A new shear key for rocking timber shear walls

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Abstract

Allowing shear walls to rock is one way of protecting structures from earthquake damage, or at least minimising the damage. Walls allowed to rock must have the ability to resist both overturning moment and lateral forces. While resistance to overturning is typically provided by self-weight, post-tensioned cables, and/or damping devices acting as hold-downs, a particular challenge is to provide adequate resistance to lateral forces, which will not interfere with the function of the devices chosen to resist overturning. During an earthquake, there will typically be high contact forces between the shear keys and shear walls. Friction induced by these contact forces can add to the moment resistance against overturning – often in an unpredictable way. While supplemental moment resistance could be considered a desirable outcome in the case of non-rocking walls; in the case of rocking walls, their load limiting ability could be compromised. A new shear key concept, that is both simple and economical, is proposed and implemented at the bottom centre of an experimental rocking timber wall. Under loading, the shear key performed as intended, providing adequate lateral resistance, while at the same time allowing the wall to rock in the intended manner.

Keywords: rocking walls, shear walls, load limiting, shear keys, friction damping

1. BACKGROUND

Recent years have seen increasing focus on the implementation of damage avoidance philosophy in seismic structural design. Allowing structures to uplift or to rock is one way in which base shears can be capped, thereby limiting stresses on the structural members below the desired design level (see for example Kodama and Chouw, 2002, Ormeno et al., 2012, Ali et al., 2013, and Qin et al., 2013). For purely rocking structures, damping is primarily achieved through the impact of the structure on the foundation. In the structure proposed by the authors, damping, during the nonlinear phase of behaviour, is instead achieved mainly through hysteretic damping provided by slip-friction connectors (also known as slotted-bolt connectors). Early research on these connectors carried out by Popov et al. (1995) and Clifton et al. (2007) has adopted them for use in steel moment frames. Slip-friction connectors mobilise friction between steel plates in order to prevent slip up to a predetermined force threshold. Upon this threshold being attained, sliding commences, and the applied force is limited, ideally, to the threshold force. This connector resistance (or strength) is found as follows:

$$F_{slip} = \mu_{sf} n_s n_b T_b \tag{1}$$

, where μ_{sf} is the coefficient of friction between the steel surfaces of the connector, n_s is the number of interfaces along which sliding takes place (typically 2), n_b is the number of bolts applying normal force across the plates, and T_b is the tension in each of the bolts. A typical slip-friction connector is shown in Fig. 1(a) and the idealised hysteretic relationship obtained from component tests is shown in Fig. 1(b).

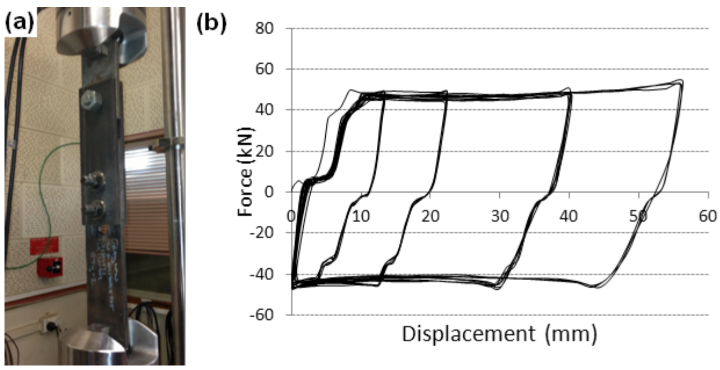

Fig. 1. (a) Slip-friction connector in MTS machine, (b) typical hysteretic behaviour from component testing.

Loo et al. (2012) has proposed the use of slip-friction connectors with uplifting timber shear walls and carried out numerical studies on such structures, with promising findings in terms of ability of the connectors to cap forces on the walls and allow them to re-centre. This work has now moved to the experimental phase. The concept of using slip-friction connectors as hold-downs to resist overturning is illustrated in Fig. 2. Also shown is the shear key to resist base shear.

