Steel Shim Hardness Effects on Asymmetric Friction Connection Performance

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ABSTRACT

This paper describes Asymmetric Friction Connection (AFC) large displacement cyclic sliding tests with two M24 bolts and shims consisting of Grade 80 and Grade 500 Bisalloy steel plates. It was shown that for the low hardness (Grade 80) steel plates that under cyclic testing there was considerable noise, vibration and a temperature increase of up to 30˚C. The compression forces in the bolts decreased by up to 90% and groove depths of up to 2 mm occurred in the shims and up to 6 mm and the sliding plate. The hysteresis loop shape for small cycles up to ±40 mm sliding distance was quite stable and nominal sliding strength divided by the total proof load was 0.64, with minimum and maximum strengths ranging from 0.66 to 1.36 times this. Furthermore, the strength was not constant over the sliding range and degradation occurred after increased cycles of loading, especially cycles to more than 40 mm. For high hardness (Grade 500) shims, the sliding behaviour caused a temperature increase of 16℃, and there was a quiet stable hysteresis loop. The effective coefficient of friction was 0.155 during the initial cycles and the peak coefficient reached 0.18 in the sliding cycles to ±40 mm. The friction coefficient computed as the actual sliding strength divided by the total instantaneous bolt load, was 0.21 to 0.26. Minimum and maximum strength values were 0.92 and 1.15 respectively indicating little variation in strength. After the bolt retightening at the 2nd run, the average effective coefficient of friction was stable with a value of 0.2.

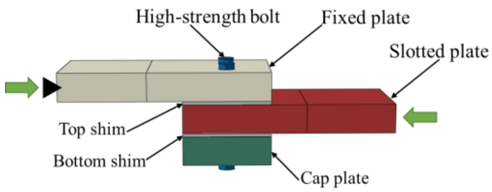
Keyword: Low-damage building, Friction connections, Steel plate hardness, Abrasion resistance

1 INTRODUCTION

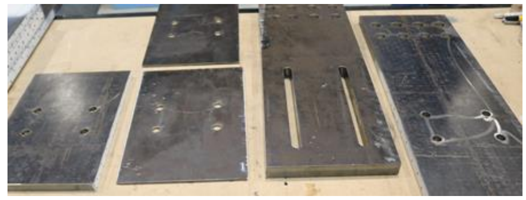
Friction connections have been used as passive energy dissipaters in seismic structural systems around the world. For example, Symmetrical Friction Connections (SFC) have been used in Concordia University Library Building (1991) and Boeing Commercial Airplane Factory (2001, Everrett, USA) by Pall Dynamics Limited (PDL). Torre Cuarzo (2018, Mexico) and Lincoln Hub (2019, Christchurch) by Quaketek Inc. Also, Asymmetric Friction Connections (AFC) have been implemented in the Te Puni Buildings (2007, Wellington, New Zealand), The Forte Health Center (2012, Christchurch, NZ), The Terrace Project (2018, Christchurch, NZ), Turanga Central Library, (2018, Christchurch) and others. Also, Tectonus devices have been used in the new Nelson Airport (2018).

Sliding friction devices were applied and tested at the X-type braces by Pall and Marsh, [1] as one of the first bracing frames which used the concept of energy dissipation by frictional resistance. The energy dissipation mechanism through the sliding of clamped plates was experimentally tested by Fitzgerald et al. [2] and named slotted bolted connections. Shim material effects were investigated by Grigorian and Popov [3]. They developed symmetric friction connections (SFC) and showed brass in contact with mild steel induces stable friction force. The behaviour of SFC in concentrically braced frames with various shim materials also was investigated by Tremblay [4]. Brass and aluminum showed low strength, low melting temperature and excessive wear in combination with mild steel material; however, high-strength shims proposed more stable strength.

