# Experimental verification of slip-friction connectors intended for implementation in rocking timber shear walls

W.Y. Loo, C. Kun, P. Quenneville & N. Chouw

*Department of Civil & Environmental Engineering, University of Auckland, Auckland.*

2013 NZSEE Conference

**ABSTRACT:** Slip-friction connectors mobilise frictional forces across steel plates and exhibit elasto-plastic force-displacement behaviour under loading. They have been proposed for use as hold-down connectors for timber shear walls, and numerical studies have demonstrated their ability to cap activated base shear on these walls during an earthquake. This is achieved by allowing controlled uplift and rocking of the walls, upon the uplift force on the connectors reaching a pre-defined threshold. Re-centring potential of the walls after a seismic event has been found to be excellent. In order to develop the concept for practical implementation, slip-friction connectors, consisting of abrasion resistant Bisalloy 400 centre plates sliding between Grade 300 mild steel plates, were tested in order to confirm their suitability for implementation in actual shear walls. Unlike typical symmetric friction connectors, the use of brass shims is avoided, and hence it is expected that this will reduce cost and inconvenience in their fabrication. With minor pre-conditioning, the connectors were generally found to perform well under testing. Their sliding characteristics were stable, and strength and stiffness were maintained under repeated cycles of loading. A 2.4 x 2.4 m rigid wall of 45 mm thick LVL panels with slip-friction and shear connectors has been prepared at the University of Auckland, and an initial test result is presented in this paper.

## 1 INTRODUCTION

Passive energy devices primarily rely on the dissipation of seismic energy through the work done against frictional forces between steel plates. These devices were pioneered by Grigorian and Popov (1994), and because of their cost effectiveness and simplicity of fabrication have seen use in steel moment frames (Clifton 2005), proposed for use in concentrically braced frames (Butterworth 2000), and have been tested for use as hold-down connectors in rigid pre-cast concrete panels (Bora et al. 2007).

The symmetric slip-friction connectors tested by Grigorian and Popov obtained stable elasto-plastic sliding characteristics only when shims of half hard cartridge brass were inserted between the mild-steel plates of the connectors. Symmetric connectors place minimal shear and bending stresses on the bolts clamping the plates of the connector together, while at the same time allowing for excellent elasto-plastic behaviour. This paper introduces a new concept in the design and fabrication of slip-friction connectors, in which shims (of brass or any other type of material) are not required. The mild steel centre-plate is instead replaced with a plate of abrasion resistant steel, and this centre plate slides directly against the two mild-steel outside plates. This gives rise to sliding characteristics at least as desirable as those found by Grigorian and Popov for connectors with brass shims. This paper provides some background to what motivated the investigation of this new connector, experimental verification of the connector, and an initial test result of a shear wall with the connectors implemented.

## 2 BACKGROUND

### 2.1 Timber shear walls with slip-friction connectors

Based on a series of numerical investigations, it has been shown that timber shear walls implementing slip-friction connectors are likely to perform well in terms of protecting the sheathing, framing, and nailed connections from high stresses and unacceptable deformations during major earthquake events (Loo et al. 2012b). Furthermore it has been found that multi-storey buildings of highly stiff cross laminated timber panel shear walls with slip-friction connectors at the base have excellent re-centring capability (Loo et al. 2012a).

The results of these studies, however, assume the force displacement characteristics of the hold-down connectors have a single and constant peak load relative to displacement – that is the force displacement behaviour is required to be as close as possible to the elasto-plastic ideal. The connector should also be cost effective and fabricated from easily obtainable materials. A new type of symmetric connector is proposed in this paper, and some results from testing carried out presented.

### 2.2 Slip-friction connectors

Slip-friction connectors (also known as slotted-bolt connectors) have seen increasing interest over the past two decades. Grigorian and Popov showed in 1994 the feasibility of using the friction between steel plates to dissipate seismic energy. Their work showed that for connectors under what is known as symmetric sliding, the behaviour of steel against steel provides undesirable stick slip behaviour and unpredictable force-displacement behaviour. Thus up until recently, slip-friction connectors have been configured with the use of thin half-hardened cartridge brass shims separating the steel plates of the connector. Figure 1 shows the difference between connectors in asymmetric and symmetric sliding.

