Experimental Response of Full Scale Curved Surface Sliders Equipped with High Dissipation Sliding Material

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SUMMARY:
In the last years, the availability of testing facilities of large capabilities, able to perform testing programs of full scale devices under realistic loading conditions, improved the familiarity with the behaviour of isolators as curved surface sliding bearings. Although the tribological properties of the sliding interfaces are of major importance for the proper response of sliding devices, a relatively limited number studies is available on the behaviour of engineering plastics investigating the influence of pressure and sliding velocity replicating service parameters typical of seismic devices.
The present paper illustrates the experimental campaign carried out at the Bearing Tester System of the EUCENTRE TREES Lab of Pavia (Italy), on 2 full scale devices equipped with a newly developed material. A proper experimental protocol has been defined, with the objective of characterizing all the response quantities of interest, with a focus on the dependence of the frictional properties of the sliding material on the seismic operating conditions.

Keywords: Seismic isolation, curved surface slider, experimental response, velocity, vertical load.

1. INTRODUCTION

Seismic isolation is based on the principle of uncoupling the structure from the earthquake motion. In the last years, the Curved Surface Slider (CSS), known also as Friction Pendulum System bearing (FPS, Zayas et al. 1987) has become a widely used device for seismic isolation of structures.
The Curved Surface Slider (CSS), and its more recent evolutions in double and triple Curved Surface Sliders are sliding recentering devices based on the principle of the sliding pendulum motion (Zayas et al. 1987, Fenz and Constantinou, 2006). The base device consists of two sliding plates, one of which with a spherical stainless steel surface, connected by a lentil-shaped articulated slider covered by a Teflon-based high bearing capacity composite material. In the double surface version the system is comprised of two sliding concave surfaces with a slider, which can be articulated or not, covered on the upper and lower sides with the sliding material. During the ground shaking, the slider moves on the spherical surface lifting the structure and dissipating energy by friction between the spherical surface and the slider.
The tribological properties of the sliding interfaces are of major importance for the proper response of sliding devices. Generally, in such kind of devices, one of the two surfaces is made of a hard metal alloy, usually austenitic steel, aluminium alloy or chromium plated steel, and the partner by a thermoplastic self-lubricating polymers.
In the latest years material science has made large progresses for what concerns the development of high performance materials, whose application found large space in many engineering fields.
The original employment in bridge bearings of thermoplastic polymers such PolyTetraFluoroEthylene (PTFE, Teflon) and Ultra High Molecular Weight PolyEthylene (UHMWPE) has naturally implied

their use in seismic isolators, which however require specific properties mainly related to the typical seismic service conditions, with regard not only to contact pressures, but also to sliding velocities and temperatures. Starting from the well know PTFE material, each manufactured has currently studied and developed sliding materials, generally of polymeric nature, with enhanced properties aimed to bypass the well-documented shortcomings of Teflon, which are mainly represented by the marked cold flow under stress and the highest wear among the semicrystalline polymers, which easily leads to an early component failure (e.g. Jia and Yang, 2012).
A new material has been developed by the Politecnico of Milano (Dubini, 2010, and Quaglini et. Al., 2011) and preliminarly tested on small scale specimens, in order to identify the thermal, physical and mechanical properties. Since, due to scale effects, the friction values obtained in the small scale tests can not be directly related to the isolator, in a second phase the material has been installed on full scale CSS devices in order to evaluate and monitor the response of the material in realistic operating conditions.
The present paper illustrates the experimental campaign carried out at the bearing Tester System of the EUCENTRE TREES Lab of Pavia (Italy), on 2 full scale devices, with 2 different versions of the newly developed material, for a total of 4 CSS. A proper experimental protocol has been defined, with the objective of characterizing all the response quantities of interest. The focus was on the dependence of the frictional properties of the sliding material on the CSS operating conditions (vertical load, pressure, velocity). Results of the horizontal tests are presented in terms of the main quantities of interest, focusing on the dependence of all studied quantities on the test velocity and vertical load, and temperature.

