Is the Asymmetrical Friction Connection (AFC) a low damage dissipater?

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ABSTRACT: Asymmetrical Friction Connections (AFC) are used in structures in earthquake zones to dissipate energy without causing major damage to the structural members. This means that the structure itself does not require replacement after a major seismic event. Testing of these connections has been undertaken and degradation in strength has been observed. However, (i) reasons for this degradation have not been clear, (ii) a means of assessing the strength degradation has not been available, (iii) the importance of the strength degradation (which is related to the amount of strength degradation) has not been described, (iv) the ability to reinstate the joint using new bolts is not known, and (v) effective friction factors for the connection after connection reinstatement are not known. This paper describes the testing of AFC specimens with high hardness shims (i.e. Bisalloy 500) under increasing cyclic displacements to address the issues stated above. Tests were conducted twice with the same setup. In the second test, the change in performance as a result of the first test was able to be observed. Then the bolts were replaced and tests were conducted twice more.

1 INTRODUCTION

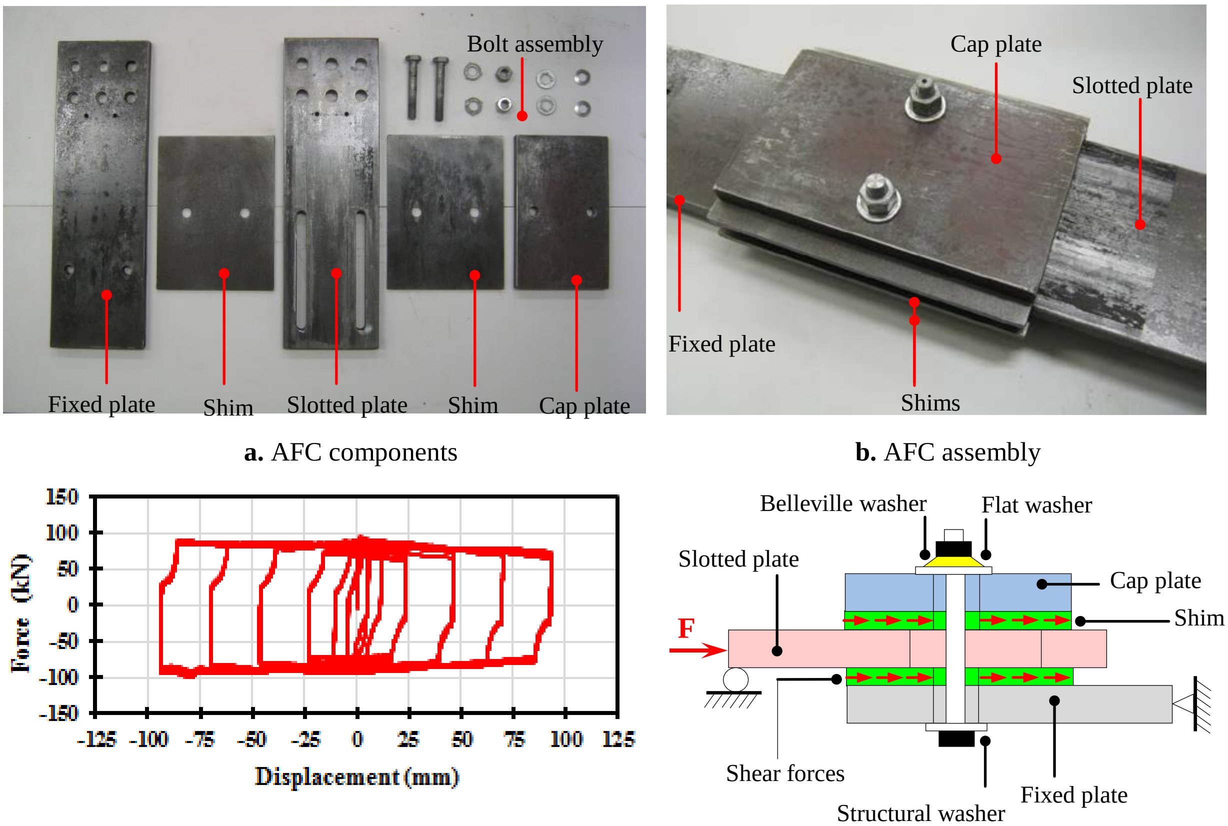
Asymmetrical Friction Connections (AFC) have been recently proposed and applied as seismic energy dissipaters in several structural systems in New Zealand. Testing of AFC components and beam column joints equipped with this type of dissipater demonstrated stable hysteretic behaviour, and the ability to absorb a significant amount of seismic energy with low damage (Clifton 2005). Testing aiming to describe the behaviour of AFCs considering different assembling methods, different surface conditions, as well as long term effects such as corrosion have been also undertaken by Chanchi et al. 2013. Results show that by assembling AFCs either with high or low hardness sliding surfaces, and using Grade 8.8 bolts (i.e. 660 MPa yield strength) tensioned up to the proof load, a predictable hysteretic behaviour can be achieved. Applications of AFCs on different braced framing systems where AFCs act as fuses protecting the structural system by imitating the amount of seismic force that the system can absorb were also proposed by MacRae 2008, and these applications are under experimental research at University of Canterbury – New Zealand (Chanchi et al. 2014). AFCs have been qualitative categorized by several researchers as a promising low damage dissipater that can be applied in different structural systems (Clifton 2005, MacRae 2008, Chanchi et al. 2013). However, to date there is no study that quantifies the strength degradation that this dissipater undergoes under cyclic load. For that reason, this paper aims to propose a simple methodology to quantify the strength degradation of AFCs, and answers following questions:

