# An Experimental Study on the Asymmetric Friction Connection (AFC) Optimum Installed Bolt Tension

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2017 NZSEE Conference

**ABSTRACT:** The Asymmetric Friction Connection (AFC) is an energy dissipating component, consisting of five steel plies all clamped by the fully tensioned High Strength Friction Grip (HSFG) bolts according to the current New Zealand practice. The AFC was originally proposed through the developments of the Sliding Hinge Joint (SHJ) connection, a damage resistant alternative for the seismic Moment Resisting Steel Frames (MRSFs). The AFC can also be used in other types of the seismic resisting systems such as braces and rocking shear walls and columns. However, a concern with the AFC is its post sliding elastic strength reduction. The main reason of this is the reduction of the AFC clamping force generated by the high strength bolts that is caused during the sliding. One of the main reasons behind this post earthquake bolt tension loss is the interaction of tensile force, bending moment, and shear force in the bolts during the stable sliding state, which can plastify the bolts material and result in bolt tension loss.

This paper presents the results of a set of experimental tests on the MTS AFC test setup on a range of the installed bolt tension all in the bolts elastic range, to reach the optimum value. This optimum bolt tension is recommended in this paper. Belleville Springs have also been demonstrated by the authors as a key component for the AFC detail to give optimum performance.

## 1 INTRODUCTION

The Sliding Hinge Joint (SHJ) is a beam-column connection developed by Clifton (2005) as a low-damage seismic resisting system for moment resisting steel frames (MRSFs). The SHJ reduces post-earthquake overall cost of building repairs and inconvenience experienced by those whom occupy the building. The SHJ achieves this desired response by remaining rigid under Serviceability Limit State (SLS) loading and being able to slide during Ultimate Limit State (ULS) conditions. By facilitating large beam-column relative rotation, the structural members sustain minimal damage. The overall functionality of the SHJ can be attributed to the behaviour of the Asymmetric Friction Connections (AFCs), the SHJ energy dissipating sliding components, positioned at the bottom of the beam (Figure 1). The AFC comprises of the beam bottom flange or web, a shim, cleat, another shim, and the cap plate all clamped by the pre-tensioned high strength bolts. All of the AFC plies have the circular holes except the cleat having the slotted holes to allow the AFC to slide.

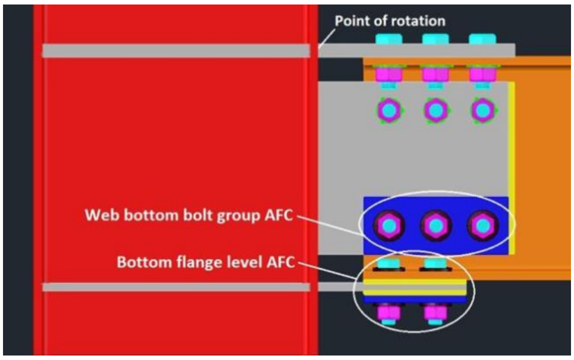


Figure 1. The layout of the SHJ with AFCs (Ramhormozian, Clifton et al. 2016)

During earthquake-induced sliding, the AFCs are exposed to inelastic action and this causes them to suffer a loss in elastic strength. One of the main reasons for this post-sliding elastic strength reduction is the additional moment, shear, and axial forces develop in the AFC bolts during sliding (Ramhormozian, Clifton et al. 2014). If installed conventionally, the AFC bolts are yielded during installation and are subsequently forced into double curvature (Figure 2) as they are plastically deformed under the immense forces. This causes the bolts to lose a significant proportion of their installed tension, which can only be remedied by retightening or replacing the bolts.