2. RESPONSE MODIFICATION FACTORS ON THE RESPONSE OF CSS DEVICES

The slider is the critical component of the Sliding Pendulum device, since its friction properties, together with the radius of curvature, determine the response of the seismic isolator.
The tribological system of the slider consists of a pair of curved surfaces, one of which is made of a thermoplastic polymer, and the other by a hard metal, usually austenitic steel, aluminium alloy or chromium plated steel.
Currently, PTFE and UHMWPE materials are employed in sliding isolators, as inherited from the bridge bearing tradition. PTFE was introduced in bridge bearings about 50 years ago, due to its very low coefficient of friction (less than 0.01 in lubricated conditions, Eggert and Kauschke, 2002).
The major drawbacks of PTFE consist in its low wear endurance and its low carrying capacity that significantly reduces at increasing temperature. The UHMWPE, as an alternative to PTFE, features higher resistance to wear and lower coefficient of friction at moderate or low temperatures, but it is characterized by a lower melting temperature and a wear rate strongly affected by the surface temperature (Baker et al., 2001).
The performances of PTFE and UHMWPE are today well understood and used as the basis for the development of the relevant standards, their behaviour is yet not well known under large velocities coupled with high pressures (related to the reduced size of the devices in which they are installed) and localized high temperatures. This is due to the fact that friction and wear of thermoplastics are complex processes, largely affected by operating conditions.
Currently, only a small number of available studies on the tribological behavior of engineering plastics investigated in detail the influence of pressure, sliding velocity and roughness replicating service parameters typical of seismic devices. Among these, only the friction behavior of PTFE has been studied in detail under seismic conditions (e.g. Mokha et al., 1990), and it is generally acknowledged that i) its coefficient of friction increases as the sliding velocity does, up to a certain velocity after which friction remains constant or decreases gradually; ii) the coefficient of friction decreases at increasing of the contact pressure; iii) the coefficient of friction is affected by the environmental temperature and the roughness of the partner surface.

2.1. Dependence of the dynamic friction coefficient on velocity, (temperature) and pressure

The dynamic friction coefficient is known to be velocity and pressure dependent (e.g. Constantinou et al., 1990). The velocity dependence can be modeled according to the following relationship (Eqn. 2.1):

$$\mu_d = f_{\max} - (f_{\max} - f_{\min}) \exp(-\alpha |\dot{u}|) \tag{2.1}$$

where f_{max} and f_{min} are the sliding coefficients of friction at large and nearly zero sliding velocities, respectively, and α is a rate parameter, that controls the transition from f_{min} to f_{max} (for example, a value of α=100 s/m is used for PTFE material, Constantinou et al., 1990).
The sliding velocity affects the coefficient of friction through the mechanism of heat generated by friction. Most polymers softens at relatively low temperatures, and this feature, combined with the low thermal conductivities of the polymer may lead to the softening of the plastic material because of local increase of temperature at the interface of sliding surfaces. When the softening of polymer occur, its coefficient of friction tends to decrease, according to a mechanism of "thermal control of friction" (Ettles, 1987). The latent heat of melting imposes a limit on the increase in temperature, such that the friction coefficient reduces when the softening temperature is reached.
The dependence of the coefficient of friction on velocity according to the model is illustrated in Fig. 2.1 (left).