Asymmetric Friction Connections (AFC) were introduced and tested by Clifton [5] as sliding hinge joint and further developed by MacRae et al.[6]. Recent studies were conducted on mild steel and aluminum shims in SHJ, brass, aluminum and high-strength Bisalloy with different grades for AFC [7-9]. The AFC in the bracing system is assembled by the fixed plate (here the brace section, the column and beam section at the base and beam-column connections), the slotted plate (gusset plate), the cap plate (outer plate) and two thin steel shims as shown in Figure.1. The plates are usually clamped together using high-strength structural bolts (usually grade 8.8), are tightened to their proof load level. Structural washers or Belleville washers are also used.



(a)



(b)

Figure 1. AFC. (a) assembled specimen (b) component; left to right: cap plate, shims, slotted and fixed plate

The use of these connections and the selection of material connections is determined based on the results of test programs. Shim materials such as brass, mild steel, high-hardness steel, brake pads and etc. have been used, on the sliding surfaces. The effects of different shims have also been evaluated within the last three decades. These tests have generally been limited to small (less than 50 mm) sliding displacements (e.g. Clifton, Khoo, etc.) [5, 9-11]. When large displacements have occurred this has been done with small (M16) bolts (e.g. Chanchi [7]). There is a need to test connections with larger and more realistic bolts to large sliding displacements. This paper seeks to address this issue and to evaluate the effects of shim hardness by answer the following questions:

1. What is the physical performance of AFC with different shims?
2. How does the bolt post-tension force change with shims type?
3. How does the hysteresis performance change with shims hardness?
4. What are the design implications of the findings above?

2 EXPERIMENTAL TEST

Experimental tests were conducted on one specimen with Bisalloy Grade 80 and one specimen with Bisalloy Grade 500 as steel shim material. Here the results of only six runs on two specimens were discussed as a part of large experimental tests which evaluated a number of factors. Test specifications for shims and bolts are presented in Table 1. In both specimens at the end of the first test-run enough time was allocated to cool down the components and cleaning debris then the second and the third runs were conducted. Test#1-Run2 was carried out using replaced bolts. For the third run repeated without any changes; however, on Test#2-Run2 the bolts were tightened again. They were replaced for the third run.

Table 1. Summary of the testing program.

Test	Run	Shims Bisalloy	Shims Hardness HBN	High strength Structural Bolts Grade 8.8	Initial bolt force [kN]
1	1	G 80	270	2M24× 160 mm	210
	2	G 80	270	New M24 bolts	210
	3	G 80	270	Repeated	Repeated
2	1	G 500	480	2M24× 160 mm	210
	2	G 500	480	Retightened	210
	3	G 500	480	New M24 bolts	210

Specimens comprised the steel plates Grade 300, high-strength structural bolts Grade 8.8 to AS/NZS 1252 [12] and Bisalloy Grade 80 and 500 with Brinell hardness values of 270 HB and 480 HB respectively. The slotted plate was 600×250×32 mm with 200 mm long and 26 mm wide slot holes. All other plates were with 2 mm clearance for M24 bolts (26 mm). The fixed plate was 600×250×25 mm, the cap plate was 300×250×20 mm and the shims were 300×250×6 mm. Plates were clamped by two M24 bolts of 160 mm long (95 mm shank and 32 mm threads as grip length) considering the force washer thickness (washer load cell). The bolts were tightened to provide 210 kN tension force as their required proof load level [13], which was controlled by the force washers and the ultrasonic elongation tension monitor.

All surfaces were cleaned by acetone and a light wire brushing to remove any lubricant, dust, rust, corrosion and particles owing to cut and drilling holes. The bolts are delivered from suppliers or manufacturers without appropriate protection in the face of environmental conditions. These bolts had variable lubrication level. This lubricant material also absorbed dust and particles in a period of storage or transformation. Preliminary studies had indicated that this resulted in different friction coefficients between the bolt threads and the nut which affect the bolt tension force as well as the bolt loosening both after tightening, and during the sliding tests. As a result, all bolts were brushed, cleaned with acetone and lubricated with a thin layer of Opal Hi-Load as a high-quality multipurpose grease containing molybdenum disulfide. This was done by placing the lubricant in the threaded nut and then running the nut up and down of the bolt threaded length. The amount of the lubricant was determined such that it should cover the whole thread with none left over after removing the nut. The AFC specimens were tested on a Dartec universal machine with a capacity of 10 MN. The test setup comprised a fixed bracket at the top of Dartec and a moving bracket at the bottom side, both Grade 350 mild steel. Figure 2.

