A 'Shim-less' Slotted Bolt Energy Dissipating Connector

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SUMMARY:

The use of slotted bolt energy dissipaters is widely employed in the steel construction industry. Research on their utilisation in timber structures, particularly shear walls, has also showed early promise. Slotted bolt connectors can either be in symmetric sliding or asymmetric sliding. In symmetric sliding the middle plate slides between the two outer plates, with the outer plates moving together at exactly the same rate, each taking half the force of the middle plate. Unlike the case with asymmetric sliding, symmetric sliding places little bending, shear or bearing stresses on the tension bolts which are used to mobilise frictional resistance across the plates. However mild steel against mild steel in symmetric sliding has been shown by previous researchers to produce a jagged, unpredictable force displacement behaviour. Up until now this problem has been obviated by the insertion of brass shims between the steel plates. However, brass shims adds to the cost of the connector through the cost of the brass itself and the fabrication process. Furthermore the required type of hard cartridge brass can in some places be difficult to procure. The use of brass shims also introduces the potential problem of dissimilar metals corrosion. In this paper, the authors describe how employing a high strength abrasion resistant steel for the middle plate which slides directly against the two mild steel outside plates results in excellent elasto-plastic behaviour. Shims are not used. With the careful use of Bellville springs to calibrate tension forces on the bolts, the force threshold to mobilise sliding is highly predictable. The cost of using this readily available alloy steel plate is cheaper than that which would be required for the provision of brass shims. The connector is of significantly simpler configuration, and the problem of dissimilar metals corrosion is avoided.

1. INTRODUCTION

In recent years, earthquake engineering research and design has increasingly emphasised not only collapse avoidance and the protection of life and limb, but also the design of structures capable of surviving severe earthquake events without incurring significant damage. There are various ways in which this damage avoidance philosophy can be implemented. Among these the use of 'passive' energy dissipaters, in which energy is dissipated through friction between sliding plates, is seeing increasing interest. These connectors are commonly referred to as "slotted-bolt" connectors, and they have been researched for use, and in some cases already implemented in actual construction, in braced frames, moment resisting frames, and as shear wall hold-down connectors. Pioneering research into the feasibility of slotted-bolt connectors (SBCs) was researched by Popov et al. (1995) and excellent sliding behaviour can be achieved by mild steel plate connectors, provided the individual plates are separated by, and slide directly against brass shims.

Loo et al. (2012) have described the possible use of SBCs as hold-downs for timber shear walls. As part of this research, exploratory tests have been carried out at the University of Auckland on an improved SBC which would allow for steel to slide directly against steel. This can be achieved through the use of an abrasion resistant steel plate inserted between mild steel plates. The need for expensive, and in some cases difficult to procure brass shims is avoided, and problems with corrosion are reduced. Sliding of mild steel against abrasion resistant steel is shown to produce hysteretic behaviour which is highly elasto-plastic, and ideally suited for use as a passive energy dissipating device in a variety of structural engineering contexts.

2. BACKGROUND

Popov et al. (1995) described a suite of tests that were carried out on SBCs at the University of California, Berkeley. SBCs of 16 mm A36 mild steel plates were tested in symmetric sliding. The mechanism of *symmetric* sliding as opposed to *asymmetric* sliding is shown in Figure 1. Popov et al. found that mild steel against mild steel friction interfaces produced extremely erratic and uneven force-displacement behaviour. However when shims of half-hard cartridge brass were placed between the sliding steel surfaces, stable and uniform, rectangular hysteresis loops were obtained. Popov et al. further tested the connectors in a braced structure which was placed under earthquake excitation on a shake table. Performance was found to be excellent, and energy dissipation could readily be increased by increasing design ductility.