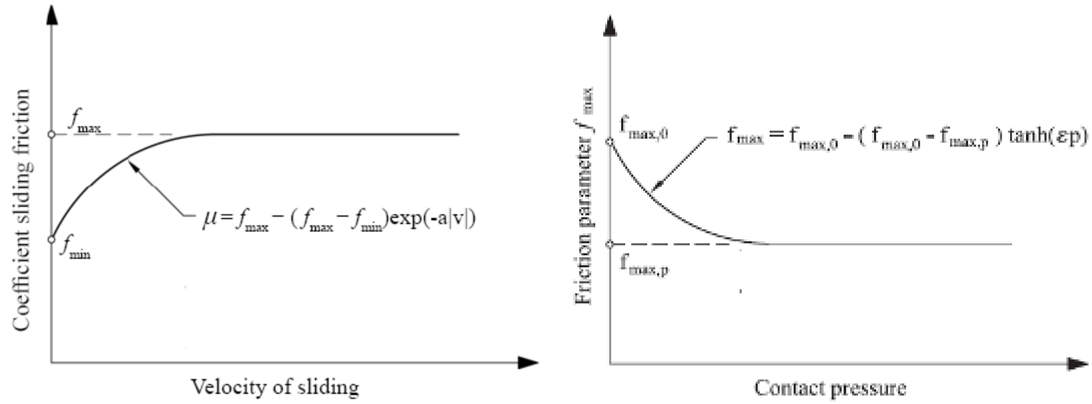

Figure 2.1. Variation of coefficient of friction with velocity of sliding (left) and pressure (right)

In general, parameters f_{max}, f_{min} and α are functions of bearing pressure and temperature. However, the dependence of f_{min} and α on pressure is negligible (compared with that of f_{max}) and can be neglected (Tsopelas et al., 1994).
A representative expression (in case of Teflon) describing the variation of parameter f_{max} with pressure is given by Eqn 2.2:

$$f_{\max} = f_{\max 0} - (f_{\max 0} - f_{\max p}) \tan(\varepsilon p) \tag{2.2}$$

where parameter f_{max} ranges from $f_{max\,0}$, at almost zero pressure, to $f_{max\,p}$, at very high pressure; p is the bearing contact pressure; and ε is a constant that controls the variation of f_{max} between very low and very high pressures. Fig. 2.1 (right) shows the assumed variation of friction parameter f_{max} with pressure (typical behaviour in case of Teflon, Soong and Constantinou, 1994).

3. EXPERIMENTAL CAMPAIGN

A testing campaign has been carried out on 2 full scale devices equipped with a newly developed material, tested on the Bearing tester System of the EUCENTRE TREES Lab of Pavia (Italy).
The newly developed material, labelled L-SLIDE, is a compound of PTFE and fillers (Dubini 2010 and Quaglini et. Al., 2011), with compressive strength higher than 90 MPa and melting temperature of 320 °C. The design specifications required for the material consisted in a coefficient of friction in seismic conditions larger than 0.10 to provide high damping capacity to the isolation system, and in the order of 0.05 at low velocities to allow service movements.

Two different version of the material (L-SLIDE-B and L-SLIDE-CF) with expected different thermal behaviour have been employed in the tested isolators.
A dedicated experimental protocol has been defined, with the objective of characterizing all the response quantities of interest. The prototypes has been designed and equipped with special instrumentation (sensors, thermocouples, etc.), in order to monitor the surface heating.
The tested device consists of a single sliding surface CSS, with L-slide at the sliding interface and a lower friction material (H-SLIDE) at the rotation interface of the articulated slider. The H-SLIDE is a blend of PolyEthyleneTerephtalate (PET) with compressive strength higher than 90 MPa and melting temperature above 250 °C, that was proposed for pendulum isolation systems designed to protect buildings subjected to medium and strong seismic actions in climatic regions with shaded air temperature between –10 °C and 50 °C (Quaglini et al. 2009).
Two devices have been tested per each sliding material, for a total of four bearings, labelled CAR77-1 and CAR77-2 (equipped with L-SLIDE-B) and CAR77-3 and CAR77-4 (with L-SLIDE-CF).