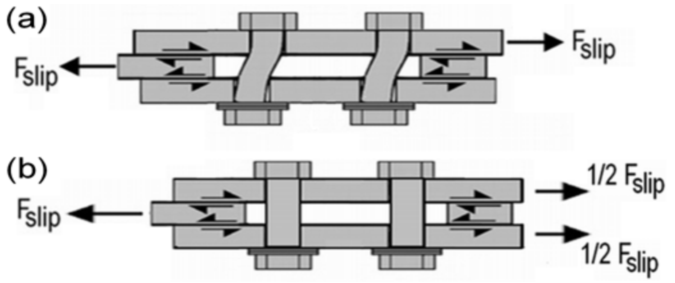


***Figure 1.*** *Slip-friction connector with (a) asymmetric mechanism, and (b), with symmetric mechanism.*

Compared to the symmetric connector, asymmetric connectors tend to place complex combined stresses on the bolts, and the force displacement behaviour has a double plateau. This is related to the manner of sliding, with displacement taking place first between the outside plate that is directly loaded (top plate in Figure 1(a)) and the centre plate, and only with increasing displacement and transfer of increasing shear force through the bolts, is sliding initiated between the other outside plate (bottom plate in Figure 1(a)) and the centre plate. Only when sliding takes place across both interfaces does the asymmetric connector achieve its full connector strength, $F_{slip}$. However, the case of the symmetric connector is different (see Figure 1(b)). The two outside plates of the symmetric connector are each loaded by an external force, $F_{slip}/ 2$, equal in direction and magnitude with each other, as can be seen in Figure 1 above. The centre plate resists the sum of these two external forces, and there is only tension stress on the bolts clamping the plates together. Unlike the case of the asymmetric connector, the bolts are rarely in bending or shear (except in the rare instance that the magnitude of sliding is so large causing the bolts to impact against the slot ends). This is because under loading, sliding across both interfaces occurs at the time in symmetric connectors. This results in the force-displacement behaviour having a single peak force; with the hysteretic loops having close resemblance to the rectangular loops characteristic of ideal elasto-plastic behaviour.

It should be noted that despite the simplicity of the symmetric connector, in terms of both hysteretic behaviour and induced stresses, the asymmetric connector does have advantages in certain contexts over the symmetric connector. This is particularly the case at the joint locations of steel moment frames, where the flag shaped loops of the asymmetric connector do provide an ad-hoc re-centring effect during and after earthquake excitation.

Asymmetric connectors have been tested and used extensively in New Zealand in steel moment frames, and have been proposed and tested for use in braced frames. Bora et al. (2007) have tested asymmetric connectors as hold-downs for pre-cast shear walls, in thereby supplying global ductility to walls constructed of brittle material. In the case of the slip-friction connectors and their uses described above, whether asymmetric or symmetric, half-hard cartridge brass shims are required in order to provide smooth and stable sliding, and protect the mild steel surfaces from damage. However, brass shims are relatively expensive (compared with steel), not always readily available at all locations, and furthermore introduce the problem of differential corrosion between dissimilar metals.

Partly in order to avoid the drawbacks of brass shims, Khoo et al. (2012) reported on tests carried out on asymmetric connectors intended for use in steel moment frames, but with the typically used brass shims replaced by shims of abrasion resistant steel. The results were encouraging, and Khoo et al. clearly showed that the greater the difference in hardness between two contacting steel surfaces, the more smooth, stable, and predictable the sliding behaviour. Encouraged by these results, the authors propose something similar in the context of symmetric connectors. However, unlike the connectors of Khoo et al., instead of using abrasion resistant steel as shims, it was decided to avoid the use of shims altogether and simply replace the mild-steel of the centre plate with a plate of abrasion resistant steel. Hence, in addition to avoiding the use of brass shims, and associated issues with cost and procurement, the use of any type of shim whatsoever is avoided.

