Low damage braces using Asymmetrical Friction Connections (AFC)

2014 NZSEE Conference

J. Chanchi Golondrino

University of Canterbury, New Zealand – National University of Colombia, Colombia

R. Xie, G. MacRae, G. Chase & G. Rodgers

University of Canterbury, Christchurch, New Zealand

C. Clifton

University of Auckland, Auckland, New Zealand

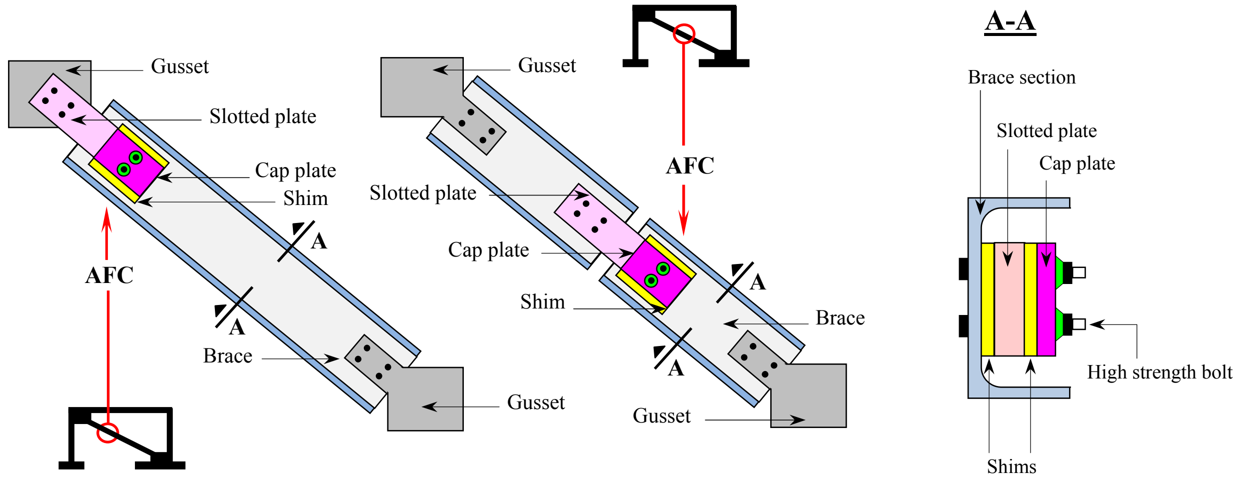
ABSTRACT: Braces equipped with Asymmetrical Friction Connection (AFC) details, assembled with Bisalloy 500 shims and placed at one end of the braces, have been tested quasi-statically. It is shown that braces equipped with AFC details are characterized by a repeatable hysteretic behaviour with strength degradations up to 10%. This degradation corresponds to the case where braces are subjected up to 40 cycles across the effective stroke of the connection with no components replaced or bolts re-tensioning. Also, out-of-plane brace deformation slightly causes a change in strength with axial displacement. Effective friction coefficients ranging between 0.16 and 0.20 were obtained for AFC braces.

1 INTRODUCTION

The concept of Asymmetrical Friction Connections (AFC) was recently developed and applied as energy dissipater in steel moment resisting frames systems in New Zealand (Clifton 2005). Testing of the connection subassembly as well as beam-column joints equipped with this type of connection have demonstrated that this technology can be considered as a reliable means of dissipating energy and controlling the level of damage of structural systems subjected to severe seismic events (MacRae et al. 2010) . The initial development and applications of this technology was based on placing AFC details in beam-column joints, where energy is dissipated as the beam rotates and overcomes the friction resulting from the total clamping force provided by bolts in the AFC detail (Clifton 2005). Another configuration that has been proposed by several researchers is based on placing the AFC detail at the end or within braces, where energy is dissipated as the brace experiences axial elongations (Butterworth 1999, MacRae 2008, Chanchi et al. 2012). This configuration can be used in different structural systems such as single, concentrically and eccentrically braced or it can be also used to retrofit existing buildings. The brace configuration can be considered more versatile than the beam-column configuration not only because offer more possibilities of placing AFC details according the structural needs; but also because braces using this type of technology can be assembled on the shop, which enhances the quality control of the assembling process and reduces the erection time of the structural system. To date there are no details of any experimental programme showing the behaviour of braces equipped with AFC details; for that reason this paper aims to describe the quasi-static hysteretic behaviour of braces equipped with AFC details at one end of the brace (brace-gusset connection type).