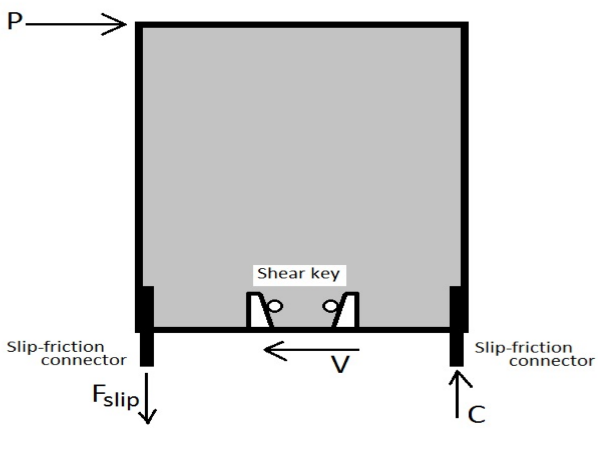

Fig. 2. Wall with slip-friction connector and shear key

Ideally the implementation of slip-friction connectors on the wall would allow the wall to almost exactly reflect the hysteretic behaviour of the connectors (see Fig. 1(b), however this is not the case because there is an effect from permanent and imposed loads on the structure, and also from frictional effects of the shear key. This paper discusses an experimental wall with slip-friction connectors, and the method adopted for resisting base shear.

2. INTERACTION OF SHEAR KEY AND SLIP-FRICTION CONNECTORS

A 2.4 m x 2.4 m shear wall was constructed from laminated veneer lumber (LVL) panels of 45 mm in thickness with slip-friction connectors implemented as hold-downs. The slip-friction connectors are shown in Fig. 3(a) and the shear key in Fig. 3(b).

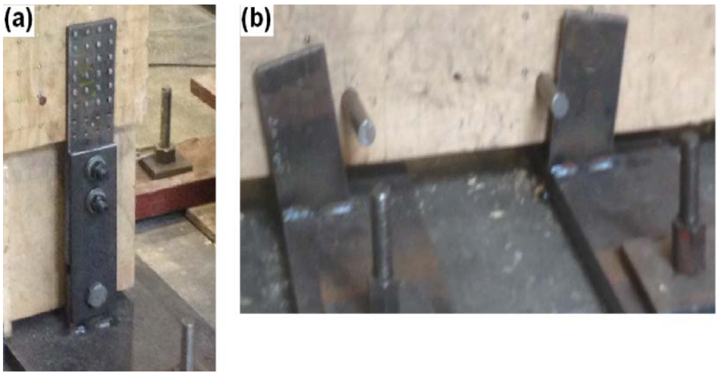

Fig. 3. (a) Slip-friction connector at bottom corner of wall, (b) shear key.

The shear key consists of two 25 mm diameter steel rods inserted through the base of the wall with the two rods bearing against vertical steel plates welded to the foundation. Note that the edges of the plates against which the steel rods are sloped at a slight angle (12 degrees to the vertical, this in order to reduce frictional effects and to facilitate overturning of the wall).

The forces on the wall are shown in Fig. 4. Note that the forces provided by the slip-friction connectors and the forces on the steel rods of the shear pin are the maximum potential mobilised forces.

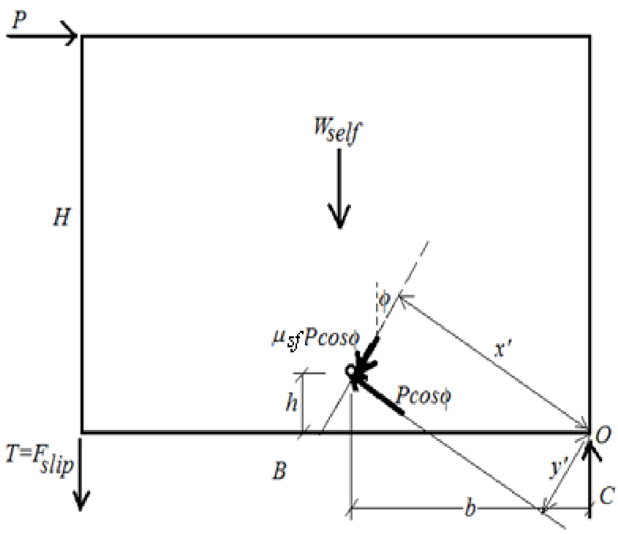

Fig. 4. Forces on shear wall.

