Clamping Force Effects on the Behaviour of Asymmetrical Friction Connections (AFC)

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SUMMARY
Asymmetrical Friction Connections (AFC) have been recently developed and applied in New Zealand as a low damage damping solution. Research has shown that this connection can be considered as an efficient and economical connection for dissipating energy on different steel framing systems. This paper reports on the quasi-static testing of Asymmetrical Friction Connections using Bisalloy 500 shims, and assembled with torque levels ranging from 20 to 500 N-m. Effects of increasing assembly torque on the stability of the hysteresis loop and on the sliding force developed by the connection are presented. A simple model to predict the applied bolt tension and the efficiency of the nut rotation method are also discussed. Results show that by developing the proof load on the bolts, stable hysteresis behaviours and approximately 85% of the maximum sliding force of the connection can be achieved, and also that variability in the applied bolt tension should be considered as a part of the design procedure of the connection.

Keywords: Asymmetrical Friction Connections, Clamping Force, Energy Dissipation, Torque Control Method

1. INTRODUCTION

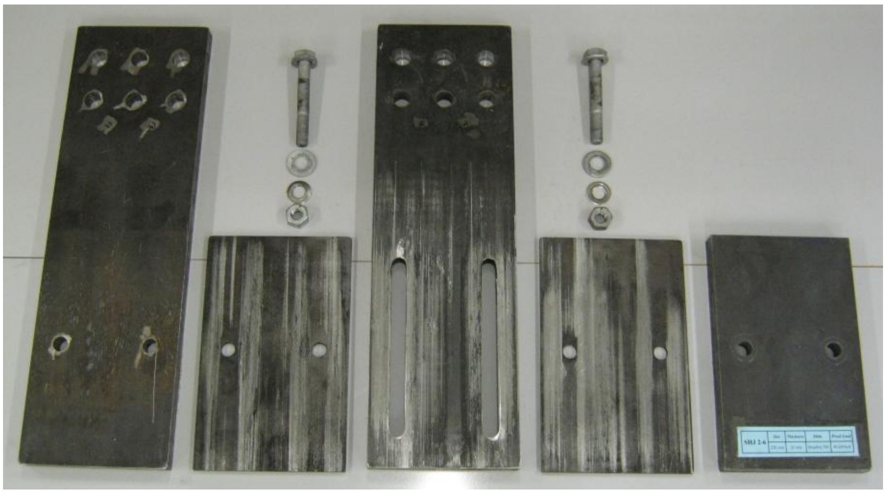
The Asymmetrical Friction Connection (AFC) concept was developed by Clifton (2005) and MacRae and Clifton (2010). The initial development was based on testing small connection components using brass shims, and two large scale beam column subassemblies some with floor slab. Research by Mackinven (2006), Khoo et al. (2011), and Chanchí et al. (2012) have extended the application of this concept to different shim materials, such as aluminium, mild steel and different Bisalloy grades. Results showed that stable and reduced degradation on the hysteretic behaviour of AFC specimens can be achieved by using high hardness shims such as Bisalloy 400 or Bisalloy 500. Although, a large number of experiments have been carried out to describe the hysteretic behaviour of the connection, there is a need for developing design and construction guidelines to regulate the application of this technology and ensure predictable performance. For that reason this paper aims to answer:

1. What is the effect of increasing the assembly torque value on the hysteretic behaviour of AFC specimens?
2. What is the assembly torque value required to guarantee stable hysteretic behaviors of AFC specimens?
3. Is the nut rotation method an effective alternative for assembling AFC connections using Belleville washers?
4. Is the sliding capacity of AFC connections influenced by the magnitude of assembly torque?
5. What is the magnitude of the friction coefficient of AFC specimens using Bisalloy 500 shims as a function of assembly torque?

