A unique rocking wall – its motion and mechanics

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ABSTRACT: The authors have previously reported on their success in imparting elasto-plastic characteristics to a rigid timber shear wall through the use of steel slip-friction connectors. In this paper the unique rocking characteristics of the same wall are discussed. The rocking motion of the wall with slip-friction connectors is unlike that of a free-rocking structure - in which there is always contact with the foundation at some point along the base. Instead, the wall with slip-friction connectors can become 'air-borne' for a significant part of its motion. With the implementation of slip-friction connectors and the novel shear key adopted by the authors, the rocking motion can be divided into six distinct phases (three associated with both directions of racking force). The mechanics and motion of each phase is introduced, and it is shown how the configuration of the shear keys and their placement along the base of the wall can either hinder or advantage the re-centring potential of the system. Where the shear-key acts at a distance greater than half-the-length of the wall away from the corner about which rocking takes place, the shear key acts as a fulcrum that tends to force the previously uplifted end of the wall downwards, thus aiding re-centring. The result is hysteretic loops that are not only elasto-plastic, but also conspicuously flag shaped. The concept described has promise not only for timber structures, but likely for steel and concrete rocking structures as well.

1 INTRODUCTION

Slip-friction connectors (also known as slotted-bolt connectors) are cost effective and efficient type of supplemental energy dissipation device, used in seismic resistant structures. The connectors remain rigid up to a pre-defined slip threshold, F_{slip} – with the slip-threshold being achieved, sliding is initiated and energy dissipated through friction. There are basically two types of slip-friction connectors, asymmetric, and symmetric. Both these types consist of three steel plates. In the case of the asymmetric connector, the external load is applied to one of the outside plates and the centre-plate, whereas with symmetric connectors the load is applied symmetrically (see Figure 1(a)). While asymmetric connectors have undergone tests and implementation in actual steel structures (Clifton et al. 2007; Khoo et al. 2012), the connector type of interest in this article is the symmetric type.

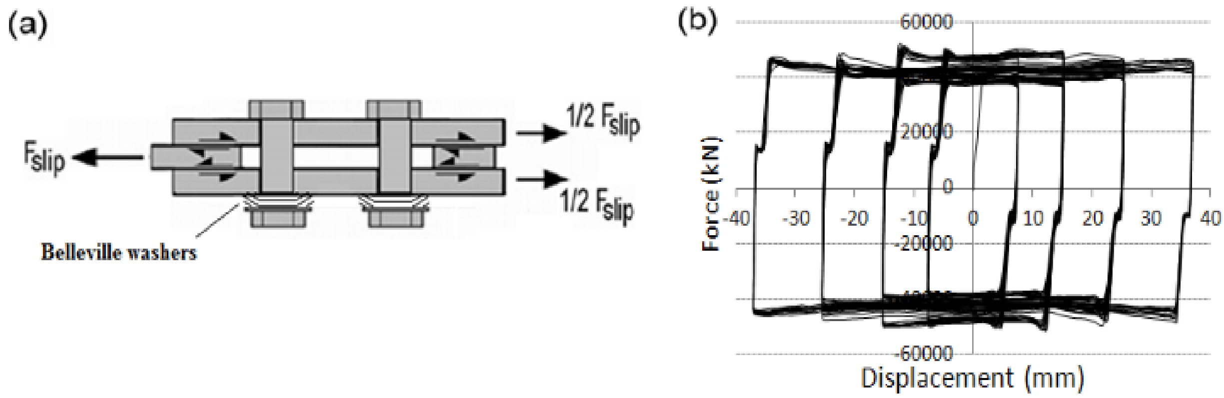

Figure 1. (a) Symmetric slip-friction connector, and (b) typical hysteretic behaviour.