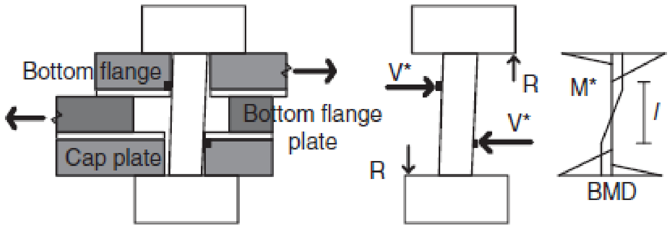


Figure 2. Idealization of the AFC bolt behaviour (MacRae, Clifton et al. 2010)

The loss in bolt tension does not influence the behaviour during a severe earthquake, however it results in a significant reduction in the threshold at which sliding commences subsequent to this earthquake. This may mean the bolts require retightening following a severe event in order to prevent subsequent sliding under a serviceability limit state earthquake or ultimate limit state wind event, which will be time-consuming and costly. To alleviate these adverse effects and help with the enhancement of the SHJ, the AFC bolts are recommended to be installed in their elastic range, to have a dependable elastic deformation capacity under severe sliding conditions. However, the optimum level of installed bolt tension needs to be further investigated. This is the main focus of this paper. Additionally, the use of Belleville springs is proposed and shown as a positively influential parameter to decrease the post-test AFC bolt tension loss.

## 2 BACKGROUND TO THIS RESEARCH

As the AFC undergoes sliding, it is evident that the bolts experience a reduction in installed bolt tension (Clifton 2005; Khoo, Clifton et al. 2012; Ramhormozian, Clifton et al. 2015). This causes the AFC to potentially initiate sliding under less intense loading conditions to that which was originally required by the pre-loading state of the AFC bolts. This does not necessarily always affect the strength stability during a ULS cyclic loading regime but is often more significant afterwards. Hence the issue might not be generally critical for one earthquake but mainly for several, especially if inspection and remediation are not performed. The loss of installed bolt tension partially arises from the imposed moment, additional tension, and shear which force the bolts to plasticise as they are pushed into the inelastic range. The combination of these actions along with potential prying of the cleat causes the bolt to potentially stretch plastically and experience tension loss. Furthermore, the abrasive nature of the sliding action also causes the contact surfaces of the AFC plies to diminish, further contributing to the reduction in the AFC bolt tension. Installing the AFC bolts in their elastic range is considered as a key factor to minimize this inelastic AFC bolt deformation during sliding, and also to potentially decrease the wearing of the AFC plies sliding surfaces.

The recent findings of Ramhormozian, Clifton et al. (2016) highlight the importance of conducting a pre-installation check of the bolts. It was identified that bolts with poor thread and surface finish quality performed considerably worse and failed to reach the specified level of installed tension. It is believed that this unsatisfactory performance stems from plastic strain which develops from interaction of torsion and tension, during the installation process (Ramhormozian, Clifton et al. 2015). It is recommended that a free-nut turn check be carried out prior to any testing. This process involves dividing the bolts into different categories based on whether they turn freely, almost freely, or experience issues with turning. Only bolts of the first category are kept and used in testing to improve the consistency of results. This research also recommends the application of molybdenum disulphide paste to the bolts prior to installation, to alleviate these undesirable effects (although if the bolts are supplied properly prelubricated, this will not be necessary).

In order to overcome the limitations of the SHJ and any friction sliding seismic resisting system, it was recommended that Belleville Springs (BeSs) be introduced to the friction connections to improve the functionality of the system, introducing a higher residual connection strength and generating more consistent strengths values (e.g. (Grigorian and Popov 1994; Clifton 2005; Khoo 2013; Ramhormozian, Clifton et al. 2014; Ramhormozian, Clifton et al. 2015)). Belleville springs are conical washers that have a predictable response when compressed and they help preserve the installed bolt tension during loading. These observations were confirmed by a series of tests conducted by Ramhormozian, Clifton et al. (2015) both with and without Belleville springs. The procedure involved dynamically loading the AFC assembled with the High Strength Friction Grip (HSFG) property class 8.8 bolts to 50% of the proof load. This yielded a very promising outcome, as the average bolt tension loss for no springs was 60%. Whereas, the average tension loss for the system involving Belleville springs under all four AFC bolts was 35%.