## 3 CONFIGURATION OF THE PROPOSED CONNECTOR

The connectors tested were based partly on the connectors tested by Grigorian and Popov (1994), and fabricated to fit into the MTS machine at the University of Auckland. The configuration is simple. Three steel plates were clamped together using M20 fine threaded bolts, with tension maintained through the use of stacked Bellville washers. The two outside plates were of Grade 300 mild steel, and the centre plate of Bisplate 60 or 400. The connector is shown in Figure 2.

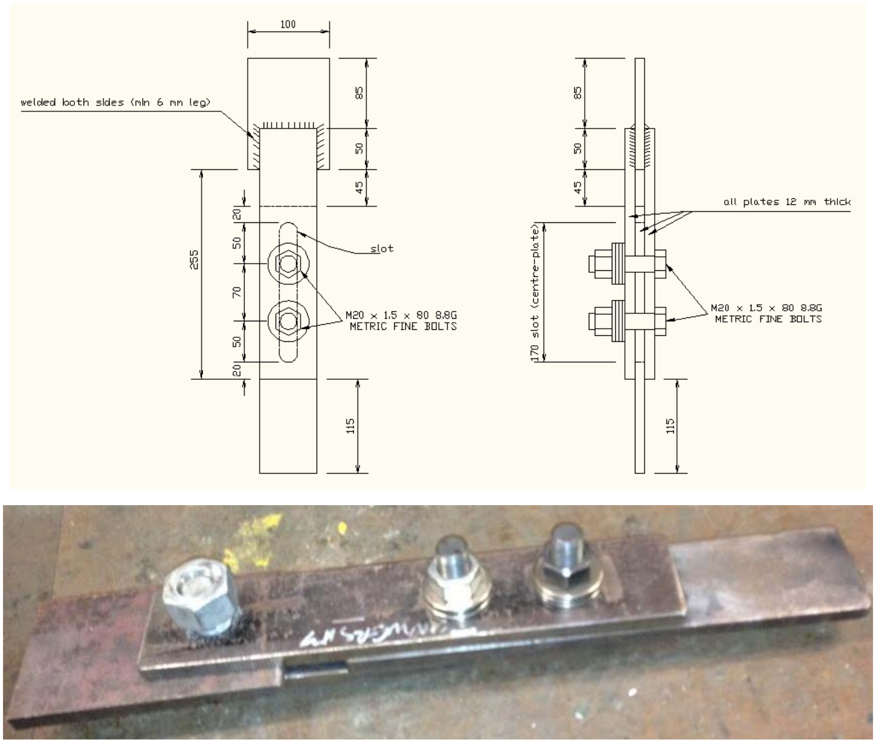


***Figure 2.*** *Dimensions of tested connectors (top), and connector with tightened bolts (bottom).*

A major point of difference was the alignment of the bolts. The connectors of Grigorian and Popov are placed side by side. The connectors used in the tests of this paper, are aligned along the length of the connector (Figure 2).

Section 4 describes a simple method to achieve and maintain tension in the tension bolts. Some test results obtained on the connectors are presented in Section 5.

## 4 A SIMPLE PROCEDURE TO ACHIEVE THE DESIRED BOLT TENSION

Bellville washers are a type of spring which resembles a washer. Their frusto-conical shape provides the washer with the characteristics of a spring, with the amount of deflection having a linear relationship to the applied compression force on a washer (this linear relationship breaks down somewhat near the point where the washer is close to its maximum possible deflection). In their tests Grigorian and Popov utilised Bellville washers to apply tension, $T_b$, to the bolts of the symmetric connector, with $T_b$ being related to the force on the connector as follows:

$$F_{slip} = 2 n_b T_b \mu \tag{1}$$

where $n_b$ is the number of bolts, and $\mu$ the coefficient of friction between the sliding plates. To ensure that a certain tension force is achieved and maintained Grigorian and Popov (1994) relied on the use of direct tension indicator washers. Bellville springs were used to achieve and maintain a tension force, while the direct tension indicator washers confirmed the load achieved. While suitable for use in an experimental setting, direct tension indicator washers in the context of the fabrication workshop or construction site could prove to be problematic – particularly in terms of cost and availability. Direct tension indicator washers are typically available only for certain discrete forces, which can often be different from the desired target force.

