Steel Innovations Conference 2013
Christchurch, New Zealand
21-22 February 2013

RECENT RESEARCH ON TWO LOW DAMAGE DAMPERS APPLICABLE TO STEEL FRAMING SYSTEMS

J. Chanchí[1], G. A. MacRae[2], J. G. Chase[3], A. Scott[4], G .W. Rodgers[5] and G. C. Clifton[6]

ABSTRACT

This paper summarizes experimental testing carried out on Asymmetrical Friction Connections (AFC) and High Force to Volume (HF2V) devices. Hysteretic behavior considering the effect of assembly, surface conditions, and corrosion for AFC specimens, and energy dissipation mechanism of straight shaft configurations for HF2V devices are reported. Stable hysteretic behavior of AFC specimens are achieved by using shim materials such as Bisalloy 400 and 500. The sliding capacity of the connection can be reduced up to 50% when using surface treatments such as sand blasting or alkyd and inorganic zinc silicate coatings. Increments on the sliding force ranging from 7 - 25% were obtained for AFC specimens subjected to a corrosive regime. In the case of HF2V devices it is shown that straight shaft configurations can dissipate energy by subjecting the lead to single shear stresses in the range 25 – 30 MPa. A simple model to quantify the sliding force of HF2V devices with this shaft configuration and characterized by thin walled lead cylinders is also discussed.

1. Introduction

Asymmetrical Friction Connections and High Force to Volume devices have been recently developed by Clifton (2005) and Rodgers (2009) respectively. Initial developments of these technologies have demonstrated stable and repeatable hysteretic behavior with minimum degradation or damage when testing small components or beam column subassemblies (MacRae and Clifton 2010, Mander 2009, Rodgers 2009). Given these desirable characteristics they have been categorized as low damage damping solutions and already implemented in different structural systems in New Zealand (MacRae and Clifton 2010). Recent research carried out at the University of Canterbury has been focused to provide further insight on the behavior and application of these technologies as low damage damping alternatives for steel braced framing systems. As part of this research several configurations to equip braced frames with AFC and HF2V have been proposed (Chanchí et al. 2012), and topics such the effect of different shim materials, surface conditions and corrosive conditions on the hysteretic behavior of long slotted full scale AFC specimens, as well as the hysteretic behavior of HF2V devices with straight shaft configurations have been experimentally validated. Experimental results presented in this paper are from the quasi–static testing carried out using sine wave inputs with velocities of 10mm/s and 0.15 mm/s for AFC and HF2V specimens respectively. These results can be used for planning or designing applications that follow same configuration and specifications as those described in this paper.

2. Asymmetrical Friction Connections (AFC)

2.1 Concept

Asymmetrical Friction Connections were built using three steel plates, two thinner plates termed shims, high

---

[1] PhD Student, Dept. of Civil Engineering, University of Canterbury, New Zealand – Assistant Professor, Dept. of Civil Engineering, National University of Colombia, Colombia, (jose.chanchigolondrino@pg.canterbury.ac.nz)

[2] Associate Professor, Dept. of Civil Engineering, University of Canterbury, (gregory.macrae@canterbury.ac.nz)

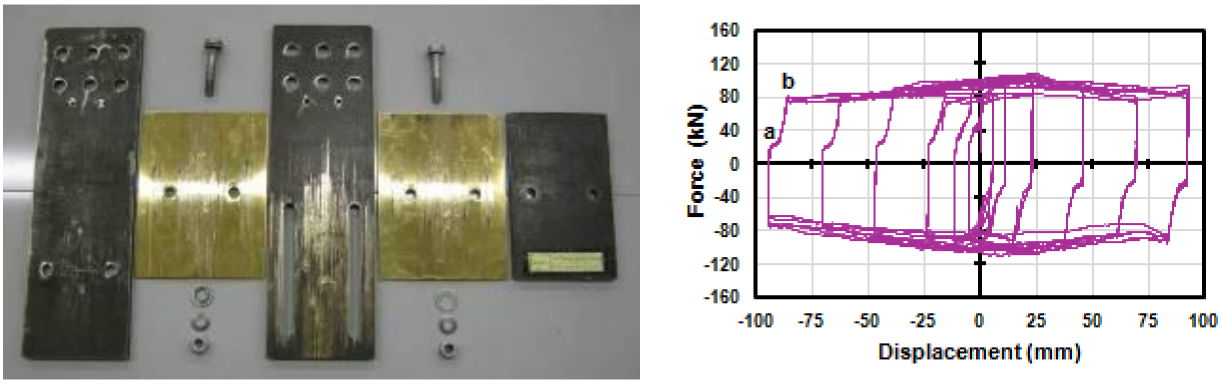
[3] Professor, Dept. of Mechanical Engineering, University of Canterbury, (geoff.chase@canterbury.ac.nz)

[4] Lecturer, Dept. of Civil Engineering, University of Canterbury,(allan.scott@canterbury.ac.nz)

[5] Lecturer, Dept of Mechanical Engineering, University of Canterbury, (geoff.rodgers@canterbury.ac.nz)

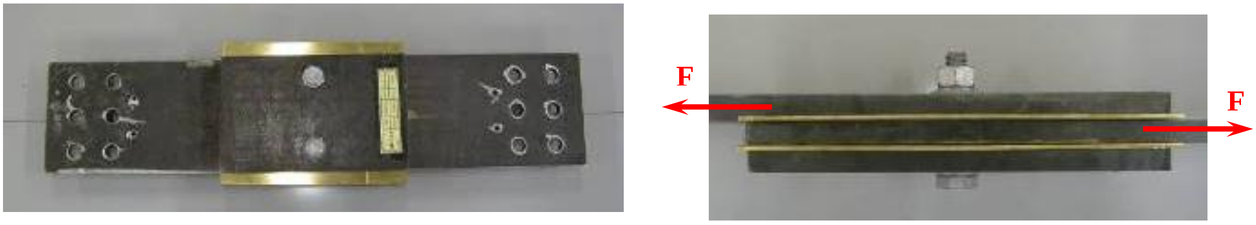
[6] Professor, Dept. of Civil Engineering, University of Auckland, (c.clifton@auckland.ac.nz)

strength bolts and Belleville washers. This type of connection dissipates energy through the sliding of the central slotted plate between the shims and two external plates (Fig. 1.a - c). Asymmetrical Friction Connections can be used to dissipate energy in beam-column joints or in braces of different steel framing systems because they can dissipate large amounts of energy with almost no damage on the connection subassembly or in the structural system; and also because this type of connection is easy to build and costs are comparable to conventional construction (MacRae and Clifton, 2010). Hysteresis loops of Asymmetrical Friction Connections can be considered as bilinear for sliding lengths less than 50mm and almost square for sliding lengths near 220mm. This change is due to the sliding length required by the connection to move from the first sliding state to the fully activation of the two sliding interfaces as shown as segment a-b in Fig. 1d.