2 CONCEPT

AFC braces are braces equipped with an Asymmetrical Friction Connection detail (AFC) that can be either placed at one end of the brace or within the brace. In this type of braces the AFC detail is considered as an energy dissipater that absorbs energy via friction, and protects the brace from any limit state such as yielding or buckling. Friction in AFC braces is developed when a slotted plate attached to one end of the brace is pulled or pushed across two shear planes generated by two shims placed at both sides of the slotted plate and that are clamped to the brace section by means of high strength bolts and a cap plate (Fig. 1).

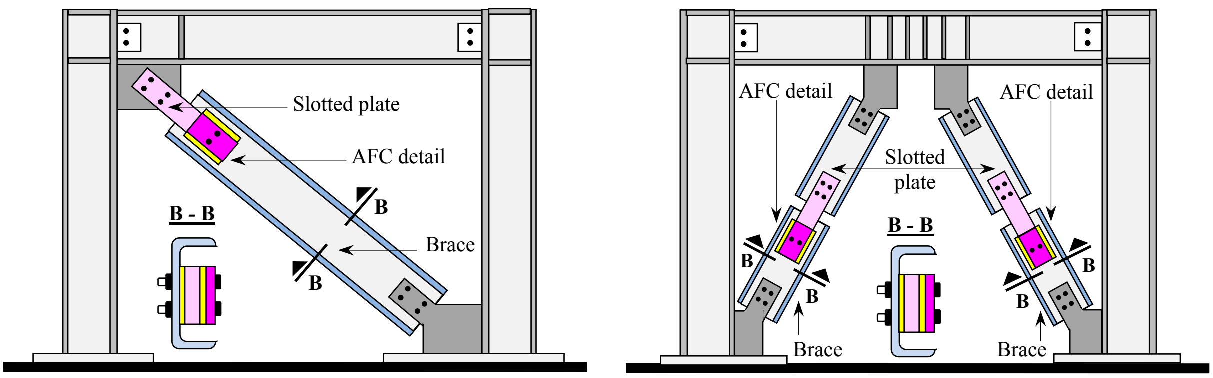


a. AFC braces longitudinal view　　**b.** AFC detail cross section

Figure 1. Possible configurations of AFC braces

3 APPLICATIONS

AFC braces can be considered as a passive damping solution to dissipate seismic energy in braced frames. Structural systems with single, concentrically, and eccentrically brace configurations can be implemented using AFC braces (Fig. 2). In these systems, AFC braces dissipate seismic energy as the structural systems deform laterally and induce axial forces that trigger the sliding mechanism in the AFC details (Butterworth 1999, MacRae 2009, Chanchi et al. 2012). Once the sliding mechanism is activated, braces act as fuses that allow the slotted plate to slide at a constant load; thus limiting the amount of seismic force that the structural system can absorb during a seismic event. The design methodology for this type of structural systems is based on considering the load that activates the sliding mechanisms on AFC braces for computing the structural system load demand, and for designing the different structural members. By doing that, no limit stage is reached before or when the sliding mechanisms are activated; so that the structural system can deform at a predefined load with no structural damage.



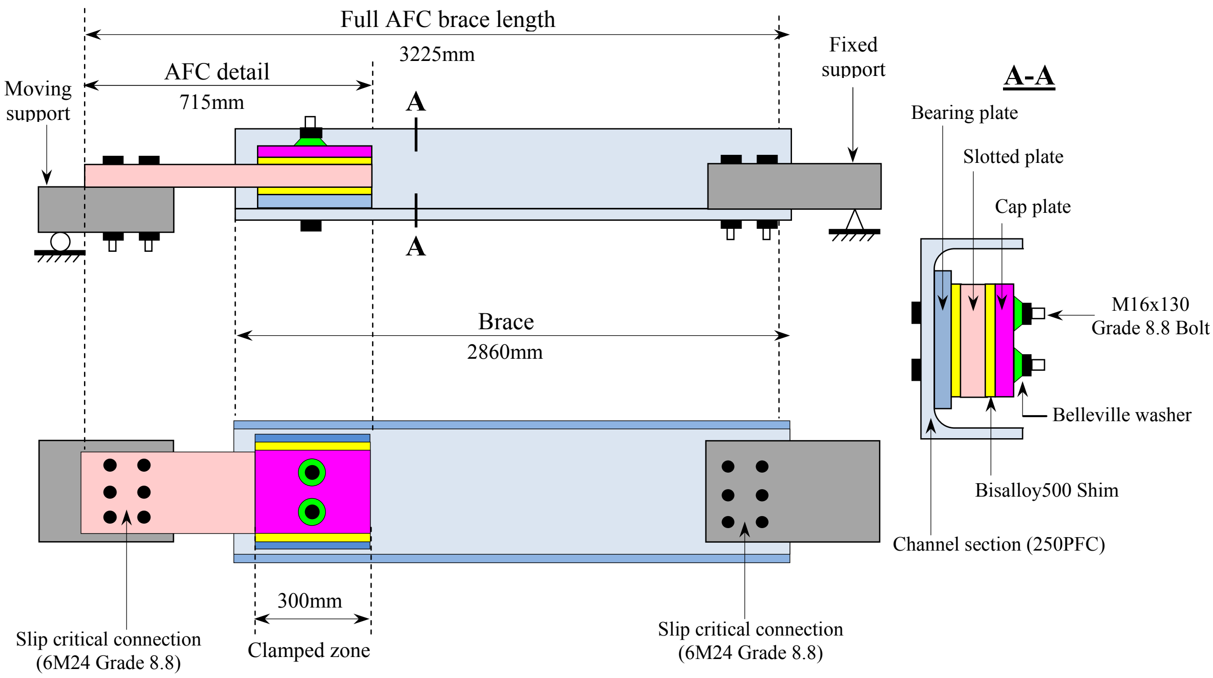
a. Single braced system with AFC brace　　**b.** Eccentrically braced system with AFC braces