The bolts that clamp the plates together, typically rely on the use of Belleville washers to achieve and maintain the target tension force, T_b. The slip-threshold, F_{slip} of the connector relates to the tension force as follows:

$$F_{Slip} = n_b n_s \mu T_b \tag{1}$$

Loo et al. (2014a) carried out tests on symmetric connectors with centre-plates of Bisalloy 400, and G350 mild-steel as the outside plates (all faying surfaces in the clean mill-scale condition, and obtained sliding behaviour of a highly elastoplastic nature (Figure 1(b)). Subsequent to confirmation of the reliability and stability of sliding of the connectors, they were implemented in an experimental shear wall as hold-downs

The experimental wall and its set-up is shown in Figure 2 (Loo et al. (2014b) provides a comprehensive discussion of the set-up and results). The 2.44 x 2.44 m wall panel was assembled from two 1.22m × 2.44 m × 45 mm LVL panels. Screws were used to join the panels via vertical studs and top and bottom plates. The wall was designed to remain elastic up to a racking force of approximately 120 kN (the actual maximum test force adopted was around 60 to 65 kN). All displacement controlled tests were quasi-static in nature. The general set up is shown in Figure 2(a). Figure 2(b) shows the data acquisition system and hydraulic controller. The slip-friction connector is shown in Figure 2(c) – note the timber rivets used to attach the connector to the wall. The shear key is consists of steel rods through the base of the wall which bear on upright steel plates, with the edges at a slight angle (12 degrees) from the vertical.

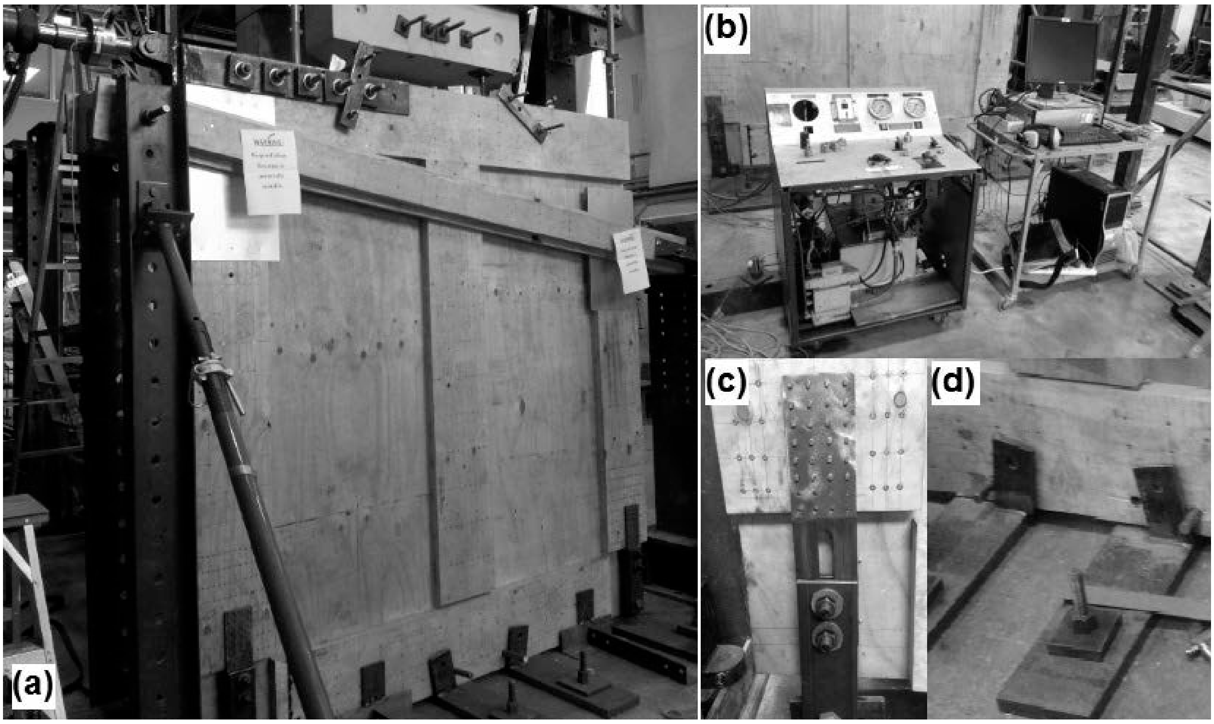

Figure 2. (a) General setup – note the connection of the actuator to the top-left corner of wall, with force transfer plates bolted against Belleville washers, (b) actuator controller and data acquisition system, (c) slip-friction connector, and (d) shear key.

