
Variations of the Design Parameters in Friction-Sliding Seismic Resisting Connections

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ABSTRACT

To improve the seismic resilience and environmental performance of buildings, low damage design concepts have been developed and implemented in recent years. One of them is to use friction sliding connections (FSCs) as dissipative connection while the other structural elements are designed to resist the over-strength actions from the FSCs while remaining effectively elastic. This paper presents a background to the recent developments and recommendations to design and install FSCs. It also elaborates on the key design parameters of two types of FSCs, namely asymmetric and symmetric friction connections (AFCs and SFCs), requiring a predictable and stable hysteretic response under both quasi-static and dynamic loadings. The variation of sliding shear forces of FSCs and their reasons are explained, which are identified through experimental data using statistical analysis. Finally, the strength reduction and over-strength factors needed to consider in designing structural systems using these FSCs, are explained along with further research required in this area. This paper, which will also be presented in the 12th International Conference on Behaviour of Steel Structures in Seismic Areas (STESSA), briefly explains the experiments along with their results.

1 BACKGROUND

Recent research on connections for seismic resisting steel frames is more and more focusing on low-damage connections with the aim of reducing or mitigating structural damage and allowing quick post-earthquake inspection and recovery. Several experimental studies (Ramhormozian et al. 2019, Fang et al., 2022; MacRae

et al., 2024) have shown the benefits of friction-sliding connections (FSCs), asymmetric and symmetric friction connections (AFCs and SFCs), for seismic resilience the AFC and SFC are illustrated in Figure 1. These connection typologies, using slotted bolted connections primarily in steel framed buildings, ensure sufficient energy dissipation capacity and limit forces transferred through these connections. The reliability and efficiency of such FSCs depends on stable frictional resistance on the sliding surfaces to provide reliable energy dissipation. Providing consistent and predicable performance has been one of the challenges with FSCs, given possible strength variation due to 1) sliding interfaces conditions considering consistency of surface treatment, surface erosion and wearing under cyclic loads and/or potential dependency of the interface coefficient of friction to the sliding velocity under dynamic loads which is dictated by the building's vibration characteristics during an earthquake and 2) bolt tension (i.e. clamping force) variation during sliding as well as immediate loss of preload right after installation, and short-term and long term loss prior to and following cyclic loads. This paper presents the current design considerations and ongoing research needs to improve them.

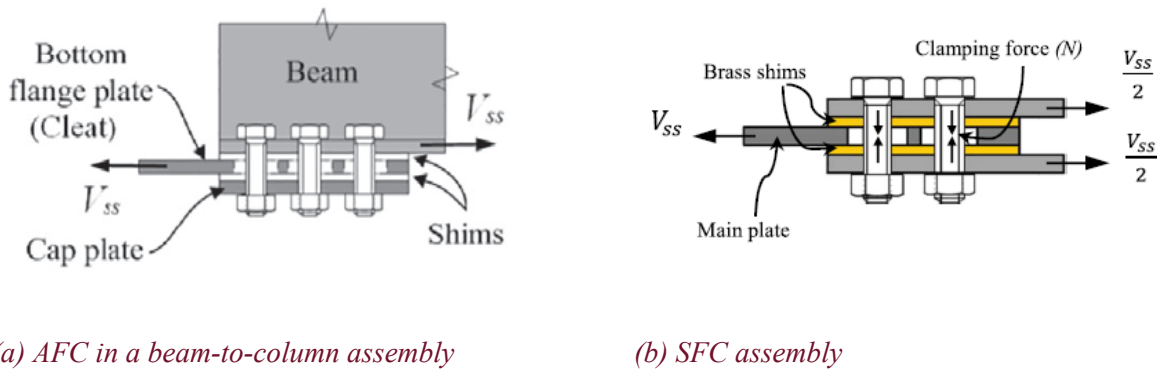


Figure 1: Illustration of typical FSCs (Khoo et al., 2015) – (V_{ss} =stable sliding force)

2 DESIGN PARAMETERS

2.1 Determination of nominal strength

FSCs used for seismic applications are often required to exhibit reliable hysteretic behaviour over repeated cycles. Following the determination of the design actions through codified seismic analysis under the design level, the design sliding shear capacity of a FSC, ϕV , can be evaluated using equation (1).

$$\phi V = \phi n \mu N \quad (1)$$

ϕ is the strength reduction factor. The number of friction interfaces, n , is self-explanatory, while the coefficient of friction (CoF), μ , depends on the type and condition of the friction interfaces selected. The total clamping force, N , was traditionally provided through fully tensioned high strength friction grip (HSFG) bolts. One can argue that equation (1) is based on few simplified assumptions including 1) the total frictional force is directly proportional to the applied load (Amontons 1st Law); 2) the total frictional force is independent of the apparent area of contact (Amontons 2nd Law) and 3) the total frictional force is independent of the sliding velocity (Coulomb's Law).