Figure 2. Application of AFC braces in braced structural systems

AFC braces are desirable not only because the force that triggers the sliding mechanism can be accurately predicted when using high hardness shims such As Bisalloy 400 or Bisalloy 500 **(**Chanchi 2012); but also because the assembling process as well as pricing are similar to conventional bracing systems.

4 MATERIALS

Braces were assembled using Grade 300 steel hot rolled profiles with parallel flange channel section (250PFC). At one end of braces the channel web was used as fixed plate to assemble the AFC detail; at the opposite end of braces as well as at the end of slotted plates, slip critical connections of 6 M24 Grade 8.8 bolts were used (Fig. 3a). The AFC detail was characterized by a 200 mm slot, 6 mm thick Bisalloy 500 shims, and 2 M16 Grade 8.8 bolts of 130 mm length (100 mm grip length) with single Belleville washers. The slotted and cap plates were assembled using Grade 300 steel plates of 40 mm and 16 mm thickness respectively. To avoid bearing failure of the channel web due to the force transmitted by bolts at the AFC detail location, the web of the channel was strengthen by welding a 16 mm thick Grade 300 steel plate (Fig. 3b).



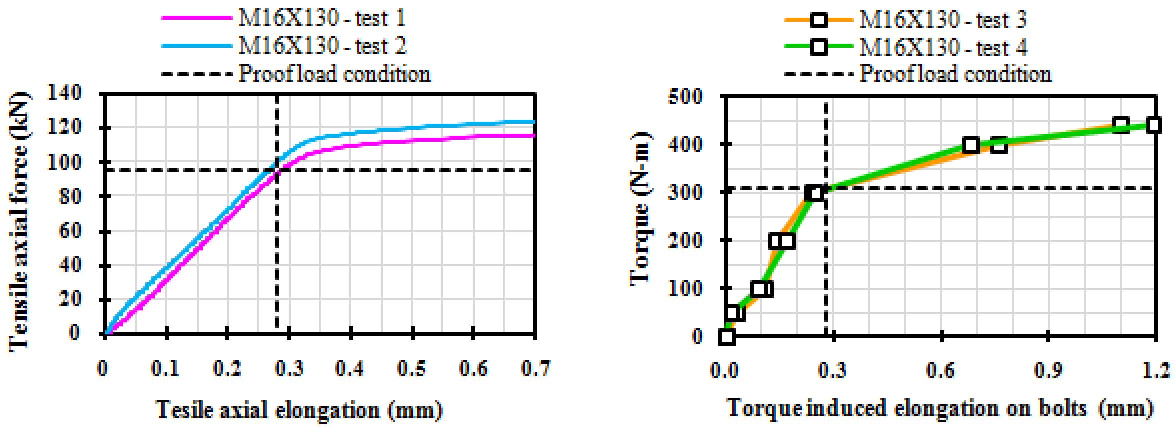
a. AFC brace longitudinal brace configuration **b.** Cross section at the AFC detail

Figure 3. AFC brace specimen configuration

5 METHODS

5.1 Assembling Methods

Assembling of the AFC detail was carried out using a calibrated torque wrench. The torque required to tension the bolts up to the proof load (proof load torque) was extrapolated from a relationship between torque and induced bolt elongation. This relationship was developed by increasing the torque and recording the bolt elongation on two bolts with same assembling configuration as that one used in the brace (Fig. 2a). The bolt elongation used to extrapolate the assembling torque was defined as the elongation exhibited by two bolts when reaching the proof load from tensile testing (Fig. 2b). Using the above methodology a torque value of 310 N-m from the hand tight condition was defined as proof load torque. This torque value corresponds to a nut rotation between 1/4 and 1/2 turn when using the nut rotation method.