In order to avoid the use of direct tension indicator washers, it was decided to achieve the desired load by instead deflecting the washers by a set amount, typically to what is known as their 'flat deflection'. This can be done by rotating the nut securing the washers until they are just resting on the top surface of the washers ('finger tight'), and then by the use of a common adjustable spanner, turning the nut further by a calculated number of rotations, the rotations being a function of the required displacement.

However, the deflection of a single Bellville washer tends to be very small. For example, a Solon M20-L-3.4 Bellville washer has a maximum deflection of 0.91 mm, while a M20-L-3.4-177 washer has a deflection of just 0.76 mm (Solon Manufacturing Co. 2012). Thus it is typically unrealistic to expect that basing the displacement of a single Bellville spring on the number of rotations of the nut, will provide anywhere near the required accuracy. For example, with a typical Grade 8.8 structural bolt with a pitch of 3 mm, an M20-L-3.4-177 washer would only require 0.76 mm / 3 mm = 0.25 turns. For such a small amount of rotation, the margin of error on site would be expected to be a significant percentage of the required rotation. Obviously, the larger the number of rotations of the nut required in flattening the washers, the greater both the accuracy and precision in achieving the required number of rotations, and hence the required tension force.

In order to maximize the number of rotations of the nut to achieve the flat load, a fine threaded bolt (1.5 mm pitch distance) was used instead of the more commonly used structural bolts of 3 mm pitch distance. This in itself doubles the number of rotations of the nut required, for any given stack of Bellville springs.

Additionally, by stacking the Bellville washers in series, the stiffness of the stack is the stiffness of a single Bellville washer divided by the number washers in series. It should be noted that Belleville washers stacked in parallel increases the load, but not the deflection (stiffness increases), while Belleville springs stacked in series increases the deflection, but not the load (stiffness decreases). Figure 3 shows the difference between Bellville washers in parallel and in series.

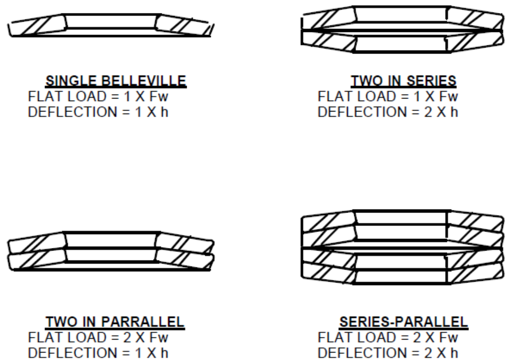


***Figure 3.*** *Bellville springs in series and parallel (from Davet 1997).*

The relationship used to obtain the number of rotations, $n_{rot}$ is as follows:

$$n_{rot} = n_{ws} \delta_{flat} / pitch \tag{2}$$

where $n_{ws}$ is the number of Bellville washers stacked in series, and $\delta_{flat}$ the deflection required to flatten a single washer. For example, in the case of the M20-L-3.4-177 washers with a fine threaded bolt, used in all the tests described in Section 5, three washers were stacked in series, thus requiring 3 x 0.76 / 1.5 = 1.52 turns. Turning the nut by 1.52 rotations (compared to just 0.25 turns if only one washer was used with a coarse threaded bolt) reduces the percentage error, if we assume the margin of error in turning the nut is the same in both cases.

