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Seismic performance of damage avoidance pre-cast concrete shear walls using innovative self-centring friction joints

F.M. Darani, P. Zarnani & P. Quenneville
Auckland University of Technology (AUT), Auckland, New Zealand.

E. Haemmerle
University of Auckland (UoA), Auckland, New Zealand.

ABSTRACT

Ductile concrete shear walls are suitable for protecting buildings from collapse due to earthquakes. 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 minimise 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-centring are provided. The newly developed Resilient Slip Friction Joint (RSFJ) is a damage-avoidance structural connection which satisfies all these requirements. In this research, an experimental study is carried out at the joint component level to verify the developed analytical model to predict the load-displacement relationship of the RSFJ. Also, the performance of rocking wall systems with RSFJ hold-downs is explained. An analytical model is then developed in order to design the components of the joint. The effect of cracks in rocking concrete walls with hold-downs is also assessed. A structural configuration is then proposed for rocking pre-cast concrete shear walls with RSFJs as hold-downs using post-tensioning rods or tendons to minimise the effect of cracks in wall's behaviour.

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1 INTRODUCTION

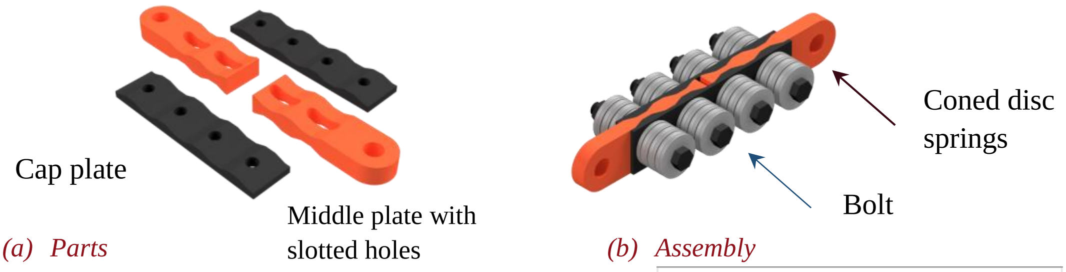
Ductile concrete shear walls have widely been used in earthquake resisting systems. High stiffness and high strength, as well as acceptable ductility levels, can be named as positive points of such lateral load-resisting walls (Paulay and Priestley, 1992). Yielding of the longitudinal bars is the main source for dissipating seismic energy in these walls to provide the required ductility. To achieve the required level of ductility, many details should be taken into account which makes the design procedure of conventional concrete shear walls complicated. For example, concrete confinement, reinforcement of the potential plastic hinge regions and avoiding brittle failure modes, could be named as the design and practical challenges (Paulay and Priestley, 1992). Shear failure, wall toe crushing and local buckling of the wall segments are some of the brittle failure modes which are observed during the past earthquakes (Kam et al., 2011) and should be avoided. Furthermore, the traditional design which is based on ductile concepts is costly to be repaired or reconstructed after moderate to severe earthquakes. It should be noted that the cost of business interruption should also be added to the expenses mentioned above. Following 2010 and 2011 Canterbury earthquakes and the consequent 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.

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 (Priestley et 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 has been proposed by researchers to improve the seismic response of the rocking wall systems. Yielding, friction and viscous damping have been suggested, tested and used in rocking shear walls (Sritharan et al., 2015).