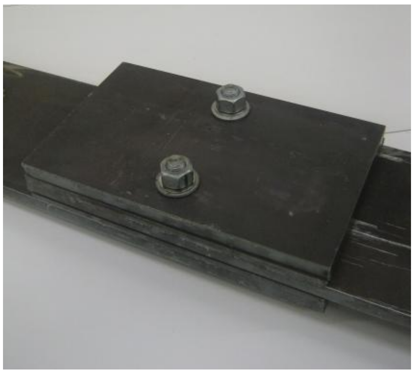
2. ASYMMETRICAL FRICTION CONNECTIONS (AFC)

Asymmetrical Friction Connections can be defined as an arrangement of three steel plates and two thinner plates termed shims, assembled with high strength bolts and Belleville washers. Asymmetrical

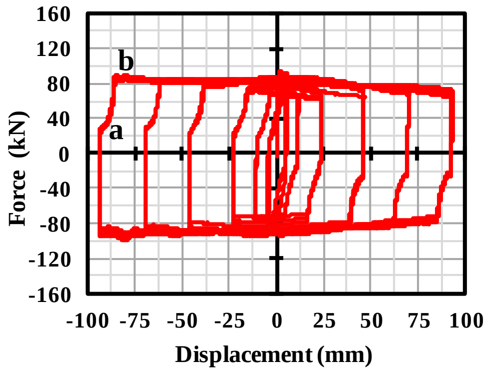
Friction Connections can be used to dissipate energy on beam-column joints or in braces of different steel framed systems. They are desirable because they can dissipate large amounts of energy with almost no damage in the connection itself or in the structural system (MacRae and Clifton, 2010). The Hysteresis loop of the connection can be considered as bilinear for sliding lengths less than 50mm and almost square for sliding lengths near to 220mm (Chanchí et al. 2012). This change is due to the sliding length required by the connection to move from the first sliding stage to the fully activation of the two sliding interfaces (segment a-b Figure 2.1c). There are two typical applications developed for AFC connections, one is a moment-resisting beam column configuration (Clifton 2005) and the other is a sliding brace configuration (MacRae 2008, Chanchí et al. 2012). This paper describes research on AFC's developed for the later application. Figure 2.1 presents components, assembly and a hysteresis loop of an AFC specimen using Bisalloy 500 shims.



a. Left to right : bottom plate, shim, slotted plate, shim, cap plate



b. AFC assembly

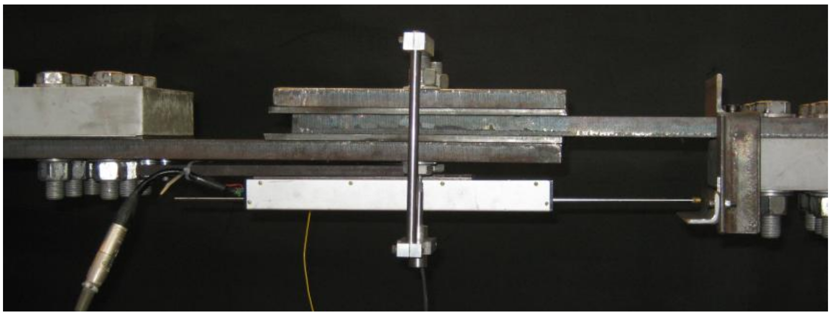


c. Hysteresis loop

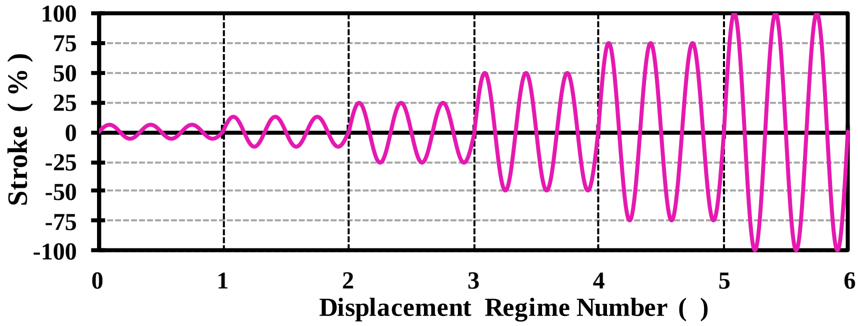
Figure 2.1. AFC using Bisalloy 500 and 2 M16 Grade 8.8 galvanized bolts