a. Components of AFC specimen

d. Hysteresis loop of AFC specimen



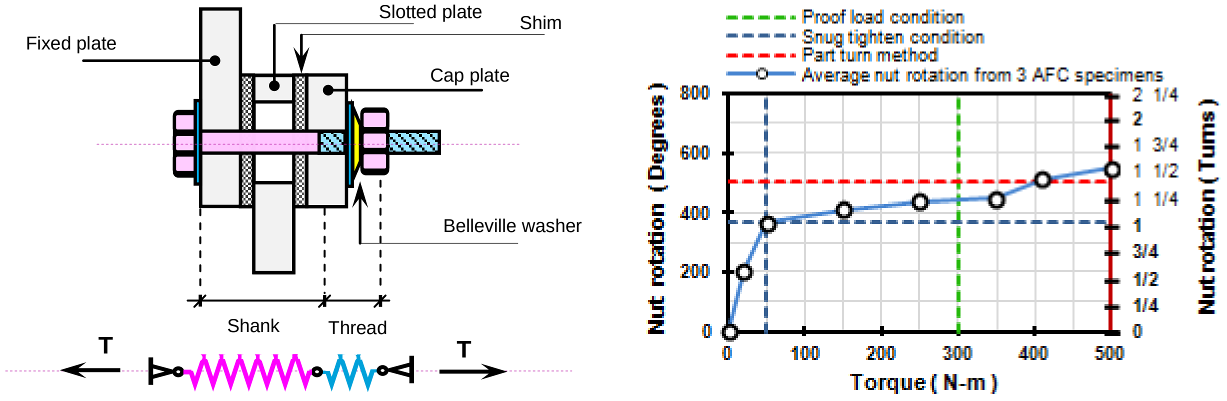
b. Plan view of AFC specimen

c. Detail of AFC joint

Figure 1. AFC using UNS C26000 – ½ Hard Temper Brass shims and 2 M16 Grade 8.8 galvanized bolts assembled with a single Belleville washer.

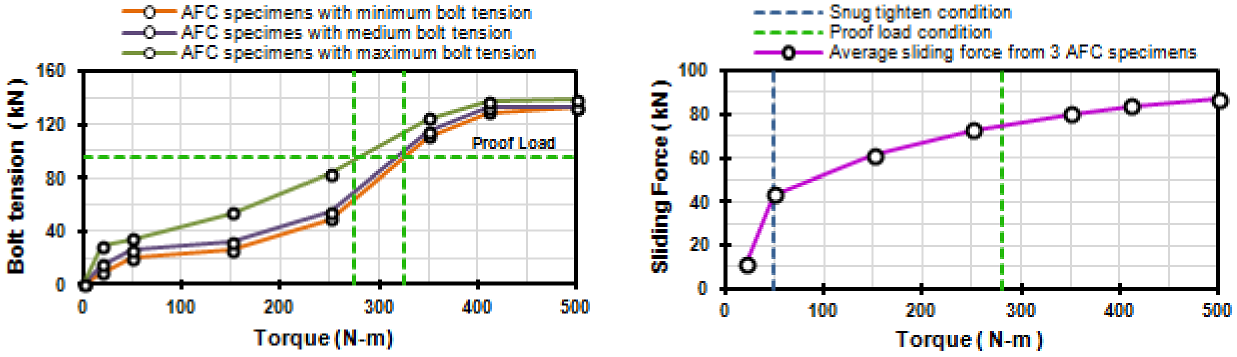
2.2 Assembling

According to NZS 3404 (2009) friction type connections shall be assembled guarantying that the minimum tension force per bolt is the proof load. To fulfill this requirement in Asymmetrical Friction Connections the assembling process can be carried out either using the part turn method or the torque control method. In the nut rotation method, bolts are tightened up to nut rotations of 1/3 to 2/3 of turn depending on the bolt length as described in clause 4.2.6.2 - NZS 3404 (2009). This method is generally accepted as typical construction practices in New Zealand given the simplicity of its application on site. The torque control method is based on tighten the bolts to certain amount of torque defined from experimentally developed torque–bolt tension relationships. This method is not generally accepted for structural applications due to the variability of the torque – bolt tension relationships associated with the surface finish of bolts (NZS 3404, 2009). Results reported by Chanchí et al. (2011) on the prediction of the installed bolt tension for both assembling methods when using a two spring model show that the part turn method can develop tension forces beyond the proof load and close to the to the bolt ultimate strength (Fig. 2a and Fig. 2b). Results also show that the application of the torque control method can result in lower bolt tension levels with considerable variability in the case of galvanized bolts (Fig. 2c). For that reasons the need to implement a method to assemble AFC specimens that guarantees consistent and repeatable bolt tension forces is required. In addition, it was also highlighted by Chanchí et al. (2012) that asymmetrical friction connections can develop 50% of the maximum sliding force when they are assembled with torque values correspondent to the snug tighten condition, and that approximately 90% of the maximum sliding force can be developed when assembled with the torque that developed the proof load condition (Fig. 2d).



a. Bolt assembly model

b. Torque – nut rotation relationship



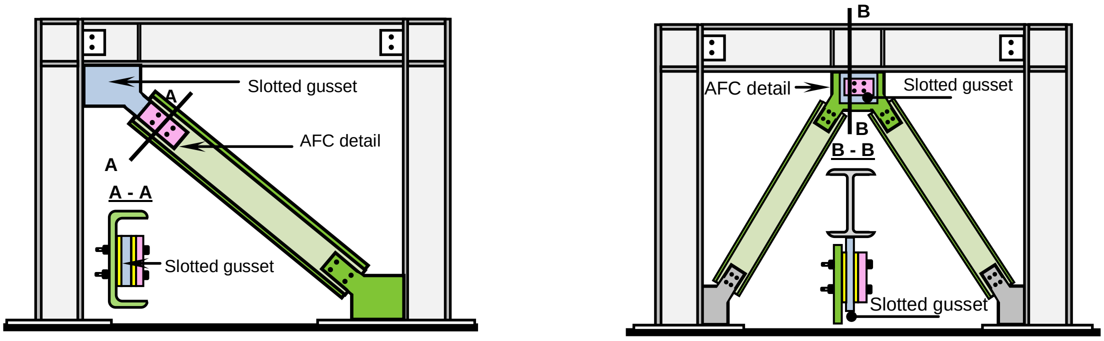
c. Torque – predicted bolt tension

d. Torque – sliding force relationship

Figure 2. Assembling relationships for AFC specimens using and 2 M16 Grade 8.8 galvanized bolts with single Belleville washer.