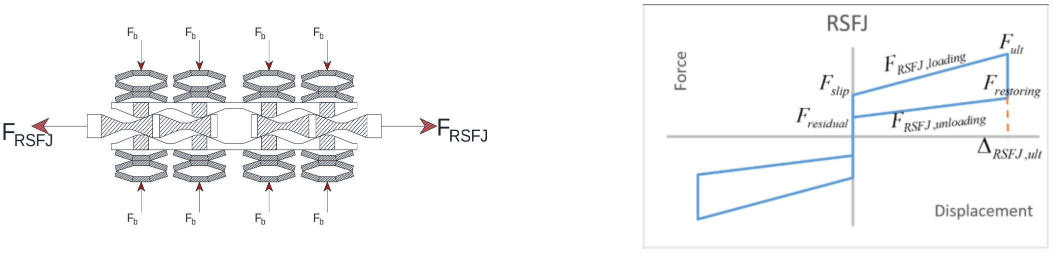
Resilient Slip Friction joint (RSFJ) is a new technology introduced by Zarnani and Quenneville (2015) which provides self-centring and energy dissipation in one compact damage-free connection. This new seismic technology minimises the earthquake damage and helps the building to be quickly operational after earthquakes. The objective of this research is to assess the seismic performance of rocking pre-cast concrete shear walls with RSFJ hold-downs. In the following sections, the basic equations and hysteretic curve of the RSFJ are introduced. Furthermore, design challenges for implementing the joint in rocking concrete shear walls will be discussed and a configuration for this type of lateral load resisting system is suggested.

2 RESILIENT SLIP FRICTION JOINT (RSFJ)

The components and assemblage of the RSFJ are shown in Figure 1. The outer cap plates and the middle plates are grooved and clamped together using high strength bolts. When the imposed force to the joint overcomes the frictional resistance between the surfaces, the centre slotted plates start to slide and energy will be dissipated through cycles of sliding. The specific shape of the grooved plates along with the use of disc springs and high strength bolts provide the desirable self-centring characteristic for this slip-friction joint. The angle of the grooves is designed in such a way that at the time of unloading, the reversing force induced by the elastically compacted disc springs is larger than the resisting friction force acting between the plates' surfaces. Therefore, the system is re-centred by the reversing force upon unloading (Zarnani et al., 2016). The flag-shaped response of RSFJ and its characteristics are shown in Figure 1.



(a) Parts *(b) Assembly*



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

Figure 1: Resilient Slip Friction Joint

Considering the free body diagram of RSFJ (Figure 1c), The slip force of the connection can be determined by

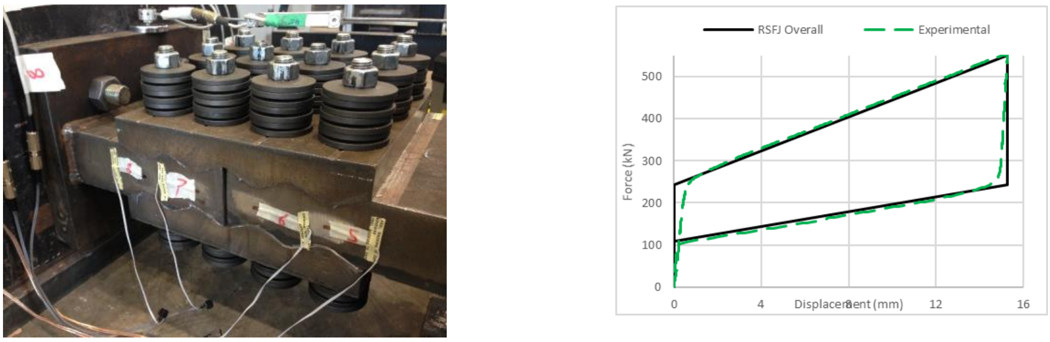
$$F_{slip} = 2n_b F_{b,pr}\left(\frac{\sin\theta+\mu\cos\theta}{\cos\theta-\mu\sin\theta}\right) \tag{1}$$

In which, θ is the grooves angle; µ is the coefficient of static friction and can be considered equal to 0.18; $F_{b,pr}$ is the bolt clamping force as a result of being pre-stressed; and n_b is the number of bolts on each splice. The residual force at the end of unloading is calculated by Equation 2.

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

In this section, the experimentally achieved the load-displacement response of an RSFJ is compared to the analytical models.

The test setup is shown in Figure 2a. The experimental load-displacement response is compared to the analytical predictions in Figure 2b. As can be seen from the graphs, the response is well predicted using the analytical model. Considering the flag shaped 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.