In order to confirm the validity of the above method, various combinations of Bellville springs were placed between two 24 mm thick steel plates. Both plates had a 20 mm hole in the centre, through which a Grade 8.8 fine threaded M20 bolt passed through the plates and the Bellville stack between the plates. Based on the flat deflection reported by the manufacturer, and a thread pitch of 1.5 mm, the number of rotations required to flatten the washer was found from Equation 2. This attempted deflection was compared with the measured displacement between the plates at eight locations on the edges of the plate (found by vernier calipers). Results from one of the trials carried out is shown in Table 1.

**Table 1. Bellville deflection calibration results for three Bellville washers in series***

| Initial gap (mm) | Final gap (mm) | Displace. (mm) | Difference from attempted displace. (mm) | Displace. (% of attempted displace.) |
|---|---|---|---|---|
| 13.73 | 9.60 | 4.13 | +1.85 | 181.4 |
| 13.07 | 9.39 | 3.68 | +1.40 | 161.4 |
| 12.59 | 9.77 | 2.82 | +0.54 | 123.7 |
| 12.19 | 10.90 | 1.29 | -0.99 | 56.6 |
| 12.03 | 11.84 | 0.19 | -2.09 | 8.3 |
| 12.55 | 12.17 | 0.38 | -1.90 | 16.7 |
| 13.30 | 11.86 | 11.86 | -0.84 | 63.2 |
| 13.52 | 10.31 | 10.31 | 0.93 | 140.8 |
| | Average: | 2.14 | -0.14 | 94.0 |
| ** Three M20-L-3.4-177 in series has a flat deflection of 0.76mm x 3= 2.28 mm* | | | | |

From Table 1, it can be seen from this single trial, that the proposed method results in a measured deflection that aligns closely to the manufacturer's reported flat deflection (on average 94% of the desired displacement of 2.28 mm).

## 5 TESTING AND RESULTS

The displacement time-history schedule used for the testing (see Figure 4) was based on that of Grigorian and Popov (1994) and consisted of 7 sets of 10 cycles of increasing amplitude to a maximum of 38 mm, and then decreasing amplitude. The connector set up in the MTS machine is also shown in Figure 4.

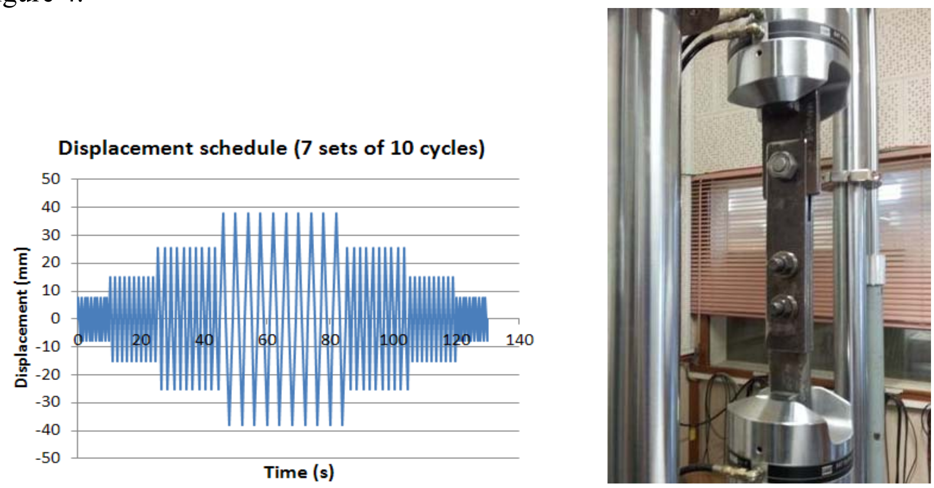


***Figure 4.*** *Displacement time history schedule used in testing (left), and setup in the MTS machine (right).*

While all the tested connectors had mild steel outside plates, the slotted centre plates varied in material type. A large number of tests on different connectors were carried out, a subset of the test results are presented in this paper to demonstrate how the connectors performed and its relationship to various factors.