## 3 THE AFC EXPERIMENTS ON THE 500KN MTS MACHINE

As it currently stands, there is limited knowledge surrounding the optimum level of the AFC installed bolt tension within the elastic range. Therefore, the core focus of this paper has been to determine this optimum level of installed bolt tension. Another objective also exists in the use of BeSs in conjunction with the optimum level of installed bolt tension once it is determined.

### 3.1 Test setup

In order to simulate the AFC sliding behaviour and to determine the loss of installed bolt tension, a specially designed test rig was used. The basic arrangement and testing procedures were adopted based on previous research (Ramhormozian, Clifton et al. 2016) and involved the use of the 500kN MTS machine. The testing arrangement comprises of a multi-layered system which connects directly to the arm of the MTS machine and a thick base plate. The base plate is secured into position using the strong floor and attached to this is the beam bottom flange plate. The cleat, shims and cap plate are then introduced to the test rig to simulate the AFCs as depicted in Figure 3. The entire mechanism transfers only vertical load to the cleat along the slotted holes.

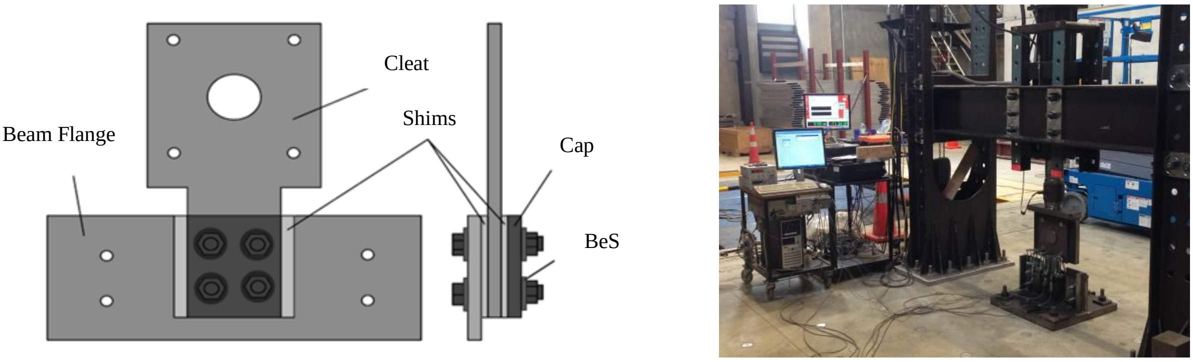


Figure 3. AFC test setup on the 500kN MTS machine (Ramhormozian, Clifton et al. 2016)

### 3.2 Loading regime

A loading regime was implemented using the MTS machine and followed a specific pattern, consisting of varying three Serviceability Limit State (SLS) and two Ultimate Limit State (ULS) loadings. A wind down followed by the first ULS event is depicted in Figure 4; this represents the winding down of an earthquake event. The loading regime was defined in terms of displacement and the original configuration was firstly proposed by the SAC-Joint-Venture (2000). This was later adopted by Clifton (2005). Further modifications were made by Ramhormozian, Clifton et al. (2015) and further adjustments were also made by Ramhormozian, Clifton et al. (2016) to decrease the frequency of the loading in order to satisfy the requirements of the MTS machine. Following the first period of quasi-static SLS loading, a wind down period was also introduced before the ULS component was initiated. In terms of displacement, the maximum amount imposed by the MTS arm to the system during experimentation was ±14.3mm.