1. What is the strength degradation of AFC specimens using Bisalloy 500 shims when subjected to cyclic load?
2. What is the effect of bolt replacement on the strength degradation of AFC specimens using Bisalloy 500 shims and subjected to cyclic load?

3. What is a simple methodology to assess the degradation of AFC specimens?
4. Can an AFC be regarded as a low damage dissipater?

2 ASYMMETRICAL FRICTION CONNECTION (AFC)

AFCs are a type of friction connection comprising three steel plates, and two thinner plates termed shims. This connection is assembled by placing the shims at both sides of a slotted plate, and by sandwiching this shims-slotted plate arrangement between a short plate termed cap plate, and a long plate termed fixed plate (Figs. 1a, b). High strength bolts tensioned up to 70% of the ultimate strength (proof load) and assembled with structural, flat, and Belleville washers are used to clamp together plates and shims. AFCs can be used to dissipate seismic energy in different structural systems; energy is dissipated when the slotted plate is forced to slide across the connection arrangement and the force is transmitted via shear forces (Fig. 1c). By using Bisalloy 500 shims (Chanchí et al. 2013) an almost square and stable hysteretic behaviour can be achieved (Fig. 1d).



a. AFC components **b.** AFC assembly

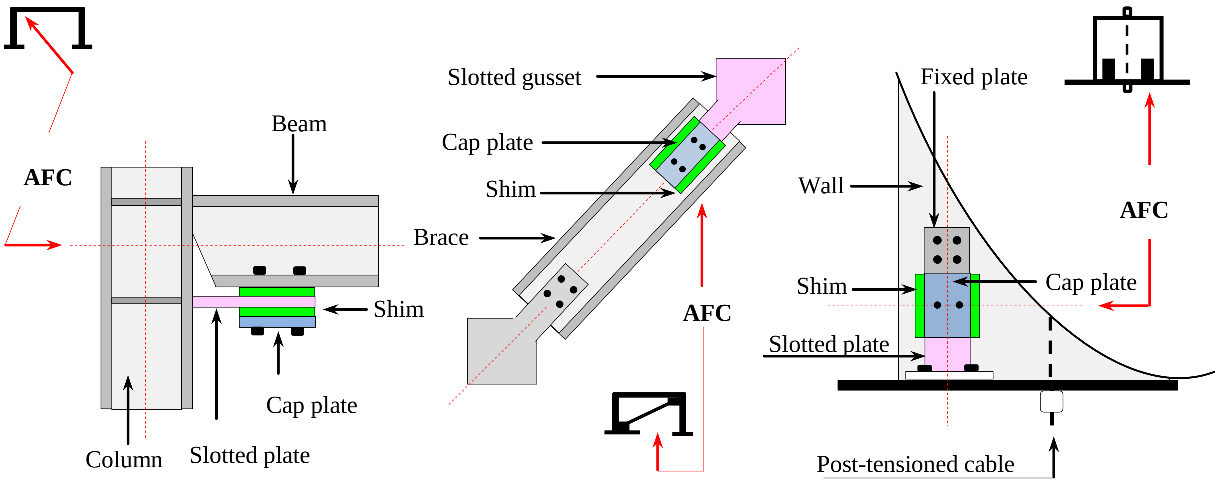
d. Hysteresis loop of AFC with Bisalloy 500 shims **c.** Mechanism of force transmission in AFCs

Figure 1. Assembly and behaviour of AFCs.