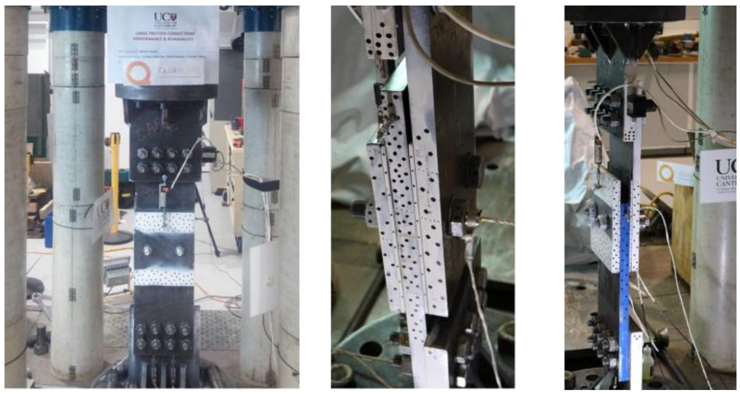


Figure 2. AFC specimen and test setup under the DARTEC machine

Instrumentation comprised the Dartec load cell, linear and rotational potentiometers, two force washers (HBM 400kN), an ultrasonic bolt tension monitor (Mini-Max Dakota), a surface roughness meter SJ-210 (Mitutoyo), and high-resolution cameras for particle tracking. The bolt tension forces also were measured and verified in terms of the bolt length changes after the tightening, during the tests and at the end of the tests using the bolt ultrasonic tension monitor. The surface roughness parameters of eight sliding surfaces were measured (both sides of the shims and their adjacent plate contact surfaces) before the assembly and after dismantling at 10 to 20 points. The plates' and the bolts' temperatures were monitored continuously on the outside of all plates and the bolts with a digital thermometer. Also, the components relative displacements were determined by using four high-resolution cameras at the four sides of the specimen using particle tracking procedures. The AFC specimens were subjected to three similar cycles as eight different amplitudes with increasing the sliding length (24 cycles in total) according to ACI report T1.1-01. The total cumulative travel was 2625 mm at the end of the first run using eight displacement regimes ranging between 1.25 mm to 80 mm, Figure 3. The second run was conducted with the same condition after about 30 minutes which allowed the specimen to cool down. The loading velocity was 1 mm/s at the initial cycles and then increased to 3 mm/s for sliding lengths of 60 mm or greater.

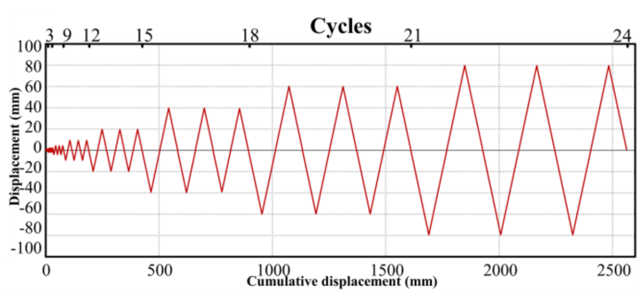


Figure 3. Loading protocol

3 RESULTS AND DISCUSSION

In Test#1 significant noise and vibrations occurred from the initial sliding and loose debris fell off the specimen. Particles (larger than 1 mm in diameter) were clearly observed at the end of the sliding plates, as shown in Figure 4a where some flakes of the maximum dimension of 8 mm may be observed. The specimen temperature increased from 18˚ to 46℃ at the end of the first run. The bolt elongation reduced from the initial tightening value of 0.37 mm to about 0.1 mm at the end of the first run. Also, the sliding strength decreased to about 13% of its maximum value. Therefore, instead of repeating the test, the second run was conducted using a set of fully tightened new bolts. In Test#2, loose debris was in form of fine (less than 1mm) black dust Figure 4d, there was no significant noise or vibration, and the maximum temperature was 34℃ which was 16℃ greater than the initial 18℃. Also, the temperature rose only 10℃ in Run2 and the observed noise and vibrations were much less than that of Run1 and Test#1.