2.3 Applications

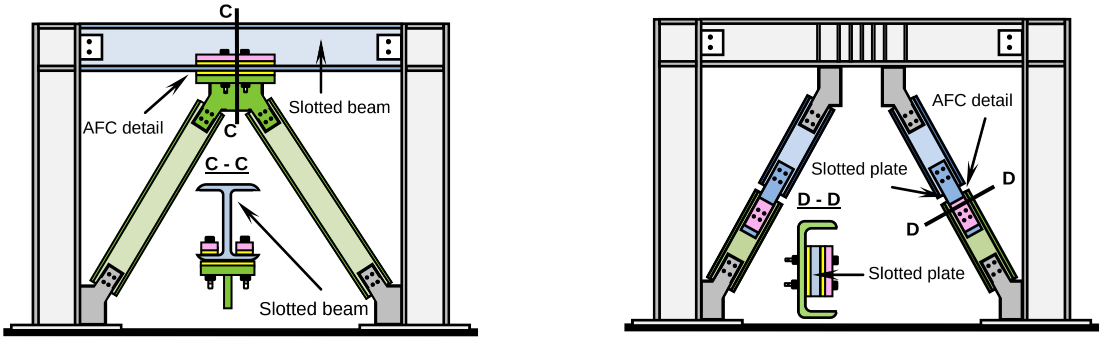
Several applications of Asymmetrical Friction Connections as a damping alternative for steel framing systems have been proposed by Butterworth (1999), MacRae and Clifton (2010), and Chanchí et al. (2012). These applications are based on placing the AFC detail at locations where considerable force and displacement demands are expected such as beam-column joints or within braces. In braced systems the AFC detail can be placed at the end of the brace for single brace configurations (Fig. 3a) or within the brace in the case of eccentrically braced systems (Fig. 3d). In these configurations the sliding mechanism is expected to occur collinear to the brace alignment. For concentrically braced systems the AFC detail can be placed on the bottom flange of the beam (Fig. 3b) or on a gusset placed underneath of the beam bottom flange (Fig. 3c), either case the sliding mechanism is expected to occur parallel to the beam axial axis. The design criteria of these applications is based on providing a brace cross section that allows sliding on the AFC detail prior to the brace or other frame components reach a limit state of strength such as yielding or buckling (Tremblay 1993). The limit state of deformation can be controlled by sizing adequately the length of the slot according the expected drift limits of the frame (Chanchí et al. 2012).



a. Single braced frame

b. Concentrically braced frame

Figure 3. Possible applications of Asymmetrical Friction Connections on braced frames



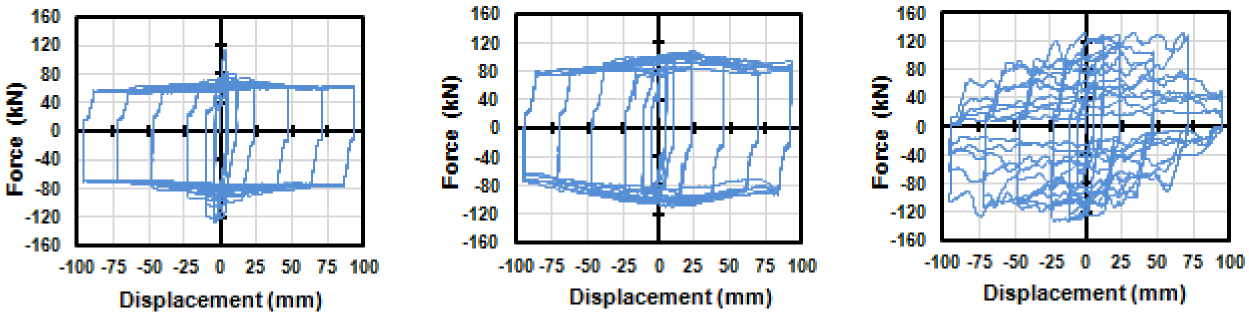
c. Concentrically braced frame

d. Eccentrically braced frame

Figure 3. Possible applications of Asymmetrical Friction Connections on braced frames

2.4 Shim effects

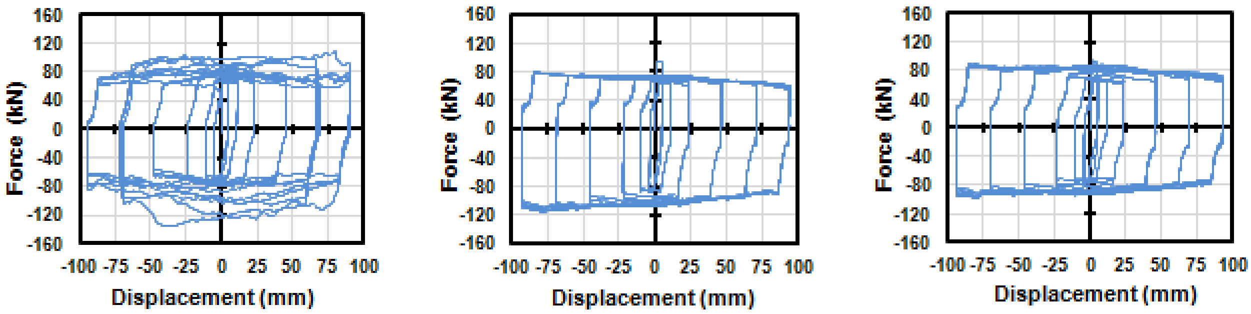
The hysteresis loop stability of Asymmetrical Friction Connections has been found to be dependent on the hardness of the shim material (Khoo et al. 2011, Chanchí et al. 2012). Stable hysteresis loops can be expected for shim materials with hardness values either well above or well below the hardness of the connection steel plates. While for harder materials such as bisalloy 500 and bisalloy 400 the hysteresis loop is characterized by constant sliding force across the full sliding length of the connection (Fig. 4f and Fig. 4e), for softer materials such as aluminium or brass constant the hysteresis loop is characterized increased sliding forces for sliding lengths less than 25mm (Fig. 4a and Fig. 4b). Both groups of shim materials are characterized by minor surface degradation given that during the sliding mechanism only small amounts of wear particles are produced and they adhere to the sliding surfaces (Grigorian and Popov 1994).