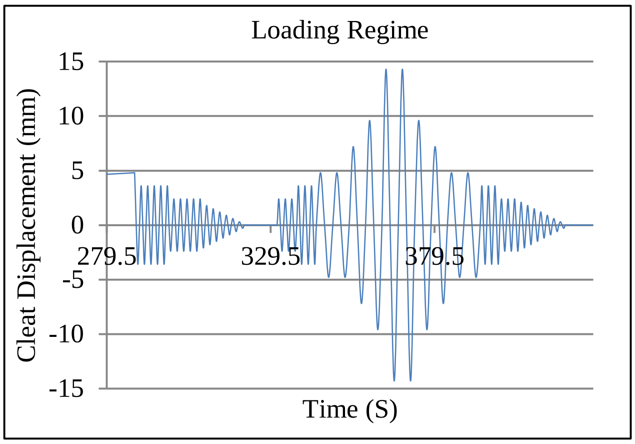


Figure 4. Wind down following the quasi-static, and then ULS loading (Ramhormozian, Clifton et al. 2016)

### 3.3 Bolt preparation

Due to the size restrictions of the high precision donut load cells, instead of using the commonly used galvanised high strength friction grip (HSFG) property class 8.8 bolts, the 3/4 imperial black bolts of property class 10.9 were used to ensure the compatibility between the components, as ensuring tension loss being measured to the highest degree of accuracy was essential.

Each individual bolt was prepared by adhering to the recommendations of (Ramhormozian, Clifton et al. 2016). The first stage of this process was to conduct a "Free-turn of nut" check to identify any bolts with poor thread and finish quality (Figure 5a). Failed bolts were removed from testing as they have a tendency to develop plastic strain during installation as a result of their imperfections. Following this, the tips and heads of the accepted bolts were made smooth using a lathe (Figure 5b) in order to improve the reliability of elongation measurements using the ultrasonic bolt meter. Prior to installation, the bolt threads were applied with a molybdenum disulphide paste (GA 50 Molybond) to act as a lubricant.

a) b)

Figure 5. a) Free-turn of nut check b) Bolt prepared using lathe

### 3.4 Preparation of sliding surfaces

A wire brush was used to remove any unwanted surface corrosion and residue from the AFC plies surfaces. The AFC plies were supplied in 2014 and were made from Grade 350 steel except the shims being made from high hardness Raex 450 grade plate. The sliding surfaces were initially prepared to St2 standard, however due to brushing the surfaces, the surface profile was smoother than that of St2 standard.

### 3.5 **Measurement**

The following key parameters were measured throughout the testing procedure: applied load on the cleat, bolt tension of all bolts, bolt elongation, cleat and bolt temperature, relative displacement of the AFC plies, and relative rotation of the nut-bolt assemblies.

The internal load cell of the MTS machine continuously measured the force required to impose a certain amount of displacement, as specified by the loading regime. The entire system is bound by the clamping force provided by the bolts and can be determined by evaluating the summation of the individual bolt tensions. Four high precision load cells (model THD-50K-W) were placed under the bolt head (Figure 6a) to measure the initial applied tension and to establish the loss of tension following the loading procedure. Initially, hardened washers were specially fabricated and used to protect the donut load cells during sliding and to ensure an accurate reading of the load cells.

The relative displacements of the AFC plies during sliding were measured using a series of portal gauges which were fastened into position using tack welds on the shims, cleat, cap plate and the beam-flange plate. Four separate elongation measurements were taken for each individual bolt throughout the loading process using the ultrasonic G5 tension meter (Figure 6b). Changes in length were recorded pre-installation, post-installation (after tightening), after loading, and once the nuts had been loosened. This was conducted with the intention of understanding the interaction between the plies and the amount of tension loss. Temperature readings were also taken in unison with the elongation measurements. Calibration of the load cells, portal gauges and the ultrasonic G5 tension meter were carried out before testing could commence.

3



a) b)

Figure 6. a) High precision load cells under bolt head b) Ultrasonic G5 tension meter

### 3.6 **Installing the bolts**

Once all of the AFC plies were placed into the test rig, the nuts were tightened by hand using a ring spanner to achieve a snug fit. A standard torque multiplier (V-RAD 16 Electric Torque Wrench) was used to achieve the desired level of tension. The tension was varied as a percentage of the bolt proof load (185kN) and this was accomplished by carefully monitoring the output for each load cell and making the appropriate adjustments using the torque multiplier. As shown by Table 1, the investigated installed tensions were kept well within the elastic range.