After the tests, the specimens were disassembled and the inspection of the surfaces was conducted. In Test#1 severe damage, galling and material removal along the slotted holes occurred in the form of grooves 10 mm to 200 mm in length, 1-10 mm in width and 1- 6 mm in depth as shown in Figures 4b and 4c for the shim and slotted plate respectively. Approximately 60% of the loose debris from the sliding surfaces, with irregular shapes and various diameters, came out from between the sliding surfaces during the testing. The remaining particles were trapped between the plates and caused severe abrasive wear after the adhesive wear. The damage, in terms of length and number of grooves, on both sides of the slotted plate in Test#1 was similar. In Test#2, the damage on the side of the slotted steel plate in contact with the shim and fixed steel plate was almost twice that of the slotted steel plate on the cap plate side. Figures 4e and 4f show the polished/scoured areas parallel to the slotted holes, between the holes and also beside the holes toward the edges, on the slotted plate and the shim surface of Test#2. The wear particles were 80% less than for Test#1; however, two grooves with 40 mm in length, 5 mm in width and 1 mm in depth were observed. The slotted plate as the main component of AFC was reused with the new shims and bolts.

(a) *Fallen flakes (Test 1 –B80)*

(b) *Bisalloy 80 shim* (Test 1)

(c) *Slotted plate (Test 1- B80)*

(d) *Fine particles (Test 2)*

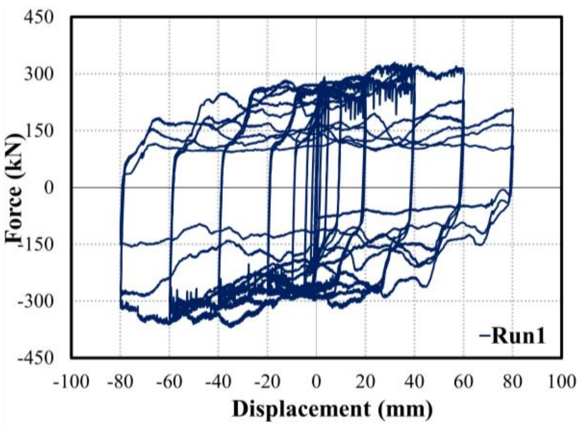
(e) *Bisalloy 500 shim (Test 2)*

(f) *Slotted plate (Test 2 – B500)*

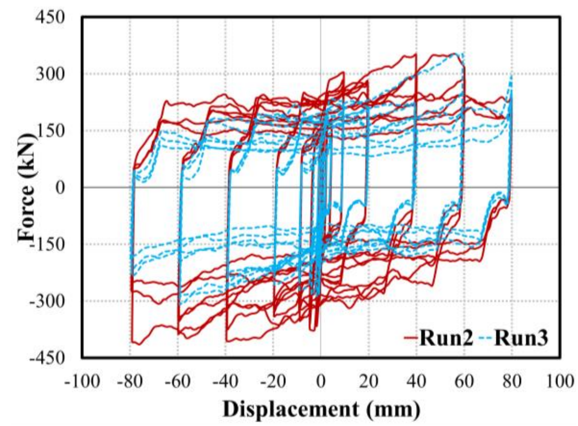
Figure 4.Tested plate surfaces and debris

