

Full paper

Proposed method of bolt tightening for seismic friction-sliding connections

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Abstract

Seismic friction sliding structural connections have been a focus of research and development for over four decades. One of the challenges in the design and implementation of these connections is achieving accurate and precise clamping force through bolt tightening. An overestimated clamping force can lead to premature sliding, while an underestimated force can delay the onset of sliding and cause excessive damage during a severe earthquake. Achieving a precise clamping force during installation and maintaining it throughout the structure's lifetime is important. Well-designed Belleville Springs (BeSs) have been identified as a component in enhancing the seismic behaviour of these connections, by ensuring stable sliding behaviour and maintaining clamping force under both static and dynamic conditions. However, there is a lack of standardized methods for tightening bolts with BeSs to achieve a desirable level of bolt tension within the elastic range. This paper presents findings from bolt tightening experiments conducted on various configurations and BeS types and arrangements. Parameters such as imposed torque on the nut, BeS deflection, and nut rotation were analyzed. A nut rotation-based method is proposed to ensure that the desired level of bolt tension is achieved in both on-site and workshop applications.

Keywords

Seismic friction-sliding connections, Belleville Springs (BeSs), Bolt tightening, Clamping force, Bolt preload, Slotted bolted connection

1 Introduction

Seismic friction-sliding structural connections have been the focus of research and development for over four decades (e.g. [1-9]). One common type of these connections is the Slotted Bolted Connection (SBC), which consists of several metal plates clamped together by bolts. One or more of these plates include slotted holes to allow sliding to occur. SBCs act as energy-dissipating fuses within a structural system, i.e. they are designed to slide in a stable manner at a pre-determined sliding force during a severe earthquake. This sliding action dissipates input energy through friction, and limits the maximum force to a pre-set level (the SBC's sliding force), preventing overloading of the connected members. Examples of seismic-resistant systems using SBCs include the Rotational Slotted Bolted Connection (RSBC), FREE from DAMage (FREEDAM), and

the Sliding Hinge Joint (SHJ) beam-column connection details for Moment Resisting Steel Frames [10-12]. The RSBC and FREEDAM details employ symmetric plate arrangements, while the SHJ uses an asymmetric arrangement for their SBCs.

Two parameters influencing the design and behaviour of friction-sliding structural connections are the clamping force provided by the bolts and the coefficient of friction at the sliding interfaces. An overestimated clamping force can lead to premature sliding under service conditions, while an underestimated clamping force may delay the onset of sliding in severe earthquake, resulting in an excessive damaging force being imposed on the members connected by the friction-sliding connection, and potentially leading to member or system failure. Therefore, it is crucial for these connections to achieve a clamping force, at the time of installation, as close as possible to the design

value, and maintain it throughout the structure's lifetime. However, most bolt tightening methods specified by standards have not been specifically developed for seismic friction-sliding structural connections, but rather for conventional structural bolted connections, where, as mentioned earlier, achieving a precise level of bolt tension is not as critical.

Previous studies had demonstrated that seismic friction-sliding structural connections are prone to experiencing post-sliding clamping force loss (e.g. [4, 5, 10-14]). The improvements observed in several experiments using Belleville Springs (BeSs) suggested that further research was needed to explore and establish the use of BeSs in these connections. Ramhormozian et al. [15, 16] conducted both analytical and experimental research to establish the design and implementation of (BeSs) as a key component for significantly improving the seismic behaviour of friction-sliding structural connections, which have also been implemented in practice [17, 18]. They demonstrated that amongst the benefits of tightening bolts in their elastic range and implementing well-designed BeSs according to their recommendations, the BeSs effectively maintain the clamping force during and after sliding and provide more stable sliding behaviour. D'Antimo et al. [19] also experimentally demonstrated the benefit of using BeSs in short- and long- term retention of the clamping force.

However, there were no recommendations in the literature for a method of tightening bolts with BeSs, specifically in seismic friction-sliding structural connections, to consistently achieve a reliable level of installed bolt tension within the elastic range. As mentioned earlier, the primary available methods are mostly those specified in standards for conventional bolted connections to achieve a dependable minimum installed bolt tension; exceeding this in practice is not detrimental as it is with friction sliding connections. This presents challenges, particularly when following standards like NZS3404 [20], which primarily recommend snug tightening, and subsequent full tensioning using the part-turn method of tightening. The former method can result in significant variation in the delivered clamping force, while the latter exceeds the elastic range of the bolt preload.

This paper, which is a concise summary of research findings that have been presented in greater detail in a journal article [21], proposes a feasible and reliable method for tightening bolts with BeSs within the elastic range of bolt preload, ensuring any desired level of bolt tension to be achieved at installation, whether on site or in a workshop.