3. EXPERIMENTAL METHODS

Twenty one AFC specimens with 220mm slot, Grade 300 steel plates 20mm thickness, Bisalloy 500 shims 6mm thickness, single Belleville washers 1.45mm thickness, and two M16 Grade 8.8 galvanized bolts 110 mm length were tested. Connections were assembled by tensioning bolts to different levels using a calibrated torque wrench (torque control method). Although, the torque control method is not generally accepted for structural applications in the New Zealand Steel Construction Standard (NZS 3404, 2009 – clause C.4.2.6.1*)*, it was considered in this research as an alternative to systematically control the specimens assembly process. Torque values of 20, 50, 150, 250, 350, 410 and 500 N-m from the finger tightened condition were applied without any additional lubrication on bolts to that applied as specified by AS/NZS 1252, at each torque level three AFC specimens were assembled. Additional requirements related to number of free threads during bolt tensioning were satisfied as described in clause 4.2.4.1.2 (*NZS 3404, 2009)*; for instance, connections were characterized by grip lengths of 76 mm and 7 threads within the grip length when using 110 mm bolt lengths. Testing was carried out on a shaking table using a horizontal setup instrumented with a load cell and a potentiometer across the connection stroke. The sliding mechanism was initiated by applying a displacement regime on the slotted plate connected to the shaking table. The displacement regime comprised 20 sinusoidal cycles with a maximum velocity of 15mm/s and amplitudes varying from 3.13 to 100% of the connection slot. Figure 3.1 presents the testing setup and the input displacement regime.



a. Testing setup



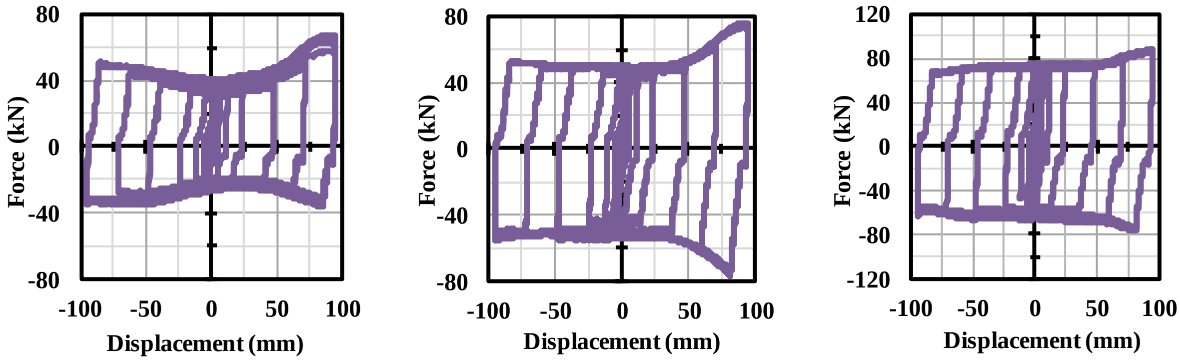
b. Imposed displacement regime

Figure 3.1. Testing setup of Asymmetrical Friction Connections and input displacement regime