a. 5005GP Series Aluminium

b. UNS C26000 - ½ Hard Temper Brass

b. Mild steel



c. Bisalloy 80

d. Bisalloy 400

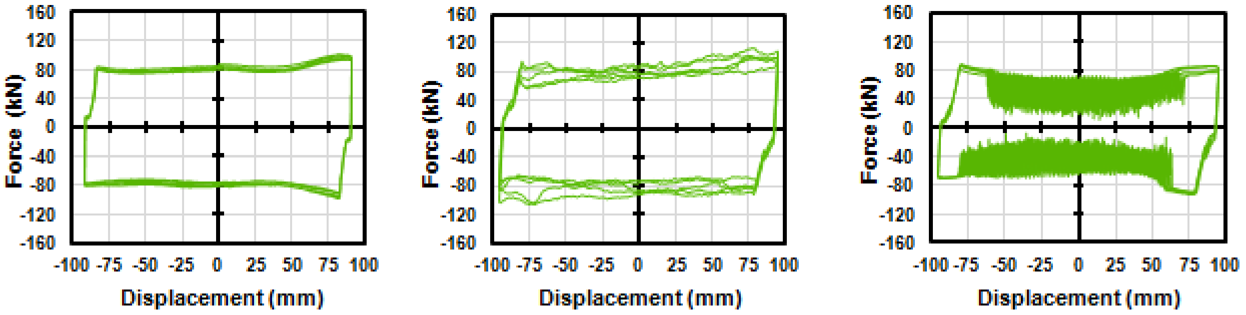
e. Bisalloy 500

Figure 4. Hysteresis loops of AFC specimens using 2 M16 Grade 8.8 galvanized bolts with single Belleville washer and different shim materials

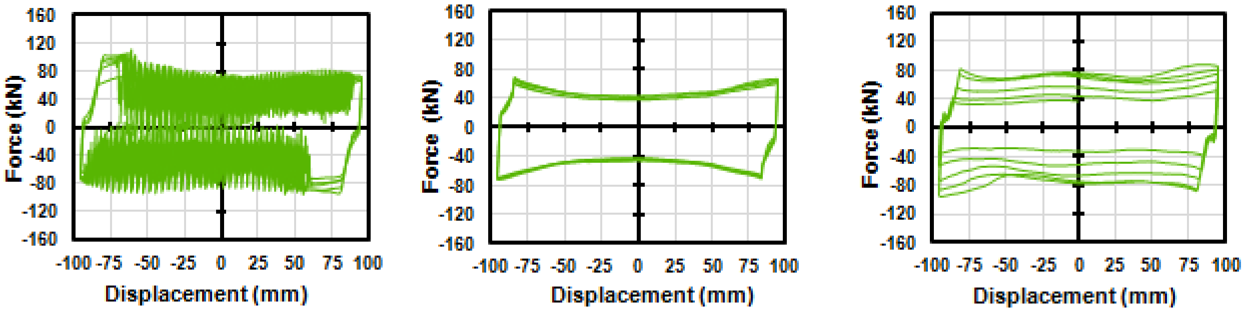
Non-stable hysteresis loops can be expected for connections using shim materials such as bisalloy 80, or mild steel shims, where the shim hardness is close or similar to the hardness of the connection steel plates (Fig. 4c and Fig. 4d). This instability is due to the large amount of work hardened wear particles produced during the sliding mechanism that abrade the sliding surfaces in an irregular pattern (Grigorian and Popov 1994 and Khoo et.al. 2011).

2.5 Coating effects

The effect of different surface treatments on the hysteretic behavior of Asymmetrical Friction Connections using bisalloy 500 shims is under research at University of Canterbury. Surface conditions including sandblasting primary treatment and coatings such as alkyd primer, and inorganic zinc silicate solvent borne have been considered as an alternative to prevent atmospheric corrosion issues as recommended in clause 6.3 - AS/NZS 2312 (2002). Two cases were considered on the application of the surface conditions described above, an initial case where the sand blasting treatment, alkyd primer, and inorganic zinc silicate coatings were applied over whole contact surfaces of AFC specimens, and a second case where the alkyd primer and inorganic zinc silicate coatings were applied over all surfaces except for the surfaces where the specimen depends on developing the frictional resistance as specified in clause 4.2.4.3 (b)-NZS 3404,(2009). Preliminary results on the quasi-static testing of those two groups of AFC specimens show that the sand blasting primary treatment reduces the stability of the hysteresis loop and increases no uniformly the sliding force of the specimen across the sliding length up to 20% of the sliding force developed by specimens with clean surfaces as rolled (Fig.5a and Fig.5b). These effects on the hysteresis loops are most likely associated with the non-homogeneous application of the blasting treatment on the sliding surfaces of the specimens.



a. Cleaned surfaces as rolled b. Sand blasted c. Partially coated with Alkyd 40μm DFT*



d. Fully coated with Alkyd 40μm DFT* e. Partially coated with Zinc 75μm DFT* f. Fully coated with Zinc 75μm DFT*

Figure 5. Hysteresis loop of AFC specimens with 2 bolts M16 Grade 8.8 and Bisalloy 500 shims using different coatings (*DFT: Dry film thickness)

Alkyd coatings generate hysteresis loop with fluctuating sliding forces, magnitude of the sliding force can vary between 25 and 120 % of the sliding force of the sliding force developed by specimens with clean surfaces as rolled (Fig.5c and Fig.5d). These fluctuations can be associated to the development of a stick-slip mechanism caused by the irregular degradation and removal of the coating. Zinc coatings reduce the sliding force of the specimen as the number of load cycles and the sliding distance of the specimen are increased. Reductions up to 50% of the sliding force developed by specimens with clean surfaces as rolled can be considered as the critical effect when using this type of coating (Fig.5e and 5f). These force reductions are associated with the loss of bolt tension generated by the coating degradation and removal presented during the development of the sliding mechanism.