Table 1. Installation tension of the bolts and the corresponding test number

| Installation of Bolts | |
|---|---|
| Test no. | % of bolt proof load (180kN) |
| 1 | 30% |
| 2 | 30% |
| 3 | 30% |
| 4 | 40% |
| 5 | 40% |
| 6 | 50% |
| 7 | 60% |
| 8 | 60% |
| 9 | 55% + BeSs |
| 10 | 50% |

### 3.7 Introduction of the customized Belleville Springs (BeSs)

Once the optimum level of installed tension was ascertained, the final procedure was to conduct a test incorporating the use of customized BeSs. Ramhormozian, Clifton et al. (2016) have proven the effectiveness of using BeSs to enhance the performance of the SHJ, for example, in terms of reducing the amount of tension loss. This will provide an indication about the overall maximum effectiveness that can be achieved using the system.

## 4 RESULTS & DISCUSSION

### 4.1 'Free-turn of nut' check

Out of the total number of bolts ordered from the supplier, 29.9% (43 bolts) failed to pass the 'free-turn of nut' criterion recommended by Ramhormozian, Clifton et al. (2016). The primary cause of failure was due to poor thread quality, likely to have occurred during fabrication or transportation of the bolts. The failed bolts were excluded from being used in testing due to concerns over plastic torsion strain developing during installation. With nearly one third of the bolts showing inadequacy, this emphasises the current issue faced by industry and the need to adopt a standardised system to ensure consistent and quality performance of bolts (Ramhormozian, Clifton et al. 2016).

### 4.2 Initial observations on the AFC bolt self-loosening and changes to methodology

Following the completion of the first two tests at 30% of the bolt proof load, markings etched onto the bolts and nuts indicated that there was relative rotation between the two components. The sliding action of the connection was causing the nuts to self-loosen, further contributing to a loss in bolt tension. The source of the issue was determined to be a combination of the two following key factors:

- Interaction between the load cells surfaces and the surrounding washers surfaces all being much smoother than a typical steel surface.
- Relatively low level of installed tension and consequently, the small amount of applied clamping force.

The smooth exterior surface of the washers was allowing slip to occur and the eventual loss of tension was relatively significant. Based on these observations, a change in the test setup was required and this involved replacing the hardened washers with two additional shims. The aim of this was to enhance the grip between the bolt head and the surrounding components. The use of steel shims would also reflect the level of friction provided, in reality, which makes it an even more appropriate modification. This yielded significantly improved results, as demonstrated by the performance of test 3 conducted at the same level of installed tension. In addition to the new shims, a locking-nut was introduced, after the completion of test 5, to further reduce relative rotation between bolt body and nut. In practice, the nut locking could be more easily achieved with Loktite. The partnership between these two imposed changes produced minimal post-sliding rotation, confirming that the loss in tension could not be attributed to this observation.

As previously mentioned, the first two tests conducted with an installed tension equal to 30% of the bolt proof load (55kN) performed poorly suggesting that this was not the ideal level of tension. The methodology for test 3 was altered to limit the amount of relative rotation between the nut and bolt. Although installed with the same initial tension, the imposed provisions resulted in an improvement with around 10kN being restored by each bolt. It can be concluded that 30% is not the optimum level of installed bolt tension and this is strongly supported by the fact that 87% of the installed tension was lost during testing (Figure 7).

Tests 4 and 5 were carried out with an installation tension of 40% (70kN) of the bolt proof load which provided a marginal improvement to that exhibited by the 30 % group. The remaining post-sliding tension was found to be 12kN and once again, this was a small fraction of the original applied force. Overall, the percentage of tension loss was 72% (Figure 7) and, thus, 40% (70kN) of the bolt proof load was also considered to be not the optimum level of tension.