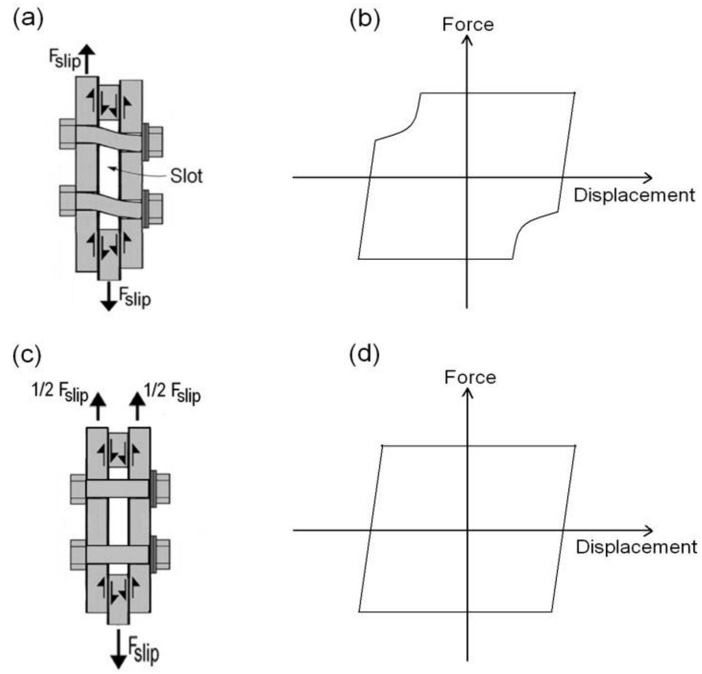

Figure. 1. Slotted bolt connectors: (a) asymmetric mechanism and (b) associated hysteretic behaviour; and (c) symmetric mechanism and (d) associated hysteretic behaviour.

An asymmetric connector has the external loads applied to the central slotted plate and one of the outside plates (see Figure 1(a)). The movement of the outside plate, which is not directly subjected to external load, is 'dragged' along by the tensioned bolts, in the direction of movement of the loaded outside plate. Thus various complex stresses are placed on the bolt, and also around the bolt holes. Nevertheless the asymmetric connector has been shown by Clifton et al. (1998) to be able to perform in a satisfactory manner. SBCs in symmetric sliding (see Figure 1(c)) work with the connector load, F_{slip}, being applied to the central slotted plate (as with the asymmetric connector), and $½F_{slip}$ applied to each of the outside plates. Provided the bolts do not impact the slot ends during earthquake excitation, there are only longitudinal tensile stresses on the bolts. The hysteretic behaviour of such connector tends to be rectangular (see Figure1(d)) as opposed to non-rectanglar (see Figure 1(b)).

Butterworth (2000) discussed the use of SBCs in ductile concentrically braced frames, and found from time-history analyses that such frames could achieve structural ductility factors ranging from 6.7 to 18.6, with base shears readily controlled and limited by varying the slip threshold of the connectors. For moment resisting frames, Clifton et al. (2007) describes a cost effective sliding hinge joint which utilises an asymmetric sliding action (see Figures 1(a) and 1(b)) which responds to design level earthquakes with non-rectangular hysteresis loops without material damage to the frames.

For timber structures, Filiatrault (1990) found that placing SBCs at the corners of shear walls can effectively limit forces on the wall and thereby reduce inelastic damage. Duff et al. (1998) investigated the use of SBC devices in timber T-connections, obtaining promising results; with the T-connections displaying excellent hysteretic characteristics in terms of energy dissipation, all the while experiencing negligible reduction in strength and stiffness during cyclic loading.

Bora et al. (2007) investigated the use of asymmetric SBCs with brass shims in pre-cast concrete walls, and found that the connectors could supply ductility to these otherwise brittle structures, and effectively limit base shear.

Khoo et al. (2012) investigated the use of abrasion resistant steel for use as shims in asymmetric SBCs, in lieu of brass. It was found that the sliding of mild steel against an abrasion resistant steel shim of significantly higher hardness, would enable the connectors to produce stable and consistent sliding characteristics.