3 APPLICATIONS OF AFC

AFCs can be used to dissipate seismic energy in framed or rocking wall based structural systems (Fig. 2). In framed systems the AFC detail can be placed in beam column joints where dissipation occurs when the beam rotates (Clifton 2005), or within braces where dissipation occurs when the brace elongates (MacRae 2008; Chanchí et al. 2014). In the case of rocking wall systems, AFC details can be placed at both sides of the wall on the base connection following configurations suggested by Bora et al. 2007. In this configuration, dissipation occurs as the wall experiences rocking or uplifting. Applications of AFC details are desirable not only because assembling process and cost are similar to traditional bolted connections; but also because components are replaceable, and the capacity of the connection can be accurately controlled by using high or low hardness shims (Chanchi et al. 2013).

Another significant advantage in the case of braces equipped with AFC details is that they can be assembled in the shop, so reducing the erection time and improving quality control on site.

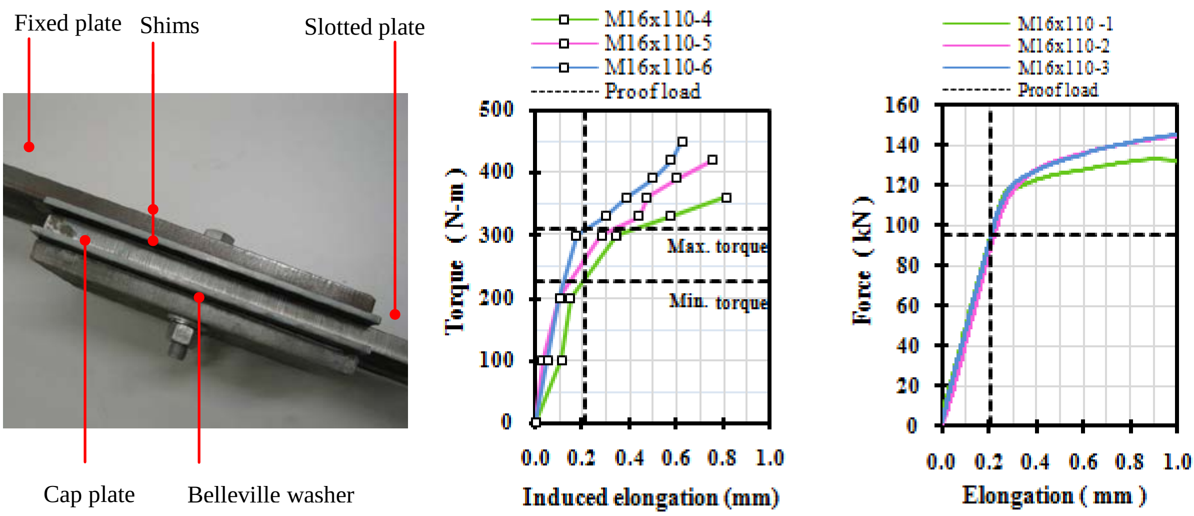


a. AFC on beam-column joints **b.** AFC on braces **c.** AFC on rocking walls

Figure 2. Applications of AFCs on different structural systems.

4 MATERIALS

Two AFC specimens with 200mm slots were assembled using 20mm thick Grade 300 steel plates, 6mm thick Bisalloy 500 shims, and two M16 x 110mm Grade 8.8 galvanized bolts with 72mm shank. Surfaces of plates and shims were used as bare condition, and impurities of sliding surfaces were removed by using a thin layer of acetone applied with a rag. Bolts were assembled with structural, flat, and single Belleville washers; structural washers were located under bolt heads and Belleville and flat washers under nuts (Fig. 3a). A calibrated torque wrench was used to tension bolts up to the proof load; in the pre-assembling stage the single Belleville washers were not flat, and they became flat at tensioning forces well below the bolt proof load.