2.6 Corrosion effects

Another experimental programme that is underway at University of Canterbury is associated with the quantification of the corrosive effects on the hysteretic behavior of Asymmetrical Friction Connections using bisalloy 500 shims. In this experimental programme, AFC specimens with similar surface conditions as those described in section 2.5 were subjected to a cyclic corrosive regime comprised of a wetting and drying stages that were cyclically repeated until evidence of mass loss on the specimens was detected. While in the wetting stage AFC specimens were immersed during 8 hours in a salt water solution with a concentration of 3.5%, an oxygen concentration of 5.7 mg/lt, and a constant temperature of 40°C; in the drying stage specimens were exposed during 16 hours to a hermetic condition at a constant temperature of 40°C. Preliminary testing carried out with up to 24 corrosive cycles show that specimens with sandblasting primary treatment exhibited loss of mass due to the development of localized pitting and crevice corrosion; and specimens with alkyd primer and inorganic zinc silicate coatings gained mass as a result of the development of fine filaments composed of corrosion products located underneath the coating (i.e filiform corrosion). Also, zinc coatings were found to be more effective than alkyd coatings in preventing the mass loss and the deterioration of the exposed surface of the specimen as shown in Fig. 6.

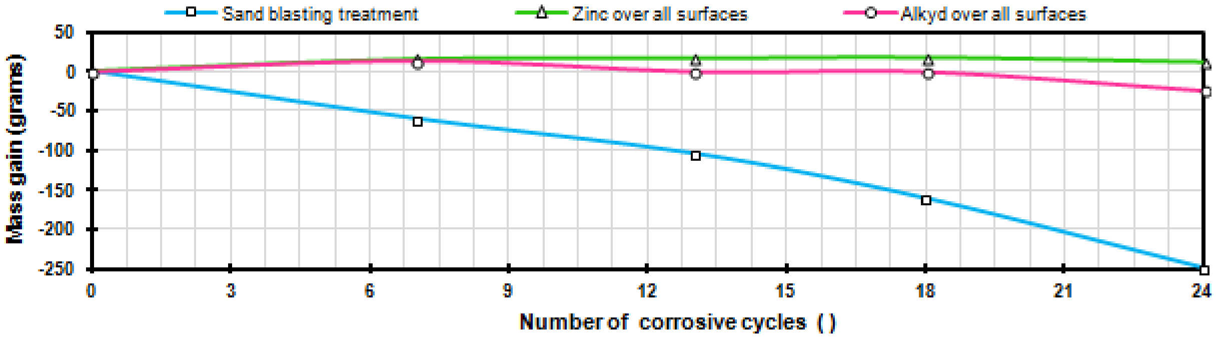
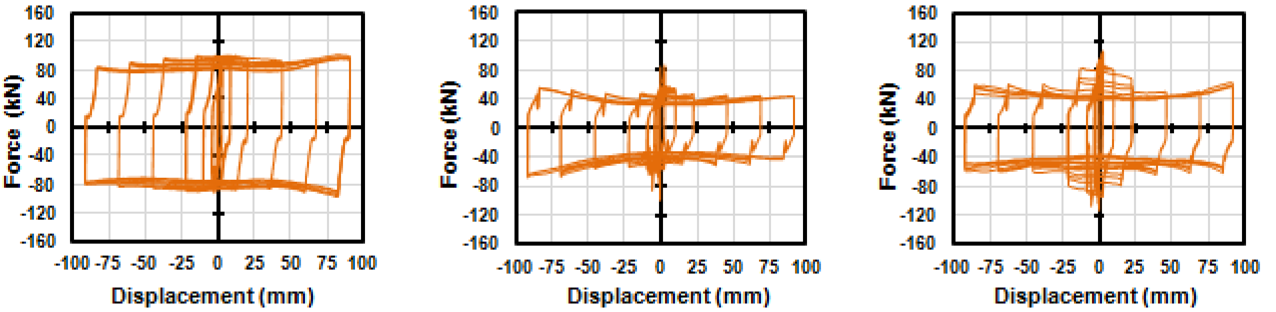


Figure 6. Mass variation of AFC specimens with 2 bolts M16 Grade 8.8 and Bisalloy 500 shims subjected to 24 corrosive cycles.

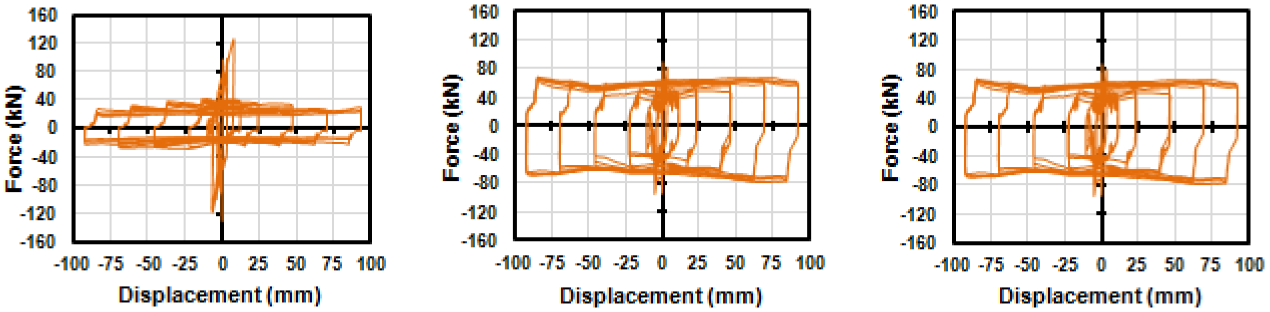
To quantify the effect of corrosion on the hysteretic behavior of the connection, AFC specimens subjected to the corrosive regime described above were subjected to a quasi-static load testing. The hysteresis loop of corroded specimens is characterized by the development of increased sliding forces at the onset of the fully activation of the sliding mechanism for sliding lengths lower than 10mm (Fig. 7). These increments are associated with extra force required by the connection to remove the corrosion products deposited at the external interfaces between the slotted plate and shims. Initial increase of sliding forces was found to vary between 7 and 25 % of the siding forces recorded for non corroded specimens with similar surface conditions, lower and upper limits of this range correspond to sand blasted treated and alkyd coated specimens respectively. After the initial cycles remove the corroded material, no changes were noted on sliding forces when compared with those associated with the non-corroded condition (Fig. 5 and Fig. 7).