3.1.The Eucentre TREES Lab Bearing Tester System

The experimental tests illustrated in the following have been performed at the numerical and experimental laboratory TREES Lab of EUCENTRE (Pavia, Italy). The facility has been specifically designed according to the most innovative technologies and high performance equipment, and allows conducting static and dynamic experimental research on large and full-scale prototypes.
The Bearing Tester Machine is used to carry out static and dynamic experimental tests on isolation and dissipation devices. The base table (1.7 m x 4.3 m) allows vertical, longitudinal, roll, pitch and yaw controlled degrees of freedom, under a static vertical load up to 40000 kN and an additional dynamic vertical load up to 10000 kN. The BTS Controller is a real-time, digital controller that provides PID closed loop control with a delta-p feedback signal. It consists of a MTS console assembly, associated cabling and control software.

3.2.Testing Protocol

The main issues in testing a device with such a relevant friction coefficient are the post-earthquake re-centering issue and the fact that a large number of subsequent cycles, without a proper idle time, may led to a significant heating and wearing of the sliding material, which may be even more important for large velocities and vertical loads.
Fig. 3.1 shows the sliders of the two devices CAR77-1 and CAR77-3 (L-SlideB and L-SlideCF, respectively) before the test, while the same sliders after the test are shown in Fig. 3.2. It is possible to observe that the materials are worn, due to the highly demanding testing protocol. Abrasion and wear resulted in little portions of detached material and change of color of the L-Slide B slider surface, passed from green to black.

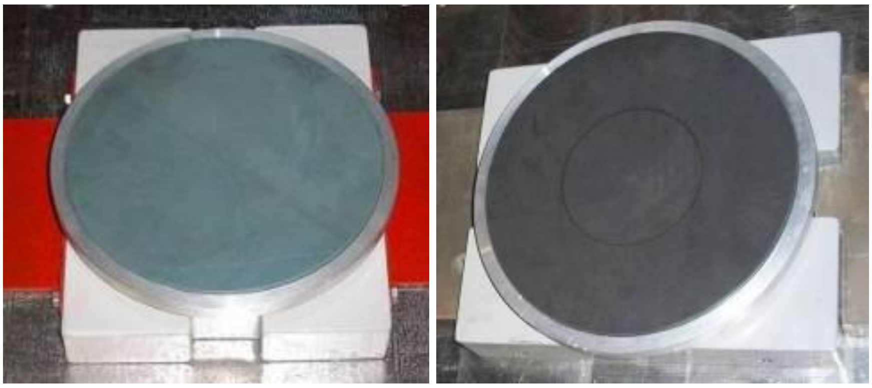

Figure 3.1. Sliders of devices CAR77-1 (L-SlideB, left) and CAR77-3 (L-SlideCF, right) before the test

Figure 3.2 Sliders of devices CAR77-1 (L-SlideB, left) and CAR77-3 (L-SlideCF, right) after the test

The testing protocol has been studied in order to have relevant information on the device response related to: i. the test velocity, ii. the applied vertical load, iii. the heating and wear of the material. Consequently the testing protocol, consists of:

- Pre-tests (vertical compression, for settlement): two cycles of loading of the device at the design vertical load and at twice such a value.
- Static friction coefficient tests: a very slow tests, to characterize the friction coefficient for slow movements.
- A series of dynamic tests at the design frequency f_d = 0.25 Hz and increasing displacement up to the design displacement d_d = 250 mm (0.25, 0.50 and 1.00 d_d). such tests have been run with a significant number of cycles (10 to 20), in order to check also the stability of the device response at repeated cycling.
- High velocity test at d_d and 2 f_d, followed by dynamic tests at d_d and at the design vertical load V_d, with increasing frequency from 0.2 f_d to 2 f_d.
- Dynamic tests at d_d and f_d, with increasing vertical load from 0.5 V_d to 1.7 V_d.