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

Figure 2: Experimental testing on an RSFJ

3 LOAD DISTRIBUTION BETWEEN RSFJ GROOVES

To design the plates of the RSFJ, the performance of the plate should be carefully investigated. While the finite element models show an accurate representation of the RSFJ plates, they require considerable computational effort each specific design. Accordingly, a simplified analytical spring model with enough accuracy can save both time and computational effort. RSFJ in most of its applications is being used as an axially loaded element. It is also composed of triangular grooves and flat plates. This type of simplicity in loading and geometry provides an opportunity to develop a simplified analytical model for load distribution between RSFJ parts. Here, a stiffness-based model is developed to predict the load distribution between RSFJ parts. The RSFJ is divided into several parts and each part is modelled by an appropriate shear/flexure or axial spring. The results are then verified via experimental and numerical modelling.

The distribution of the external forces inside the joint depends on the relative stiffness of the segments. Therefore, the RSFJ can be divided to grooves with shear and flexural deformation and axially deformed parts including flat plates and grooves. The appropriate stiffness of these segments can be calculated using the mechanics of materials rules.

The unit load method is used to calculate the shear and flexural stiffness of the triangular grooves. Each groove is assumed to be a cantilever column. Only the effect of the horizontal load, F_h, is considered in the calculation of the deformations while the effect of vertical load, F_V, is neglected as the vertical axial deformations can be ignored for horizontal load distribution (Figure 3).

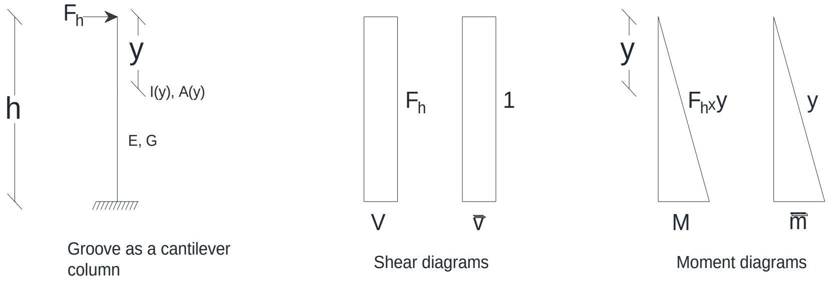


Figure 3: Shear and bending diagrams for cantilever grooves

Considering the shear and bending diagrams of the grooves (Figure 3), the derived deformation integrations are as Eq. 3 and Eq. 4.

$$\Delta_b = \int_0^h \frac{\overline{m}M}{EI_{(y)}} dy \tag{3}$$

$$\Delta_v = \frac{6}{5}\int_0^h \frac{\overline{v}V}{A_{(y)}G} dy \tag{4}$$

Where Δ_b is the bending deformation of the grooves while Δ_v denotes the shear deformation of the groove. The parameters $\overline{m}$ and $\overline{v}$ are internal moment and shear due to the virtual unit load acting on the same point and direction as F_h, while M and V are the internal moment and shear due to F_h, E and G are the modulus of elasticity and shear modulus, respectively. $I_{(y)}$ and $A_{(y)}$ are section moment of inertia and section area, respectively which vary along the height of the grooves.

The accuracy of the proposed model is assessed using detailed numerical models. Software SAP2000 is used to model an RSFJ with three grooves at each side (Figure 4a). The simplified model is also shown in Figure 4b and the results are compared. It is clear that the results are in agreement with each other.

4 ROCKING CONCRETE WALLS WITH RSFJ HOLD-DOWNS

In this section, the cracking performance of rocking concrete shear walls with RSFJ hold-downs is assessed based on the numerical modelling. A previously tested fixed base high-damage designed concrete shear wall was selected and modelled as a rocking shear wall by 1) removing the foundation part and adding two RSFJs in the wall bottom corners; and 2) disconnecting the wall from the foundation by modelling a compression-only connection (closed gap) between the wall and its foundation. This concrete shear wall was designed and tested by Lefas et al. (1990). The concrete compressive strength of the tested wall was 36 MPa and the tensile strength was 2 MPa.