4. RESULTS AND ANALYSIS

4.1. Hysteresis loop shape

Stability and shape of the hysteresis loop of AFC specimens was found to change at different torque levels. Unstable and constricted hysteresis loop shapes were recorded across the total sliding length for torque levels below 50 N-m (Figure 4.1a). At torque values of 50-150 N-m more stable and almost rectangular shapes were found for sliding lengths up to 50mm. However, unstable and partially constricted shapes were developed for sliding lengths between 50 and 220 mm (Figure 4.1b). Stable and almost rectangular shapes across the total sliding length were recorded for torques greater than 350 N-m. AFC specimens exhibited constricted and partially constricted shapes because the bottom plate rotates due to the connection asymmetry. As the bottom plate rotates, the cap plate and the top shim rotate certain amount depending on the bolt tension. This rotation moves apart one end of the top shim from the slotted plate, while the other end gets closer so that the slotted plate surface is not in full contact with shim surfaces. This effect is more accentuated at low torque values, where the bolt tension is not enough to minimize the cap plate and top shim rotation. This effect also causes differences on the magnitude of the sliding force developed by the connection on the loading and reversal loading conditions. Results show the benefit in terms of stability and hysteresis loop shape when assembling AFC specimens with torque values near to 350 N-m. Figure 4.1 shows hysteresis loop shapes for different assembly torque values.

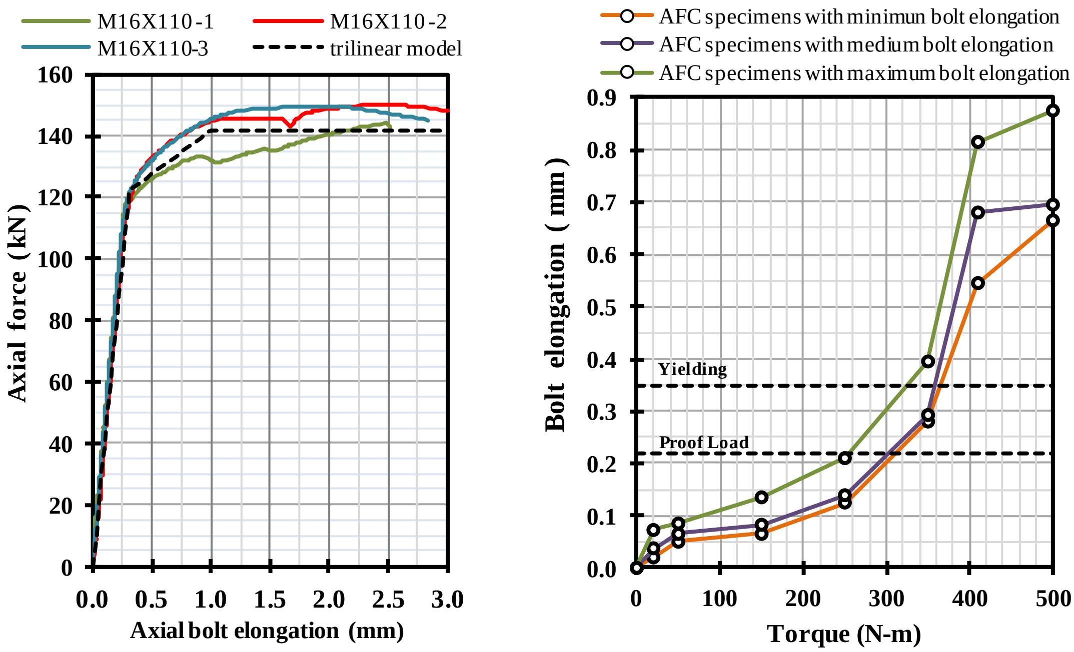


a. Torque 50 N-m **b.** Torque 150 N-m **c.** Torque 250 N-m

Figure 4.1. Hysteresis loop shapes of AFC connections assembled with different torques values

4.2. Induced bolt elongation during assembling process

Average bolt elongations measured from the finger tighten condition when assembling twenty one AFC specimens using seven torque levels (i.e. three AFC specimens at each torque level) are presented in Figure 4.2b. Although considerable variability in the elongation magnitude was presented as a result of the slight different surface conditions on the threads, three elongations tendencies can be noticed. An initial increasing bolt elongation proportional to the torque value up to 350 N-m, significant bolt elongation increments in the range 350 - 410 N-m, and lower bolt elongations than those recorded in the initial range for torque values of 410-500 N-m. The first tendency matches with the elastic zone, and the second and third tendency match with the yielding zone exhibited by bolts when subjected to an axial tension testing (Figure 4.2a),where the bolt grip length was considered as testing length, and the bolt was assembled from the finger tighten condition using a single Belleville washer. Matching elongation values of Figure 4.2b and 4.2a, it can be predicted that bolts reach the proof load value (95 kN) with a torque value near to 300 N-m, and yield with a torque near to 360 N-m.