For a detailed description of the slip-friction connectors, and the shear keys and how they interact the reader is referred to Loo et al. (2014b).

This article describes the unique motion characteristics of the experimental wall, influenced by the slip-friction connectors and shear keys, and contrasts the motion with that of a free rocking wall. The configuration of the shear key and its effects on re-centring capability is emphasised.

2 FREE ROCKING COMPARED WITH FRICTION DAMPED ROCKING

Seismic forces can be capped on a structure by allowing free rocking. Kelly (2009) provides a tentative procedure for free rocking blocks, and the previous NZ design code (NZS4203 1984) allowed rocking as a means of capping earthquake forces on a structure, provided the threshold force to induce rocking was greater than half the elastic design force. For a free rocking structure, some part of the base of the wall is always in contact with the foundation.

This is not the case for a wall with the slip-friction/shear key configuration of Figure 2. For such a wall the motion is divided into essentially three different phases: rotation about the left or right base corner, pure translation, and rotation about the shear pin. These are illustrated in Figure 3(a) to (c), respectively. From Figure 3(c) in particular it can be seen that the entire base of the wall is vertically offset from the foundation during the illustrated phase (note that this can also be the case for the phase illustrated in Figure 3(b)).

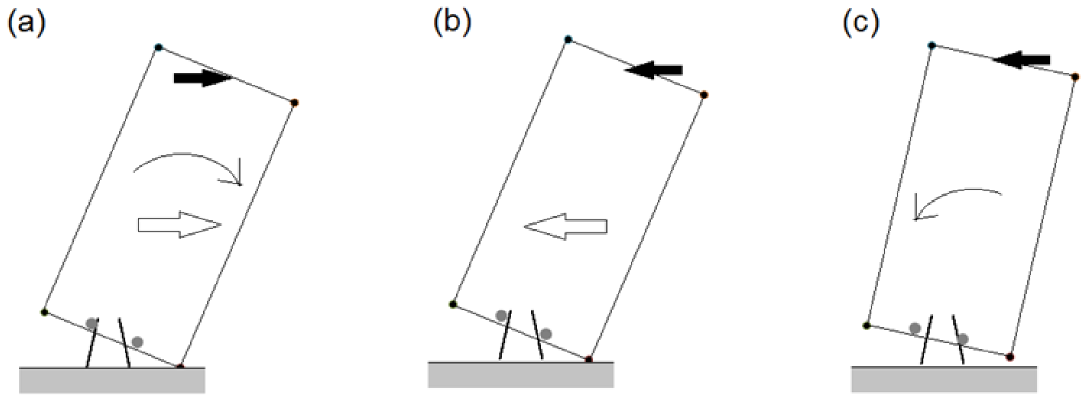

Figure 3. (a) Wall pivots about right base corner, (b) wall translates horizontally towards shear plate, and (c) slip-friction connector, and (d) rotation of the wall about the right shear pin.

If a displacement schedule (Figure 4(a)) is applied to the wall, the difference in displacement time-histories for a freely rocking wall (Figure 4(b)), and a wall with slip-friction connectors (Figure 4(c)) is shown. It is clearly seen that a freely rocking wall has one or the other base corner of the wall in contact with the foundation at all times, whereas the wall with slip-friction connectors is 'airborne' for a significant part of its motion.