The hysteretic behaviour of Test#1-Runs 1-3 is shown in Figure 5a and b. The overall performance for all runs was similar with significant strength fluctuations, strength degradation and instability. Although the overall behaviour of the specimen was unstable, the strength plateaued and remained about 280 kN for the sliding to ±40 mm in Test#1-Run 1. This is associated with an effective friction coefficient of 280 kN/(2× 2 ×210 kN)=0.334, where 210 is the bolt proof load, and there are 2 bolts and 2 sliding surfaces. The maximum strength reached 380 kN but declined to 54 kN at the end of the test as shown in Figure 5b. Sliding on one surface of the plate occurred earlier at a force of about 185 kN for the AFC before the bolt inclined, increased in strength more slowly, and then caused sliding on the second surface (MacRae et al.[6]).

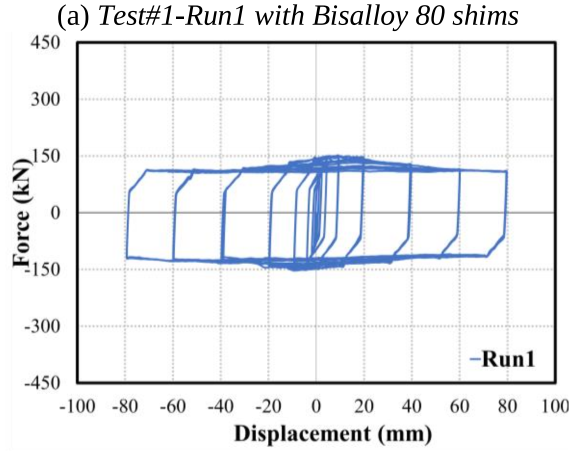
The hysteretic behaviour of Test#1-Run 2 and Run 3 is shown in Figure 5b. Before the 2nd run, the specimen was cooled down and the bolts were replaced but the shims remained. The 3rd run was conducted after about one hour after Run2 without any change to the specimen. The overall behaviour in Run2 and 3 was similar; however, the bolt axial force due to loosening and yielding reduced to 50% of the initial value at the end of the 2nd run. The strength variation between compression and tension was 420−350=70 kN in Run2 which is of greater magnitude than that in Run 1 of 370−330=40 kN increased in the 2nd run. Degradation also decreased in Run2 compared to Run1. The degradation, defined as the maximum strength minus the final cycle strength at zero displacements, is 370−50=320 kN (= 86%) in Run1 which is greater than that in Run2 of 420−190=230 kN (= 55%) and Run3 of 350−100=250 kN (= 71%). For the cycles to ±40 mm, the degradation for Run1 was 370−280=90 kN (= 24%).



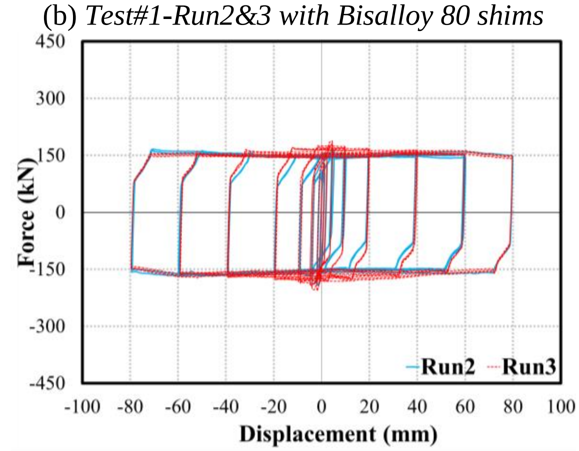
(a) *Test#1-Run1 with Bisalloy 80 shims*