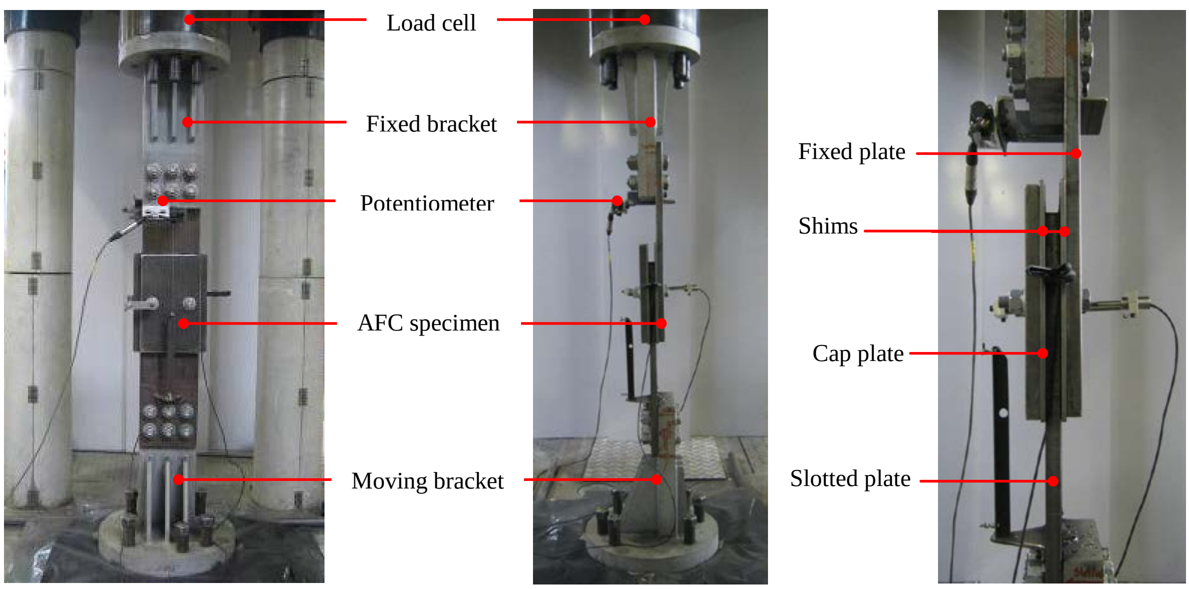
a. AFC assembly **b.** Torque relationship **c.** Tension relationship

Figure 3. AFC assembly and assembling relationships.

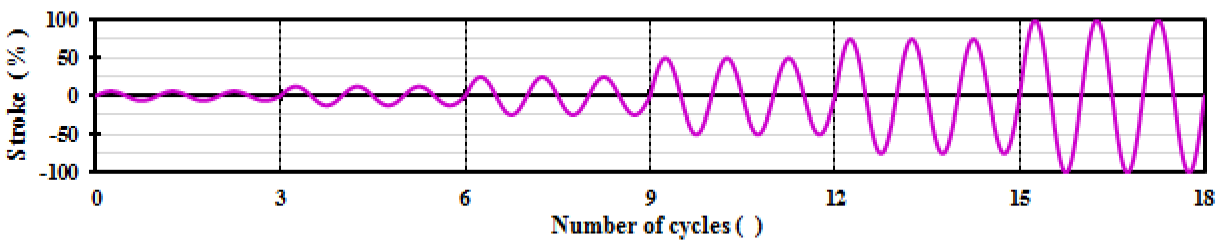
Assembling procedure of AFC specimens was based on using a torque that tensions bolts up to the proof load (proof load torque). This torque was defined by developing a relationship between torque and induced bolt elongation on three bolts using similar assembly as that one used in AFC specimens, and where the torque was gradually increased from the finger tight condition to the bolt failure (Fig. 3b). In this relationship, the proof load torque was considered as the torque that induces a bolt elongation similar to that one recorded in a tension test when bolts reach the proof load (Fig. 3c). Using these relationships a torque of 300N-m was chosen as the assembling torque; this value corresponds to nut rotations of 1/4 –1/2turn.