The main quantities characterizing the device response are: the breakaway (or static) friction coefficient μ, the dynamic (or sliding) friction coefficient μ_d, the post-yielding (restoring) stiffness K_r, which can be considered as primary parameters, and the equivalent viscous damping ξ and the effective stiffness K_{eff}, which are dependent from previous parameters and from the test characteristics or from a combination of them. Per each test, the reference response quantities have been reported for the third cycle.
In addition, particular attention has been devoted to the device thermal response, which has been monitored by means of an array of five thermocouples installed within the upper sliding plate, from the center every 62.5 mm along the sliding direction, at a depth of 18 to 28 mm from the sliding surface, according to the scheme in Fig. 3.3. The first 3 positions are the most sensitive to heating, since corresponding to the slider imprint, which is crossed with double frequency respect to the most external positions.

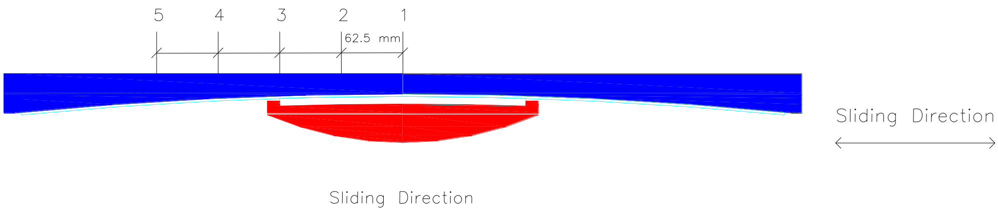

Figure 3.3 Thermocouples location scheme.

3.3. Test Results

At a first glance, it has been observed a certain degree of stability of response to repeated cycles, relatively low idle time necessary to restore the initial device temperature (mainly due to the heat dissipation provided by the full scale steel device) and significant dependence of the friction coefficient on both velocity and vertical load.

3.3.1. Dynamic friction coefficient

For the dynamic friction coefficient it is evident a dependence on the vertical load for both materials. A minor dependence on the velocity is detectable.

The dependence of the dynamic friction coefficient on the test velocity is shown in Fig. 3.4 (left), where the 3rd cycle friction coefficient ranges from 7.8% to 5,2% for velocity increasing from 393 mm/s to 786 mm/s, maintaining constant the design vertical load and given the same test displacement. Material B appear to be slightly more sensitive to the velocity increase, while the velocity influence is less evident for material CF. The decreasing friction coefficient with velocity can be explained with the phenomenon of the thermal control of friction, as previously discussed.

The gradient of the friction coefficient at increasing vertical load is very important (Fig. 3.4, right), where the 3rd cycle friction coefficient ranges from 9,8 % to 4.0 % for vertical loads increasing from 736,5 kN to 2504,1 kN, given the same test displacement and design velocity.

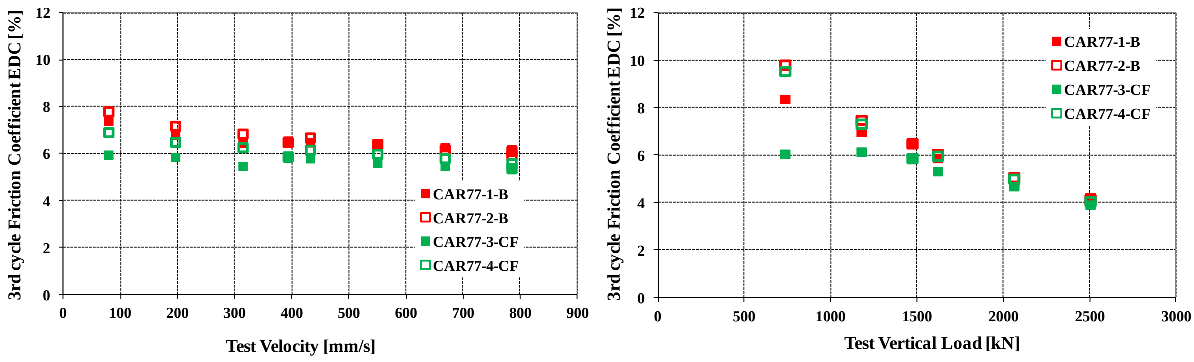

Figure 3.4. Dynamic Friction Coefficient at the 3rd cycle as a function of the test velocity and vertical load [%]

3.3.2.Breakaway friction coefficient

In Fig. 3.5, the variation of the Breakaway friction coefficient as a function of the test velocity and vertical load, respectively, has been reported.

