Low damage brace using a Symmetrical Friction Connection (SFC) detail

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ABSTRACT: This paper reports on the quasi-static testing of a brace equipped with a symmetrical friction connection detail at one end of the brace. The symmetrical friction connection detail was assembled using Bisalloy 500 shims, and two Grade 8.8 - M16x100 galvanized bolts. Result show that the hysteresis loop of the brace is almost rectangular and that effective friction coefficient for quantifying the force that activates the sliding mechanism on the symmetrical friction detail varies in the range 0.21-0.33. Results also show that the strength degradation on the symmetrical friction connection detail is around 25% when subjecting the brace to a total cumulative travel of 6000mm. Given the stable hysteretic response and the low strength degradation exhibited by this type of brace, it can be considered as a low damage dissipater that can be incorporated in different structural systems for dissipating seismic energy.

1 INTRODUCTION

1.1 SFC brace concept and applications

SFC braces are braces equipped with a slotted plate that can either be placed at one end or within the brace. The slotted plate can slide when the brace is axially deformed, and this sliding occurs across two shear planes located at both sides of the slotted plate. The two shear planes can be generated by the section of the brace of by two thin plates termed shims that are inserted between the brace section and the slotted plate (Fig. 1).
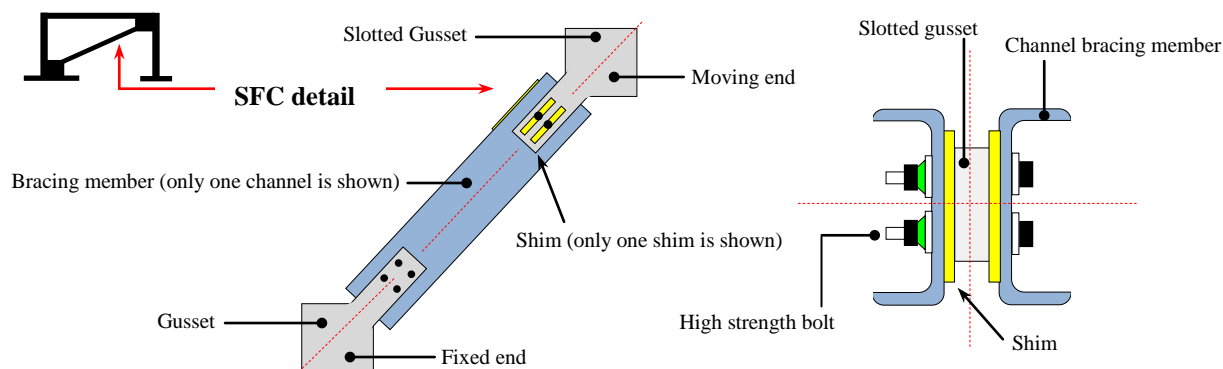

Figure 1. SFC brace configuration and cross section.

The Symmetrical Friction Connection (SFC) detail, is assembled by clamping the brace section, the slotted plate, and the shims if needed by means of high strength bolts (i.e. Grade 8.8 bolts) tensioned up to the proof load. To ensure a stable hysteretic behaviour of the brace, the slotted plate or the shims depending on the SFC detail configuration should be manufactured with a material with greater hardness than the hardness of the brace material. Materials such as Grade 300 Mild Steel on the slotted

plate, and Bisalloy 400 or Bisalloy 500 on the slotted plate or on the shims can be used in SFC details as reported by Chanchi et al. 2013. SFC braces can be used to dissipate seismic energy on braced frames or to strengthen existing moment resisting frames. In both applications the brace is placed in the frame in such a way that one end of the brace is bolted on the gusset restricting the displacement of the brace, for that reason this end is termed fixed. On the other end termed moving end the slotted plate is bolted on the gusset allowing the slotted plate to slide when the axial force induced by the seismic force on the brace is greater than friction force on the SFC detail. The SFC detail can be also assembled by slotting the gusset so that the slenderness of the slotted plate is not a critical factor on the design of the brace.