(b) *Test#1-Run2&3 with Bisalloy 80 shims*



(c) *Test#2-Run1 with Bisalloy 500 shims*

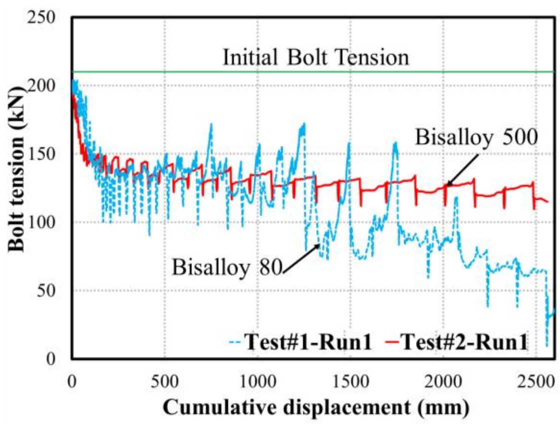


(d) *Test#2-Run2&3 with Bisalloy 500 shims*

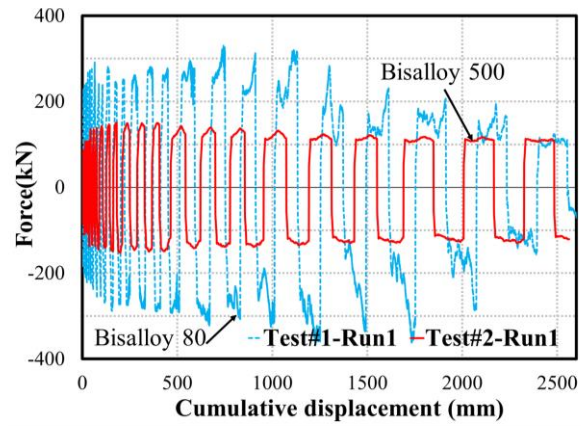
Figure 5. AFC hysteresis shape

Figures 5c and d show the force-displacement response of Test#2 with Bisalloy 500 shims. The overall behaviour was stable with an almost rectangular shape. In the first run, the sliding force to initiate the sliding was 85 kN on one side of the slotted plate. The strength for sliding on both sides was 105 kN after 3 cycles to ±2.5 mm. The strength increased to 120 kN after 85 mm cumulative travel as the first steady state (9 cycles). Then after 110 mm cumulative displacement (sliding length ±10 mm) the maximum strength of 150 kN was reached. The strength plateaued there until the end of cycle 18 with a cumulative displacement 855 mm at a sliding length ±40 mm. The sliding force reduced gradually to 130 kN at ±80 mm sliding length (with a cumulative displacement 2480 mm) as shown in Figure 6b. The specimen with the retightened and replaced bolts (i.e. Runs 2 and 3 respectively) also had stable loops but with higher strength from the first run because there was less surface degradation as a result of steady state wear mechanism after the first run as shown in Figure 5d. The 2nd run first cycle displayed a significant variation between tension and compression strength of 125 kN and 180 kN respectively at ±5 mm sliding length. The peak strength only remained for the very small cycles and then reached the stable strength of 160 kN in both directions. This strength remained almost consistent until the end of the test. Strength was slightly greater than the Run 1 strength because the surface condition was different as the same shims were used, but the wearing had already taken place. There was less degradation as many of the loose particles had fallen out from the sides and ends of the sliding region and also through the slotted holes during Test#2-Run1.Test#2-Run3 had a force-displacement response similar to the 2nd run. The peak strength occurred after the 6th cycle at ±5 mm displacement and was 186 kN in tension and 202 kN in compression. At the displacement of ±20 mm, the strength stabilized to 155 kN and then remained almost constant. This indicates less than 10% strength degradation.

The bolts were tightened to 210 kN as the proof load of the M24 bolts (the green line in Figure 6a) which reduced to 200 kN before sliding due to the bolt self-loosening or creep. In Test#1, the bolt tension force remained constant up to 30 mm cumulative travel (four cycles) and then reduced to 150 kN after 70 mm more sliding at the end of cycle 9 (±5 mm displacement). For displacements larger than ±40 mm (cycle 18) the bolt force was similar and strength was stable. For the cumulative displacement larger than 1250 mm the bolt force reduced to 10% of the initial value at the end of the run as shown in Figure 5a. Loose-wear particles, surface degradation, moment-shear-axial force interaction and nut rotation because of vibration within the sliding runs; all contribute to the bolt tension force decrease. In Test#2, the bolt tension force reduced to 130/200= 65% of the tension at the beginning of the test for the Run1 and 71% and 75% for the 2nd and 3rd run respectively.