d. Cleaned surfaces as rolled

e. Sand blasted

c. Partially coated with Alkyd 40μm DFT*



d. Fully coated with Alkyd 40μm DFT*

e. Partially coated with Zinc 75μm DFT*

f. Fully coated with Zinc 75μm DFT*

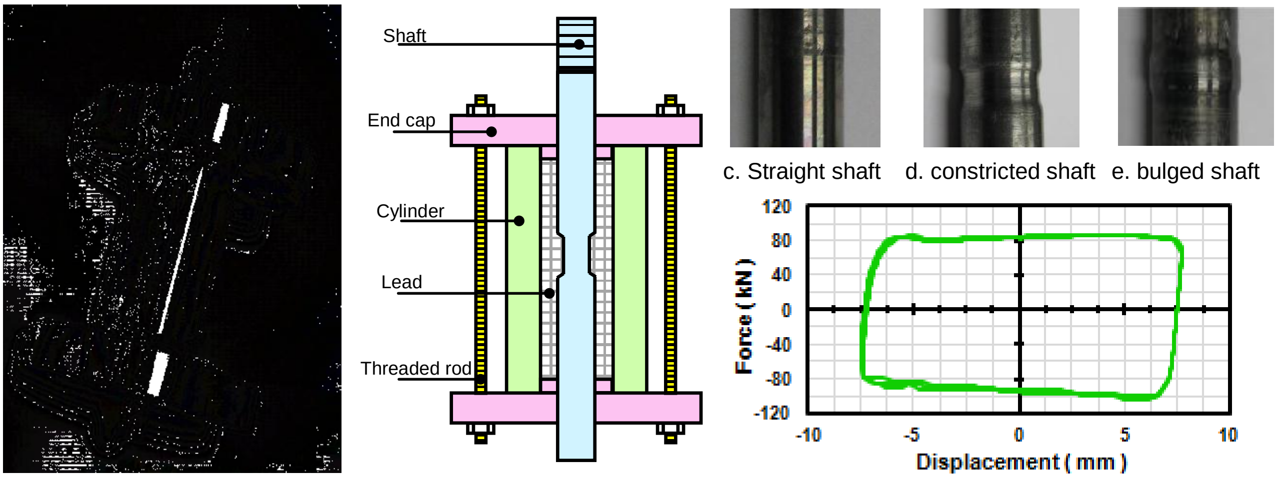
Figure 7. Hysteresis loop of AFC specimens with 2 bolts M16 Grade 8.8 and Bisalloy 500 shims after being subjected to 24 corrosive cycles (*DFT: Dry film thickness).

The corrosive regime adopted in this preliminary testing show that specimens with sandblasted treatment underwent a noticeable mass loss when compared with that one exhibited by specimens with alkyd coating (Fig. 6); corrosion rates associated with these surface conditions were found to be 1009 and 81 μm/y respectively. By expressing these values in terms of the maximum corrosion rate defined by AZ/NZ 2312 (2002) in Table B1 – Appendix B for one year exposure in zones with low and high corrosive environments (i.e. Category A and D), it can be seen that these preliminary corrosion cycles represent exposure periods of 40years for sand blasted specimens and 3years for alkyd coated specimens in the case of low corrosive environments such as rural or urban areas. In the case of high corrosive environments such as sea shores, these preliminary corrosion cycles represent 12years for sand blasted specimens and 1 year for alkyd coated specimens.

3. High Force to Volume devices (HF2V)

3.1 Concept and assembling

High Force-to-Volume (HF2V) devices are lead dissipaters consisting of a straight, bulged or constricted shaft encased in a thick walled cylinder. The space between the cylinder and the shaft is filled with lead, which is kept in place by two end caps fitted at the cylinder ends (Fig. 1 a – e). The energy dissipation mechanism of this type of lead damper is based on the relative movement of the shaft respect to the cylinder, and it depends on the geometrical configuration of the shaft. While devices with straight shafts or with an almost straight configuration dissipate energy via friction (Chanchí 2011); devices with pronounced bulges or constrictions dissipate energy by extruding the lead through the space between the bulge and the cylinder (Rodgers 2007, Cousins and Porritt 1993). In both cases, the hysteresis loop of the device can be described as almost square with enclosing areas of 80 and 90% of a perfect square hysteresis Coulomb model.



c. Straight shaft d. constricted shaft e. bulged shaft

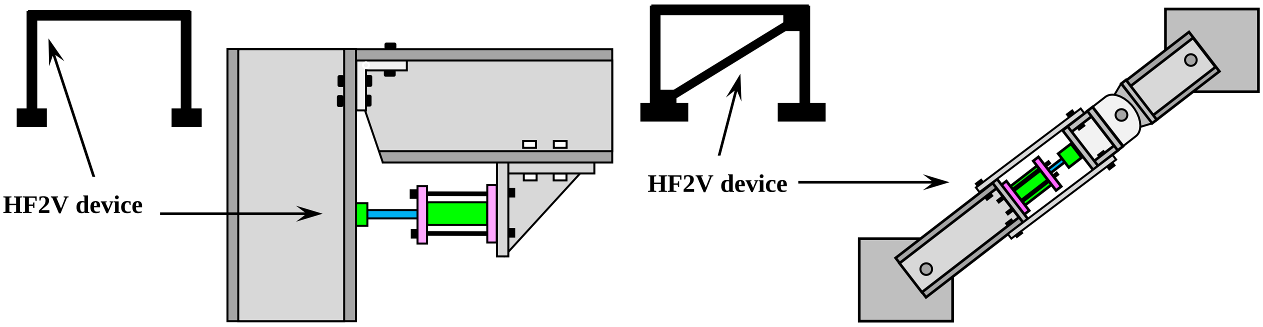
a. External view b. Internal view f. Hysteresis loop of constricted device

Figure 8. Components, assembling and hysteresis loop of constricted HF2V device with 10mm shaft

Assembling process of HF2V devices is carried out by connecting the end caps with high tensile threaded rods. These threaded rods are gradually bolted at the same time that pre-stress force ranging 100 to 150kN are uniformly applied on the end caps (Rodgers 2009). At the end of the pre-stress process end caps should be in full contact with the steel cylinder so that the lead cylinder is confined in a hermetic condition that avoids any lead leakage.