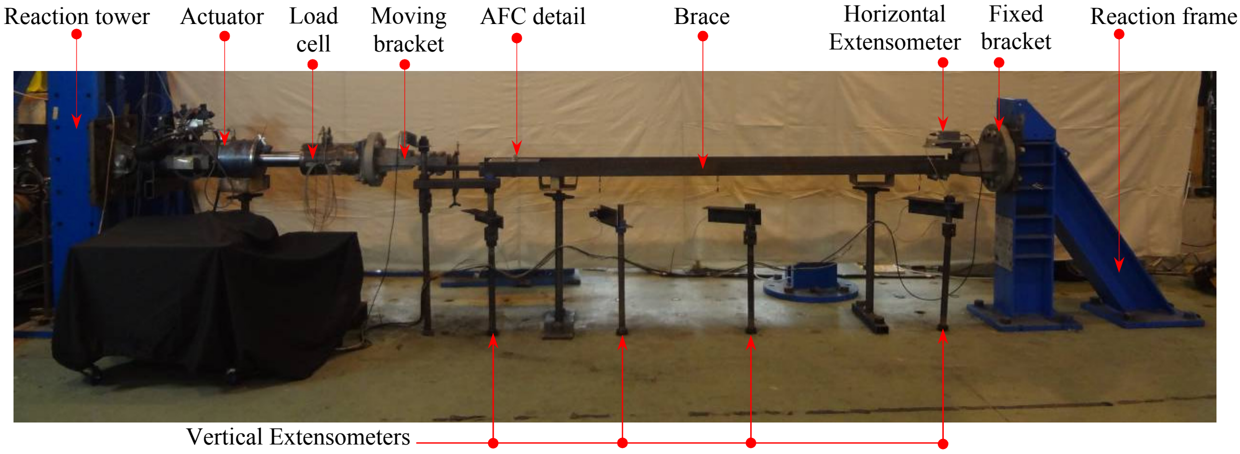
a. Tensile testing relationship **b.** Torque – induced bolt elongation relationship

Figure 4. Relationships used for assembling AFC details

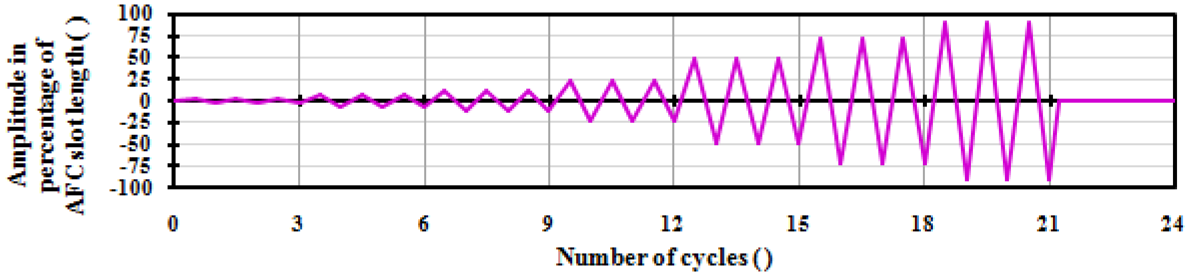
5.2 Testing Methods

Braces were tested in a horizontal setup constituted by a fixed and a moving support. The fixed support was assembled with a bracket bolted on a reaction frame, and the moving support with a bracket attached to an actuator bolted on a reaction tower. Ends of the braces were bolted on the fixed and moving support by using slip critical connections. The ends of braces with AFC detail were bolted on the moving support, so that forces imposed by the actuator could drive the slotted plated as the stroke of the actuator is developed; the other end of the brace was bolted to the fixed support. This setup was instrumented with a load cell in series with the actuator, one extensometer placed horizontally across the brace length, and four extensometers placed vertically at each quarter of the brace length (Fig. 5a).