5 TESTING METHODS

Testing of SFC specimens was conducted using a vertical setup in a Dartec 10MN axial testing machine. Setup was constituted by a moving bracket attached to a servo-controlled actuator, and a fixed bracket attached to a rigid crosshead. The slotted and fixed ends of specimens were respectively connected to the moving and fixed bracket by means of slip critical connections assembled with 6 M20 Grade 8.8 bolts. This setup was instrumented with a load cell placed in series with the brackets, and a potentiometer placed across the connection stroke (Fig. 4). Sliding of the slotted plate was induced by imposing a displacement regime comprised of 18 sinusoidal cycles with maximum amplitudes in the range of 6.25-100 % of the specimen effective stroke (□95mm), and maximum velocity of 10mm/s.



a. Frontal and lateral view of testing setup **b.** AFC specimen



c. Displacement regime

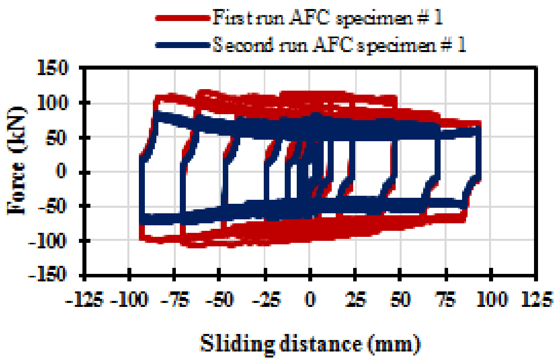
Figure 4. AFC testing setup and displacement regime.

Two AFC specimens were tested with no replacement of plates or shims; each specimen was subjected to four runs of the displacement regime. Between runs a time of 15 minutes was used to allow connection components to cool down to room temperature. Initial two runs were carried out on both AFC specimens without bolt replacement, no bolt re-tensioning between the first and second run was applied. Final two runs were carried out on same AFC specimens with a new set of bolts tensioned up to the proof load; no re-tensioning between the third and fourth run was applied.

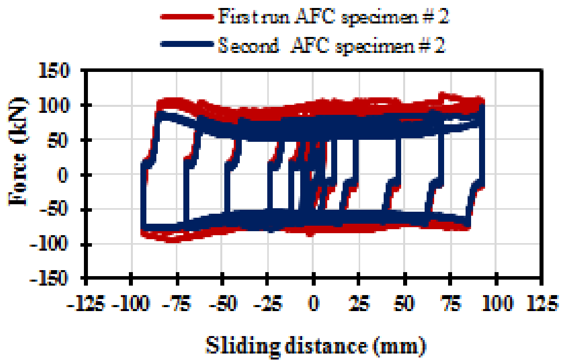
6 RESULTS AND ANALYSIS

6.1 Qualitative assessment of strength degradation

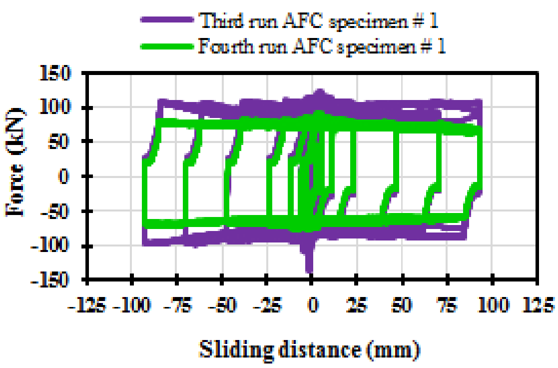
Hysteresis loop of AFC specimens is almost rectangular; the post-yielding zone is non-horizontal due to the development of prying forces between the slotted plate and shims. These prying forces are developed as a result of the secondary bending that the connection undergoes when the driving force on the slotted plate is transmitted to the fixed plate. When comparing hysteresis loops recorded in the first and second run (i.e. brand new sliding surfaces and brand new bolts) of the displacement regime for both AFC specimens (Fig. 5a, 5b), it can be seen that the force that activates the sliding mechanism of the slotted plate (sliding force) reduces as sliding distance and number of cycles increase. This strength reduction is due to loss of bolt tension presented as sliding surfaces degrade not only as a result of the sliding mechanism, but also because prying forces loosen bolts. Hysteresis loops recorded in the third and fourth run (i.e. degraded sliding surfaces and brand new bolts) of the displacement regime for both AFC specimens exhibited a similar trend on strength reduction as that one observed on the first and second run (Fig. 5c, 5d). It can be also seen that by replacing bolts the strength of AFC specimens was fully restored. However, increased forces at the initial cycles were developed as result of the degradation that the zone around the bolt hole undergoes due to the clamping stress concentration. These increased forces were reduced at further cycles when AFC specimens experienced loss of bolt tension.