1.2 Research background

The concept of SFC braces used as dissipaters in framed buildings was initially introduced by Pall & Marsh 1982. In the initial proposal of this type of braces the SFC detail was assembled with non-metallic shims made of a heavy duty brake lining pad material. Testing of the SFC detail subassembly showed that the hysteresis loop is square, repeatable, and that the brake lining pads exhibited a negligible fade when subjected to a number of cycles comparable to the cycles that a brace can undergo during a severe earthquake (Pall and Marsh 1982). This SFC detail was placed in both directions of an X brace system, where the braces are connected with four links that activate the sliding at the SFC detail in both directions (Fig. 2a). The experimental validation of the SFC X bracing system was carried out by Filiatrault and Cherry 1987 when testing in a shaking table a 1/3 scale model of a 3 storey building initially assembled with a SFC X bracing system, and assembled twice more with a moment resisting frame system and with a bare X bracing system. Results of this experimental work confirmed that the SFC X bracing system has a superior seismic performance when compared with the two other type of systems because no damage occurred in any member of the SFC X bracing system compared with the large inelastic deformations observed in the two other type of systems when subjected to earthquake records with peak accelerations of 0.90 g. FitzGerald et al. 1989 proposed a type of SFC brace assembled with two channels back to back as bracing members and with two SFC detail located at one end of the brace. The SFC details were located at each side of the gusset plate and they were assembled by slotting the gusset plate and the channels, and by providing a cap plate at each end of the bolt (Fig. 2b). Quasi-static testing of the SFC brace showed that the hysteresis loop is rectangular and comprises two post-yielding zones associated with the sliding of the gusset plate and the cap plate. Results also show that the hysteresis loop is stable when using steel – steel interfaces without inserting any type of shims.
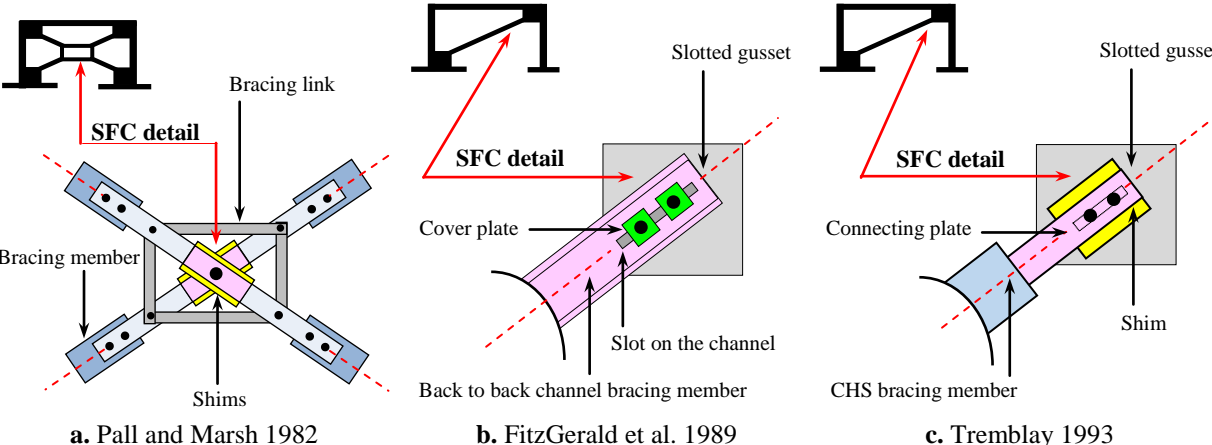

| **a.** Pall and Marsh 1982 | **b.** FitzGerald et al. 1989 | **c.** Tremblay 1993 |

Figure 2. SFC details for different brace configurations proposed on different research works.

Tremblay 1993 proposed a type of SFC brace assembled with a circular hollow section (CHS) as bracing member and with the SFC detail at one end of the brace. The SFC detail was assembled by using shims, slotting the gusset plate, and by sandwiching the gusset plate and the shims with two plates welded to the CHS (Fig. 2c). Testing of the SFC brace assembly using Mild Steel shims and Cobalt alloy shims was undertaken in quasi-static conditions. Results showed that the sliding surfaces