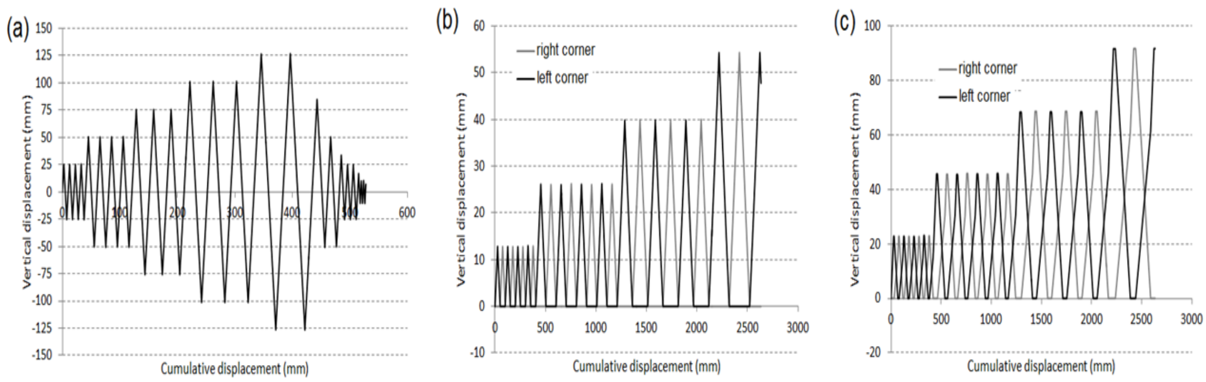

Figure 4. (a) Displacement schedule, (b) displacement time-history for free rocking wall, and (c) displacement time-history for rocking wall with slip-friction connectors and shear keys.

Equations for the motion of the wall for each of the phases of motion can be derived and are described in a separate article under preparation, and the theoretical motion of the wall explored using an algorithm programmed into Matlab or a spreadsheet. For quasi-static testing (with minimal inertial and damping effects), the force on the wall during the phase shown in Figure 3(a), is provided by:

$$P = \frac{F_{slip}B + WB/2}{H - K_{mrp}} \tag{2}$$

where F_{slip} is the connector sliding force, W the gravity effects, B the width of the wall, and H the wall height. K_{mrp} encapsulates the friction effects of the shear key, and is:

$$K_{mrp} = (h^2 + b^2)^{0.5} cos\text{ø}(\mu_{sk}\cos(\text{ø} - \tan^{-1}(h/b)) - \sin(\text{ø} - \tan^{-1}(h/b))) \quad (3)$$

where h is the height of the shear pin from the foundation, b the distance of the left shear pin to the right pivot corner (and right shear pin to the left corner), μ_{sk} the coefficient of friction between the shear pin and the shear plate, and ϕ the angle of the shear plate from the vertical. Note that Equations (2) and (3) assume a nominal frictional effect between the bottom corner of the wall serving as a pivot point and the foundation. The derivation of Equations (2) and (3) are provided in Loo et al. 2014(b).

During the phase of motion shown in Figure 3(a), the left shear pin slides up the left shear plate, and the right base corner moves either to the right, or to the left, depending on the geometry of the configuration. The inclination from the horizontal is then:

$$\theta = sin^{-1}\left(\frac{y_{clp}}{R}\right) - tan^{-1}(h/b) \quad (4)$$

Knowing the inclination of the wall, and the position of the shear pin enables all other points on the wall to be readily found. For the wall under the phase of Figure 3(b), the wall is simply translated to the left. This translation terminates with contact between the right shear pin and the right shear plate, at which point there is a phase of motion (Figure 3(c)) that is essentially pure rotation about the right shear key. The racking force during this phase is found simply through consideration of moment equilibrium, and for quasi-static motion:

$$P = \left(F_{slip}(B - 2e) - W\left(b - \frac{B}{2}\right)\right) / (H - h) \quad (5)$$

where e is the distance of the centre of the slip-friction connector from the wall end. This force P for pure rotation is less than that provided by Equation (2) for rocking pivoting about the base corner, and it is this which contributes to the ‘flagging’ effect of the hysteretic relationship (see Fig. 8 or the next section).

The theoretical motion is compared with some experimental results obtained from the experimental wall, and these are presented in the next section.

3 WALL MOTION

With a displacement schedule similar to Figure 4(a) applied, the motion of the base of the wall at its centre is shown for the free rocking case (Figure 5(a)). This is contrasted with the base of the wall for a wall with slip-friction connectors and shear keys (Figure 5(b) for theoretical and 5(c) for experimental). It is clear that the experimental motion of the wall closely emulates that of the theoretically expected, and significantly differs from that of a free rocking block (Figure 5(a)).