While for most of the quantities, it is evident the dependence on the vertical load, for the breakaway friction coefficient there is apparently a more significant sensitivity to the velocity, for both materials. It has to be observed that such a response may be due to the different acceleration experienced by the device at the different test: some recent study (Salvatore et al., 2011) reports the possible influence of the acceleration on the breakaway friction coefficient. Moreover, it has to be noted that the temperature can hardly influence the breakaway friction coefficient, due to its transient nature.

The Breakaway friction coefficient ranges from a value of 9,7% to a value about 32%, for velocity increasing from 393 mm/s to 786 mm/s (Fig. 3.5, left), while it ranges from a value of 24% to a value of 11%, for vertical loads increasing from 736,5 kN to 2504,1 kN (Fig. 3.5, right).

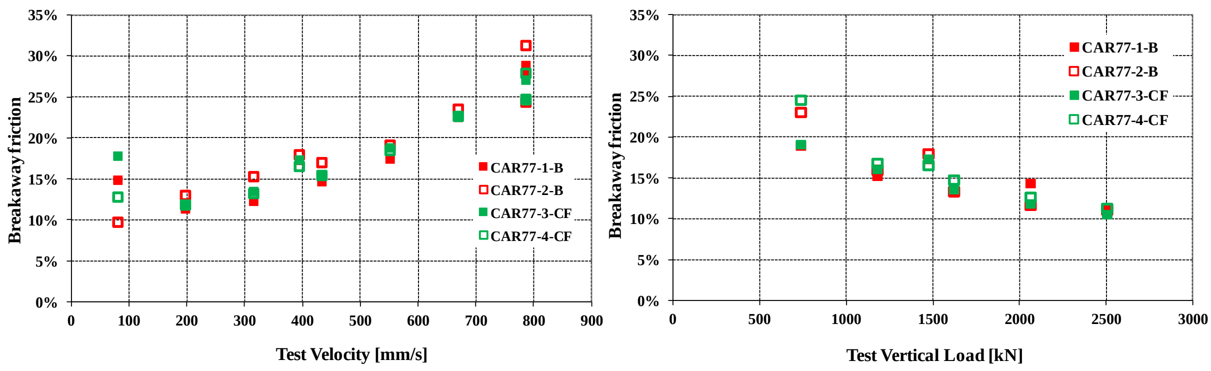

Figure 3.5. Breakaway Friction Coefficient as a function of the test velocity and vertical load [%]

3.3.3. Restoring Stiffness

The restoring stiffness for a CSS should be a solely function of the acting vertical load and of the equivalent radius of curvature of the device, without any dependence on the sliding material properties. Given that the radius of curvature is constant for each device, the parameter is expected to have a direct linear dependence on the vertical load, as conformed in Fig. 3.6 (right). No dependence on the velocity is consistently detectable (Fig. 3.6, left).

For both Materials L-SLIDE-B and L-SLIDE-CF the restoring stiffness ranges from 150 kN/m to about 610 kN/m, for vertical loads increasing from 736,5 kN to 2504,1 kN. At the design vertical load, at the design vertical load the values ranges around values of 340 kN/m (Fig. 3.6, left).