of SFC braces using Mild Steel shims underwent significant degradation and the hysteresis loop is unstable, and with low predictability when compared with the performance of the braces using Cobalt alloy shims. For that reason, the use of dissimilar materials at the sliding interfaces of the SFC detail was suggested aiming to achieve a stable and predictable hysteretic behaviour of the brace. More recently, Chanchi et al. 2013 tested full scale SFC assemblies with dissimilar sliding interfaces by sliding a slotted plate of Mild Steel over steel shims of different hardness such as Mild Steel, Bisalloy 80, Bisalloy 400, and Bisalloy 500. Results showed that by using a shim material with a hardness of at least 2.5 times the hardness of the slotted plate the degradation mechanism is adhesive producing very stable hysteresis loops and low degradation on the sliding interfaces. From the above research background it can be seen that different SFC braces configurations have been proposed in order to achieve a seismic brace dissipation mechanism that is inexpensive, easy to assemble, and with stable hysteresis behaviour. Following these research directions this paper proposes a SFC configuration that combines the brace configurations proposed by FitzGerald et al. 1989 and Tremblay 1993 with the concept of using high hardness shims at the SFC detail proposed by Chanchi et al. 2013. For that reason this paper aims to answer following questions:

1. What is the hysteresis loop shape of the SFC brace, and what are the influence of the construction tolerances over the hysteresis loop shape?

2. What is the effective friction coefficient that represents the behaviour of the SFC detail for the cases where the sliding surfaces are brand new and degraded?

3. What is the strength degradation of the SFC detail after being subjected to 40 quasi-static cycles with a cumulative travel of 3526mm?

4. How the hysteretic behaviour of the SFC brace can be modelled in terms of the assembling conditions of the SFC detail?

2 MATERIALS

The SFC brace was assembled using two channel sections placed back to back (Fig. 3). The chosen channel section was a 250PFC defined as a Grade 300 steel hot rolled profile with parallel flanges. The AFC detail at one end of the brace was characterized by a 200mm slot, 6mm thick Bisalloy 500 shims, and 2 M16 Grade 8.8 bolts of 100mm length (90mm grip length).
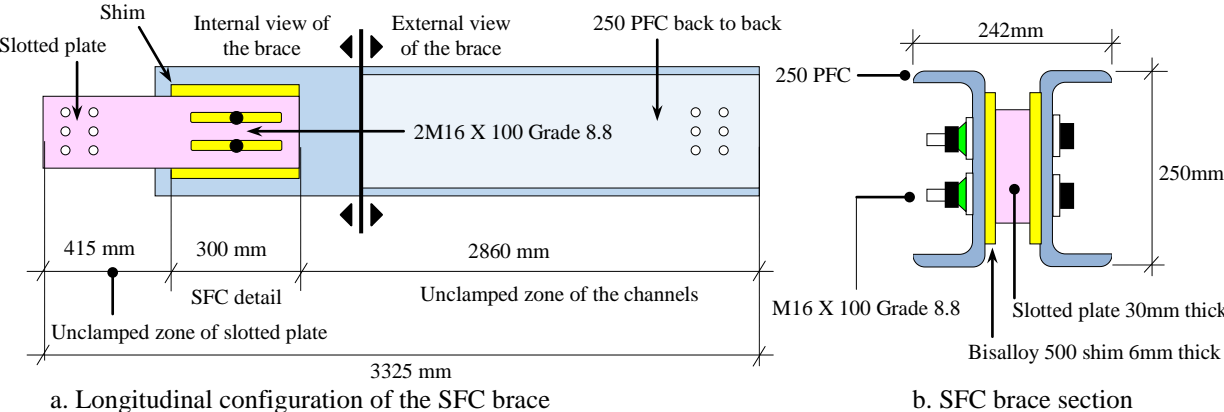

Figure 3. AFC brace specimen configuration.

The fixed plates of the SFC detail were assembled using the webs of the channels, and the slotted plate was assembled using a Grade 300 steel plate of 30mm thickness (Fig. 3b). The full length of the SFC brace was 3225mm, and this length comprises of the unclamped zone of the slotted plate, the SFC detail, and the unclamped zone of the channels. Lengths of these zones corresponded to 415mm, 300mm, and 2860mm respectively (Fig. 3a).