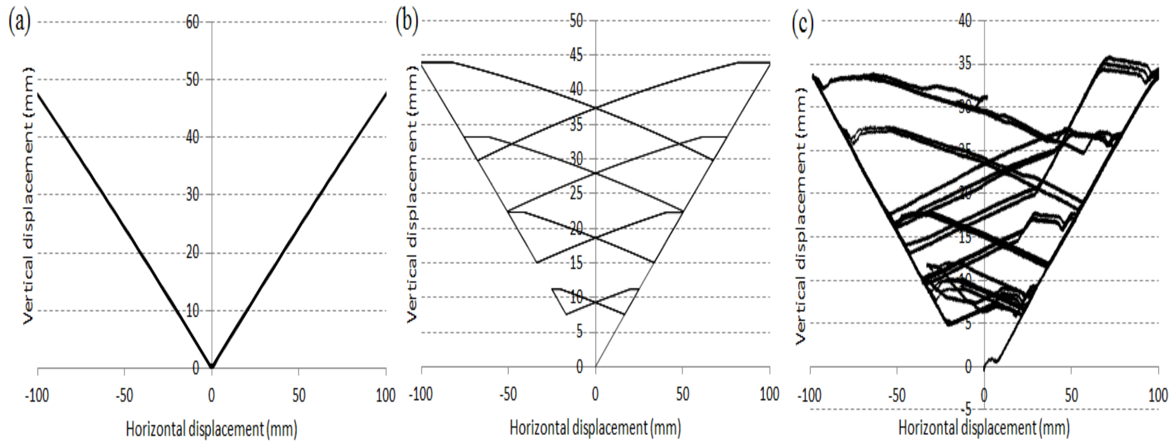

Figure 5. Motion of point at base of wall. (a) Free rocking wall, (b) theoretical result for wall with slip-friction and shear keys, and (c) experimentally obtained result for 2.44 m × 2.44 m wall with the initial location of each shear pin/shear plate pair at 1.46 m from the opposite end of the wall, and 50 mm above foundation level.

Figure 6 shows the motion of the base corners of the wall for the same 2.44 x 2.44 m wall with initial shear pin/shear plate pair at b = 1.8 m from the opposite end of the wall and 50 mm above foundation level. Theoretical are compared with the experimental results. It can be seen that the wall repeatedly returns to foundation level at both ends. Note that this only occurs if the distance $b > B / 2$ where B is the wall width. In the hypothetical case where $b < B / 2$, say b reduced from 1.8 m to 1.1 m, the wall corner ascends upwards and does not return to foundation level (see Figure 7).