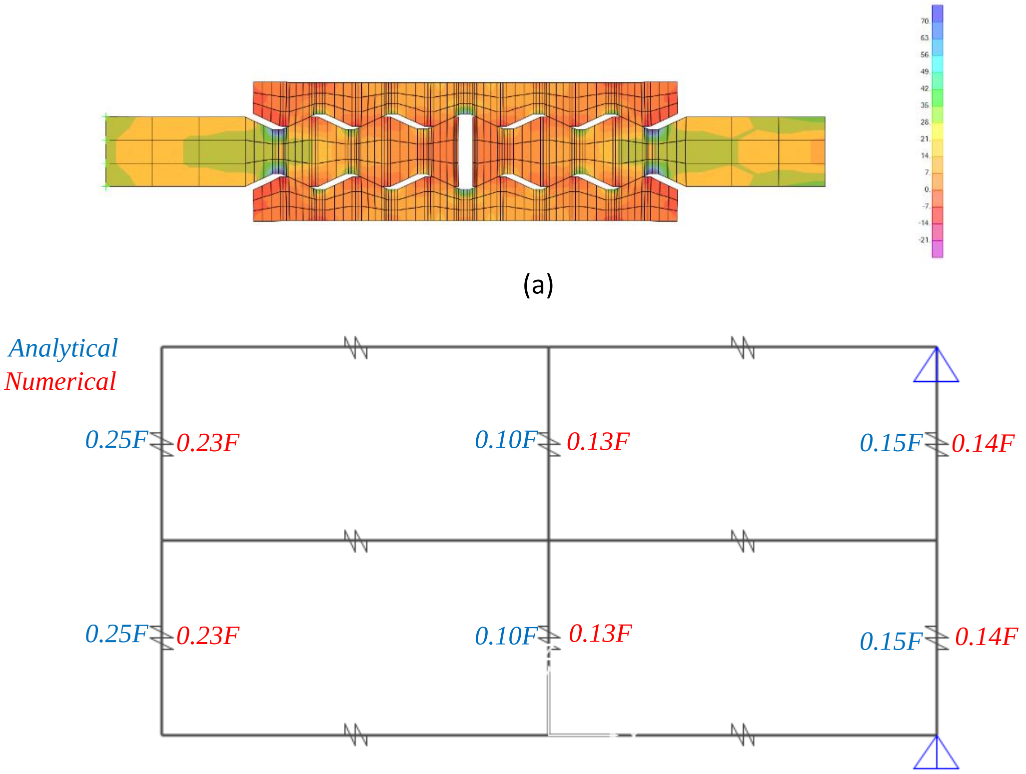


Figure 4: a) Numerical modelling b) Analytical model and comparison of the results

A numerical model was used to investigate the exact behaviour of the proposed rocking wall system with RSFJs. Software VecTor2 (Wong et al., 2013) was used to model the structure. The program default assumptions were used for modelling the reinforced concrete material behaviour. RSFJ hold-downs were modelled using the truss element. The RSFJ loading behaviour is modelled using the "ductile reinforcement material" option in the software. The appropriate reinforcement material property, representing the behaviour of the RSFJ, was then assigned to a truss element. It should be noted that the RSFJ unloading stage could not be modelled in VecTor2 and therefore, this software is not a suitable choice for dynamic analysis of the proposed system. This software is sufficient for performing a pushover analysis to assess the behaviour of the concrete specially at the final loading stage. The applied vertical load was considered to be zero simulating a wall only transferring the lateral forces. Pre-stressing forces were applied on the wall top and bottom corners to produce average stress of less than one-third of concrete compressive strength. The pre-stressing force was not evenly distributed across the section given the post-tensioning elements were just used at the corners. The maximum pre-stressing stress in the concrete was about 10 MPa with an approximate average of 5 MPa across the whole section.

To model the shear key, the base nodes were restrained against the horizontal movement. The compression only reinforcement materials were assigned to a configuration of X shaped truss elements to model the compression only connection between the wall base and the foundation. Accordingly, the wall could easily rock around the base while the compression only elements performed like a closed gap between the wall and its foundation.

