NEW ZEALAND SOCIETY FOR
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Seismic Resilient Structures Using Pre-Cast Pre-Stressed Concrete Panels for Modular Construction

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ABSTRACT

Earthquake resiliency combined with sustainability can be achieved through state of the art technology and construction methods. In this paper, a new construction methodology is proposed for resilient and sustainable concrete structures. A resilient or Damage Avoidance Design (DAD) solution is proposed for pre-cast concrete rocking walls using a novel self-centring damper. A new procedure has been proposed to pre-stress the pre-cast concrete walls to reduce steel reinforcement, construction complexity and site work and consequently carbon footprint. First, the overall system configuration and lateral load performance is described. Then, the design steps of the proposed structural system will be discussed. The details of the construction methodology and applicability for modular construction is also presented in this paper. Finally, the performance of the proposed system is verified through experimental investigation.

1 INTRODUCTION

Rocking concrete shear walls have been developed as a damage avoidance solution for DAD (Mander and Cheng 1997, Holden et al 2003, Mander 2004). Unbonded post-tensioning (Henry 2011) has been used to control the rocking motion and to provide controlled self-centring capability.

The concept of rocking motion has always been a point of interest for researchers and engineers (Henry 2011). During the past earthquakes, it has been observed that the structures which unexpectedly rocked around their base suffered from less damage compared to those of fixed base. Therefore, several different systems incorporating rocking motion have been introduced for earthquake resistant structures.

The most common way of implementing a controlled rocking behaviour is to use post-tensioning (PT) cables along with supplemental yielding dampers. However, other types of energy dissipaters such as friction or viscous dampers have also been used in the PT rocking wall structures (Marriott et al 2008). It should be noted that using on-site post-tensioning causes construction complexity and additional labour. Also, yielding dampers should be inspected after moderate to severe earthquake and repaired or replaced if required. The results showed that the additional dampers effectively reduce the seismic demand if they are properly designed.

Considering the previous research related to the rocking wall structures, it is observed that a limited effort has been made in developing rocking walls with self-centring dampers (Mottier et al 2018, Hogg et al 2020). These devices provide self-centring and energy dissipation in one compact connection (Golzar et al 2018, Wang et al 2019) and can be used for controlling the rocking motion. The use of Self-centring Structural Connector (SSC) (Darani et al 2018), in rocking concrete walls, is investigated in this study. Then, the performance of the system is examined via large-scale cyclic testing.

2 CONCEPT DEVELOPMENT AND ANALYTICAL INVESTIGATION

The proposed concept is suitable for prefabricated construction and promotes modular construction and the use of pre-cast concrete in seismic resisting structures.

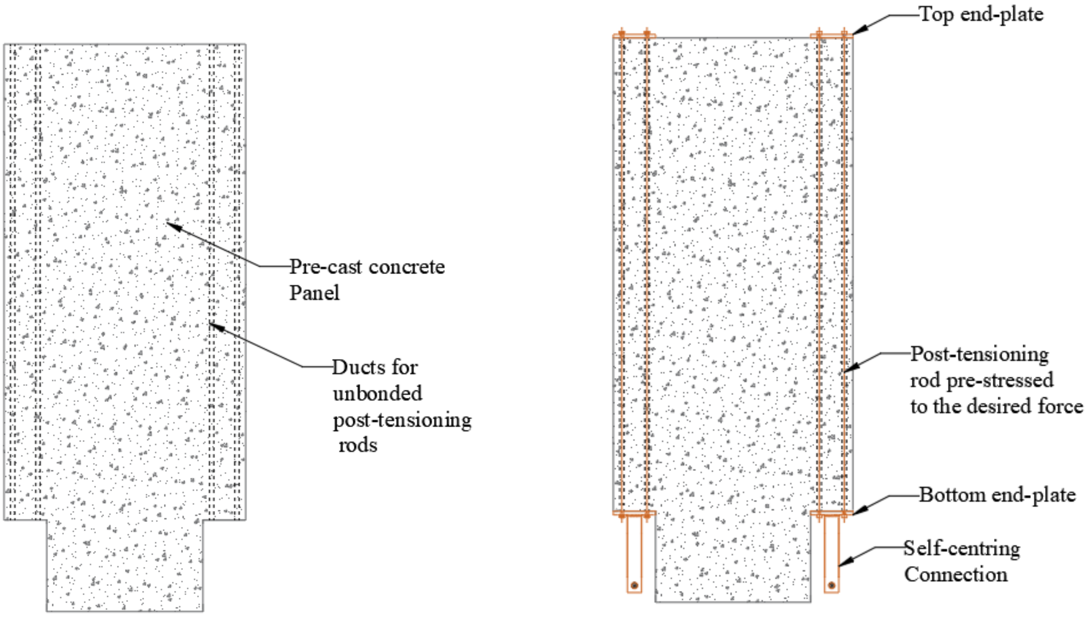
Pre-stressing has always been a well-accepted method to control the cracking and deflection in reinforced concrete. Pre-stressed and post-tensioned members have widely been used in the construction industry. The concept of off-site pre-stressing and/or post-tensioning of prefabbed reinforced concrete is not common for seismic resisting elements. Even though on-site unbonded post-tensioning is used for concrete rocking systems, the design complexity and the extra on-site work required for post-tensioning is one of the challenges from both design and construction points of view. In the proposed solution, the advantages of post-tensioning are used while on-site extra work is not required as the post-tensioning can be done in the factory.