Firstly, in order to confirm the results of Grigorian and Popov (1994) in respect of mild steel sliding directly against mild steel, a connector with a mild steel slotted centre plate was tested. The force time history result is shown in Figure 5, and as can be seen the sliding characteristics were highly unstable and unpredictable, as would be expected.

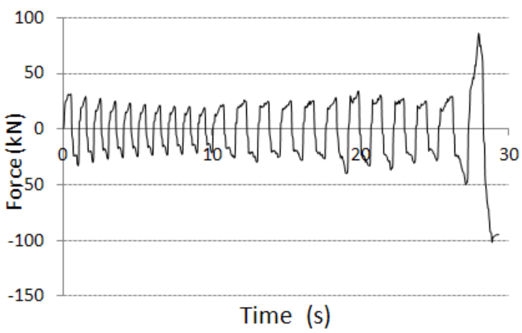


***Figure 5.*** *Force-time history of connector with mild steel centre plate.*

Mild steel typically has a Brinell hardness of below 200 HB, with Khoo et al. (2012) reporting a measured value of 168 HB for Grade 300 mild steel cleats. For asymmetric connectors, Khoo et al. found that abrasion resistant steel shims, when forced into sliding against mild steel, possessed desirable sliding characteristics - with the performance improving with greater disparity in hardness between the type of abrasion resistant steel used on the one hand, and the mild steel cleats on the other hand.

For the symmetric connectors the authors tested connectors with mild steel outer plates sliding directly against Bisplate 60 and Bisplate 400 with respective Brinell hardness' of 210 HB and 400 HB (Bisalloy Steels 2012). A typical result, for Bisplate 400, is shown in Figure 6.

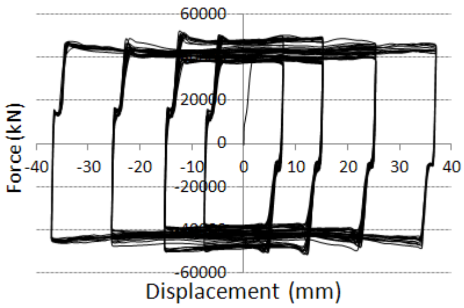


***Figure 6.*** *Hysteretic behaviour of connector with Bisplate 400 slotted centre plate.*

From further tests (not shown here) it was found that Bisplate 400 has superior performance in terms of the stability of its hysteretic behaviour and constancy of peak force, when compared with Bisplate 60. This result for *symmetric* connectors is consistent with the results of Khoo et al. for *asymmetric* connectors, in which the harder the steel shims (and consequently the greater the difference in hardness between the shims and steel cleats) the more stable the sliding.

From Figure 4, it can be seen that the connection force averages around 45 kN for both cases. Thus, the force over each sliding interface is half of this figure, i.e. 22.5 kN. Given that the flat load of a M20-L-3.4 Bellville washer is 37810 N, and that two of these bolts are used, the total normal force over each sliding interface is hence 37810 N x 2 = 75620 N. This implies a coefficient of friction, μ, of 22500 N / 75620 N = 0.30. In the absence of coefficient of friction data available for abrasion resistant steel against mild steel sliding, it should be noted that this result compares closely with a μ of 0.30 to 0.35 for mild steel upon mild steel sliding, indicated by Grigorian and Popov (1994).

It should also be noted that the result of Figure 6, showed several initial cycles of loading at lower levels of force, prior to the load increasing to a higher and constant level. This is more clearly seen in Figure 7, which shows only the first few cycles of loading. This curious result was further explored by re-fabricating new connectors, pre-loading them with several cycles of forced displacement loading, until they appeared to attain a peak load. The connectors were then disassembled and the conditions of the plates compared with the case before any loading had occurred whatsoever. Visually, the surface of the pre-conditioned connectors appeared little different from the surface before loading, apart from a few minor striations.

