wall test result.

5. Conclusion

In this paper, the performance of a rocking shear wall was assessed. Two different self-centring devices were considered. Analytical equations were developed and compared to experimental results. The results have shown that the proposed system is capable to dissipate input energy in a repetitive manner.

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