In this concept, as shown in Fig. 1, a concrete panel that is already post-tensioned in the factory using unbonded rods is transferred to the construction site and then mounted and connected to the foundation using the self-centring hold-downs. It should be noted that the post-tensioning aims to prevent the wall from cracking and therefore an internal post-tensioning of the wall prior to mounting will suffice. This means that there is no need to use unbonded PT cables to connect the wall to its foundation. It is also not required to use complex connection detailing or a highly reinforced panel with special seismic detailing. In most cases, a minimum required reinforcement could be enough. The details of the developed concept are presented as follow.

As shown in Fig. 1, firstly, the concrete panel should be post-tensioned internally using unbonded rods up to a certain pre-stressing force level. The post-tensioning force can be applied using a rod or cable inserted through the ducts in the boundary regions of the wall and connected to the endplates (Fig. 1).

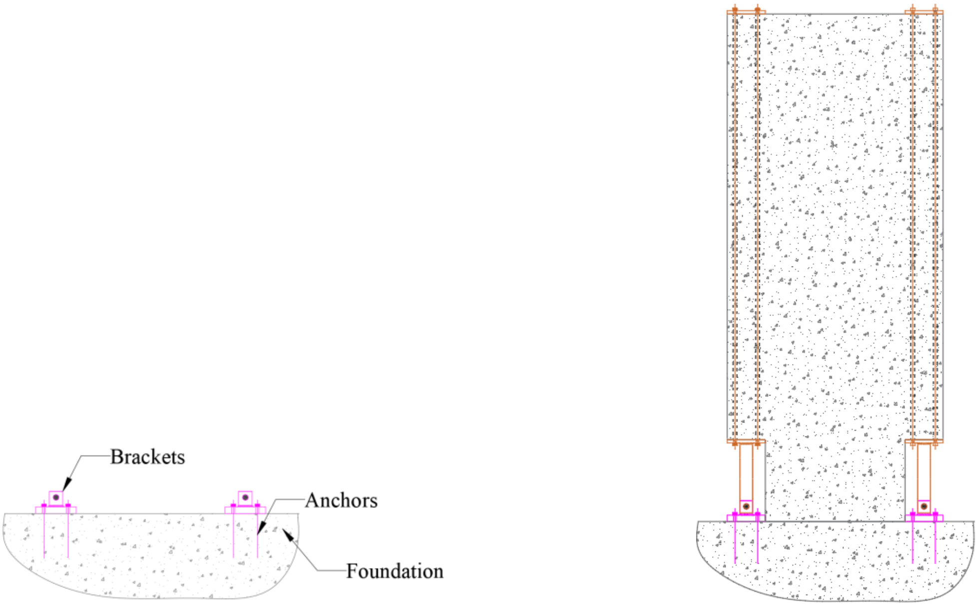
In order to eliminate the tension cracks, a pre-stressing concept is developed. In this concept, the pre-cast concrete panel is connected to the foundation using the self-centring dampers. This precast concrete panel is post-tensioned using unbonded cables or rods. After manufacturing and considering proper timing for the concrete curing, the pre-cast concrete panel will be compressed using the unbonded tensioning elements. Post-tensioning can be done either at the factory or the construction site when the wall is laid down on the floor. The proposed procedure decreases the construction time and costs in comparison to the current on-site post-tensioning concepts. The wall can then be mounted vertically and get connected to the foundation using the brackets.