Figure 5a shows the deformed shape and cracking pattern of the rocking wall at 3% drift. Minor tension cracks occur around the wall base due to stress concentration. However, these cracks are acceptable in the proposed system as they will be closed by the elastic response of the reinforcing steels in the cracked regions upon unloading and no residual deformation will be observed. In addition, the extension and propagation of these cracks are not that much considerable in reducing the initial elastic stiffness of the system. In Figure 5b, the deformed shape of the wall is shown when the pre-stressing force is not applied. It can be seen that the cracks are propagated more extensively with higher crack opening gaps at the connections position.

The reduction in the initial stiffness and steel strain distribution along the section are shown in Figure 5c and 3b. The effectiveness of the pre-stressing can be easily recognised as reinforcing steel is yielded when pre-stressing force is not applied.

Further study on the reversed cyclic behaviour and strength and stiffness degradation of these walls should be done to find out if this stress limit is acceptable for earthquake loading condition.

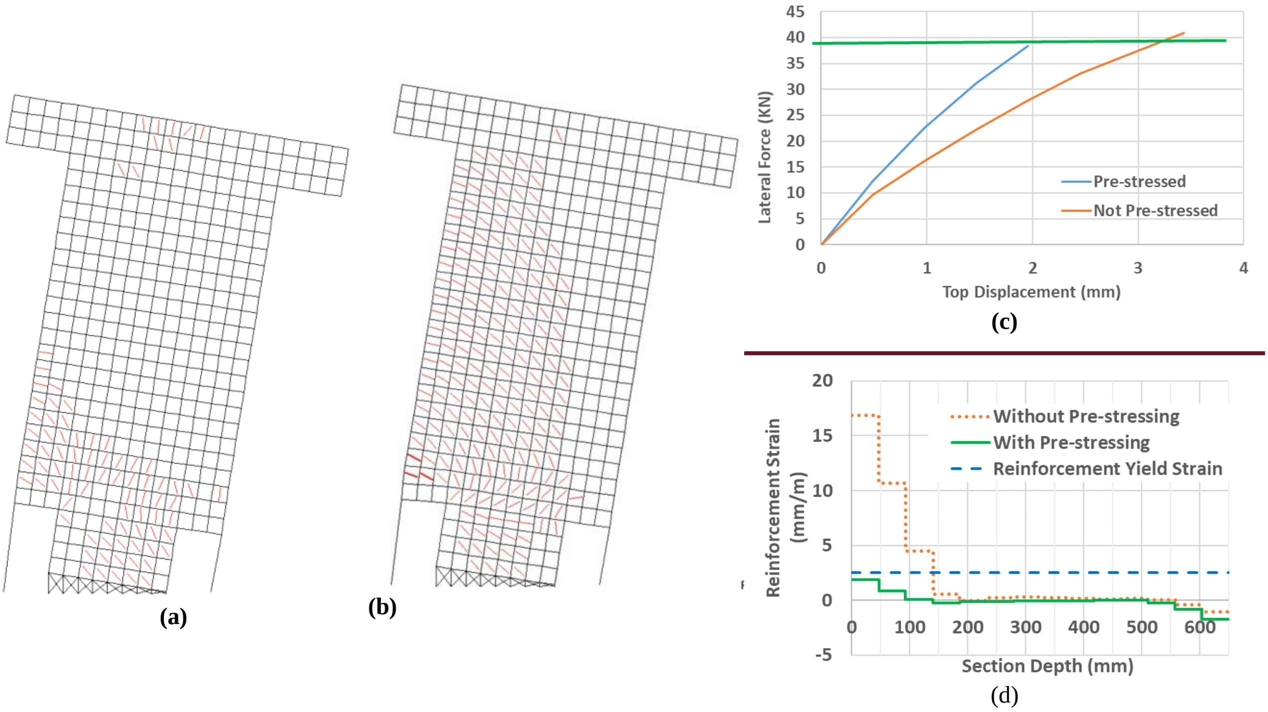


Figure 5: Modelling observations: (a) Deformed shape and cracking pattern of the rocking wall at 3% drift with pre-stressing and (b) without pre-stressing, (c) initial stiffness of the systems (b) Distribution of strain in reinforcing steel along the section

5 POST-TENSIONED PRE-CAST CONCRETE PANELS WITH RSFJ HOLD-DOWNS

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. As discussed in the previous section, 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 by applying pre-stressing forces on the wall using practically simple solutions.