Loo et al. (2012) has proposed the use of SBCs as hold-downs for timber shear walls. From an extensive numerical investigation, Loo et al. found that SBCs with a symmetric sliding mechanism, have the potential to perform well with timber shear walls; limiting base shears on these walls, and efficiently dissipating energy, while at the same time allowing the walls to re-centre after an earthquake.

While Popov et al. (1995) have amply demonstrated that symmetric SBCs work well with brass shims, the authors propose a symmetric SBC which avoids the use of any type of shim, and simply places a slotted central plate of abrasion resistant steel directly against mild steel outer plates. The following sections discuss exploratory tests carried out on the proposed 'shim-less' symmetric connector.

3. TESTING

An SBC was fabricated that would work in symmetric sliding. The details are shown in Fig. 2.

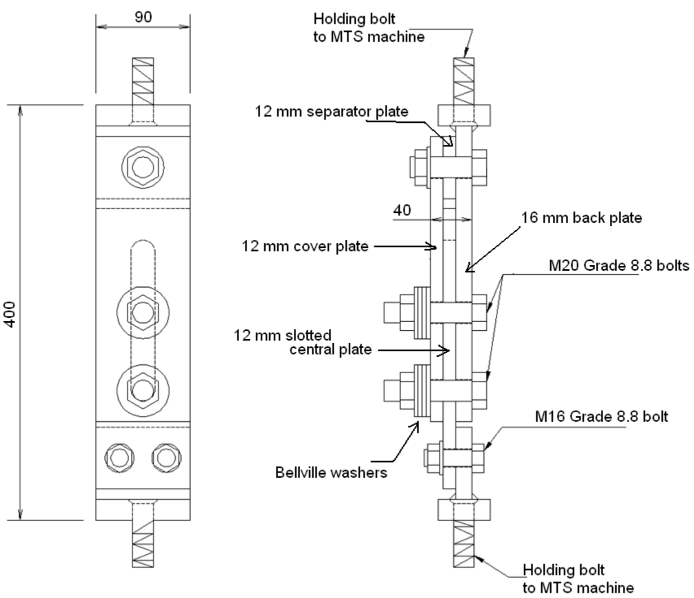

Figure 2. Shim-less SBC connector configuration (symmetric sliding action).

The connector consists of a back plate, which would be intended to move with an uplifting structure, such as the shear walls with an uplift capability described by Loo et al. (2012). The back plate moves in lock-step with the cover plate, and is separated from the cover plate by a separator plate. One M20 Grade 8.8 bolt transfers shear between these two plates, enabling them to move together. The cover, back, and separator plates are all of Grade 350 mild steel. The slotted middle plate which slides between the cap and back plate is of Bisplate 400, an abrasion resistant steel. Bisplate 400 is manufactured in Australia by Bisalloy Steels Pty Ltd, and is a through hardened, abrasion resistant steel plate, recommended for use for chutes, storage bins, earthmoving buckets, and cutting edges, among other utilisations. Bisplate 400 has a tensile strength of 1320 MPa, and its Brinell hardness is typically around 400 HB (reference to Bisplate 400).

Grade 8.8 M20 structural bolts are used to apply tension across the plates. Bellville springs are used to obtain and maintain tension forces in the bolts which go through the slotted central plate. The specifications of the Bellville springs (manufactured by Solon Manufacturing Co., USA) used in this testing are presented in Table 1 below:

Table 1. Solon Bellville springs used in testing

Part Number	Inside dia. (mm)	Outside dia (mm)	Thickness (mm)	Deflection (mm)	Overall height (mm)	Flat Load (N)
M20-40-1.5-177	20.599	40.005	1.118	1.575	2.692	4003
M20-40-2.25-177	20.599	40.005	0.787	2.337	3.200	14995

For these exploratory tests the Bellville washers were simply flattened by feel and by sight – this is not the ideal method to achieve the most accurate results – however it was deemed sufficient for these exploratory tests, in which the main objective was to investigate whether or not elasto-plastic hysteretic behaviour could be achieved. The Bellville washers can be stacked in either series or parallel to either increase the deflection or the force respectively.