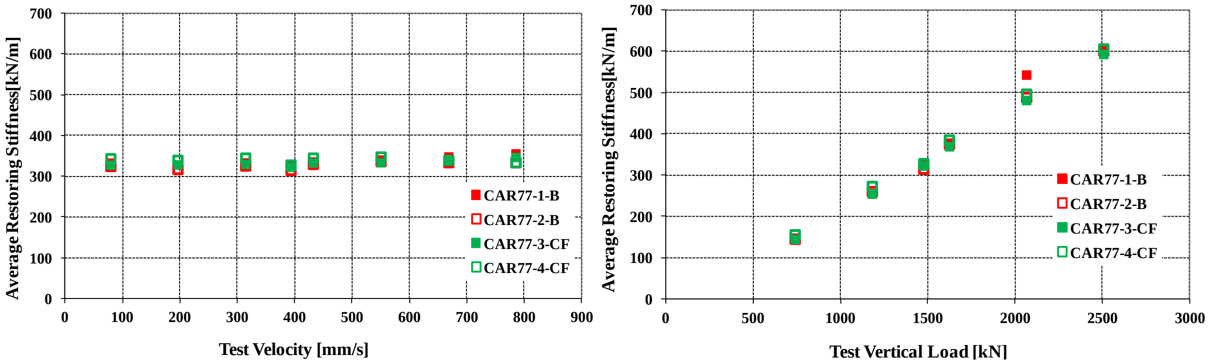

Figure 3.6. Restoring Stiffness at the 3rd cycle as a function of the test velocity and vertical load [kN/m]

3.3.4. Damping

Since the dissipation depends on the friction coefficient, damping depends on both vertical load and velocity, but the variation with the vertical load is more important (Fig. 3.7, right). For both Materials L-SLIDE-B and L-SLIDE-CF, the 3rd cycle damping ranges from about 42% to about 25%, at increasing vertical load, while the bandwith is slight narrower (38% to 26%) at increasing velocity.

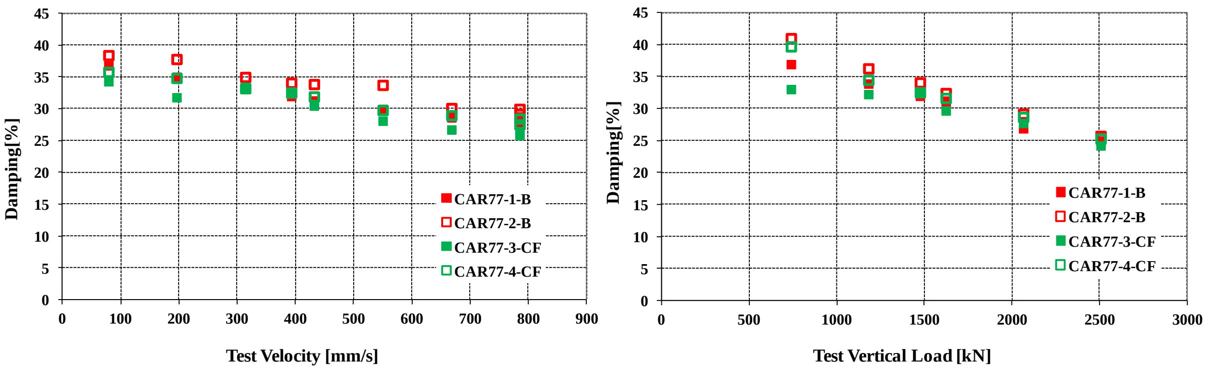

Figure 3.7. Damping at the 3rd cycle as a function of the test velocity and vertical load [%]

3.3.5. Effective Stiffness

The last parameter to be evaluated is the Effective Stiffness. The most evident dependence of such response quantity is on the vertical load (Fig. 3.8, right), while the dependence on the velocity is not really important (Fig. 3.8, left). The Effective Stiffness in both materials ranges from about 400 kN/m to about 2000 kN/m, at increasing vertical load; the values of the L-SLIDE-B are sligthly higher than those of L-SLIDE-CF. At the design vertical load values ranges around 800 kN/m.