a. Bolt axial testing results **b.** Bolt elongation for different torque levels

Figure 4.2. Bolt elongation for axial testing and different assembling torques

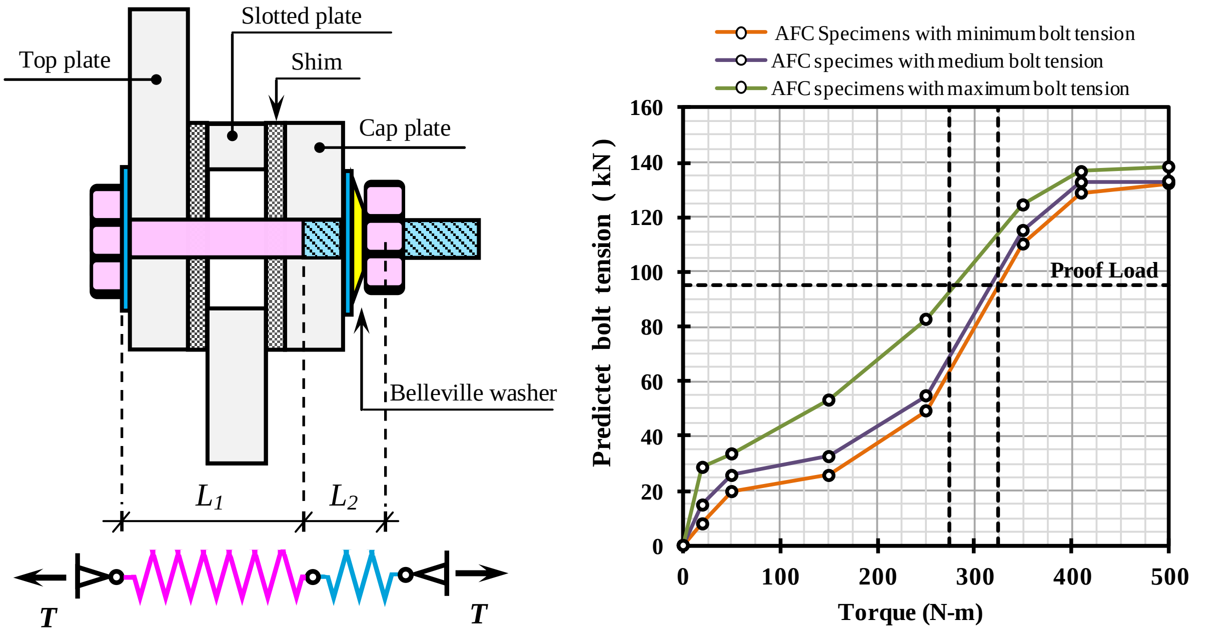
4.3. Induced bolt elongation during assembling process

Aiming to predict the applied tension on bolts during the assembly process, a similar approach to the one suggested by the Steel Structures New Zealand Standard (NZS 3404, 2009) was considered. In this approach the applied bolt tension (T) is predicted considering that the shank and treaded portions of the bolt included in the connection behave as two springs in series (Figure 4.3a), and that the sandwiched plates are rigid and stiff compared to the bolt. This model is represented by Equation 4. 1**,** where δ is the bolt elongation, E is the elasticity modulus calculated using Equation 4.2 and the trilinear axial force – bolt elongation model presented in Figure 4.2a**,** L_1 is the shank length, A_1 is the shank area, L_2 is the threaded length and A_2 is the bolt tension area. Using bolt elongations presented in Figure 4.2b**,** standard geometrical properties of bolt assembly (nut, washer and Belleville washer), and applying Equation 4.1 bolt tension forces for three AFC specimens at each torque level were calculated (Figure 4.3b).