a. AFC specimen # 1 with brand new sliding surfaces and brand new bolts



c. AFC specimen # 2 with brand new sliding surfaces and brand new bolts



b. AFC specimen # 1 with degraded sliding surfaces and brand new bolts

d. AFC specimen # 2 with degraded sliding surfaces and brand new bolts

Figure 5. Hysteresis loops of two AFC specimens with brand new and degraded surfaces.

6.2 Qualitative assessment of strength degradation

The effective friction coefficient (Equation 1) was calculated as the ratio between the total sliding force ($F_{sliding}$) from the two bolts considering the two shear planes and the bolt proof load (F_{proof}).

$$\mu = \frac{F_{sliding}}{2 \times 2 \times F_{proof}} \quad (1)$$

The effective friction coefficient was calculated at different sliding distances for the four runs of the displacement regime in both tests of AFC specimens. At each sliding distance, the sliding force in Equation 1 was considered as the average sliding force of both specimens and assessed across the tensile and compressive post-yielding zones. 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 24mm (Fig. 6).

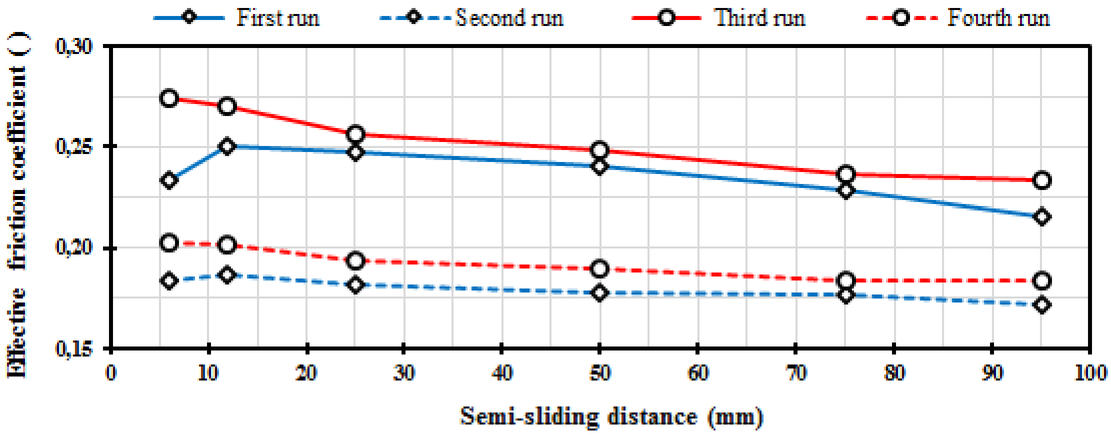


Figure 6. Average effective friction coefficient from two AFC specimens for first, second, third and fourth run.

The greatest values of effective friction coefficients were exhibited at those runs where bolts were brand new (first and third run), and ranged from 0.22 to 0.27. Lowest and less variable effective friction coefficients were exhibited for cases where no bolt replacement was made (third and fourth run). In this case the effective friction coefficient ranged from 0.17 to 0.20, and stability of the effective friction coefficient is attributed to the reduced influence of prying forces when bolts underwent loss of tension.

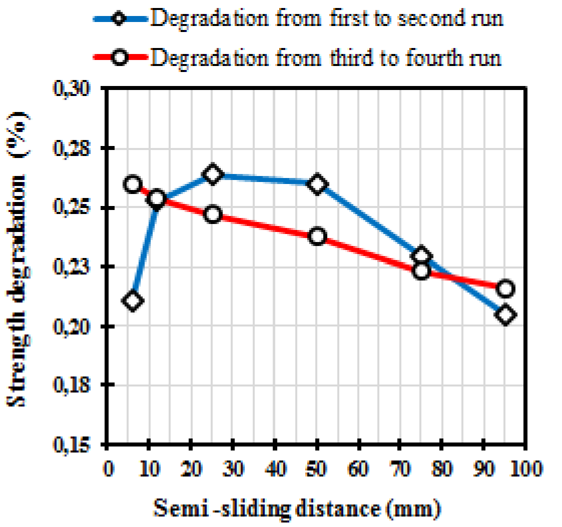
6.3 Quantitative assessment of strength degradation

