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The influence of surface preparation and the lubricating effect of mill scale on the performance of slip-friction connectors

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HIGHLIGHTS

- Abrasion resistant steel on mild steel produces stable sliding when surfaces are in the clean mill-scale condition.
- Where faying surfaces are polished so that bright steel is visible, severe frictional behaviour invariably arises.
- In one instance of polished on polished sliding, the test was terminated due to the surfaces friction welding together.
- The observed sliding behaviours of various surface types can be explained in the context of the adhesion theory of friction.
- The clean mill-scale condition should be specified in the design and implementation of slip-friction connectors.

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ABSTRACT

Slip-friction connectors have already seen implementation at the beam-column joints of numerous constructed multi-storey steel buildings, and are currently being researched for use as shear wall hold-downs, inter-wall energy dissipaters, column base hinges, and as the connectors between floor diaphragms and shear walls. Regardless of the context in which they are employed, the critical aspect of their seismic performance is the ability to provide stable sliding at a predictable structural load. If the connector strength spikes to a value significantly above the intended slip force, this would obviate the main purpose of these devices, which is to shield structural members from plasticisation. Researchers have recently found that connectors involving abrasion resistant steel in sliding against mild steel will typically exhibit stable sliding. The hardness differential of the two types of steel has been proposed as the main reason for this, and indeed stability of sliding does tend to increase with increasing difference in steel hardness. However, the experiments described in this article would suggest that other factors are also involved. Tests were carried out on slip-friction connectors in which the sliding surfaces were either in the clean mill scale condition, or had the mill scale completely removed through a process of either grit blasting or grinding. Aligning with previous research, those situations in which both the opposing surfaces in sliding are of clean mill scale, are invariably associated with highly stable sliding characteristics. However, where only one of the opposing sliding surfaces is of clean mill scale, and the other grit blasted or polished, stable sliding will eventuate only after a substantial amount of cumulative travel at low loads. Where both surfaces at a sliding interface have had mill scale completely removed, the sliding behaviour is erratic and characterised by frequent load spikes. During one test seizure occurred from friction welding. The results suggest that while dissimilar metallic hardnesses at the sliding surfaces is a necessary condition for stable sliding, it is an insufficient one, and the influence of surface preparation and the presence of mill scale are equally important. The experimental observations are then explained in the context of current tribology theory. To minimise the possibility of design loads being significantly exceeded during a seismic event, it is strongly recommended that the sliding surfaces of slip-friction connectors are in the clean mill scale condition prior to their installation.

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1. Background

Damage avoidance in seismic design, is essentially about enabling non-linear behaviour at specific locations in a structure,

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but without the normally associated material damage. Slip-friction connectors are a cost-effective way to achieve this. These connectors consist of steel plates that resist loading through mobilisation of static friction, up to a pre-defined slip threshold, F_{slip}. This slip threshold caps the magnitude of seismic forces acting on those structural elements that are intended to remain elastic. At the same time, seismic energy is dissipated through Coulomb damping [1].

Fig. 1(a) shows a *symmetric* slip-friction connector in which the two external plates resist exactly half the load applied to the centre plate. Fig. 1(b) shows an *asymmetric* connector in which external loads are applied to the centre plate, and only one of the external plates. The slip threshold, F_{slip}, is a function of both the preload in the structural bolts, and the coefficient of friction, μ. The desired preload can be achieved in various ways, such as through the use of direct tension indicator washers [2], by tightening the bolts just beyond the proof load [3], or by tensioning against a stack of Belleville washers [4,5].

Previous research has confirmed that mild steel to mild steel sliding is prone to severe stick-slip behaviour and load spiking [2,5]. In response to this, researchers inserted wafer thin brass shims between the mild steel surfaces, and this resulted in stable sliding with excellent elastoplastic characteristics [2,3,6].

In recent years, Khoo et al. [7] and Chanchi Golondrino et al. [8] achieved stable sliding in *asymmetric* connectors by adopting shims of abrasion resistant steel, instead of the more expensive brass. Loo et al. [5] enabled stable sliding in *symmetric* connectors that consisted of an abrasion resistant steel centre-plate, placed in direct sliding contact between two mild steel external plates. The use of shims was altogether avoided. The theory behind why metals of different hardnesses in contact tend towards stable sliding, is described in a seminal paper by Khoo et al. [7].