(a) *The loss of bolt pretension force*



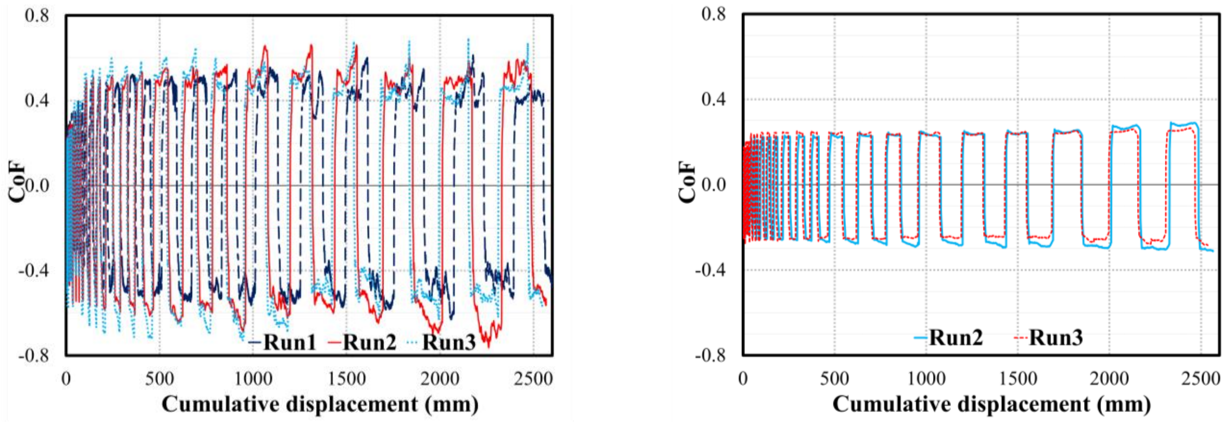
(b) *Cumulative displacement-sliding force*

Figure 6. Force comparison

The effective shear sliding coefficient ($\boldsymbol{\mu_{effective}}$) based on the theory of Coulomb, is given from MacRae et al. [6]. According to Eq. (1) where $\boldsymbol{V_{sliding}}$ is the sliding force**, n** is the number of bolts (=2 for the cases studied here), **m** is the number of sliding surfaces (2) and $\boldsymbol{T_{proof}}$ is the bolt nominal proof load (210kN).While this equation is obtained for design, it doesn't represent the actual material friction coefficient. Because the actual bolt axial force at any time is not the value of the initial force (proof load). Figure 7 is the friction coefficient computed as the sliding force divided by the instantaneous bolt tension force during the sliding tests.

$$\boldsymbol{\mu_{effective}} = \frac{\mathbf{V_{sliding}}}{\mathbf{n} \times \mathbf{m} \times \boldsymbol{T_{proof}}} \tag{1}$$

Figure 7a shows the instantaneous coefficient of friction for Test#1. In the first run, the instantaneous friction coefficient of 0.23 at the initial sliding rose to 0.28 after only 3 cycles. Then after 320 mm cumulative displacement (sliding length ±20 mm) increased rapidly to 0.5 and remained almost constant up to the end of cycle 18 (displacement ±40 mm). The friction coefficient reached to 0.54 at the peak point and then declined to 0.44 at the last 3 cycles. The force required to start sliding reduced in the 2nd and 3rd runs, which means that there was lesser friction between the surfaces. This trend continued up to ±10 mm sliding then it went up to 0.48 and 0.54 on the 2nd and 3rd run respectively. Therefore, the overall coefficient of friction trend was not stable and reliable in Test#1. Figure 7b shows the friction coefficients were almost identical in Test#2-Run2 and Run3 after the first nine cycles (displacement ±5 mm, cumulative travel of 80 mm). For these two runs with the plates which had been used and degraded within the 2625 mm cumulative displacement (the end of the 1st Run), their frictional behaviour stabilized and the instantaneous friction coefficient was almost 0.25. The average effective friction coefficient in Test#2-Run2 was 0.2, with minimum and maximum friction ranging from 0.19 to 0.21.



