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Experimental analysis on friction materials for supplemental damping devices

M. Latour *, V. Piluso, G. Rizzano

University of Salerno, Civil Engineering Department, Salerno, Italy

HIGHLIGHTS

- The frictional behavior of steel, brass, sprayed aluminum and three types of rubber all sliding on steel is investigated.
- The cyclic behavior of six interfaces is experimentally tested under cyclic loads.
- Static and dynamic friction coefficient of the interfaces is evaluated.
- The influence of flat washers or cone annular springs on the magnitude of the sliding force is investigated.
- An analytical model able to predict the response of three of the investigated interfaces is proposed.

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ABSTRACT

In this paper, the friction coefficient and the cyclic response of different interfaces for friction devices are investigated by means of experimental tests under displacement control. In particular, six interfaces have been tested: steel–steel, brass–steel, sprayed aluminum–steel and three different rubber based friction materials adopted, respectively, in automotive applications, electrical machines and applications requiring low wearing.

Static and kinetic friction coefficients have been evaluated and the influence of the interface pressure has been analyzed. The variation of the sliding force during the cyclic loading history has been investigated by comparing also the response coming from the use of different washers: circular flat washers and cone shaped annular disc springs.

The work is aimed at the investigation of friction materials to be applied within the connecting elements of beam-to-column joints according to the double split tee configuration with friction pads.

1. Introduction

Modern seismic resistant structures need to be designed in order to withstand frequent earthquakes without significant damages and to remain safe, even though a certain amount of structural damage is accepted, in case of rare seismic events. Concerning last case, as soon as the energy balance under seismic loading conditions is considered, it is clear that there are two main strategies to limit damage. The first one consists in minimizing structural damage by adding supplemental damping devices [10,38], either viscous or hysteretic. The second strategy consists in reducing the seismic input energy by means of seismic base isolation systems [1,17].

Dealing with the first strategy, the development of supplemental damping devices started in New Zealand about 40 years ago [2,9,18,33]. In particular, in the past few decades, the development of supplemental damping systems has received a great attention of academics and engineers leading to the development of a number of dissipative devices [3,6,10,19,24,33,34,37]. Many of these systems have been installed in buildings and bridges worldwide, both for seismic retrofit and for new constructions.

A wide category of supplemental dampers is based on dry friction for dissipating the earthquake input energy. In these elements, the energy is usually dissipated by means of the slippage between two surfaces in contact, which are clamped by means of the application of hydraulic pressures, electromagnetic forces or, in the simplest case, by means of high strength bolts. In particular, this last clamping method is, due to its simplicity, probably the most applied in civil engineering practice. In fact, by adopting high strength bolts, it is possible to apply a constant force on one or more surfaces in contact by simply governing the value of the tightening torque and the number and diameter of the bolts.

* Corresponding author. Tel.: +39 089964342.
E-mail addresses: mlatour@unisa.it (M. Latour), v.piluso@unisa.it (V. Piluso), g.rizzano@unisa.it (G. Rizzano).

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Friction dampers usually fall into the category of displacement activated dampers, because their sliding force is not dependent on the velocity and frequency content of the excitation. The cyclic behavior of friction dampers is usually described by means of a rigid-plastic response. Therefore, the only parameter needed by the designer is the slip force which, in turn, depends on the value of the load normal to the surfaces in contact and on the friction coefficient which is an intrinsic characteristic of the sliding interface. A great advantage of friction devices is that, they can be used to work as displacement reducers under service conditions while they can dissipate the seismic input energy under severe seismic actions.

The friction coefficient depends on different phenomena, such as adhesion, ploughing and the presence of contaminants. The modeling of these phenomena is usually studied in tribology where, in order to develop theories for predicting slip forces under static and dynamic loads, the surfaces' topography, materials' hardness, mechanical properties and the effects of interface layers are physically modeled. Conversely, in structural engineering, the properties of friction materials are typically studied by following the experimental approach which, for seismic engineering scopes is usually retained sufficient to provide the information needed for designing such devices.