Whilst still remaining with the elastic range, tests were carried out at 50% (90kN) and 60% (105kN) of the bolt proof load. The results of which showed a substantial improvement to the previously analysed tensions groups. At 50%, the bolt tension diminishes to within the range of 30kN and 38kN. Similarly, the final tension for the 60% test reduced to a value just less than 40kN. Figure 7 compares the lost bolt tension in terms of percentage, reinforcing the notion that there is marginal separation between the two outcomes as both values are around 62%. Thus, it can be concluded that optimum level of installed bolt tension is a range between 50% and 60% of the bolt proof load. A noteworthy trend that is established by the plot is that it appears to taper-off (plateau) with increasing tension groups. The behaviour of the bolts when installed to a tension higher than that of the investigated quantities is known to cause plastic deformation. This response causes a major loss in tension as bolts are forced into double curvature, further reinforcing the finding that 50% - 60% is optimum level of installed bolt tension.

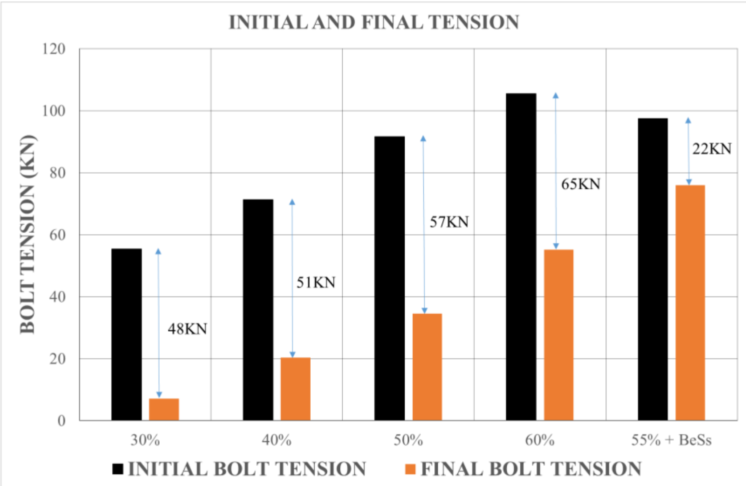


Figure 7. Comparison between initial and final AFC average bolt tension (% represents the installed bolt tension as the percentage of the bolt proof load)

### 4.3 Influence of customized Belleville Springs

One of the main reasons for conducting this research was to help with minimising post-earthquake damage. However, even at the optimum level of installed tension, bolts were still losing 60% of initial tension and therefore, would require retightening after the seismic event. The inclusion of BeSs was then made to the original test setup to examine its influence on the systems performance.

The change produced a significant improvement in terms of the amount of tension which was lost during sliding. Figure 7 reflects this impact with the test involving BeSs proving far superior to any of the other tests carried out without the device. In the end, the post-sliding tension was determined to be around 80% of the original tension. This finding provides strong evidence that the SHJ has the ability to undergo seismic events and not require any post-earthquake maintenance.

## 4.4 **Plies thickness reduction**

The ultrasonic G5 tension meter was used to measure bolt elongation throughout testing. Elongation measurements could then be used to determine the plies thickness reduction per bolt. For test 1, this involved measuring the entire length of the bolt at various stages in the testing procedure. This yielded unsatisfactory results showing a plies thickness reduction of 0.3mm, far greater than any of the other tests carried out. Consultation with an industry expert resulted in a refined methodology that was developed and implemented. The results of which were far more consistent and indicated an average reduction in the total ply thickness of 0.1mm per bolt.