Strength degradation (*sd*) of AFC specimens was quantified as function of the degradation index (Equation 2). The degradation index was defined as the ratio between the residual effective friction coefficient exhibited on a second run of the displacement regime by an AFC specimen with no bolt replacement ($\mu_{residual}$), and the initial effective friction coefficient ($\mu_{initial}$) exhibited on the first run of the displacement regime.

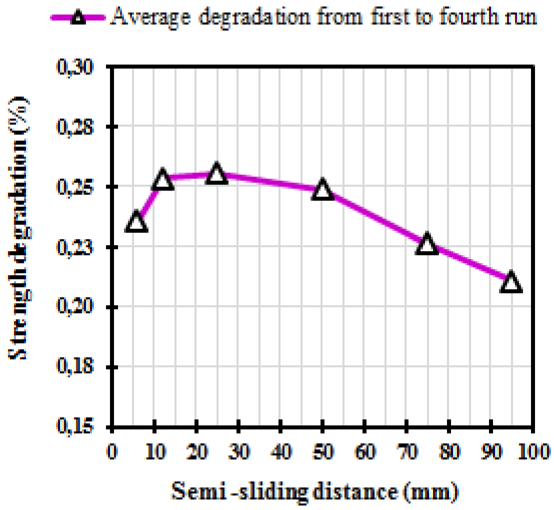
$$sd = 1 - \frac{\mu_{residual}}{\mu_{initial}} \quad (2)$$

Strength degradations from the first to second run, and from the third to fourth run of the displacement regime were calculated using the average effective friction coefficients of both AFC specimens (Fig. 7a). It can be seen that strength degradation varies with sliding distance, and this variation is more noticeable in brand new surfaces (first to second run) rather than in worn out surfaces (third to fourth run). When calculating the average degradation of both AFC specimens exhibited in the four runs of the displacement regime it can be seen that the strength degradation varies in the range 21-26%

(Fig. 7b). Given that displacement regime used in this research is more rigorous than the one reported by Grigorian & Popov 1994 as maximum expected in structural systems using friction connections when subjected a severe seismic movement; it can be argued that AFCs are not only a low damage solution but also a sustainable dissipater that only require bolt replacement to restore the full strength.



a. Average strength degradation from first to second run (brand new sliding surfaces and brand new bolts), and from third to fourth run (degraded sliding surfaces and brand new bolts)



b. Average strength degradation from first to fourth run (from brand new sliding surfaces with brand new bolts to degraded sliding surfaces with brand new bolts)

Figure 7. Assessment of degradation for brand new and degraded sliding surfaces.

7 CONCLUSIONS

This paper describes and quantifies the strength degradation of Asymmetrical Friction Connections using Bisalloy 500 shims and subjected to cyclic load; it was shown that:

1. Strength degradation is due to loss of bolt tension, and it is associated with the degradation that sliding surfaces undergo as result of the sliding mechanism and prying forces resulting from secondary bending effects in the connection.
2. A simple methodology to assess the strength degradation of AFCs under cyclic load can be based on quantifying the reduction of effective friction coefficient across the sliding distance of the connection.
3. Strength degradation varies with the connection sliding distance. Strength degradations of 21-26% can be considered as upper degradation boundary when estimating the residual capacity of AFC specimens exposed to a severe seismic event.
4. By replacing bolts, the strength of connections with degraded surfaces can be fully restored. However, increased forces at the initial sliding cycles can be developed as consequence of the localized degradation exhibited on the zone around bolt holes where clamping stresses are concentrated. Since the strength can be restored, AFCs can be qualified as a low damage and sustainable dissipaters that can be applied in different structural systems.
5. The effective friction coefficient varies with the connection sliding distance. Effective friction coefficients of 0.22-0.27 can be considered as upper boundary to estimate the strength of AFC specimens as function of the bolt proof load.

8 REFERENCES

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