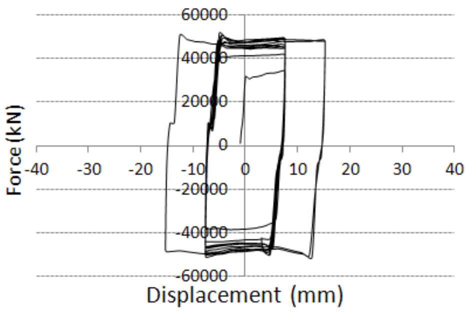


***Figure 7.*** *Initial displacement cycles showing build up to peak load.*

The connectors were re-assembled, with the plates were offset from their original position at the end of the pre-loading. The full loading schedule of Figure 4 was then applied and the connectors reached around 90% of peak strength on the first cycle, and then 100% of peak strength for the remainder of the load cycles.

## 6 IMPLEMENTATION IN RIGID TIMBER WALL

To confirm the practical applicability of using slip-friction connectors with shear walls, a 2.4 m x 2.4 m rigid timber panel has been assembled from two panels of 2.4 x 1.2 m, 45 mm thick LVL panels (supplied by Carter Holt Harvey).

Shear connectors of 25 mm smooth mild steel dowels were adopted. Two of these dowel connectors were inserted through holes drilled near the bottom centre of the wall, and these dowel connectors bear against 12 mm steel plates welded to the foundation plate, on both sides of the wall. The 12 mm steel plates are set at a slight angle from the horizontal to reduce frictional effects. The centre-plate of the slip-friction connectors are riveted to the end chords, and the outside plates bolted to the foundation. Figure 8 shows variously (a) the wall being erected, (b) a slip-friction connector during sliding, and (c) configuration of shear connectors.

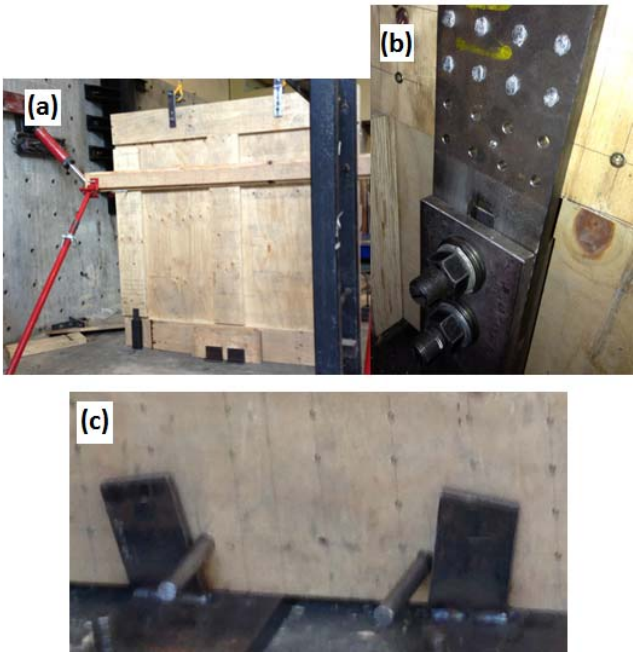


***Figure 8.*** *(a) Test wall under erection, (b) shear connectors under sliding, and (c) shear connectors.*

The walls are subjected to monotonic tests to confirm the ability of the slip-friction connectors to limit forces on the wall, to enable elasto-plastic force displacement behaviour, and to work successfully in conjunction with the shear connectors. A preliminary monotonic test result is shown in Figure 9. From the force displacement result presented, the connectors clearly have the ability to cap forces on the wall. Note the slight dip in force when sliding commences – this is probably due to the transition from static friction to dynamic friction.