To determine the nominal strength of FSCs, the CoF must be known based on the selection of friction materials and the surface conditions/profile. However, achieving a consistent surface condition/profile, even when using the same material, is not straightforward. Moreover, the HSFG bolts were traditionally fully tensioned, meaning the minimum design bolt tension or proof load is used to obtain the clamping force. In practice, however, the actual bolt tension prior to sliding is very likely to be different and usually considerably higher than the minimum design bolt tension or proof load. It is worth noting that the codified

procedure of fully tensioning guarantees a minimum bolt tension to be achieved. Both sources, i.e. clamping force and coefficient of friction, contribute to the variations in the strength of the FSC. The lower and upper bound of the variation can be represented through understrength (i.e. strength reduction) or overstrength factors when referenced to the nominal strength in structural design. Such variations can stem from multiple interactive sources, including friction interfaces (surface preparation and coatings), variation of clamping force, velocity dependent behaviour beyond Coulomb's Law, environment effects and material randomness. In accordance with capacity-design principles, the overstrength demand from the FSC should remain lower than the nominal, rather than the dependable (considering strength reduction factor), capacity of the non-dissipative member. In other words, the nominal strength of the non-dissipative member must exceed the overstrength associated with the nominal strength of the FSC. For steel structures, a strength reduction factor of 0.90 is commonly applied in New Zealand practice in most of the cases. It is crucial to identify the nominal strength of the FSC and the corresponding understrength and overstrength factors.

2.2 Recent development and current design considerations

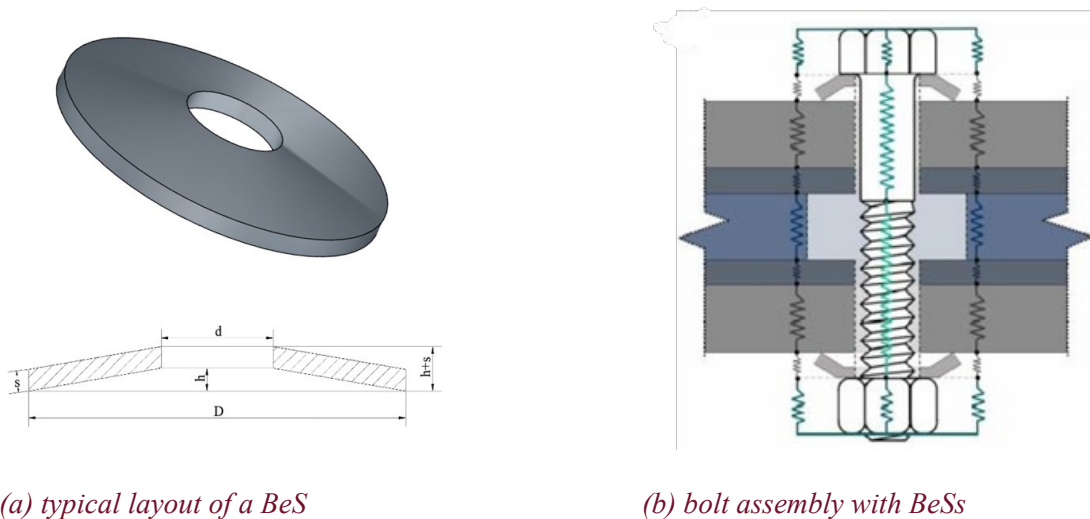
The system CoF or stable sliding CoF, μ_{SS} , is introduced by Ramhormozian et al. (2021) to determine the design sliding shear resistance, ϕV_{SS} , primarily for AFC as shown in equation (2) where N_{SS} represents the total clamping force during stable sliding.

$$\phi V_{SS} = \phi n \mu_{SS} N_{SS} \quad (2)$$

This system CoF, μ_{SS} , is suggested to be 0.50, for high hardness shims against mild structural steel, following the surface treatment procedure suggested by Ramhormozian et al. (2019). To be noted, this value is obtained based on experimental research, using different surface preparation regimes, to specially find the appropriate surface preparation procedure and its associated system CoF of the AFC with partially deflected BeSs. For SFC with BeSs, this system CoF is expected to remain similar. In addition, Sa2 or Sa2.5 as per ISO 8501 (2007) was referred to from the surface preparation, from that research, following the procedure that the fabricators used to achieve each surface treatment level. While the surface profile parameters in those experiments, such as surface roughness, associated with each surface preparation regime were measured and quantified, it is not practical to require fabricators to prepare sliding surfaces to meet such measured values. Instead, the procedure which was followed by the fabricator, was used to propose recommendations to be followed in practice. It is still challenging to consistently verify, particularly for small surface areas such as those of the shims, to consistently achieve the required surface profile via different fabricators. Therefore, careful consideration should be given to the wording of surface preparation requirements to ensure that stable and reproducible surface conditions can be consistently achieved.