3.2 Applications

HF2V devices are characterized by small sizes, low maintenance, repeatable behavior, and minimal damage (Rodgers et al. 2007). For that reasons they can be considered as an alternative to provide supplemental energy dissipation to steel framing systems subjected to seismic solicitations. Possible configurations are based on placing the device on beams, either below the bottom flange or at both sides of the web (Mander et al. 2009). In this case the device develops resistive forces against the beam rotations. It is also possible to place the device within braces where the device develops resistive forces against the brace elongation (Chanchí et al. 2011). In both configurations (Figure 9), the structural system dissipates energy by overcoming the force required to slide the device shaft rather than yielding any component of the frame. Given that during the fully activation of the shaft sliding mechanism the lead cylinder deforms plastically and recrystallizes immediately after the unloading stage, HF2V device are exposed to minimal degradation and make the structural system a low damage solution.



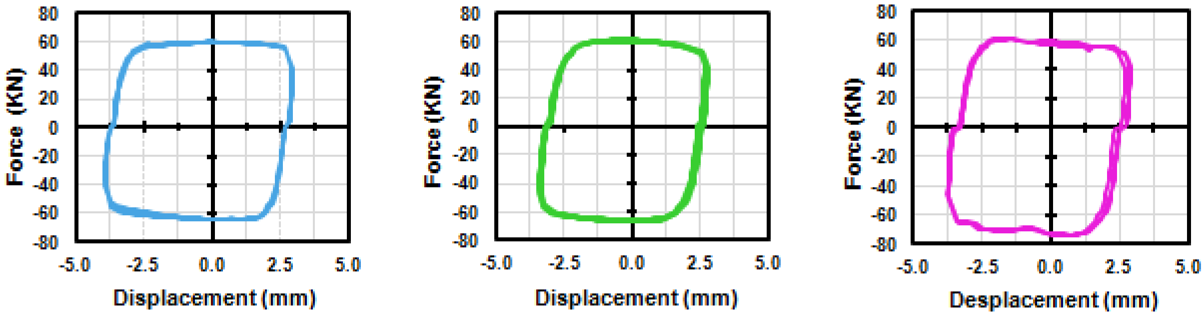
a. Beam- column joint configuration

b. Brace configuration

Figure 9. Configurations of HF2V devices on steel framing systems

3.3 Hysteretic behavior of HF2V devices with straight shaft

Testing carried out on HF2V devices with straight, bulged and constricted shaft configurations with a 12mm shaft, where the diameter of the bulged and constricted zones were only 1mm different from the shaft diameter showed that devices develop an almost square loop with similar sliding forces (Chanchí et al. 2012). In this testing the sliding force developed by devices with straight shafts was about 15% less than that one developed by devices with bulged and constricted shaft configurations (Fig. 10). Based on this, it shows that the influence of the bulged and constricted zone on the sliding mechanism is minor when the diameter of these zones is comparable with the device shaft diameter. Thus, a significant proportion of the sliding force is associated with shear stresses developed between shaft and lead rather than by localized lead extrusion expected in devices where the bulged zone diameter is considerable bigger than the shaft diameter (Rodgers 2009). Sliding forces developed by devices when loaded in compression (bottom side of hysteresis loop) were found to be slightly larger than the sliding force developed when in tension (top side of hysteresis loop). This difference ranged between 10 -15% and was attributed to the loss of pre-stress generated when one of the end cap is pushed outwards as a result of the lead shear deformation in the direction of the load. This asymmetry is not likely to affect the seismic performance of framed systems equipped with this type of device since the typical configuration is based on placing dampers at both ends of beams.



a. Straight shaft

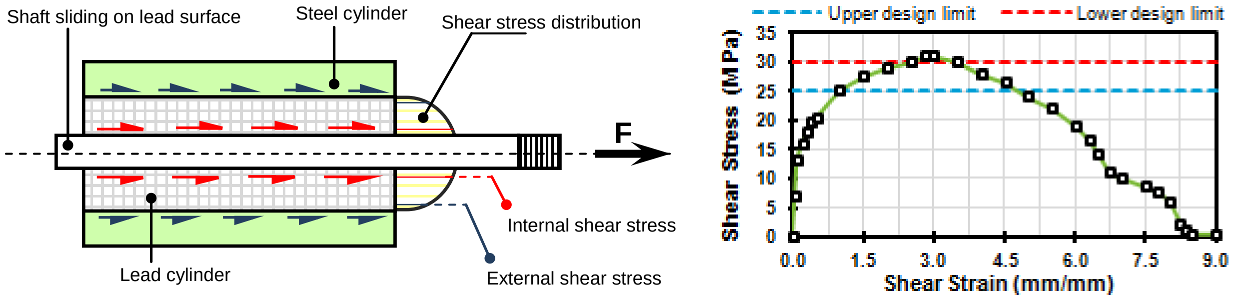
b. Constricted shaft

c. Bulged shaft

Figure 10. Hysteresis loop of HF2V devices with 12mm shaft and different shaft configurations

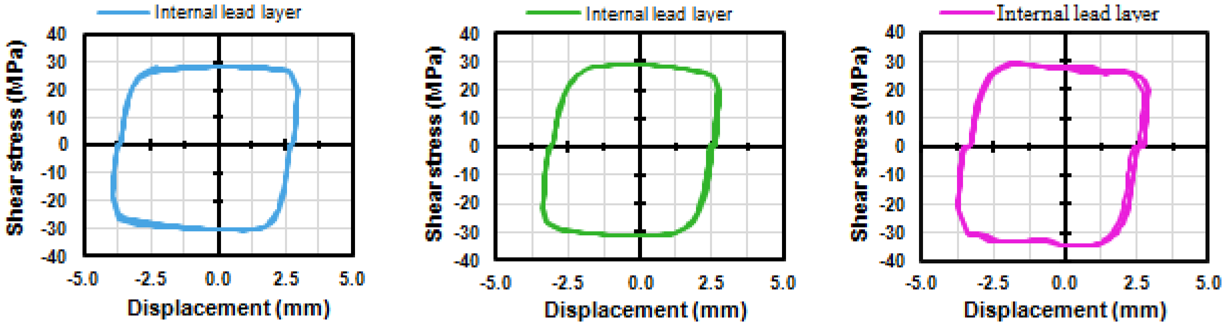
3.4 Single shear model of HF2V devices with straight shaft