Another advantage of this system in comparison to 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 dampers rather than the PT tendons.



Phase 1: In the Factory
Pre-cast concrete panel

Phase 2: Either in the factory or on-site
Post-tensioning rods added and pre-stressed with:
arrangement 1, self-centring connections already welded to the bottom endplate
or,
arrangement 2, Self-centring connections to be connected to the bottom endplate on-site using bolts or pins



Phase 3: On-Site
Brackets anchored to the foundation

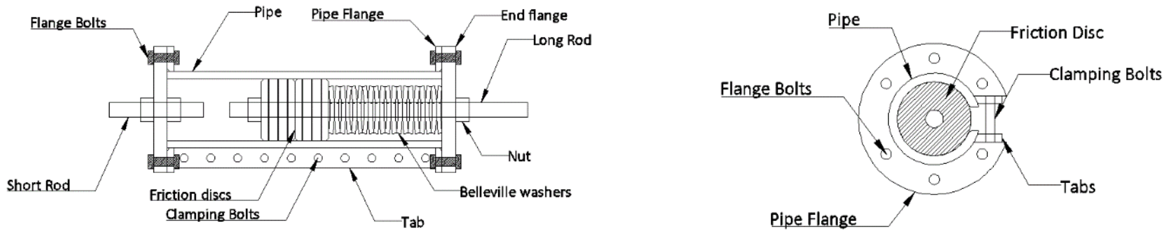
Phase 4: On-Site
Wall mounted and connected to the brackets

Figure 1. Different components and construction phases of the proposed rocking pre-cast concrete wall system.

Self-centring Structural Connector (SSC)

In this section, a brief description of the Self-centring Structural Connector (SSC) is presented. The reader is referred to Darani 2021 and Darani et al 2022, for more information.

Parts and components of the SSC are shown in Fig. 2. Disc springs are responsible for the self-centring capability. Every single spring has a specific displacement capacity, Δ_s, and a corresponding load capacity, F_s, at the maximum displacement, which is called flatness load. It should be mentioned that the stack of the springs should be pre-stressed to the desired pre-stressing force before being inserted inside the tube.



SSC Longitudinal Section

SSC Transverse Section

Figure 2. Self-centring Structural Connector (SSC).

The friction of the internal surface of the tube with friction rings is the source of energy dissipation. The tube clamping bolts are pre-stressed to the required clamping force. This force creates the normal force (perpendicular to the surface) between the disc and the tube for friction. The earthquake input energy is dissipated by friction and the self-centering capability is provided by disc springs.

3 LOAD-DISPLACEMENT PERFORMANCE OF ROCKING WALLS

The performance of rocking walls with tension-only connections are assessed and the equations are developed. The free-body diagram of the system with tension-only connections is mentioned in Fig. 3.

At the slip level, when joints have reached their slip force, the wall starts to rock.

$$F_{slip,wall} = \frac{1}{H}\left[F_{slip,joint}(L - 3e/2) + w\frac{L-2e}{2}\right] \tag{1}$$

Where, $F_{slip,wall}$ is the lateral load acting on the wall at the onset of rocking motion, $F_{slip,joint}$ is the connections' slip force and W is the weight of the wall. Other geometric parameters are mentioned on the diagram (Fig. 3).