In the technical literature several works are concerned with the characterization of the hysteretic behavior of sliding metallic surfaces with different superficial treatments clamped by means of high strength friction grip bolts. This case is particularly significant for civil engineering purposes, because the greatest part of friction dampers developed since the 1970s to be used for dissipative braces or links adopts this approach. One of the first devices of such type was that developed by [25] to be introduced at the intersection of braces, which adopted asbestos brake lining pads between the steel sliding surfaces. One of the simplest forms of friction damper has been proposed by [36] who adopted simple bolted slotted plates located at the end of a conventional bracing member. The brace-to-frame connection was designed to slip before yielding or buckling of the brace. In this device, friction is developed through the sliding of steel surfaces and, in order to maintain constant the slip load, disc spring washers were used. Another friction damper for chevron braces was proposed by [23].

An issue of paramount importance for systems using bolts as preloading elements is the maintenance of the preloading level during the device lifetime. In fact, the fluctuation of the bolt preload can lead in some cases to unstable hysteresis loops, so that the amount of energy dissipated can be somewhat unpredictable. In addition, under cyclic loading conditions, the wearing of the friction interface can lead to the partial loss of bolt preloading and, therefore, to the degradation of the slip force.

Within this framework, in this paper, an experimental study on friction materials to be applied to supplemental damping devices is carried out. In particular, six different interfaces are considered: steel–steel interface, brass–steel interface, sprayed aluminum–steel interface and three interfaces adopting different types of friction rubber-based materials. All specimens are clamped by means of high strength bolts and are tested under cyclic loading conditions. The work is aimed at understanding the potentialities of the considered materials to design new friction devices to be directly applied within the connecting elements of dissipative beam-to-column joints in MR-Frames [15,20,21], adopting as clamping method high strength bolts [22].

2. Friction theories

From the historical standpoint the major part of past tribology studies have been addressed to the investigation of friction properties of metals recognizing that there are two main sources of friction between sliding bodies: adhesion and ploughing. The adhesion component arises because when two surfaces are loaded against each other, asperities deform plastically leading to the formation of the so-called "cold-weld" junctions. Because of the intimate contact of these junctions, the shearing of the adhesive ties requires a certain sliding load. Regarding ploughing, it is due to the natural surfaces roughness, so that the relative movement between the surfaces in contact requires that one body has to lift over the other.

The simplest theory to mathematically explain the origin of the adhesion component is due to [4] who state that, being adhesion dependent on the shear resistance of the cold-weld junctions, it has to be proportional to the real contact area which, for metals with ideal elastic–plastic behavior can be assumed equal to $A = N/\sigma_0$, where A is the real area of contact, σ_0 is the material penetration hardness and N is the load normal to the surfaces. The total friction force due to adhesion (F_A) can be expressed as:

$$F_A = As = \frac{N}{\sigma_0}s \quad (1)$$

being s the force per unit of area needed to shear cold-weld junctions.

As already stated ploughing is the friction force caused by the asperities of an hard metal penetrating in a softer metal. According to Bowden and Tabor theory, this contribution is estimated as follows:

$$F_P = nrh\sigma_0 \quad (2)$$

where n is the number of asperities, r is the half-width of the asperity and h is the height of the asperity. Therefore, the total sliding force (F) due to adhesion and ploughing is given by:

$$F = F_A + F_P = \frac{N}{\sigma_0}s + nrh\sigma_0 \quad (3)$$

The ploughing component is very important during the abrasion process but, in case of metals, it has been demonstrated that such contribution is negligible compared to adhesion. Therefore, Eq. (1) explains a very important property for metals, stating that the ratio between the frictional force and the normal applied load is a constant value which does not depend on the apparent area of contact. Practically, Bowden and Tabor theory explains two of the three postulates of the classical theory of dry friction, stating that:

- The total frictional force is independent of the apparent surface area of contact.
- The total frictional force that can be developed is proportional to the normal applied action.
- In case of slow sliding velocities, the total frictional force is independent on the sliding velocity.

The first two postulates are often known as Amontons laws, after the French engineer who presented them in 1699, while the third one, is due to Coulomb [13,26].

During slippage, the classical relationship to compute the tangential force acting at the sliding interface in the direction opposed to the motion is the well-known Coulomb friction equation $F = \mu N$, where F is the sliding force, N is the normal action and μ is the friction coefficient. The force of friction is always exerted in a direction opposed to the movement (in case of kinetic friction) or potential movement (in case of static friction). According to Eq. (1) the following relationship is obtained:

$$\mu = \frac{s_0}{\sigma_0} \quad (4)$$

where s_0 is the critical shear stress of the weaker material and σ_0 is the hardness of the softest material. Eq. (4) provides reasonable results for metals, but in case of rubber-based materials, such as friction pads, the coefficient of friction should be computed