Two tests were conducted keeping the initial brace, and at each test the slotted plate, shims, cap plates, and bolts were changed. Testing of each specimen was carried out by applying on the actuator two runs of a controlled displacement regime. No bolt re-tensioning was applied after the first run of the displacement regime, so that the degradation of sliding surfaces and loss of bolt tension can be indirectly observed when comparing hysteresis loops of the first and second run. The displacement regime was applied to a constant velocity of 3 mm/s, and it comprises 20 sawtooth cycles with amplitudes between 3 and 90% of the slot length of the AFC detail (Fig. 5b).



a. AFC braces test setup



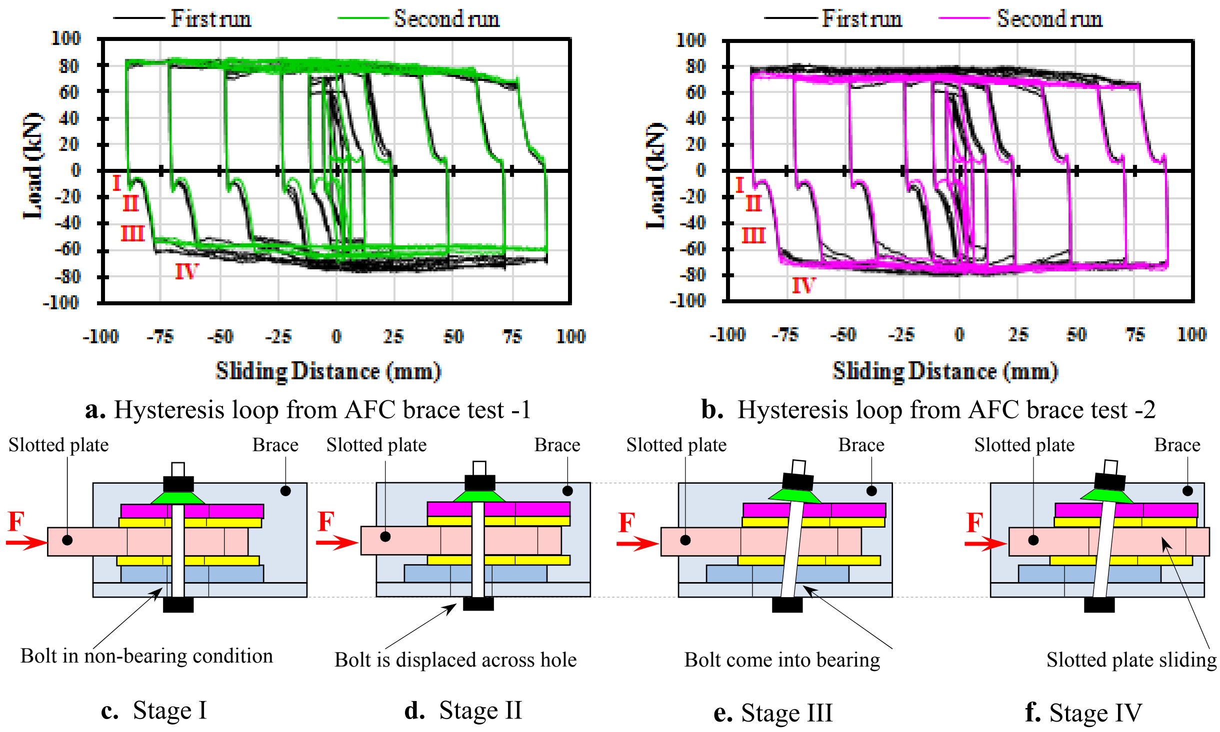
b. Displacement regime

Figure 5. AFC braces test setup and imposed displacement regime

6 RESULTS

6.1 Hysteresis loop

Hysteresis loop of AFC braces is almost rectangular, and is characterized by four stages where the stiffness of AFC braces change from a very steep tendency to an almost horizontal tendency (Figs. 6a, b). In the initial stage AFC braces exhibited a very steep stiffness due to the elastic stiffness contribution of the brace and the AFC detail components. No apparent sliding of any of the AFC detail components is presented in this stage (Fig. 6c). In the second stage, the slotted plate partially slides dragging the cap plate and both shims; which in turn push and displace bolts for a distance equal to the construction tolerance of the holes on the web channel section (Figure 6d). Given that slotted plate, cap plate, shims and bolts freely displace with no restriction until bolts reach the edge of the holes on the web channel section, AFC braces exhibit a loss of stiffness. In the third sage, bolts come into bearing with the web channel section; thus rapidly increase the stiffness of AFC braces. Bolts behave as cantilever beams supported on the web of the channel section and transversely loaded by shims and cap plate (Figure 6e). The stiffness exhibited by braces in this stage is less than the initial stiffness; that is because the initial stiffness of the AFC detail is reduced by the influence of the flexural stiffness of bolts. The fourth stage is termed post-yielding zone given that the sliding mechanism of the slotted plate is fully activated and the slotted plate can be driven to different sliding distances. In this stage the stiffness of AFC braces adopts an almost horizontal tendency as the slotted plate slides (Figure 6f).



a. Hysteresis loop from AFC brace test -1 **b.** Hysteresis loop from AFC brace test -2

c. Stage I **d.** Stage II **e.** Stage III **f.** Stage IV

Figure 6. Hysteretic behaviour of AFC braces and development of sliding mechanism in compression

The force that fully activates the sliding mechanism of AFC braces is termed sliding force, and values exhibited on the tension side of the hysteresis loop (top side) are 10% bigger than those on the compression side. This difference is attributed to bending issues of the non-clamped zone of the slotted plate, and that are caused by the asymmetry of the connection that transfers the load from the actuator to the slotted plate.