$$T = \frac{\delta \times E}{\frac{L_1}{A_1} + \frac{L_2}{A_2}} \tag{4.1}$$

$$E = \left[\frac{\Delta T}{\Delta \delta}\right] \times \left[\frac{L_1}{A_1} + \frac{L_2}{A_2}\right] \tag{4.2}$$

Results presented in Figure 4.3b show a considerable variability on the applied bolt tension when using the torque control method. This variability may be attributed to bolt fabrication issues, and to the low consistency on the bolt torsional behaviour. In addition, it can be noticed that bolts reach the proof load value (95kN) with torque values ranging from 275 to 325 N-m. From these results, an average torque value of 300 N-m from the finger tighten condition is appropriate for these AFC connections using M16 Grade 8.8 galvanized bolts with 110 mm length and Belleville washers. Also, based on these results, to ensure that the proof load is always obtained, a torque of 325 N-m is required.



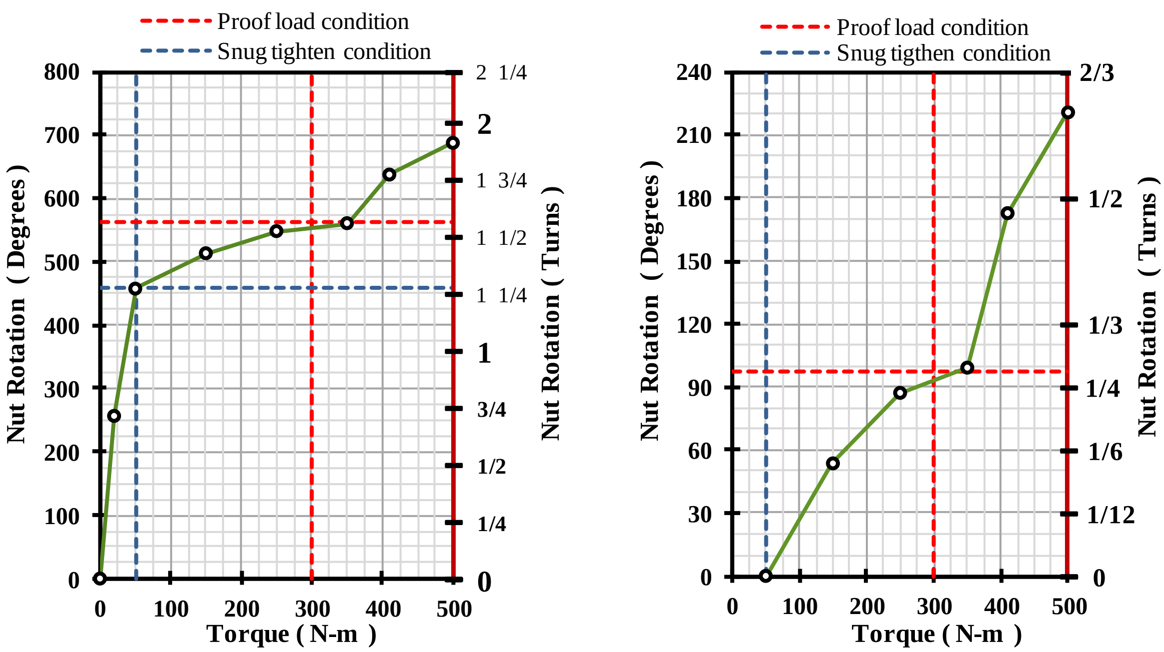
a. Bolt elongation model

b. Predicted bolt tension values

Figure 4.3. Bolt elongation model and predicted bolt tension forces

4.4. Torque – Nut rotation relationship

Average nut rotations measured from the finger tighten condition when assembling twenty one AFC specimens with the single Belleville washer using seven torque levels (i.e. average calculated from six nut rotations corresponding to three AFC specimens at each torque level) are presented in Figure 4.4a**.** Results show that the snug tighten (50 N-m) and the bolt yielding condition (350 – 410 N-m) can be respectively reached by applying nut rotations of 1 ¼ and (1 ½ - 1 ¾) turns from the finger tighten condition. In addition, it can be seen in Figure 4.4b that a nut rotation of (1/4 - 1/3) turn is required to reach the proof load condition (300 N-m) from the snug tighten condition. This range is less than the 1/2 turn value suggested for the New Zealand Steel Construction Standard (NZS 3404, 2009) for bolts without Belleville washers. When considering the Belleville washer, a greater code turn-of-the-nut method should be required. While tightening even using the 1/2 turn value ensures that the bolt has an axial force greater than the proof load, the bolt is tensioned to near its ultimate strength, which is not beneficial if the connection is used for seismic purposes. In contrast, application of the torque control method can result in lower bolt tension levels. However, considerable variations on the applied bolt tension can be expected as a result of the variable relationship between torque and bolt elongation for galvanized bolts (NZS 3404, 2009). For that reasons further research should be addressed to implement a method to assemble AFC specimens that guarantees consistent and repeatable bolt tension forces.