From Fig. 4 it can be seen that the moment resistance of the wall is found as follows:

$$M_{rw} = \frac{W_{self}B}{2} + \sum_{i=1}^{n} W_i l_i \tag{2}$$

, where W_{self} is self-weight of the structure, and W_i and l_i are respectively the weight and horizontal distance of the *i*th imposed load of a total of *n* vertical loads (excluding self-weight).

From the geometry the equation an expression for racking force, P, can be derived:

$$P = \frac{F_{slip}B + \frac{W_{self}B}{2} + \sum_{i=1}^{n} W_i l_i}{H - K_{mrp}} \tag{3}$$

, where K_{mrp} is a multiplier that encapsulates the effect of friction coefficient and geometry of the shear key on the overturning moment:

$$K_{mrp} = (h^2 + b^2)^{1/2} \cos\emptyset \left[\mu_{sk} \cos\left(\emptyset - \tan^{-1}\left(\frac{h}{b}\right)\right) - sin\left(\emptyset - \tan^{-1}\left(\frac{h}{b}\right)\right)\right] \tag{4}$$

The definitions of the parameters of Eq. 4 are shown in Fig. 4.

The wall strength, P can be plotted against Ø for various coefficients of connector strength, F_{slip}. Fig. 5 shows the relation of P with Ø for the experimental wall, with parameters μ_{sk}= 0.61, h = 0.06 m, b = 0.91 m, W_{self}= 2.8 kN. It can be seen that the strength of the wall reduces with increasing angle between the shear key and the vertical.