The maximum connector force, F_{slip}, is related to the tension in the bolts, T_b, as follows:

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

where n_b is the number of bolts, and μ the coefficient of friction between the sliding plates.

For the tests a maximum connector slip of 60 mm was used. 60 mm corresponds to a drift of 2.5% for a typical 2.4 m wide shear wall (the connectors are intended for use with shear walls). The displacement schedules (Fig. 3) were based on that adopted by Bora et al. (2007). Two frequencies were used, the first 0.05 Hz (20 seconds for one cycle), and then 0.1 Hz (similar to that used by Bora). The reason for using the lower frequency of 0.05 Hz, was initial concern that the MTS machine used would have inadequate power for testing at the higher frequency. However later tests adopted 0.1 Hz with no obvious problems observed.

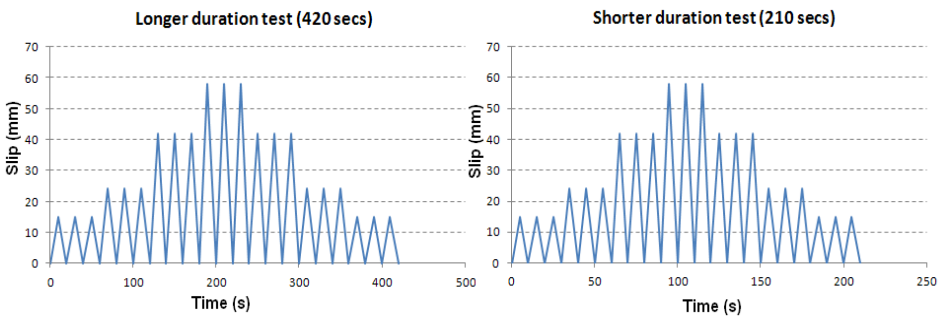

Figure 3. Displacement time-histories for tests.

Fourteen tests were carried out, one after the other, on the same single connector with a Bisplate 400 slotted central plate. Then a single extra test was carried out on the same connector, but using a mild steel slotted central plate, in lieu of the slotted Bisplate 400 plate. The test matrix is shown in Table 2:

Table 2. Test Matrix

Test	Frequency (Hz)	Middle plate	Bellville spring/s	No. stacked belvilles	Attempted tension in bolts (N)
1	0.05	Bispl. 400	M20-40-1.5-177	1	4003
2	0.05	Bispl. 400	M20-40-1.5-177	2	8006
3	0.05	Bispl. 400	M20-40-1.5-177	3	12009
4	0.05	Bispl. 400	M20-40-1.5-177	4	16012
5	0.05	Bispl. 400	M20-40-2.25-177	2	29990
6	0.05	Bispl. 400	M20-40-2.25-177	3	44985
7	0.05	Bispl. 400	M20-40-2.25-177	4	59980
8	0.05	Bispl. 400	M20-40-2.25-177	4	59980
9	0.05	Bispl. 400	M20-40-2.25-177	1	14995
10	0.10	Bispl. 400	M20-40-2.25-177	1	14995
11	0.10	Bispl. 400	M20-40-2.25-177	2	8006
12	0.10	Bispl. 400	M20-40-2.25-177	1	14995
13	0.10	Bispl. 400	M20-40-2.25-177	2	29990
14	0.10	Bispl. 400	M20-40-2.25-177	4	59980
15	0.10	G350 mild steel	M20-40-1.5-177	2	8006

The tests were carried out using the MTS machine in the Civil Engineering materials laboratory, at the University of Auckland, New Zealand, and results are shown in Figure 4, for Tests 4, 6, 13, and 15.