a. From finger tighten condition **b.** From snug tighten condition

Figure 4.4. Nut rotation values recorded for different torque levels

4.5. Sliding Force

The sliding force is defined as the maximum force developed by the connection when the sliding mechanism is fully initiated. This force level corresponds to the plateau of the hysteresis loop. It is less than the maximum force obtained as shown in Figure 4.1. Average sliding forces calculated from three AFC specimens at each torque level are shown in Figure 4.5**.** A non linear relationship between sliding force and torque can be noticed, where the sliding force ranges from 10 to 87 kN for assembly torques of 20-500 N-m. This relationship is characterized by dramatic increments on the sliding force for torque values below the torque required to develop the proof load on bolts (proof load torque), and for increment of less than 12.5% of the maximum sliding force for torque values above the proof load torque. In addition, it can be noticed that AFC specimens can develop 50% of the maximum sliding force when they are assembled with torque values corresponding to the snug tighten condition (50 N-m), and that approximately 90% of the maximum sliding force can be developed when assembled with the proof load torque. Since for these bolt-washer systems with this grip length do not provide much increase in strength above the average assembly torque corresponding to the proof load of about 300 N-m in terms of strength, and possibility of fracture failure in increased with these higher torques, a torque significantly greater than the proof-load value is not recommended.

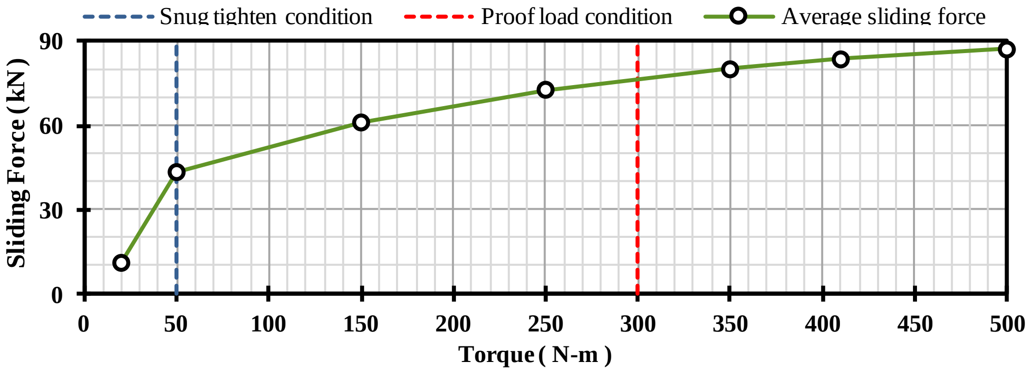


Figure 4.5. Sliding force values for different torque levels

4.6. Effective Friction Coefficient

Using the predicted bolt tension forces applied during the assembling process, considering minor tension losses during the testing, the effective friction coefficient (μ_{eff}) for each AFC specimen was calculated from Equation 4.3. In this equation F_s is the sliding force, n is the number of o bolts, η is the number of shear planes, and T is the tension force per bolt based on the measured bolt elongation at specified torque after the connection is assembled but before the sliding test is initiated. It is not the tension force in the bolt at the time of the maximum sliding force.