2 Experiments

A bolt tightening test setup was designed and secured on a solid bench, using a vice, to simulate a typical SBC. Four M20 High Strength Friction Grip (HSFG) Property Class (PC) 8.8 bolts were first snug tightened. Then, one M20 HSFG G8.8 bolt was removed and replaced with the target bolt/BeS assemblage for testing various configurations.

Two types of Belleville Spring (BeS) were used in this research: type 1 and type 2. Three sets of experiments with BeSs were conducted, using different configurations of type 1, type 2, and a combination of both types. According

to the BeSs manufacturer, the maximum linear deflection of type 1 and type 2 BeSs was 0.838 mm (at 124.7 kN) and 1.57 mm (at 110 kN), respectively. It is important to note that both BeS types were preset, and had a load capacity associated with their linear deflection which was greater than the target installed bolt tension. This follows the design procedure proposed by Ramhormozian et al. [15, 16], which suggests that the BeSs should be partially deflected at installation. All BeSs configurations considered in this research were either single or series. The typical geometric design of a BeS and possible stacking configurations are explained in [15].

The HSFG PC 8.8 Structural M20 bolts complied with AS/NZS 1252 [22]. The pitch of each HSFG PC 8.8 M20 bolt is 2.5 mm. Both ends of the bolts (tip and head) were prepared using a bench grinder to ensure they were flat and suitable for use with the digital height gauge. The length of each bolt was measured with the digital height gauge before installation. Bolt lengths were selected according to Clause 14.3.6.1.2 of NZS 3404 [20], ensuring that at least one clear thread was visible above the nut after tightening to ensure full engagement between the nut and the bolt body threads. All the received bolts were tested based on the "free turn of nut" check recommended by Ramhormozian et al. [23-25] and included in AS/NZS1252.2. All the bolts were lubricated before the tightening tests by Molybond® GA50 paste containing 50% molybdenum disulphide. The lubricant was applied along the threads, and the nut was then turned over the whole threaded part of the bolt to spread the lubricant all around the threads. This was done to minimize potential variations in the required torque for tightening the bolts.

A set of three 16 mm thick and two 5 mm thick, 250 mm × 250 mm structural steel plates were designed to represent a typical SBC, such as an Asymmetric Friction Connection (AFC) in the Sliding Hinge Joint (SHJ) [16]. The 16 mm thick plates were made from Grade 350 structural steel, while the 5 mm thick plates were made from Raex 450 abrasion-resistant (high hardness) steel. All surfaces were sweep-blasted, following typical steel fabrication practices in New Zealand. Each plate contained four standard holes, except for the middle plate, which featured four slotted holes.

A specialist donut load cell (LWO-60) was used to monitor and record the bolt tension during tightening. The load cell was positioned between two washers, which were specifically designed and supplied to ensure reliable readings. The load cell was provided by Transducer Techniques (TT) load cell manufacturer. A Starrett electronic digital height gauge was customized and used to measure the required dimensions of the bolt assembly before, during, and after tightening. The customization involved mounting a strong magnet at the base of the gauge to ensure a fixed and secure position for the most reliable readings. The change in BeS deflection during tightening was also measured using the digital height gauge. A RAD specialist smart socket was supplied and then customized for the specific needs of this research. The customization included providing adapters to match the bolt sizes used in the experiments. The smart socket enabled the recording of the peak torque applied to the nut, thereby generating a relationship be-

tween the applied torque and the installed tension measured by the load cell. Figure 1 shows the test setup and the torque multiplier.



Figure 1 Bolt tightening test setup and torque multiplier

The following procedure was followed for each bolt tightening test: 1) The following bolt dimensions were measured before installing each target bolt using the height gauge; (Total bolt length, Shank length, Thread length, Head height, Thickness of the hardened washer, Nut thickness) – 2) The target bolt was firmly hand (finger) tightened, and the following values were recorded; (Bolt's tension using the donut load cell, Height of the top of the nut and the tip of the bolt relative to the cap plate using the digital height gauge – 3) The bolt was tightened to snug-tight using a spanner, as specified by NZS 3404, which states: "The tightness of a bolt is achieved by a few impacts of an impact wrench or by the full effort of a person using a standard podger spanner." The bolt head was prevented from rotating while the nut was being turned. The following values were then recorded; (Bolt's tension using the donut load cell, Height of the top of the nut and the tip of the bolt relative to the cap plate using the digital height gauge, The angle of the nut's rotation from the hand-tight state, measured visually) – 4) The nut was turned up to a maximum tension while the bolt head was being prevented from any potential rotation when the nut was being turned, and the following parameters were recorded; (Bolt tension using the donut load cell, Height of the top of the nut and the tip of the bolt relative to the cap plate using the digital height gauge, Maximum imposed torque on the nut using the smart socket once the maximum installed tension was reached, The angle of the nut's rotation from the snug-tight condition visually.