3 METHODS

3.1 Assembling Methods

The SFC detail was assembled using the torque control method based on finding experimentally a torque that develops the proof load on the bolts (proof load torque). In this research the proof load torque was extrapolated from a relationship between torque and induced bolt elongation. This relationship was developed by gradually increasing the torque up to the torque that fail the bolt and recording at each torque the bolt elongation. These procedure was carried out on two bolts with same grip length as that one of the brace (Fig. 4a). The bolt elongation used to extrapolate the assembling torque from the torque-induced bolt elongation relationship was defined as the elongation exhibited by two bolts when reaching the proof load from tensile testing (Fig. 4b). Using the above methodology a torque value of 200N-m from the finger tight condition was defined as proof load torque. This torque value corresponds to a nut rotation between 1/4 and 1/2 turn when using the nut rotation method.
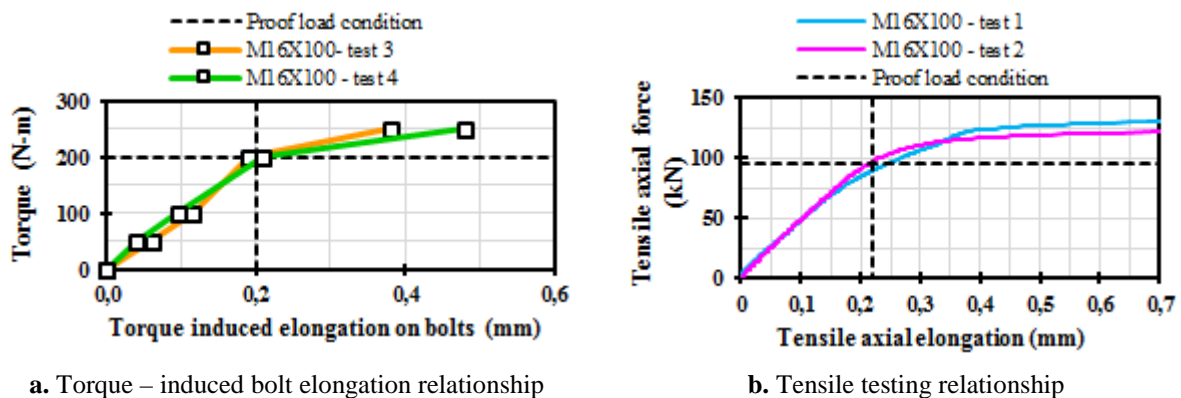

a. Torque – induced bolt elongation relationship   b. Tensile testing relationship

Figure 4. Assembling relationships for bolts Grade 8.8 M16x100mm and grip length of 90mm.

3.2 Testing Methods

The SFC brace was tested in a horizontal setup constituted by a fixed and a moving support. The fixed support was assembled with a bracket bolted on a reaction frame, and the moving support with a bracket attached to an actuator bolted on a reaction tower.
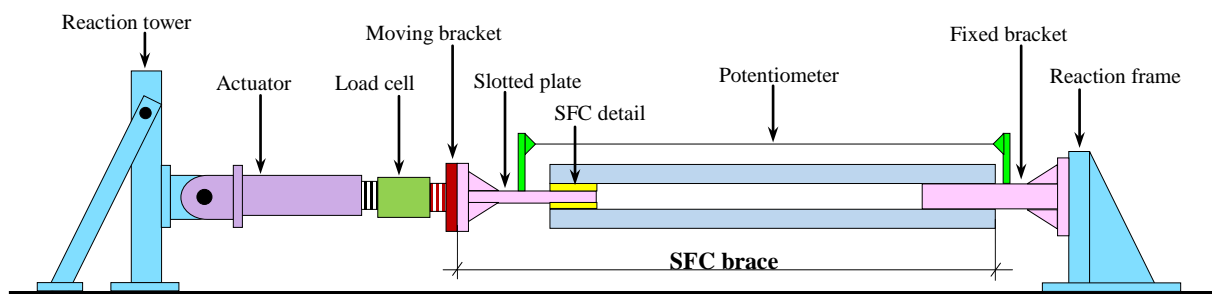
a. SFC brace testing setup
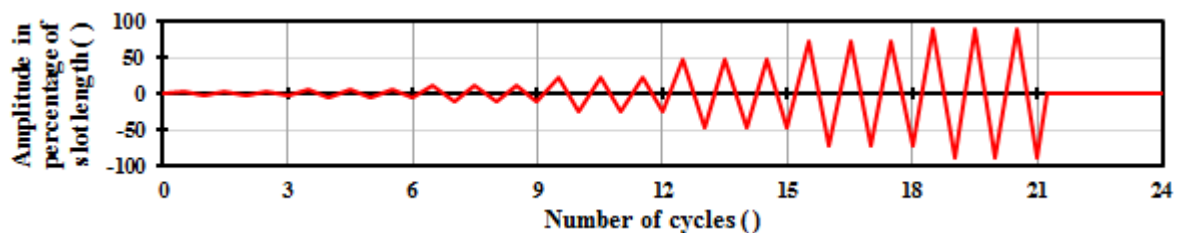
b. Displacement regime

Figure 5. SFC brace testing setup and displacement regime.