6.2 Strength Degradation

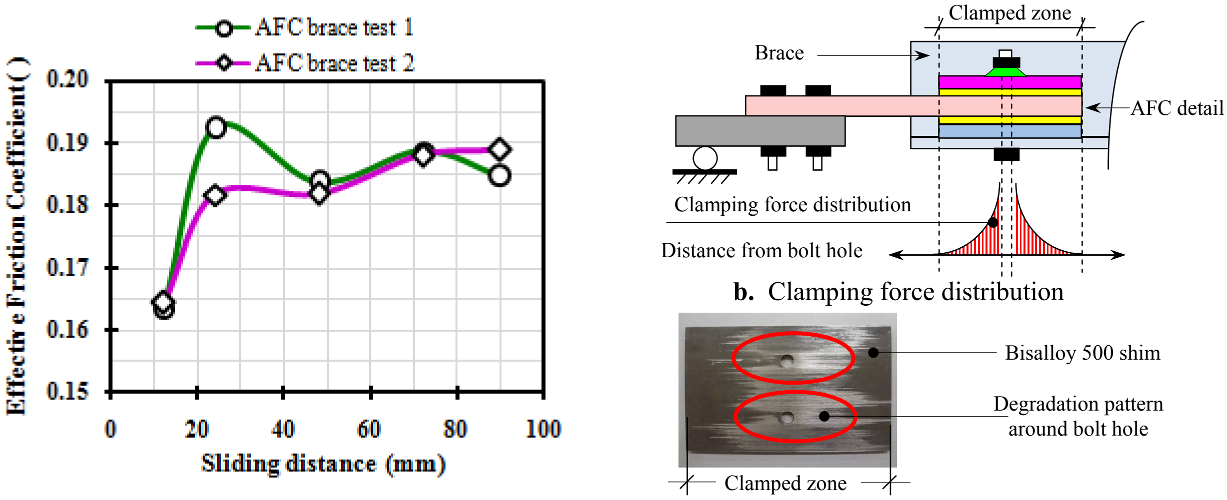
When comparing hysteresis loops obtained on the first and second run of the displacement regime for two tests of AFC braces; it can be seen that sliding forces in the second run range between 90 and 95% of the sliding forces recorded in the first run. These reductions on sliding forces are attributed to the loss of bolt tension presented as the surfaces of the slotted plate and shims degrade. Degraded material can be described as fine debris that can be associated with adhesive sliding mechanisms. In this type of sliding mechanism the product of degradation either adheres to the sliding surfaces or it is pushed out of the clamped zone producing loss of bolt tension (Grigorian & Popov 1994, Chanchi et al. 2011). Given that the strength degradation that AFC braces exhibited for a total of 40 cycles distributed across the effective slot of the AFC detail was only up to 10%, and considering that the adopted displacement regime is characterized by a cumulative travel that is approximately 150 times of that referenced by Grigorian & Popov 1994 as the maximum observed in structural systems using braces with slotted bolted connections subjected to severe earthquakes; it can be argued that AFC braces are a low damage solution that can be implemented in new structural systems to dissipate seismic energy, or as a possible solution to upgrade the seismic strength of existent structural systems.

6.3 Effective Friction Coefficient

The effective friction coefficient (Equation 1) is defined as the ratio between the total sliding force ($F_{sliding}$) from the two bolts considering the two shear planes and the minimum specified assembling force represented by the bolt proof load (F_{proof}).

$$\mu_{effective} = \frac{F_{sliding}}{2 \times 2 \times F_{proof}} \tag{1}$$

The effective friction coefficient was calculated at different sliding distances for the first run of the displacement regime in both tests of AFC braces. For each sliding distance, the sliding force in Equation 1 was considered as the average sliding force assessed across the tensile and compressive post-yielding zones of the respective hysteresis loop. In both tests it can be seen that the effective friction coefficient varies with the sliding distance, and this variation is more accentuated for sliding distances less than 24 mm (Fig. 7a).