It can be postulated that there is a relationship between the plies thickness reduction per bolt and the amount of tension loss during sliding. The quantity of tension loss remains relatively constant across all the groups. On average, this equates to a loss of 55kN per bolt (excluding the test incorporating BeSs). From the consistency between the plies thickness reduction and the tension loss it is proposed that the decrease in tension, within the tested range of the elastic installed bolt tension, can be directly attributed to the plies thinning. This is further supported by the fact that bolts were kept well within the elastic range and by the provisions which saw limited relative rotation between the nuts and bolts i.e. self-loosening.

## 4.5 **Degradation of the sliding surfaces**

A combination of the large clamping force and the sliding behaviour of the test rig causes significant degradation of the sliding surfaces. It was found that the cleats and shims exhibited major surface wear and this was mainly in the form of 'galling'. The loss of material, especially around the bolt holes, was the primary factor attributing to the reduction in plies thickness reduction. Therefore, it can be concluded that this is a root source of the loss in tension experienced by the bolts.

The introduction of customized BeSs further enhanced the performance of system by offering a substantial reduction in the amount of surface degradation. It is clearly evident that the BeSs reduced also the amount of damage and effectively minimized the amount of plies thickness reduction.

## 4.6 **Bolt and cleat temperature**

The general trend indicates that temperature slightly increases following the loading procedure. The likely cause for this change is heat transfer between the sliding components. Overall, temperature recordings exhibited no sudden increases and from this, it is stipulated that the change in temperature has no major influence over the bolt behaviour and the amount of tension lost.

# 5 **CONCLUSIONS**

The primary objective of the research was to establish the optimum level of installed bolt tension for use in the SHJ's AFC. A series of tests were carried out by varying the amount of installed bolt tension as a percentage of the bolt proof load. After the optimum tension was successfully determined, the inclusion of BeSs were made to investigate the overall effectiveness of the system and to provide an indication about the peak performance of the SHJ. The following conclusions can be drawn from this analysis:

- A large proportion of supplied bolts (29.9%) failed to meet the requirements of the 'free-turn of nut' check. This highlights a prevalent issue that currently exists within the steel industry and the need to adopt new standards to ensure consistency and the quality of bolts.
- The optimum level of installed bolt tension was determined to be 50% - 60% (90kN - 105kN) of the bolt proof load (180kN). Bolts installed within this range suffered an approximate loss of tension equal to 60%. A substantial improvement to any of the other investigated tension groups. Note that this optimum elastic installed bolt tension is lower than the conventional installed bolt tension achieved by part-turn method of tightening. Hence all of the influential parameters should be carefully taken into account to design and construct the AFC based on the proposed elastic bolt tension. This is being researched by the authors to be established.
- It is proposed that the primary cause for the loss in bolt tension, within the elastic range of the installed bolt tension, is directly related to the thinning of plies. Tests conducted without BeSs

all exhibited a similar post-test loss in bolt tension which equates to around 55kN. This matches the consistent plies thickness reduction measurements of 0.1mm. The reduction in plies thickness arises primarily from the degradation of the sliding surfaces. It is clear that this is having a profound impact on the bolt tension loss.

- The performance of the test involving BeSs suggests the vast improvement in tension loss and the minimal post-sliding surface degradation. The tension retained by the bolts was found to be around 80% of the original installed tension. This result highlights the full capability of the SHJ and that minimising post-earthquake damage can unquestionably be provided by this connection.

## 6 ACKNOWLEDGEMENTS

This research was financially supported by Earthquake Commission Research Foundation (Project 14/U687 “Sliding Hinge Joint Connection with BeSs”). The authors are grateful for this support. The first author PhD studies at the UoA is financially supported through a QuakeCoRE doctoral scholarship. This support is much appreciated. The authors would also like to acknowledge the efforts and help of Mark Byrami, the technical and laboratory staff at the Department of Civil and Environmental Engineering, the University of Auckland involved in this research in conducting experimental testing. The Authors would also like to extend special thanks to Rob Penny (Southern Quality Assurance) and Kevin Shanley (Steelmasters) for their generosity and willingness to help with the investigation.

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