Moreover, to enhance the sliding behaviour as well as post-sliding strength reduction, use of well-designed partially deflected Belleville springs (BeSs, see Figure 2) with bolts preloaded in their elastic range (instead of fully tensioning them) was proposed followed by Ramhormozian et al. (2017) developing a nut rotation based bolt tightening procedure to install the FSC bolts in the elastic range in conjunction with partially deflected BeSs (Ramhormozian et al., 2019; Ramhormozian et al., 2025). This enables the FSCs to retain the strength and stiffness of the system following a severe seismic event and/or over the lifetime of the building. Ramhormozian et al. (2021) reported that the N_{SS} to be taken as the target installed bolt tension, after considering the potential bolt tension loss and bolt tension variations. The advantage of such developments is allowing the FSC to be designed and detailed at any pre-defined required capacity. However, this also implies that the required nut rotation to achieve specific bolt tension at installation and in general the tightening procedure proposed, to be different from standardized values for traditional applications. For example, to exactly match the design action, if the required installed bolt tension on each bolt is 50 kN, that could, for example, be associated with a turn of nut for 372 degrees, which is expected to have an inherent error, although small. Moreover, appropriate rounding rules should be incorporated for practical applications

into the installation procedure. Furthermore, the implications of this rounding on both resulted overstrength and understrength factors should be explicitly considered.



(a) typical layout of a BeS

(b) bolt assembly with BeSs

Figure 2: Illustration of typical BeSs (Ramhormozian et al., 2019 and 2025)

Up to date, for AFCs used in beam-to-column connections, the overstrength factor is 1.35, which relates the extreme deformations taking also into account influence of the secondary elements such as whole beam-to-column joints' component as well as floor slab (Ramhormozian et al., 2021). For SFCs with partially deflected BeSs, the strength variation ranges between 0.80 and 1.20 of the nominal strength (Yan et al., 2025) from limited number of tests. A specific experimental campaign on sub-assemblages equipped with FSCs has been planned to enrich the dataset. Statistical analysis on the lower and upper range of system CoF and installed bolt tension is also required to revisit these factors. This paper, which will also be presented in the 12th International Conference on Behaviour of Steel Structures in Seismic Areas (STESSA), briefly explains the experiments along with their results.

3 SOURCES OF VARIABILITY

3.1 Influence of friction interfaces

The friction resistance and the repeatability of the hysteretic force displacement curves are dependent on the type of shim used. For an ideal performance, the force-displacement behaviour has to be stable, repeatable and predictable, with minimal drop in strength. It also requires a low increase in sliding friction over time and over as many installed FSCs with the same expected capacities, to allow a low overstrength factor to be used in design. Brass or mild steel shims have been researched and used in construction traditionally. The difference in hardness of the sliding interfaces, e.g. cleat and shims, minimises adhesive wear on the shims having harder surfaces, which in turn minimises abrasive wear on both surfaces, which also allows harder wear particles to embed into the softer surface which minimises wear on both surfaces (Khoo et al., 2012; Golondrino et al., 2020). The abrasion resistant steel with a high hardness, against mild steel have shown to produce stable and consistent sliding characteristics for many displacement cycles on different specimens with least material wear and the highest friction capacity per bolt. This is currently recommended in New Zealand practice. Shims of other material and coating have also been researched worldwide to deliver the same outcome including use non-metallic material (Chen et al., 2025).

3.2 Variation of clamping force

The loss of preload of bolted assemblies in FSC after installation is also a potential concern (D'Antimo et al., 2020). These variations of bolt tension are closely related to the bolt subassembly and its tightening method. When determine the strength reduction factor and overstrength factor, the short-term and long-term loss of the bolt tension as well as the influence of bolt tightening procedure should be included.

3.3 Influence of sliding velocity

Quasi-static tests are also performed to evaluate the performance of FSCs, however, dependence of the CoF and wear rate of the friction interfaces over the velocity has been reported (Rodgers et., 2018; Santos et al., 2020). In addition, Chen et al. (2025) reported that higher sliding velocities tended to induce an increase in the bolt load due to increased wear debris generation and accumulation while lower sliding velocities tended to induce a reduction in the bolt load due to wear debris evacuation. Both of these influences are expected to easily be eliminated through the use of well-designed partially deflected BeSs (Ramhormozian et al., 2017). A higher normal load was shown to enhance the velocity-dependent frictional behaviour (Chen et al., 2025). Therefore, when determine the strength reduction factor and overstrength factor, the velocity-dependended factors should be considered.

4 SUMMARY

This paper presented a background, recent developments, and the current considerations evaluating the stable sliding shear resistance of FSCs and the sources where the potential variations of the performance may come from. Considerations on evaluating strength reduction and overstrength factors for structural engineering applications are also presented. In order to obtain sufficient data for statistical analysis, further experimental research is required for which a specific experimental campaign on sub-assemblages equipped with FSCs has been planned by the authors.

5 ACKNOWLEDGEMENTS

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