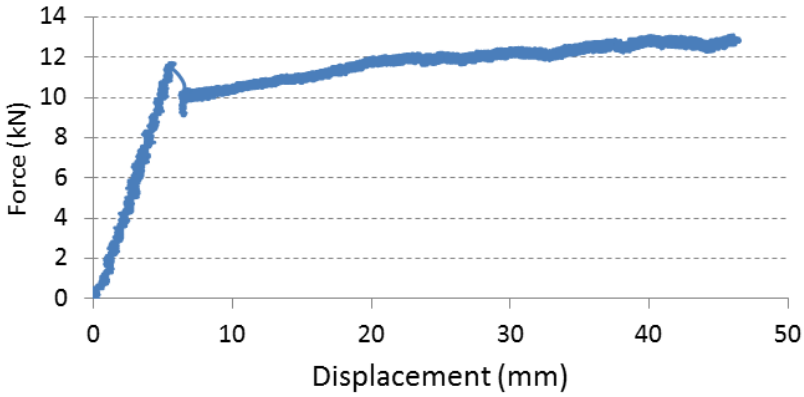


***Figure 9.*** *Monotonic force displacement test for wall system strength of approximately 12 kN.*

Cyclic tests will be carried out after the monotonic test schedule has been completed. Results from the cyclic testing of the rigid timber shear wall with slip-friction connectors will be presented at the 2013 NZSEE conference in Wellington, New Zealand.

## 7 CONCLUSIONS

This paper discussed the hysteretic behaviour of a proposed symmetric slip-friction connector that avoids the need for shims, whereas typically these connectors require expensive and not always readily procurable brass shims to enable stable sliding. Instead of shims, the centre plate of the symmetric connector is fabricated from abrasion resistant steel such as Bisplate 60 or Bisplate 400. The outer plates of the connector are of mild steel.

It has been found that

a) Stable sliding and excellent elasto-plastic hysteretic behaviour is obtained by abrasion resistant steel sliding directly against mild steel. It is apparent that the harder the abrasion resistant steel, the more stable the sliding (compare results with Bisplate 400 against Bisplate 60).

b) A simple but efficient method of obtaining and maintaining desired bolt tension is the use fine threaded bolts (of pitch 1.5 mm or less) and Bellville springs stacked in series, in order to maximise the number of rotations of the nut required.

c) Preconditioning of the connectors may be required to initialise a single and stable peak load.

d) Montonic tests show that these connectors have the ability to cap base shears on timber shear walls.

## 8 ACKNOWLEDGEMENTS

The authors are grateful to the New Zealand Ministry for Primary Industries for their support of this research.

## 9 REFERENCES

Bisalloy Steels. 2012. Bisplate Technical Guide. New South Wales – Australia.

Bora, C., M. Oliva, S. Nakaki, R. Becker. 2007. Development of a unique precast shear wall system with special code acceptance. *PCI Journal*. 52(1). 122-135.

Butterworth, J. 2000. Ductile concentrically braced frames using slotted bolted joints. *SESOC Journal*. 13(1). 39-48.

Clifton, G.C. 2005. Semi-rigid joints for moment resisting steel framed seismic resisting systems. *Published PhD Thesis, Department of Civil and Environmental Engineering.* University of Auckland – New Zealand.

Davet, P. 1997. Using Belleville springs to maintain bolt preload. Ohio – USA.

Grigorian, C. E. & Popov, E. P. 1994. Energy dissipation with slotted bolted connections. *Report UCB/EERC-94/02, Earthquake Engineering Research Center,* University of California at Berkeley – USA.

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

Loo, W. Y., P. Quenneville, N. Chouw. 2012a. Design and numerical verification of a multi-storey timber shear wall with slip-friction connectors. In Pierre Quenneville (ed.), *World Conference on Timber Engineering; Proc. Strength and serviceability – extreme events., Auckland, 15-19 July 2012.* Auckland: New Zealand.

Loo, W. Y., P. Quenneville, N. Chouw. 2012b. A numerical study of the seismic behaviour of timber shear walls with slip-friction connectors. *Engineering Structures*. 34(22). 233-243.

Solon Manufacturing Co. 2012. Belleville springs - Keeping bolted joints tight. Ohio – USA.