Most, if not all, experiments on slip-friction connectors [2,3,5,7,8] have been confined to specimens where the sliding surfaces are in the clean mill scale condition (which corresponds to the AISC defined Class A surface [9] in which loose rust and loose mill scale have been removed). What happens in terms of sliding behaviour, when one or both surfaces in sliding have mill scale removed is essentially unknown.

Slip-friction connectors are seeing increasing use in the construction industry, particularly at the beam-column joints of steel frame buildings [10,11]. One of the most recent innovations is the bi-directional sliding hinge joint, that has been adopted in the Terrace development in Christchurch, New Zealand [12]. Slip-friction connectors have also been proposed as shear wall hold-downs, with the concept successfully tested in timber walls and a design methodology proposed [4,13,14]. Because structures that implement slip-friction connectors depend on them to limit the loads they are subjected to during an earthquake, it is vitally important that the sliding behaviour is predictable, stable, and possesses minimal overstrength.

This article investigates the sliding characteristics of *symmetric* slip-friction connectors, that have their sliding surfaces prepared by inexpensive and commonly available methods. It is hoped that this will help inform their safe design and implementation, and that is the primary motivator of this research.

2. Connectors – configuration and surface preparation

Twenty connectors similar in configuration to those of Loo et al. [5] were fabricated. Two G350, 390 mm long mild steel external plates sandwiched a 295 mm long slotted centre-plate of abrasion resistant Bisalloy steel [15] (see Fig. 2(a)). All plates were 70 mm wide and 12 mm thick. The centre plate included a 170 mm × 22 mm slot. Two Property Class 8.8 M20 bolts were preloaded against stacks of Belleville washers to clamp the plates together. Four types of surface preparation were considered:

- the clean mill scale condition (CMS), achieved by simply removing all loosely adhering mill scale and rust using a rotary wire brush machine. This corresponds to a Class A slip resistant surface [16].
- mill scale removed by grit blasting (GB).
- the polished condition (POL), in which a belt grinding machine was used to remove all mill scale and other visual coatings, exposing a bare bright metal substrate.
- the polished condition subsequently roughened by grit blasting (POL-GB).

Fig. 2(b)–(d) show the methods used to prepare the surfaces. Both the grit blasting and polishing processes are rapid. In most cases, less than two minutes was required to prepare a single surface. Fig. 2(e) shows the surfaces immediately after surface preparation (note that the POL-GB case is visually indistinguishable by the naked eye, from the GB case).

3. Test procedure

The assembled connectors were subjected to the same displacement schedules of Loo et al. [5], which in turn, are based on the schedules that Grigorian et al. [2] used in tests on symmetric connectors with brass shims. The displacement amplitude was ±38 mm. The full schedule is shown in Fig. 3(a), with the loading rates included. Note that the schedule is non-sinusoidal. The time of acceleration to reach the peak loading rate, immediately after a change of loading direction is very small. It is therefore clear that the average loading rate associated with each set of loading cycles

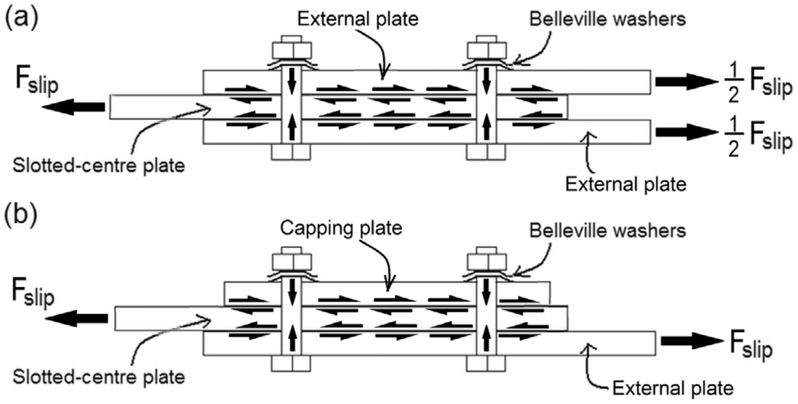

Fig. 1. Slip-friction connectors showing external loads and mobilised frictional forces: (a) Symmetric sliding mechanism, and (b) Asymmetric sliding.

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