3 Results, discussions, and recommendations

It was not possible to propose a practical and reliable torque-based method of bolt tightening with BeS, at least for the HSFG bolt assemblies supplied in New Zealand, which are not specifically made for torque control tightening. The reason is variability of the required torque to reach a specific tension. The very low coefficient of determination (R^2) values of the associated graphs confirm this. This was observed in the experiments under the lab conditions on the bolts that had passed the "nut free turn" check, and with same method of bolt preparation and lubrication. In practice, the variability is expected to be much higher. For example, Figure 2 shows the torque associated with target tension normalized to the average snug tight torque versus (BeS system deflection + Bolt

elongation) normalized to the bolt thread pitch, for the configurations combining both types of the BeSs.

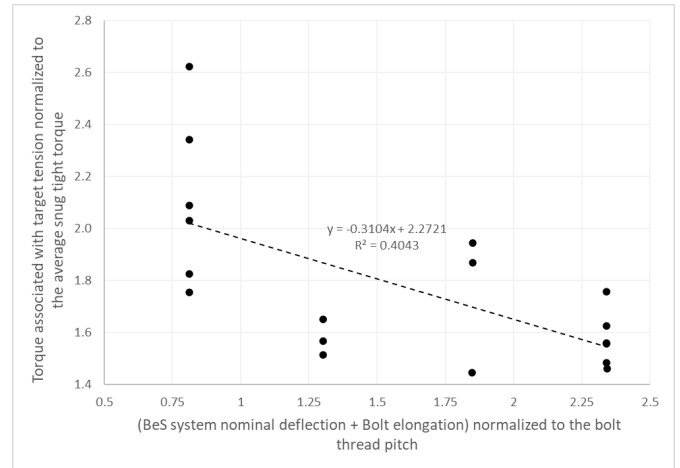


Figure 2 The relationship between (BeS system nominal deflection + Bolt elongation) and Torque associated with target tension for the tests combining both types of the BeSs

It was not possible to propose a practical and reliable BeS deflection-based method for bolt tightening with BeS, as evidenced by the very low R^2 values of the associated graphs. This observation was consistent across experiments conducted under controlled lab conditions, even with the use of the most precise customized tools available. The reason is that the deflections are small and it is difficult to set a reliable and repeatable reference point to measure the BeS deflection. Hence, it is recommended not to use a BeS deflection-based method such as using a depth micrometre or a digital gauge, to install the bolts with BeS in practice, unless a robust working procedure is established to achieve this. For example, Figure 3 shows the required post hand tight nut turn to reach the snug tight condition normalized to (the BeS system nominal deflection normalized to the bolt thread pitch), for the configurations combining both types of the BeSs.

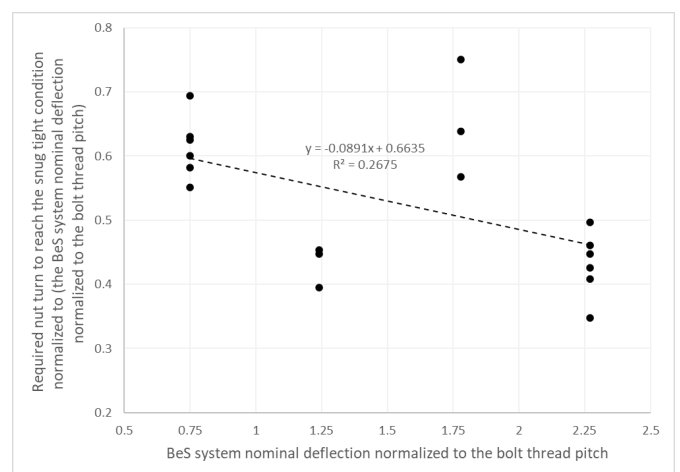


Figure 3 The relationship between BeS system nominal deflection and Required nut turn to reach the snug tight condition for the tests combining both types of the BeSs

A nut rotation-based method proved to be a potentially reliable and consistent approach, demonstrating a strong

tendency to follow a linear regression trend with high R^2 values. This method is not dependent on torque, which can be influenced by various factors such as surface conditions and coatings, and often requires specialized bolt assemblies. Additionally, it does not require direct measurement of the relatively small deflections in the BeS system. The main parameters to be correlated are the deflection of the BeS system and the pitch of the bolt. However, challenges to overcome include determining the amount of rotation, the starting point for applying this rotation, and the correct order and procedure for tightening the bolts in a connection. For example, Figure 4 shows the post snug tight and post hand tight required nut turn to reach the target tension versus BeS system nominal deflection normalized to the bolt thread pitch for the whole experiments of all types and combination of BeSs.