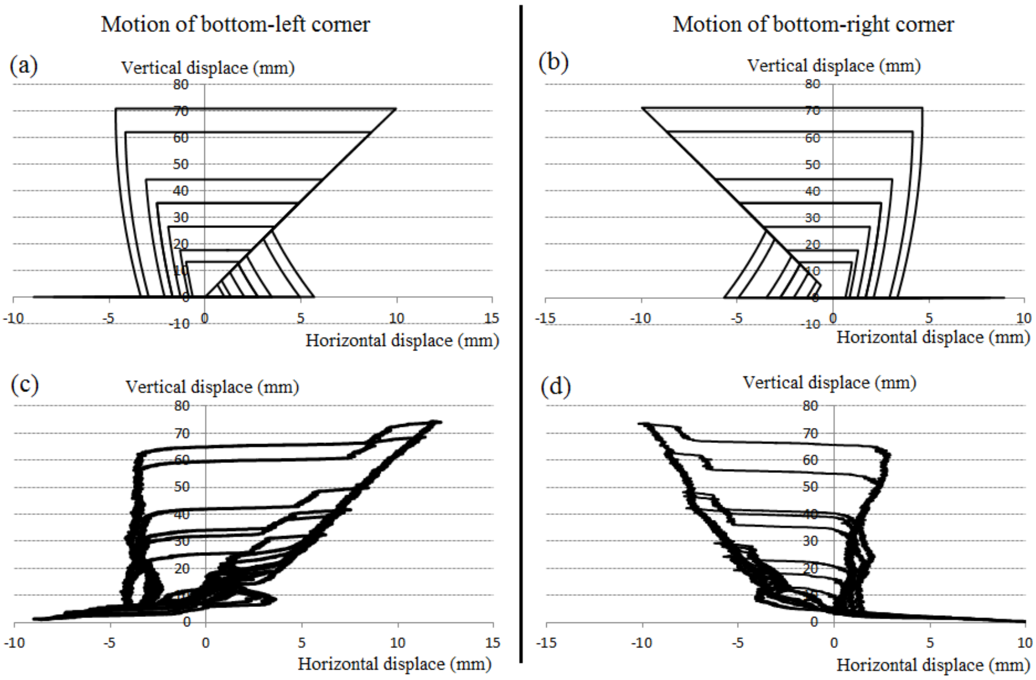

Figure 6. Motion of base of wall: Theoretical result at the (a) left corner, and (b) at the right corner, compared with the experimentally obtained for (c) left corner, and (d) right corner.

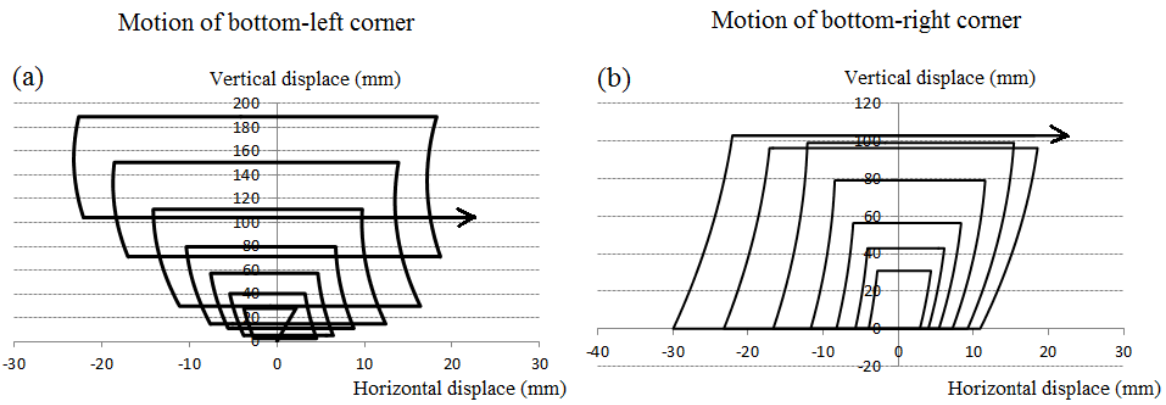

Figure 7. Effect of shear pin/plate distance, *b* < *B*/2, on (a) motion of left corner, and (b) right corner for *b* = 1.1 m.

A hysteretic result from an experiment is provided in Figure 8(a), and the force time history diagram for the same is provided in Figure 8(b). These are compared with a theoretically obtained result. There are essentially two levels of force, the higher level associated with the rocking phase in which one of the base wall corners is in contact with the foundation (see Figure 3(a)), and the other phase in which the wall rotates about the shear pin which is in contact with the shear plate (see Figure 3(c)).