$$\mu_{eff} = \frac{F_S}{n \times \eta \times T} \tag{4.3}$$

Average effective friction coefficients calculated from three AFC specimens at each torque level are presented in Figure 4.6. It can be seen that AFC specimens develop variable friction coefficients when assembled with torques below the proof load torque (300 N-m). This variability was not noticed for connections assembled with torques in the range 350 – 500 N-m, where the friction coefficient value is 0.17. Reasons for this variability at lower torques can be attributed to unstable hysteresis loops, and to the variable behaviour of bolts when subjected to torsion. Considering these results, it can be suggested that a predictable and reliable behaviour of AFC connections can be achieved by using assembly torques in the range 350 – 500 N-m.

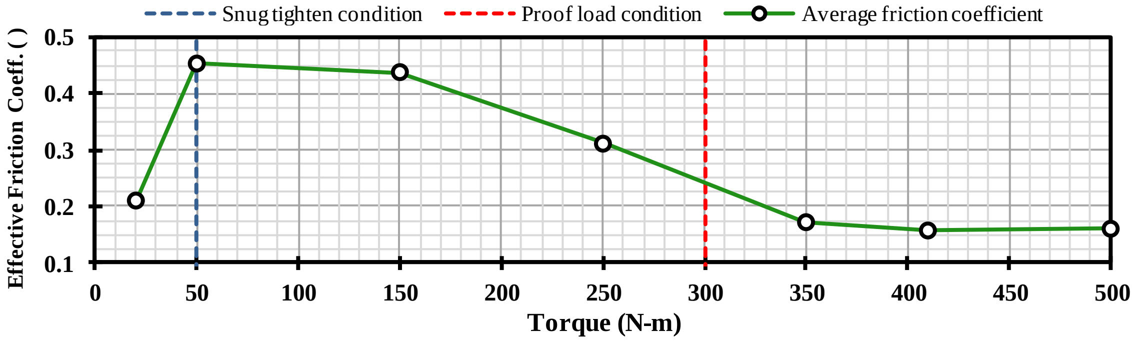


Figure 4.6. Effective friction coefficient values for different torque levels

5. CONCLUSIONS

This paper describes the effect of clamping force on the behaviour of Asymmetrical Friction Connections. It was shown that:

1. Stability and shape of the hysteresis loop of AFC specimens across the sliding length was found to be dependant of the assembling torque level. A range of torque values where stable hysteresis loops can be expected was reported.
2. A considerable variability on the applied bolt tension as a function of installed bolt torque was predicted for AFC specimens assembled with Grade 8.8 galvanized bolts, the effect of this variability should be considered in the design procedure of the connection.
3. The half nut rotation method overestimates the torque value required to develop the proof load on bolts, by using this method applied bolt tensions close to the failure load of the bolt are expected. A range of torque values where applied bolt tensions are close to the proof load was suggested.
4. A noticeable effect of the assembling torque level on the sliding force developed by AFC specimens was found for torque values below the proof load torque. Only minor increments on the sliding force level can be expected for torque values above the proof load condition, because of loss of installed bolt tension on developing stable sliding for the higher installed bolt tensions.
5. Variability of the effective friction coefficient developed by AFC specimens is influenced by the level of applied bolt tension. Ranges of assembling torques where a considerable variability and constant values of friction coefficients were reported.

REFERENCES

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.

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., MacRae, G.A., Chase, J.G., Rodgers, G.W., Clifton, G.C, and Munoz, A. (2011). Design considerations for braced frames with asymmetrical friction connections (AFC). *STESSA 2012, Santiago de Chile,* January 2012.

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.*

Mackinven, H. (2006). Sliding Hinge Joint for Steel Moment Frames Experimental Testing. *Unpublished ENCI493 Project Report*. *Department of Civil Engineering.* University of Canterbury – 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.*

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