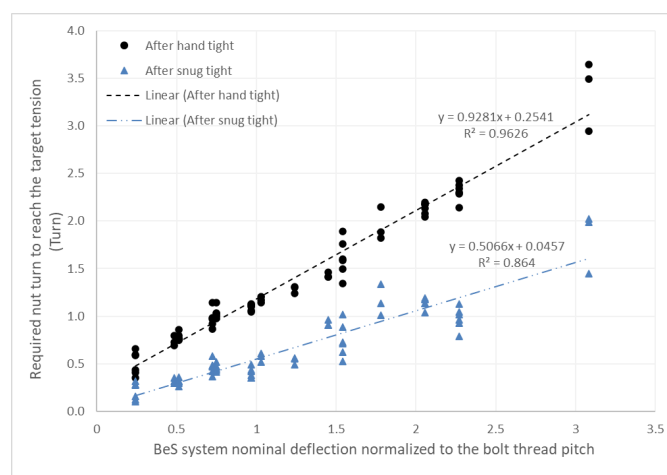


Figure 4 The relationship between BeS system nominal deflection and Required nut turn to reach the target tension (All BeS types and configurations)

The following nut rotation-based method is proposed for practical use in seismic friction-sliding structural connections:

- I. Perform the “free turn of nut” check on each bolt/nut set and reject any that do not meet the criteria. Ensure that all bolt/nut sets are properly lubricated in accordance with code requirements, and apply lubrication if necessary.
- II. Snug-tighten the bolts according to the definition provided in NZS3404 [20] to achieve the tightness achieved by the full effort of a person using a standard podger spanner. For bolts with BeSs, this can be done by applying a rotation that may be approximately at least 50% of the nominal calculated rotation required to compress the BeS system up to the target installed bolt tension. Hence it is advisable to inform the installer about the expected higher turn to reach the snug tight condition compared with the conventional practice. However, the snug tight definition is still valid and should be followed. In the case of small bolts, such as M12, where there is a risk of exceeding their elastic range during snug tightening, it is recommended to use a torque wrench and set a cut-off torque value on it. This value is recommended to correspond to approximately 70% of the proof load tension of the bolt, according to the

available charts provided by the supplier, serving as a safety measure to prevent overtightening at this stage. It is worth noting that multiple cycles of snug tightening may be required to ensure the snug-tight is achieved.

- III. Then, one by one, loosen off the bolts, hand tighten each nut then turn to the specified amount of turn to achieve the target installed bolt tension. It is recommended to start with the bolts at the least stiff part of the connection, working back in towards the stiff part of the connection. The bolt head must remain fixed while the specified amount of nut rotation is applied. The required turn can be calculated as follows: $0.25 + (0.93 \times \text{BeS system nominal deflection}) / (\text{Bolt thread pitch})$.

It is important to note that the accuracy and precision of the proposed method depend on several factors, including the accuracy, precision, and consistency of the BeS load-deflection data provided by the supplier, the accuracy, precision, and consistency of the bolt pitch, and the tolerances in the construction—specifically how closely the actual friction-sliding connection in practice matches the test setup used in this research. For instance, excessive tolerances and gaps between the connecting members may impact the accuracy of the tightening method by introducing prying force(s) and reducing the faying force(s) generated by the bolts. To ensure the reliability of the proposed method, the friction-sliding connection within the seismic resisting system should, in practice, consist of plies that are effectively in contact with minimal gaps between them. It is recommended that for specialized or unusual connection details (e.g. bolts and/or plies with unusually high or low axial stiffness or unusual stiffness ratios or specialized coatings) and/or systems with excessive tolerances, a calibration exercise be performed on the proposed method before applying it to the entire structure.

It is also recommended that the nominal deflection values for BeS used in the calculations be taken from the manufacturer's specifications for each particular BeS. In practice, field personnel may measure a higher deflection (and corresponding load) than the nominal value, which could affect the accuracy of the achieved preload. By using the nominal value from the specifications, the risk of such inaccuracy is minimized. Load-versus-deflection requirements for spring supply necessitate that the BeS supplier provide this data for each manufacturing batch.

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