A simple model to represent the dissipation mechanism of straight shafts has been proposed by Chanchí et al. (2012). In this model the friction developed between the shaft and end caps is ignored, and the lead cylinder is considered to be constituted by infinitesimal concentric layers subjected to single shear. The shear stress distribution across the cylinder thickness is considered to follow the same tendency as that one suggested by Monti (1995) when testing lead subjected to single shear from the zero shear condition up to the failure due to excessive shear strain (Fig. 11 a-b). Under this consideration, the internal lead layer of HF2V devices is subjected to the maximum shear stress and can undergo shear strains that allow the development of the total shear strength of the lead as a result of the confining condition imposed by device configuration.



a. Single shear stress distribution on HF2V devices

b. Lead shear stress and strain curve (Monti 1995)



c. Straight shaft

d. Constricted shaft

e. Bulged shaft

Figure 11. Shear model and hysteretic shear stresses of HF2V devices with 12mm shaft and different configurations

Using this approach hysteresis loops presented in section 3.3 were expressed in terms of shear stress exhibited at the internal layer of the lead cylinder. Shear stresses in the range 25 to 30MPa were found at the plateau of the hysteresis loop (Fig. 11 c – e); thus, confirming that straight shaft devices develop shear stresses close to the lead shear strength at the interface shaft-lead cylinder when the sliding mechanism of the shaft is fully activated. For that reason the sliding force (Fs) of these devices can be quantified by considering that an upper shear stress limit of 30MPa, or conservatively a lower limit of 25MPa can be developed at the surface of the internal lead layer ($A_{internal}$) as expressed in Eq. 1. This equation is applicable for thinner walled lead cylinders (i.e lead thickness less than 2.5mm); in the case of larger lead thicknesses additional research is required to validate the application of this model.

$$Fs = 25\text{MPa} \times A_{internal} \tag{1}$$

4. Conclusions

This paper discussed the behavior of Asymmetrical Friction Connections (AFC) and High Force to Volume devices (HF2V). It was shown that:

i) Assembling of AFC specimens should be carried out by a method that ensures the development of the proof load in bolts. The development of relationships prior to assembling specimens on site is advised given the variability on the surface condition of galvanized bolts.

ii) AFC specimens can develop a repeatable and stable hysteretic behavior by using shims material with hardness values well above of the steel plate hardness. Materials such Bisalloy 400 and Bisalloy 500 can be considered in the design practice.

iii) The use of coatings on AFC specimens, reduce the hysteresis loop stability and the sliding force capacity. If AFC specimens require coating given the exposure conditions, application of inorganic zinc silicate is recommended. In this case reductions of 50% on the sliding force of the specimen should be considered in the design.

iv) Corrosive environments affect the behavior of AFC specimen by increasing the magnitude of the sliding force at the onset of the fully activation of the sliding mechanism for sliding lengths less than 10mm. Given that at this stage only preliminary results are available, overstregth values of 25 % should be considered in the design process if this type of connection is planned to use in a corrosive environment.

v) HF2V devices with straight shaft are characterized by square hysteresis loops; their energy dissipation mechanism is based on the development of friction at the interface between the shaft and the internal lead cylinder layer.

vi) Sliding forces of HF2V devices with straight shaft and thin walled lead cylinders can be estimated considering that shear stresses of 25MPa are developed at the internal layer of the lead cylinder.

5. Acknowledgments

The authors gratefully acknowledge funding from the Ministry of Science and Innovation – Natural Hazards Research Platform through the “Low Damage Bridges” and “Composite Solutions” grants.

6. 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, and 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., and Clifton, G.C. (2012). Behaviour of asymmetrical friction connections using different shim materials. *Proceedings of the New Zealand Society of Earthquake Engineering- Annual Conference. Christchurch* - New Zealand.

Chanchí, J.C., Chase, J.G., Rodgers, G.W., MacRae, G.A. and Clifton, G.C. (2012). Velocity dependence of HF2V devices using different shaft configurations. *Proceedings of the New Zealand Society of Earthquake Engineering- Annual Conference. Christchurch* - New Zealand.

Chanchí, J.C., MacRae, G.A., Chase, J.G., Rodgers, G.W., and Clifton, G.C. (2012).. Clamping force effects on the behavior of Asymmetrical Friction Connections. *Proceedings of the 15th World Conference on Earthquake Engineering. Lisbon* - Portugal.

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.

Cousins, W. I. & Porrit, T. E. (1993). Improvements to Lead-Extrusion Damper Technology. *Bulletin of the New Zealand Society for Earthquake Engineering.* 26 (3), pp 342-348.

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.

Khoo, H.H., Clifton, C., Butterworth, J., MacRae, G. and Ferguson, G. (2011) Influence of steel shim hardness on the Sliding Hinge Joint. *Journal of Constructional Steel Research.*

MacRae, G.A & Clifton, G. C. (2010). New Technology Applications, Recent Developments and Research Directions for Seismic Steel Structures in New Zealand. *Asian Conference on Earthquake Engineering,* Bangkok, Thailand, 1-3 December.

Mander, T.J., Rodgers G.W., Chase J.G., Mander J.B., MacRae G. A. & Dhakal R. (2009). A Damage Avoidance Design Steel Beam-Column Moment Connection Using High-Force-To-Volume Dissipators. *American Society of Civil Engineering – Journal of Structural Engineering.* 135 (11), pp 1390 – 1397.

Monti, M.D. (1994). High Strain Cyclic Shear of Lead. *Master Thesis,* Dept. of Chemical and Materials Engineering, University of Auckland, New Zealand.

Rodgers, G. W. (2009) Next Generation Structural Technologies: Implementing High Force-to-Volume Energy Absorbers. *PhD Thesis*, Department of Mechanical Engineering, University of Canterbury, Christchurch, New Zealand.

Standards New Zealand. (2002). AS/NZS 2312: Guide of the protection of structural steel against atmospheric corrosion by the use of protective coatings. Wellington – New Zealand.

Standards New Zealand. (2009). NZS 3404: Part 1: 2009 – Steel Structures Standard. Wellington – New Zealand.

Tremblay, R. (1993). Seismic Behaviour and Design of Friction Concentrically Braced Frames for Steel Buildings. *Unpublished PhD Thesis, Department of Civil Engineering.* University of British Columbia – Canada.