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 6a). 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 costs in comparison to the current post-tensioning concepts.

The wall can then be mounted vertically and be 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 compared to current approaches.

Software SAP2000 is used to model the proposed system (Figure 6b). The analysis results in the model is compared to the analytical model developed by Hashemi et al. 2017. As can be seen from the graph shown in Figure 6c, the results are in agreement with the analytical predictions.

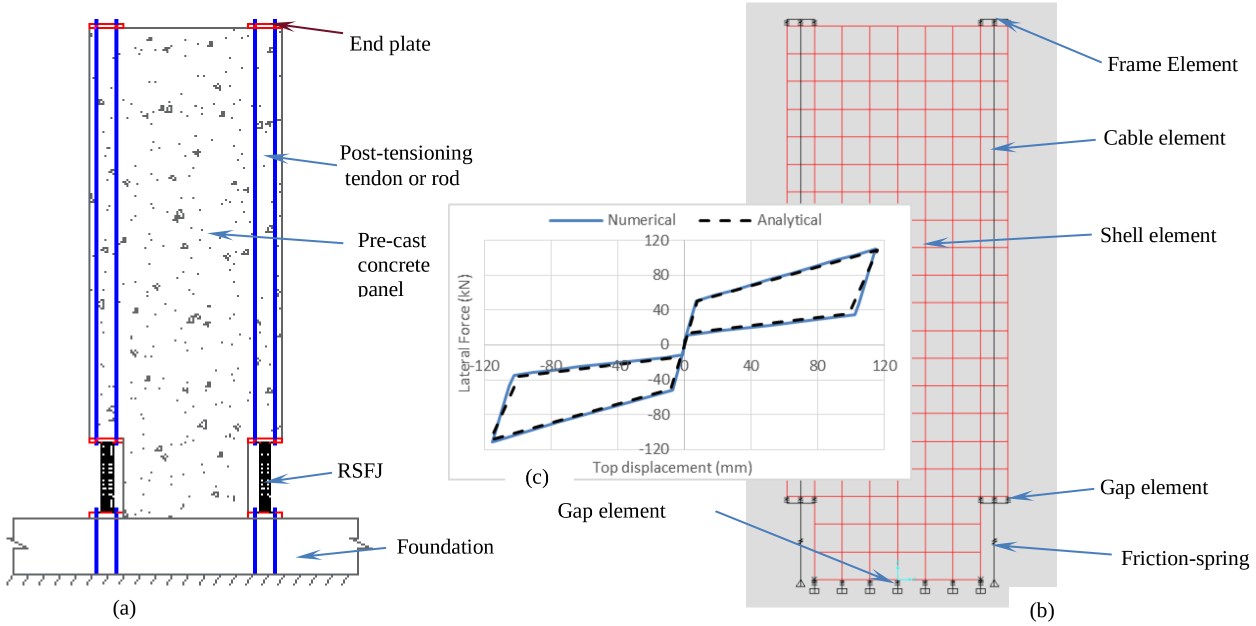


Figure 6: a) different components of the proposed rocking pre-cast concrete wall system, b) SAP2000 model, c) analytical predictions compared to numerical model results

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.

6 CONCLUSION

This paper presents a new low-damage seismic resisting system in which Resilient Slip Friction Joints (RSFJs) have been adopted for a rocking pre-cast concrete shear wall. This new system provides self-centring as well as energy dissipation through incorporating compact damage-free 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. Some of the advantages of the proposed post-tensioned system can be named as 1) minimising tension cracks 2) reducing required reinforcement 3) the pre-stressing process can be done in the factory. The seismic performance of the proposed system has been evaluated using nonlinear analysis and to be further verified by large-scale experimental testing.

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