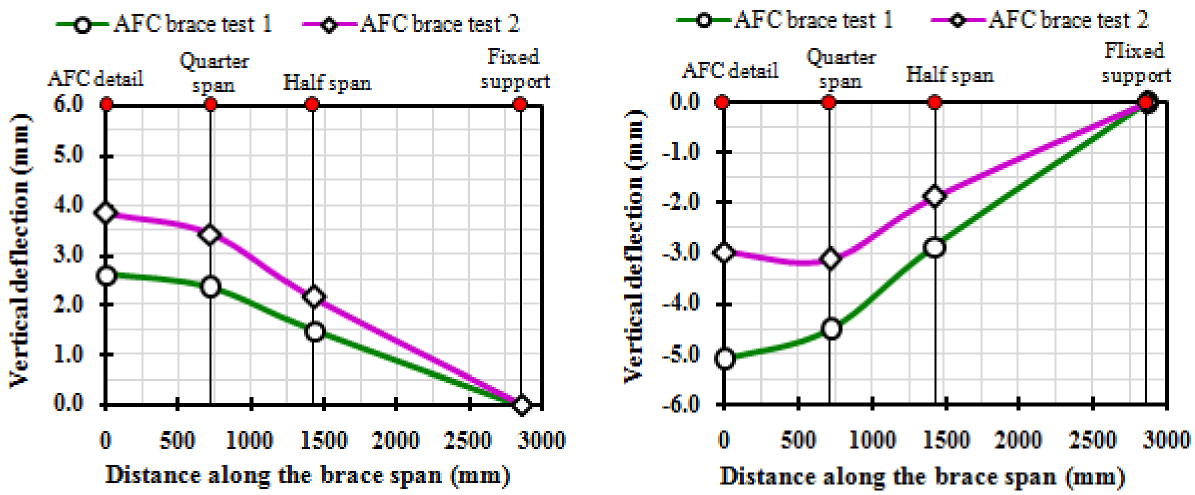
a. Effective friction coefficient **b.** Clamping force distribution **c.** Degradation on sliding surfaces

Figure 7. Effective friction coefficient, clamping force distribution and sliding surface degradation

This sliding distance dependence of the effective friction coefficient is attributed to the degradation of the sliding surfaces, and also to the real distribution of the clamping force across the sliding distance. Variation of the effective friction coefficient shows that clamping forces are more heavily concentrated around the bolt hole and decrease as distance increases from the bolt hole (Fig. 7b). This clamping force distribution can be confirmed when observing a similar pattern on the degradation of the sliding surfaces as noted in Figure 7c. For practical applications a range of values of the effective friction coefficient requires to be defined, so that the strength of AFC braces can be quantified as function of the assembling force (proof load). This range can be defined as 0.16 – 0.20 according to Figure 7a , and by using the upper limit of this range variations of the clamping force can be ignored for design purposes.

6.4 Out of plane brace behaviour

Vertical deflections of AFC braces recorded from three extensometers placed along the brace span were plotted for the case where the AFC detail develops the full stroke (± 90mm) in compression and tension (Figs. 8a, b). For both AFC braces it can be seen that maximum deflections are presented at the AFC detail location, and at both sides of the AFC detail deflections reduce with distance towards the fixed or moving supports of the brace (Fig. 9). Maximum deflections are exhibited at the AFC detail location not only because the abrupt change in stiffness when comparing the flexural and axial stiffness of the channel with those of the slotted plate; but also because the load transferred from the slotted plate to the channel is eccentric, thus the brace is subjected to a moment that produces bending around of one of the principal axis of the brace (Fig. 9). Magnitude of this moment depends on the total clamping force used to assemble the connection, on the effective friction coefficient, and on the distance between centroids of the slotted plate section and the brace section. As a result of this bending moment, the non-clamped zones of the slotted plate and the brace bend, so that when the sliding mechanism is activated the slotted plate slides prying the shim close to the channel when in compression and the shim close to the cap plate when in tension. Prying forces may increase the magnitude of sliding forces; for that reason the post-yielding zone of the hysteresis loop is not perfectly flat as expected in friction devices (Figs. 6a,b). Out-of-plane behaviour of AFC braces cannot be avoided given eccentric nature of AFC details. However, these issues can be minimized by providing a stiff slotted member with minimum eccentricity from the brace section. When designing AFC braces care should be given on checking and matching the flexural and axial capacity of the brace and slotted members. A good design practice can be based on considering the member effective length factor as 2 for the slotted member (i.e. cantilever member), and of unity for the brace member.