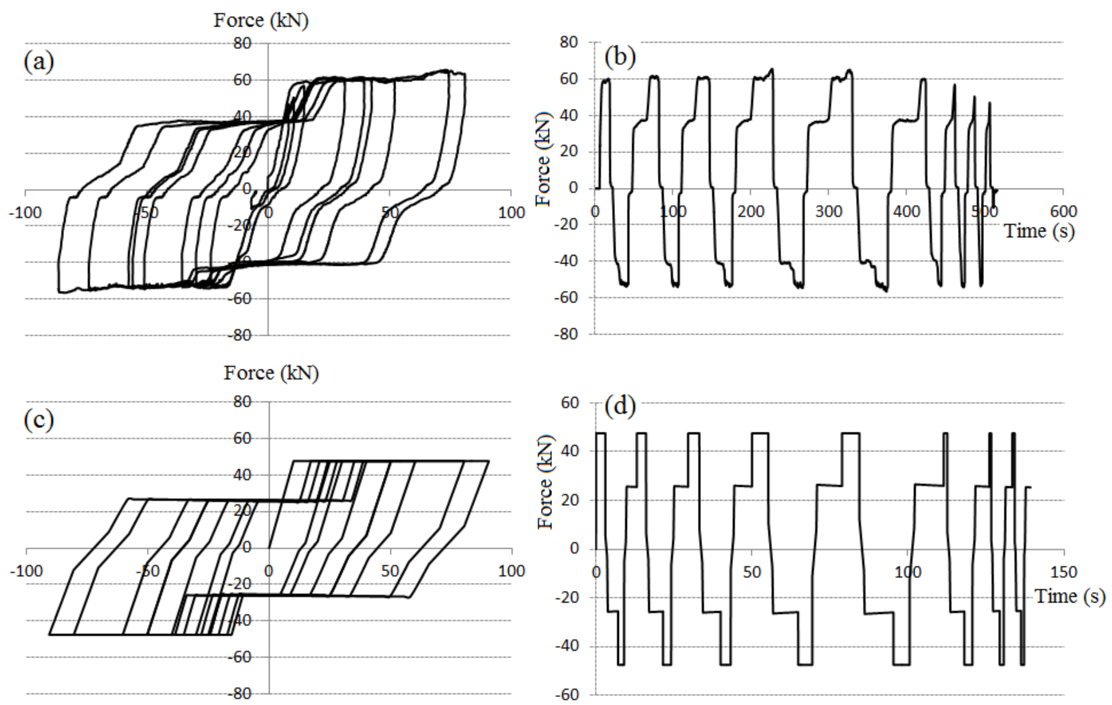

Figure 8. (a) Hysteretic result and (b) force-time history for an experimental result, compared with the (c) theoretical hysteretic and (d) force-time history.

4 CONCLUSIONS

The unique aspects of a wall with slip-friction connectors and shear keys are discussed in this paper. The rocking motion is quite distinct from that of free rocking structures and has three distinct phases (six phases if both directions are considered). This results in an interesting pattern of movements. Relationships developed by the authors are used to produce some results for the motion of the top of the wall and the base of the wall. These align well with the experimentally observed. Hysteretic results are also presented. It is emphasised that the placement of the shear keys has a strong influence on the ability of the wall to re-centre. Properly placed, the shear key will induce re-centring and contribute (in addition to vertical loading) to a flag shaped hysteresis relationship.

5 ACKNOWLEDGEMENT

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6 REFERENCES

Clifton, G.C., MacRae, G., Mackinven, H., Pampanin, S. & Butterworth, J. 2007. Sliding hinge joints and subassemblies for steel moment frames. *Proceedings of the New Zealand Society for Earthquake Engineering Conference*, Auckland, New Zealand.

Kelly, T. 2009. Tentative seismic design guidelines for rocking structures. *Bulletin of the New Zealand Society of Earthquake Engineering*. 42(4): 239-274.

Khoo, H.H., Clifton, C.G., Butterworth, J., MacRae, G. & Ferguson, G. 2012. Influence of steel shim hardness on the sliding hinge joint performance. *Journal of Constructional Steel Research,* 72(2012): 119-129.

Loo, W.Y., Quenneville, P. & Chouw, N. 2014a. A new type of symmetric slip-friction connector. *Journal of Constructional Steel Research*. 94(2014): 11-22.

Loo, W.Y., Quenneville, P., & Chouw, N. 2014b. Experimental testing of a rocking timber shear wall with slip-friction connectors. *Earthquake Engineering and Structural Dynamics*. 43(11): 1621-1639.

NZS4203. 1984. General structural design and design loadings for buildings. *Standards New Zealand,* Wellington, New Zealand.