(a) *Bisalloy G80 shims* (b) *Bisalloy G500 shims*

Figure 7. Friction coefficient AFC

4 CONCLUSIONS

This paper described shim hardness effects on the AFC behaviour. The AFC used two M24 bolts which were subjected to a cyclic displacement regime. The following was shown:

1. AFC with Bisalloy 80 displayed severe damage on the surfaces. Significant noises and vibrations occurred during the tests. Loose debris fell off the specimen and there were long and deep grooves in the wear surfaces of the sliding plates, alongside the slotted holes in sliding direction. The maximum AFC temperature of the test with Bisalloy G80 shims increased by 28℃ while that with the Bisalloy G500 shims increased only 16℃.

2. Bolt tension reduced up to 90% of the initial force in the AFC with Bisalloy 80 shims as found from washer load cells. The bolt length, as found from an ultrasonic tension monitor, decreased by up to 0.26 mm during testing, after the bolt had been proof loaded. Factors contributing to the bolt strength loss and shortening were considered to be: (i) loss of particles from the wearing surfaces resulting in grip length reduction allowing bolt shortening; (ii) creep and vibration allowing the nut to loosen and hence bolt shortening; and (iii) MPV interaction which reduces the clamping force but allows the bolt to increase in length as it yields only in tension. The maximum bolt tension loss was 65% of the initial value in the specimen with Bisalloy 500 shims in Test#2 1st Run. In the next two runs, the frictional behaviour and bolt force tended to stabilize.

3. The force-displacement loop of the AFC with Bisalloy 80 shims was irregular and scattered. It was almost rectangular and stable at the small displacements; however, this was temporary and the strength was almost doubled by further sliding. The overall behaviour of AFC with this shim material showed considerable variation and was not considered to be reliable. The variation in sliding strength was up to 700% in the sliding length of $\pm$80 mm. The hysteresis loop of the AFC with Bisalloy 500 shims was almost rectangular with a strength variation of less than 15%.

4. In tests with Bisalloy 80 shims, the effective friction coefficient, computed as the sliding force divided by the bolt proof load, ranged from 0.18 to 0.50. However, in the test with Bisalloy 500 shims, it was 0.15 to 0.21. The AFC with Bisalloy 80 shims had a maximum to minimum strength ratio of 7.4 for the 1st run. This ratio reduced in the 2nd run and 3rd run to 2.2 and 3.5 respectively from these tests alone without considering other construction variations. The maximum strength to the minimum strength ratio of the AFC with Bisalloy 500 shims was 1.25 in the first run which reduced to 1.2 in the 2nd run and to 1.06 in the 3rd run. In these Bisalloy 500 tests, the used steel plates and shims in the 2nd and 3rd runs displayed more stable behaviour because they reached their steady-state wear. The low hardness (Bisalloy80) shim tests effectively dissipated energy but were considered to be difficult to reliably use in design given (i) the large variations in strength, and (ii) the significant sliding surface damage to both the shim and steel adjacent to the sliding surface, which would require total joint replacement after an event. The high hardness (Bisalloy

500) shims had dependable performance and could be reinstated by bolt replacement or retightening and possibly with shim replacement. These shims are recommended for use in design. Bisalloy 500 shims which had been worn had even more dependable performance which makes then even better for design.

5 ACKNOWLEDGMENTS

This research was supported by the University of Canterbury, John Jones Steel, Steel and Tube, Fletcher Steel and Vulcan Steel. Also, this project was (partially) supported by QuakeCoRE, a New Zealand Tertiary Education Commission-funded Centre. This is QuakeCoRE publication number 0380.

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