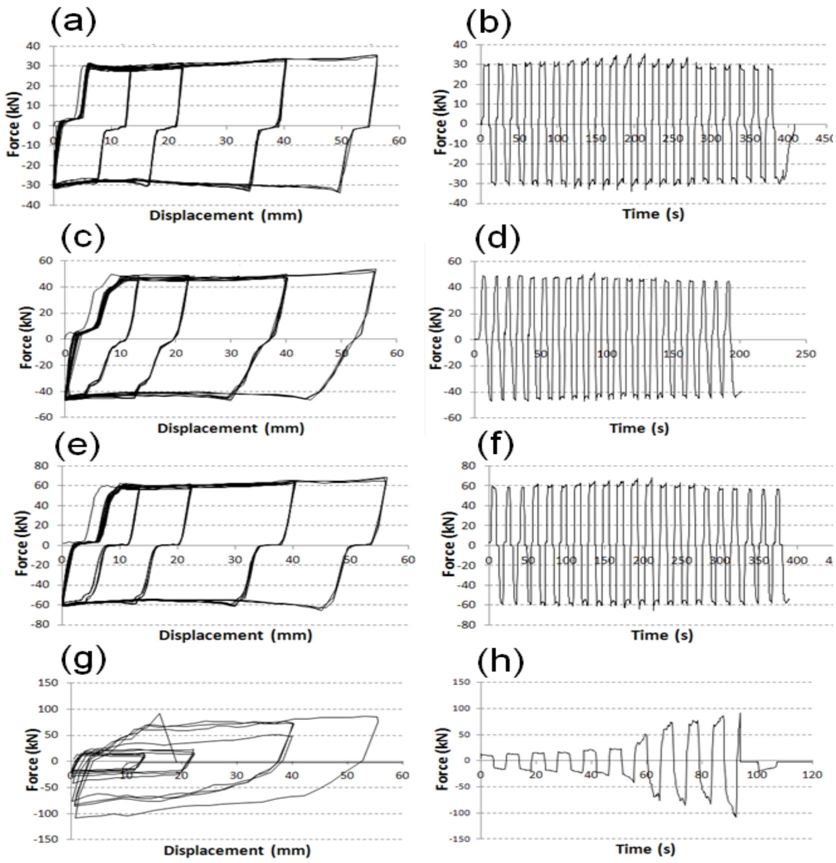

Figure 4. Test output: (a) Test 4 force-displacement, and (b) force time history relationships; (c) Test 6 force-displacement, and (d) force time history relationships; (e) Test 13 force-displacement, and (f) force time history relationships; (g) Test 15 (mild steel middle plate) force-displacement, and (h) force time history relationships.

From Figures 4(a) to 4(f), it can be clearly seen that using a hardened, abrasion resistant steel plate such as Bisplate 400 against mild-steel can provide excellent elasto-plastic behaviour for connectors using a symmetric sliding mechanism. As expected from the findings of Popov et al. (1995), mild-steel against mild-steel in symmetric sliding produces highly irregular and unpredictable force-displacement behaviour (see Figures 4(g) and 4(h)). Note that the initial slip at low loads, arises not because slippage of the holding bolts through the separator plate (refer Figure 2), and is not an artefact of the frictional sliding between the plates. This problem can be avoided in future tests, either through welding the outside plates to the separator plate, or alternatively using a bolt-hole of minimal tolerance.

5. CONCLUSIONS

Typically slotted bolt connectors rely on the use of brass shims placed between the steel plates to enable a smooth and predictable sliding action. However this involves added material and fabrication costs, and in certain locales there is the additional problem of lack of availability of the required cartridge hard brass. Brass against steel also is potentially problematic because of the potential problem of dissimilar metals corrosion.

Exploratory tests carried out on a shim-less slotted-bolt connector utilising a symmetric sliding mechanism, has shown that sliding between mild steel and abrasion resistant steel can result in force-displacement behaviour characterised by excellent elasto-plastic characteristics. It is tentatively suggested that based on the results obtained, the hysteretic behaviour of the connector is relatively unaffected by loading rate.

Further testing is currently being carried out at the University of Auckland to confirm the promising findings of this exploratory study.

ACKNOWLEDGEMENT

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