The wall top displacement is a combination of the wall rigid body rotation due to rocking and its elastic deformation. The top displacement of the wall can be calculated using Eq. 2 to Eq. 4.

$$\Delta_{wall} = \Delta_{elastic} + \Delta_{rot} \tag{2}$$

$$\frac{\Delta_{rot}}{H} = \frac{\Delta_{joint,t}}{L - \frac{3e}{2}} \tag{3}$$

$$\Delta_{elastic} = \frac{F_{wall}H^3}{3EI} \tag{4}$$

$\Delta_{elastic}$ is the elastic deformation of the wall due to F_{wall}. E and I are the modulus of elasticity and moment of inertia of the wall section.

The load-displacement equation of the wall after the slip stage can be calculated using Eq. 5.

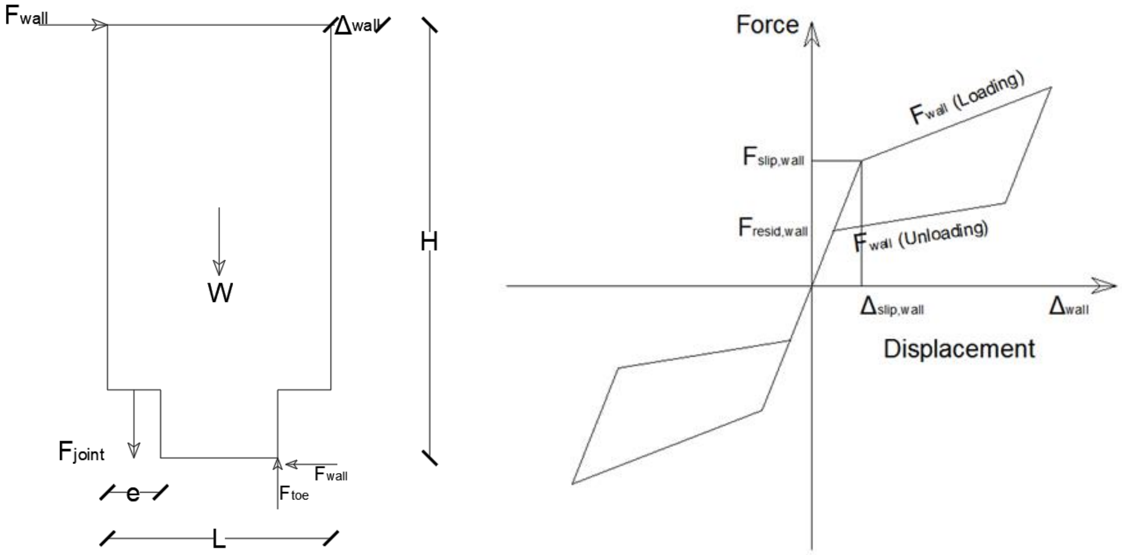


Figure 3. The free-body diagram of rocking walls equipped with tension-only self-centring connections.

$$F_{wall} = \frac{1}{H}\left[F_{joint}(L - \frac{3e}{2}) + w\frac{L-2e}{2}\right] \tag{5}$$

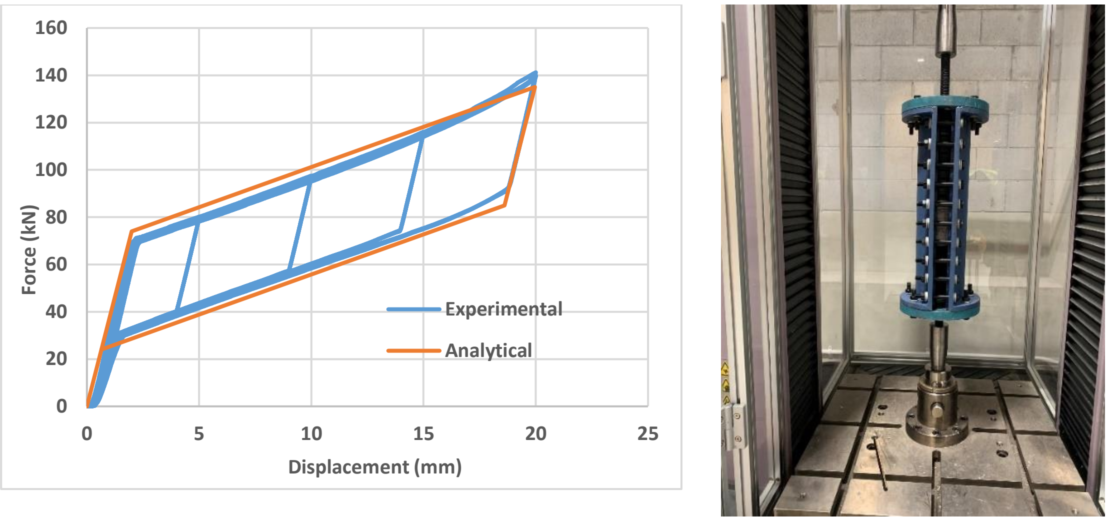
The developed equations will be verified through experimental investigation presented in the upcoming sections.