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The fixed end of the brace was bolted on the fixed support of the setup by means of a slip critical connection. The moving support of the brace (i.e. slotted plate) was welded on a bracket bolted at one end of the actuator, so that the actuator could drive the slotted plate as the stroke of the actuator is developed (Fig. 5a). This setup was instrumented with a load cell in series with the actuator and one extensometer placed horizontally across the brace length. Testing of the SFC brace was carried out by applying on the actuator two runs of a controlled displacement regime. Between the two runs a time of 15 minutes was allocated to allow the SFC detail components to cool down to the room temperature, and no bolt re-tensioning was applied after the first run of the displacement regime. The displacement regime was applied to a constant velocity of 3mm/s, and it comprises 20 sawtooth cycles with amplitudes between 3 and 90% of the total slot length of the SFC detail (i.e. 200mm). The displacement regime was characterized by a cumulative travel of 3000mm, this means that in one run of the full displacement regime the slotted plate slides a total distance of 3000mm (Fig. 5b).

4 RESULTS AND ANALYSIS

4.1 Hysteresis loop shape

SFC braces exhibited a hysteresis loop that is almost rectangular and characterized by an intermediate step that occurs in the zone where loop adopts a vertical tendency (**Fig. 6a**). The hysteresis loop is non-symmetrical, the forces on the compression side of the loop (top side) are greater than the forces on the tension side (bottom side). Either side of the hysteresis loop comprise of five stages termed: pre-sliding, limited sliding, bearing, sliding, and unloading (**Fig. 6b**).

a. Hysteresis loop

b. Priying forces on SFC detail
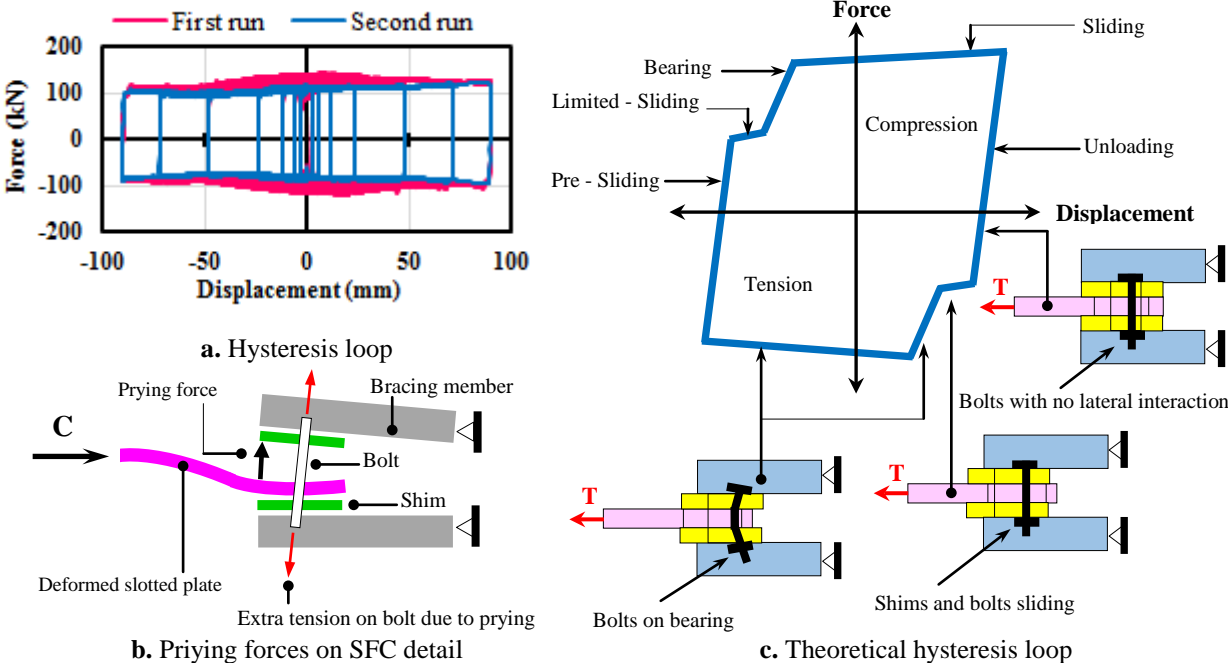
c. Theoretical hysteresis loop