a. Vertical deflections of braces in tension for a sliding distance of 90mm

b. Vertical deflections of braces in compression for a sliding distance of 90mm

Figure 8. Vertical deflections in AFC braces in tension and compression

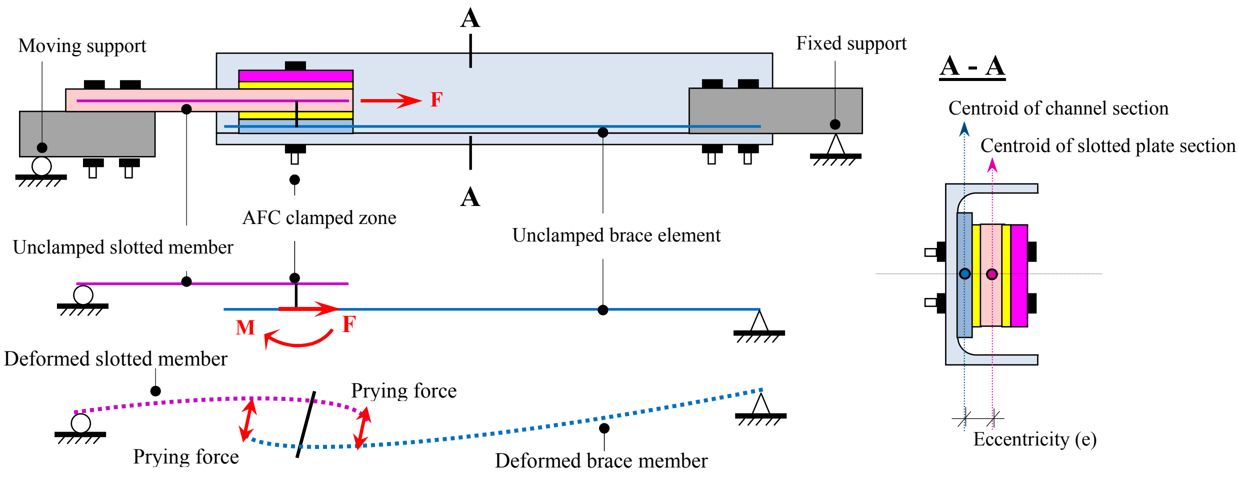


Figure 9. Vertical deflections and prying forces in AFC braces in compression

7 CONCLUSIONS

This paper describes the behaviour of AFC braces using Bisalloy 500 shims, it was shown that:

i) The hysteresis loop of AFC braces is approximately rectangular and stable. Sliding forces developed by AFC braces when in tension are different from those when in compression by 10%. This difference is attributed to prying forces developed as a result of the eccentricity between the slotted plate and the brace section.

ii) Strength degradation of AFC braces was estimated as 10%, for the case where no change of the AFC components or bolt re-tensioning was made after subjecting braces up to 40 cycles distributed across the full stroke of the connection. Reduction in strength is attributed to loss of bolt tension presented as sliding surfaces degrade. This was exacerbated by prying.

iii) The effective friction coefficient is variable with the sliding distance due to the distribution of the clamping force across the AFC detail. Effective friction coefficient ranged from 0.17 to 0.20.

iv) AFC braces underwent out-of-plane deflections as a result of bending moments generated in the load transfer mechanism from the slotted plate to the brace member. Maximum out-of-plane deflections occurred at the AFC location, causing prying forces that increase with slid.

REFERENCES

Butterworth, J. W. (1999). Seismic Damage Limitation in Steel Frames Using Friction Energy Dissipators. *6th International Conference on Steel and Space Structures* - September 1-2. Singapore.

Chanchí, J.C., MacRae, G.A., Chase, J.G., Rodgers, G.W., Clifton, G.C, & Munoz, A. (2012). Design considerations for braced frames with asymmetrical friction connections (AFC). *STESSA 2012, Santiago de Chile*, January.

Chanchí, J.C., MacRae, G.A., Chase, J.G., Rodgers, G.W., & Clifton, G.C. (2011). Behaviour of Asymmetrical Friction Connections (AFC) using different shim materials. *NZSEE - annual conference.* New Zealand.

Grigorian, C.E. & Popov, E.P. (1994). *Experimental and Analytical Studies of Steel Connections and Energy Dissipaters. Report UCB/EERC-95/13, Engineering Research Center.* San Francisco (USA).

Clifton, G.C. (2005). Semi-Rigid Joints for Moments Resisting Steel Framed Seismic Resisting Systems. *Published PhD Thesis, Department of Civil and Environmental Engineering.* University of Auckland – New Zealand

MacRae, G. A. (2008). A New Look at Some Earthquake Engineering Concepts. M. J. *Nigel Priestley Symposium* Proceedings, IUSS Press, 2008.

MacRae, G.A., Clifton, C.G., MacKinven, H., Mago, N., Butterworth, J., Pampanin, S. (2010). *The Sliding Hinge Joint Moment Connection. Bulletin of the New Zealand Society for Earthquake Engineering.* Vol.43, No 3, September.