4 SSC SHEAR WALL

The SSC joints used for the rocking wall tests were originally designed for the proof of concept of the joints (Darani et al 2022). Later, the same joints were used for the rocking concrete shear wall test. The joints are designed for an ultimate force capacity of 135 kN and a maximum displacement of 20mm. The design parameters of the SSC are mentioned in Table 1. The SSCs were tested using the UTM machine to verify the load-displacement performance of the joints. The assembled joint in the UTM is shown in Fig. 4. The load-displacement response obtained from the test is compared to the one predicted by the analytical equations verifying the accuracy of the developed model given the agreement between the results (Darani et al 2022).

Table 1. Design parameters of tested SSCs.

Δ_S (mm)	1.80
F_{pr} (kN)	49.00
F_S (kN)	110.00
n	20
Δ_{ult} (mm)	20.00
F_c (kN)	26.50
m	0.15
F_{fr} (kN)	25.00

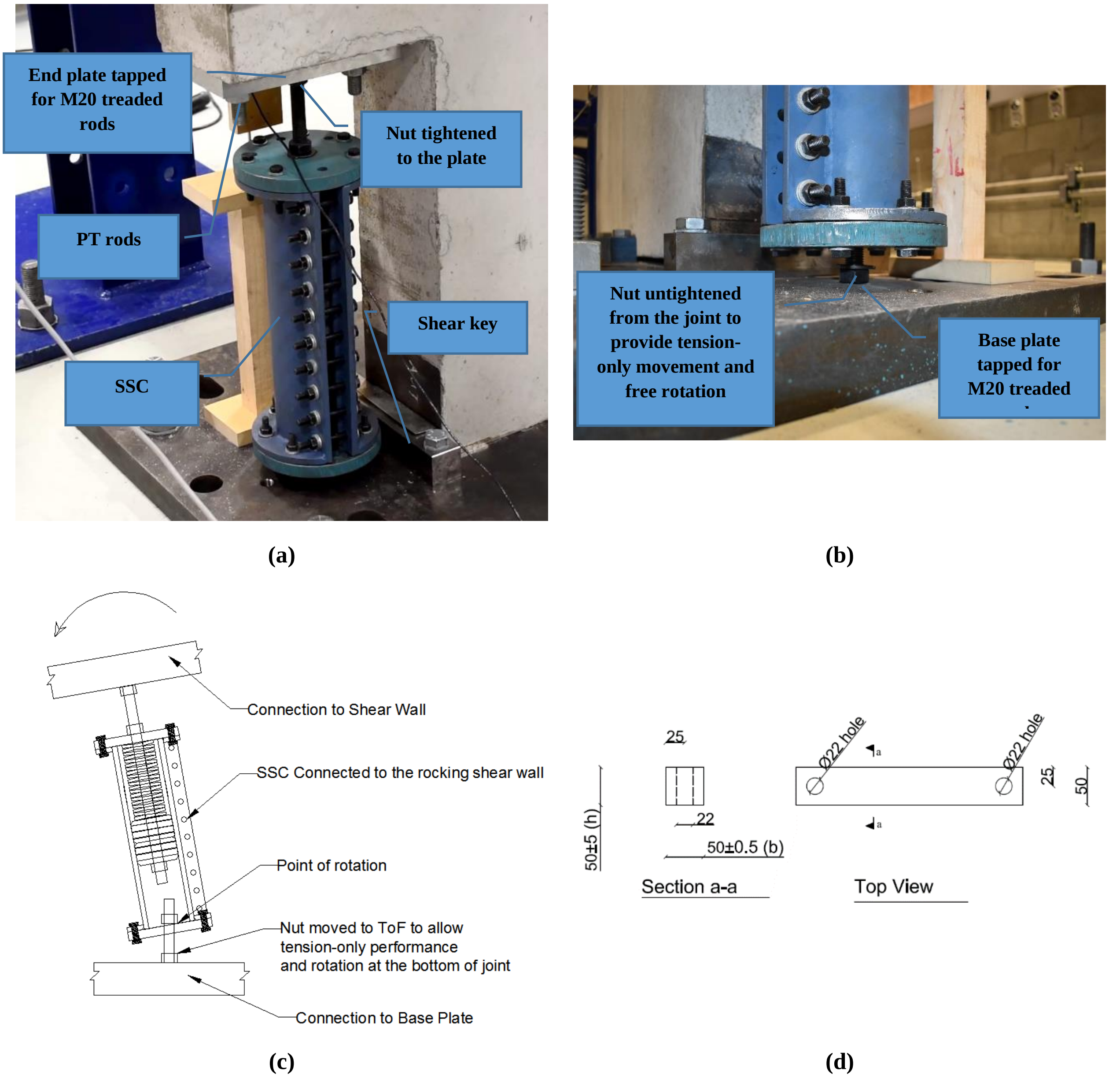


(a) **(b)**

Figure 4. SSC component test: a) comparison of analytical and experimental performance, b) test setup.

In this section, the details related to the connection of the SSC to the wall and the foundation base plate is presented. Rod M20 Grade 10.9 has been used to connect the joint to the wall endplate and the foundation. As shown in Fig 5a and b, the wall endplate and the foundation base plate were tapped for the threaded holes required for the rod connection. The SSC needed to be connected to the wall first. This was done by turning the joint to screw it to the wall endplate while the wall was horizontally laid on the floor before mounting. When the wall was vertically mounted on the base plate, the SSC needed to be twisted around its axis to be screwed to the foundation base plate (Fig. 5(a)). There should be enough engagement length for the threads to maintain the desired capacity. At this stage, the nut at the top of the SSC was tightened to the endplate restraining the joint from free rotation around its axis. Later, the nut at the bottom of the joint was tightened to the base plate to release the joint in compression and to prevent any compression force to be generated in the joint. In fact, the tension-only performance of the SSC was achieved by loosening the bottom nut as shown in Fig. 5(b). Also, it allows the joint to rotate from its bottom side to be compatible with the rotation induced by the rocking motion of the wall (Fig. 5(c)). For the SSC shear wall, two high strength steel blocks have been used at the wall toes to resist the shear force. These shear keys are shown in Fig. 5(d).