Figure 6. Hysteresis loop of SFC braces using Bisalloy 500 shims and two bolts M16 Grade 8.8.

In the pre-sliding stage the force increases in a very steep tendency until sliding is activated at the interfaces between the shims and the channels, so that in the limited sliding stage the slotted plate, the shims, and the two bolts slide for a distance equivalent to the bolt hole tolerance with a minimal force increment (Fig. 6b). This minimal force increment correspond to the force required by the shims to slide the bolts across the bolt hole. In the bearing stage, once the shank of the two bolts become into lateral interaction with the webs of the channels the force increases with a steep trend (Fig. 6b). This trend is kept until the sliding is activated at the interfaces between the slotted plate and the shims producing the sliding of the slotted plate. In the sliding stage the slotted plate slides with a force that varies with the sliding distance due to the development of prying forces between the surfaces of the

slotted plate and the shims (Fig. 6b). In the unloading stage the force decreases up to zero with the same trend observed in the pre-sliding stage, and bolts loose lateral interaction with the webs of the channels so that the semi-hysteresis cycle can be repeated in the reversal direction (Fig. 6b). Prying forces increase or decrease the friction in the SFC detail, and these prying forces are developed when the bent shape of the slotted plate slide across the clamped zone of the channels on the SFC detail (Fig. 6c). The bent shape on the slotted plate was gained as a result of the non-uniform distribution of thermal stresses presented when welding the slotted plate onto the fixed bracket, and also as result of buckling issues on the slotted plate. Due to buckling issues the bent shape on the unclamped zone of the slotted plate is increased when the brace is in compression, and conversely the bent shape of the slotted plate is reduced when the brace in tension. For that reason, the prying forces and the force required to slide the slotted plate in compression are greater than those in tension.

4.2 **Effective friction coefficient**

In order to quantify the force that fully activates the sliding mechanism of the slotted plate (strength of the connection) by means of the dry friction theory of Coulomb, the definition of a friction factor is required. This friction factor is termed effective and is defined following these assumptions: i) the friction coefficient varies as the sliding surfaces undergo degradation, and ii) the tension force on the bolts remains constant as the slotted plate slides, and this tension force is equivalent to the assembling force on the bolts (proof load). To assess the effective friction coefficient following the two assumptions mentioned above, the force across the post-yielding zone of the hysteresis loop recorded experimentally was red for different semi-sliding distances. This force was termed sliding force ($F_{sliding}$), and it was divided by the product of the number of bolts (n), number of the shear planes (m), and the bolt proof load (F_{proof}) corresponding to values of 2, 2, and 95kN respectively (Equation 1).

$$\mu_{effective} = \frac{F_{sliding}}{F_{proof} \times n \times m}$$

(1)