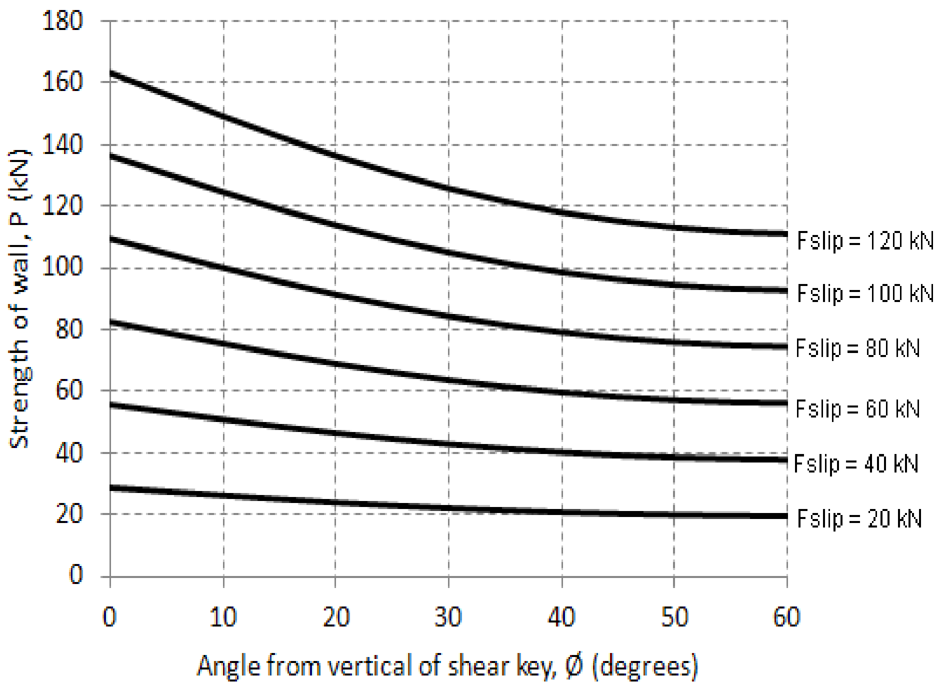

Fig. 5. Prediction of racking force, or wall strength, P

3. EXPERIMENTAL RESULT

Results from a single test are reported herein. The tension in the bolts was obtained through the use of Belleville washers. By measuring the deflection of the Belleville washers bolt tension can be obtained. The bolt tension adopted was 15.6 kN. From previous component tests on slip-friction connectors, it was determined that the coefficient of friction between mild steel and the abrasion resistant steel used in the slip-friction connectors was around 0.35 (reported in an article currently under review). From Eq. 3 the predicted connector strength, F_{slip} = 21.8 kN was calculated.

For the shear key, the coefficient of friction adopted was 0.63 (for similar metals)

These connectors were implemented in the wall. From Eq. 3 the predicted wall strength was calculated at 28.3 kN.

The wall was tested under a series of quasi-static displacement cycles. The hysteretic behaviour obtained is shown in Fig. 6.

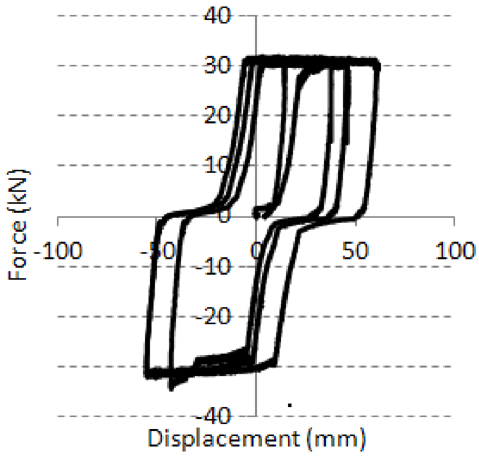

Fig. 6. Hysteretic behaviour of experimental wall

It can be seen that the wall strength was approximately 30 kN. Thus for this single example, it appears that the relationship of Eq. 3 can closely predict the actual wall strength. Note that if friction in the shear key was ignored, that is μ_{sk} = 0, the racking strength from Eq. 3 would have been approximately 22 kN. Thus the effect of friction in the shear key is not insignificant and needs to be considered when designing uplifting walls with slip-friction connectors.

4. CONCLUSIONS

An uplifting wall with slip-friction connectors utilises a new method of providing resistance to base shear. A relationship is derived to account for the frictional contribution from the shear key to resisting moment. Results from an experimental test are presented that shows the applicability of the derived relationship. While the frictional contribution to overall wall strength cannot be ignored when designing walls with slip-friction connectors, the effect of friction can be reduced by placing the contact surface of the shear pin against the shear key at a slight angle from the vertical.

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REFERENCES

Ali, M., Briet R., Chouw, N. (2013) Dynamic response of mortar-free interlocking structures, *Construction and Building Materials* 42, pp. 168-189

Clifton, GC, MacRae H, Mackinven S, Pampanin S, Butterworth J. (2007) Sliding hinge joints and subassemblies for steel moment frames. Palmerston North, New Zealand: Proc of New Zealand Society for Earthq Eng Conf.

Kodama, T., Chouw, N. (2002) Soil-structure interaction with uplift due to near-source earthquakes. *Proc. of European Conf. on Structural Dynamics*, Germany, pp. 1375-1380.

Loo WY, Quenneville P, Chouw N. (2012) A numerical study of the seismic behaviour of timber shear walls with slip-friction connectors. Eng Struct, Vol 34, No 22, pp 233-243.

Ormeño, M, Larkin, T and Chouw, N. (2012) Influence of uplift on liquid storage tanks during earthquakes. *Coupled Systems Mechanics*, Vol 1, No 4, pp 311-324.

Popov E, Grigorian C, Yang T. (1995) Developments in seismic structural analysis and design, Eng Struct Vol 17, No 3, pp 187–97

Qin, X, Chen, Y, and Chouw, N (2013) Effect of uplift and soil nonlinearity on plastic hinge development and induced vibrations in structures. *Advances in Structural Engineering*, Vol 16, No 1, pp 135-148.