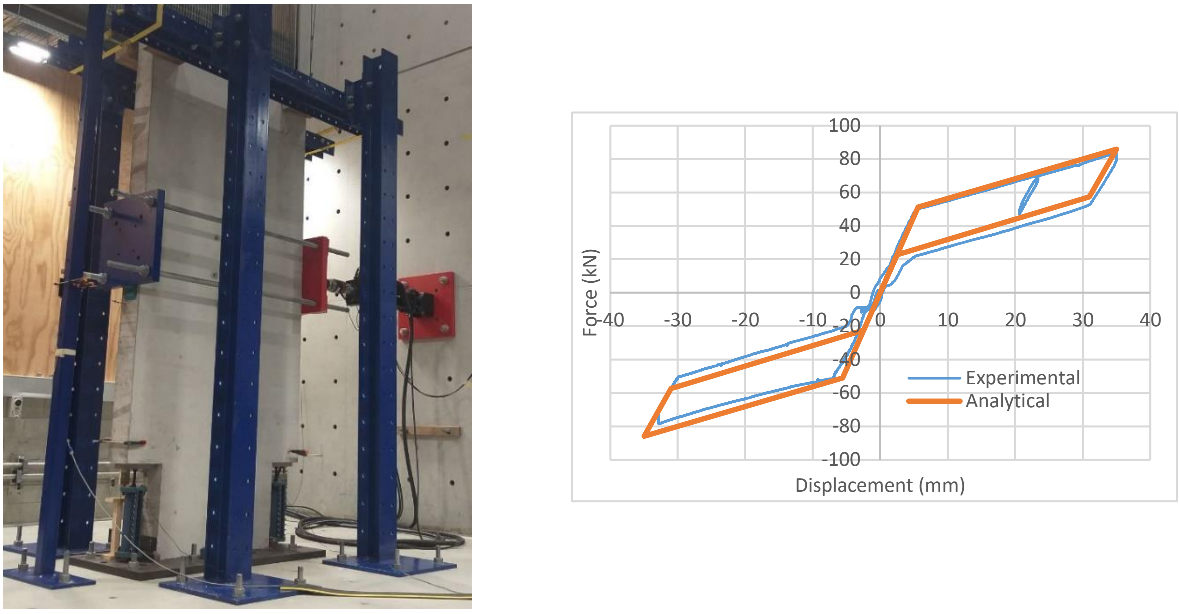
The completed test setup for the SSC shear wall is shown in Fig. 6(a). The wall was tested under 5 full cycles of lateral drift up to 1.6% where the maximum capacity of the joints was achieved. The load-displacement performance of the tested wall with the SSC dampers are shown in Fig. 6(b). The results have shown that the developed system is capable of resisting lateral loading with a repetitive and predictive response. As can be seen from the graph, the actual performance of the wall is well predicted by the analytical model. The wall, joints and their connection were inspected thoroughly after the test and no significant damage was detected confirming the robustness of the rocking-wall system developed with self-centring friction dampers as hold-downs.



(a) (b)

(c) (d)

Figure 5 SSC connection to shear wall and foundation: a) connection at the top of the joint, b) connection at the bottom of the joint, c) rotation compatibility with rocking motion, d) shear keys



(a) (b)

Figure 6. SSC shear wall: a) test setup, b) comparison of analytical and experimental results, and c) results under high-frequency loading.

Note: displacements are inferred displacements at the actuator level based on draw-wire readings

5 DISCUSSION AND CONCLUSION

This study proposes a rocking shear wall system with self-centring friction dampers as an alternative design to conventional fixed-base shear walls. Rocking shear walls can improve the seismic response of the structure considerably and mitigate the likelihood of irreparable damages.

Self-centring Structural Connectors (SSC) have been used in this study to provide the required energy dissipation mechanism. It is proposed to use the dampers at the wall base to connect the wall boundary to the foundation. The SSC provides repetitive and reliable energy dissipation and can be considered as a robust element for the damage avoidance design (DAD) system developed in this study.

It should be noted that when dampers are used as hold-downs, large bending moments are expected at the base of the wall. This bending moment results in highly reinforced sections at the base. Also, additional reinforcement is required for anchoring the dampers to the bottom of the wall. In addition, bending tension cracks decrease the stiffness of the wall significantly. Consequently, the effectiveness of the damping devices will be sacrificed as less deformation is to be transferred to the dampers due to wall flexibility as the result of cracking. A new pre-stressing method has been proposed in this study to overcome cracking related issues. In this concept, before mounting the rocking wall, the wall is internally pre-stressed before being mounted on the construction site. The benefits of the proposed pre-stressing method are as follows.

- Tension stresses and tension cracks are eliminated.

- Highly-reinforced sections are not required and usually, a minimum code reinforcement will suffice resulting in a more sustainable solution.

- There is no need to design and use embedded anchors for connecting the dampers to the wall. The end plates used for wall pre-stressing can be used for connecting the dampers to the wall.

- Complex and costly on-site unbonded post-tensioning, which is common for other rocking wall systems, is not required in the proposed system make it a suitable for modular construction and for modern methods of construction.

- The system can be optimised for mass production and modular construction as minimum site work is required for mounting and assembly.

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