The effective friction coefficient quantified for different sliding distances at the first and second run of the displacement regime on the SFC brace is shown in Figure 7a. It can be seen that while for the first run the effective friction varies in a wide range of 0.21-0.33 for the second run it varies in a reduced range of 0.25-0.27.
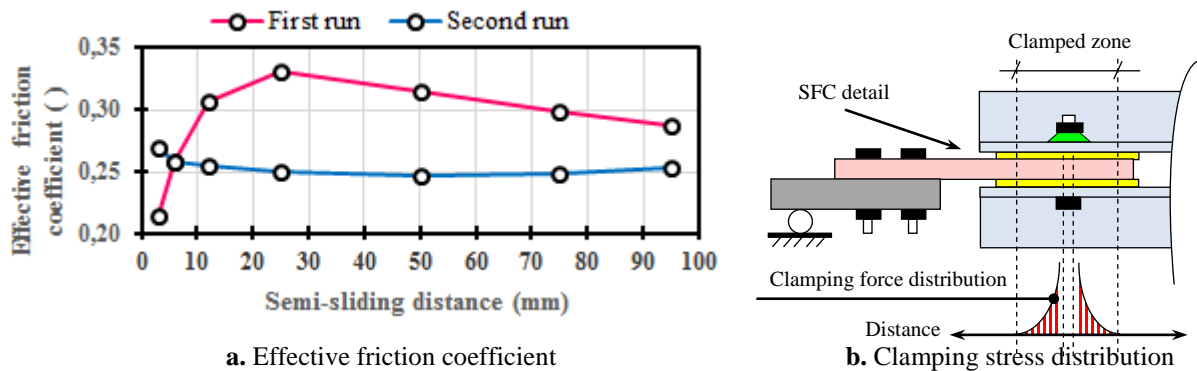

a. Effective friction coefficient   **b.** Clamping stress distribution

Figure 7. Effective friction coefficient and clamping stress distribution for SFC braces using Bisalloy 500 shims.

The effective friction coefficients calculated for the second run are less than those calculated for the first run due to the degradation that the sliding surfaces undergo. For the case of the first run, greater variations of the effective friction coefficient are observed in the range of semi-sliding distances of 3-25mm as a result of the high concentration of the clamping stresses around the bolt hole in a distance of 1.5 bolt diameter (Ito et al. 1979) as shown in Figure 7b.

4.3 Strength degradation

When the sliding surfaces of the SFC detail loose particles as debris, the channels move inwards generating a loss of bolt tension, as a consequence, the SFC detail requires less force to fully activate the sliding mechanism of the slotted plate. For that reason, the strength of the SFC detail reduces as the traveling distance of the slotted plate increases. In order to quantify the strength degradation of the SFC detail, a ratio between the effective friction coefficients calculated for the first ($\mu_{effective1}$) and second run ($\mu_{effective2}$) on the hysteresis loop was defined as the strength degradation index (SDI) (Equation 2).

$$SDI = \left[1 - \frac{\mu_{effective1}}{\mu_{effective2}} \right] \times 100\% \qquad (2)$$

The strength degradation index (SDI) was calculated for different sliding distances in Figure 8. It can be seen that for semi-sliding distances less than 6mm the strength degradation is negligible, and for sliding distances between 12 and 95mm the strength degradation varies in range of 12-25% for the case where the no shim replacement or bolt re-tensioning was carried out in the second run of the hysteresis loop. For design purposes it can be argued that the maximum likely strength degradation that this type of brace can undergo during a severe seismic movement is 25%. That is because the cumulative travel imposed on the SFC detail through the displacement regime used in this experimental work is greater than the theoretical cumulative travel estimated for braces with slotted holes during a severe seismic movement by Grigorian and Popov 1994.
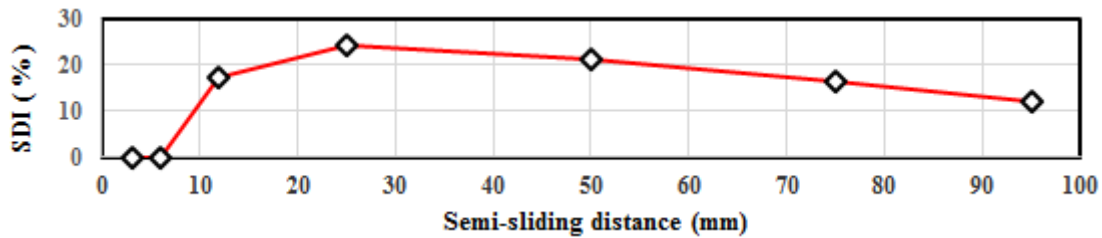

**Figure 8. Strength degradation index (SDI) for SFC braces using Bisalloy 500 shims**

4.4 Strength Assessment and approximate hysteretic model

The connection strength of SFC braces can be assessed by using the dry friction theory of Coulomb. Following this theory the strength of the connection (F_{brace}) can be expressed in terms of the number of bolts (n), the number of shear planes (m), the bolt assembling force given by the proof load (F_{proof}), and the effective friction coefficient ($\mu_{effective}$) as shown in Equation 3. In the case of the AFC brace tested in this research work, the number of bolts is two, the proof load is 95kN corresponding to bolts Grade 8.8 M16, and the effective friction coefficient that can be read from Figure 7a for Mild Steel Grade 300 surfaces sliding on Bisalloy 500 shims. In the general case of SFC braces the number of shear planes is two corresponding to the two interfaces between the slotted plate and the shims.

$$F_{brace} = n \times m \times F_{proof} \times \mu_{effective} \qquad (3)$$

The hysteretic behaviour of SFC braces can be also predicted using the dry friction theory of Coulomb. This implies that the hysteresis loop can be described by two stages: i) a first stage with a vertical trend where the force increases with no displacement of the slotted plate. This stage represent the case before the sliding mechanism of the slotted plate is activated, and ii) a second stage representing the sliding of the slotted plate by a horizontal trend with no force increment and delimited by the strength of the connection (Fig. 9a). In this model the prying forces, the buckling issues on the slotted plate, and the limited sliding of shims and the slotted plate are not considered given that the post-yielding zone of the hysteresis loop is considered flat. Figure 9b shows the hysteresis loops experimentally recorded at semi-sliding distances of 50 and 95mm and the respective theoretical model using the dry friction theory of Coulomb. It can be seen that the Coulomb model can be

considered as a good first approach for representing the hysteretic behaviour of SFC braces. In order to accurately represent the hysteretic behaviour of SFC braces the need of including prying forces, buckling on the slotted plate, and the limited sliding of the slotted plate and shims are required.
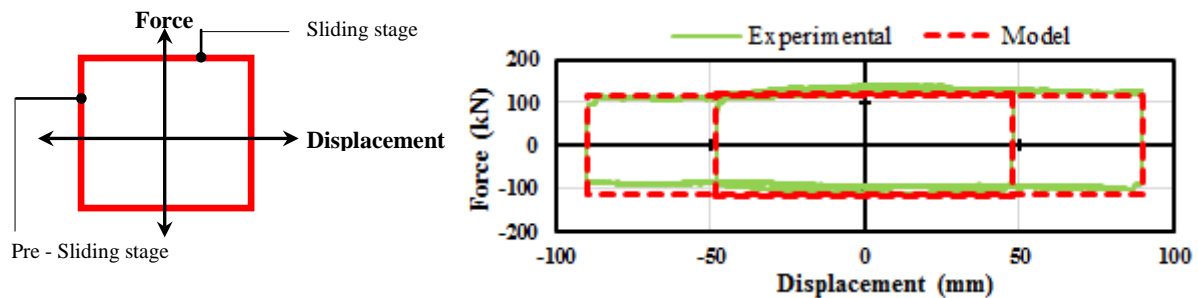
a. Hysteretic model of SFC braces   **b.** Correlation between experimental and theoretical hysteresis loops

Figure 9. Experimental and theoretical hysteresis loops of SFC braces using Bisalloy 500 shims.

5 CONCLUSIONS

This paper describes and propose a simple model to represent the hysteretic behaviour of SFC braces using Bisalloy 500 shims. It was shown that:

1. The hysteresis loop of SFC braces is almost rectangular and this shape is influenced by construction and design issues such as the bolt hole tolerance, and bent shapes of the slotted plate. While the bolt hole tolerance allows the sliding of the shims producing an steeped pre-sliding zone, the bent shape on the slotted plate produce non-flat post yielding zones.

2. The effective friction coefficient varies with the sliding distance of the slotted plate, and the greatest values were recorded for semi-sliding distances of 3-25mm. For brand new interfaces the effective friction coefficient varies in a wide range of 0.21-0.33, and for degraded interfaces it varies in a reduced range of 0.25-0.27.

3. The strength of SFC braces reduces as the sliding surfaces degrade. A maximum likely strength reduction of 25% can be expected when SFC braces with brand new Grade 300 Mild Steel – Bisalloy 500 interfaces and bolts with no re-tensioning are subjected to total cumulative travels of 6000mm in quasi-static conditions

4. A first approach on representing the hysteretic behaviour of SFC braces can be made by using a square hysteresis loop with a post-yielding zone delimited by a force given by the product of the number of shear planes, number of bolts, the bolt proof load, and the effective friction coefficient.

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