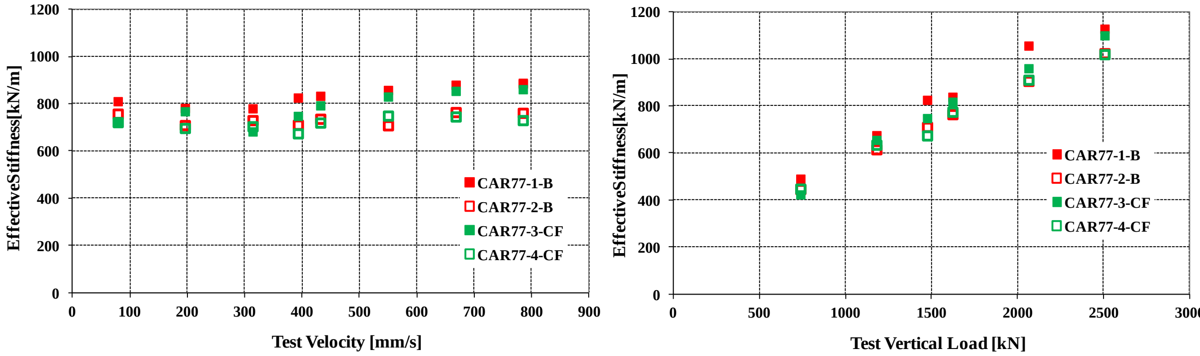

Figure 3.8. Effective Stiffness at the 3rd cycle as a function of the test velocity and vertical load [%]

3.3.6. Thermal response

In what follows, temperature results for the tests SF-3, D1-4, D2-5, D3-6 and DF-7 are provided. Despite the very high temperatures reached during the tests (up to 190°C in the case of D3 test, Fig. 3.9), it was observed that relatively low idle time was necessary to restore the initial device temperature after each test. This is mainly due to the heat dissipation provided by the full scale steel device itself, which was not detectable on the small scale test on the sliding material samples.

Fig. 3.9 shows the measurement of temperature versus time during the Dynamic test D3, for the sliding materials “L-SLIDE B” (solid line) and “L-SLIDE CF” (dashed line), at the five thermocouple locations.

During the tests, temperatures have also been monitored by means of a thermographic camera, which despite the drawback of constituting a non-continuous time-measurements, allowed to better visualise localized increase of temperature.

In the case of Dynamic 3 test, the temperatures of the L-SLIDE-B material are higher than those of the L-SLIDE-CF material. From the thermographic camera scans it was possible to note the difference of temperature between the two materials is detectable, but it is not relevant. The same response is visible in Fig. 3.9, where the continuous record of temperatures of material L-SLIDE-B are slightly larger than those recorded for the L-SLIDE-CF material. The same response is evident also in the graphs “peak temperature versus velocity” (Fig. 3.10).

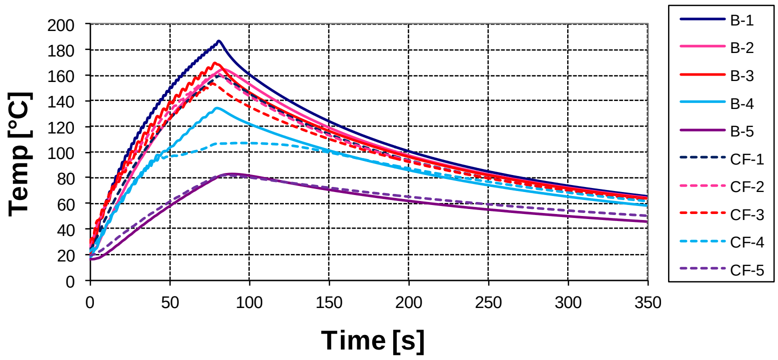

Figure 3.9. Temperature v time, Dynamic 3 Test, CAR//-L-SLIDE B and CAR77-4-L-SLIDE CF

In Fig. 3.10 the variation of the peak temperature as a function of the test peak velocity for both materials is shown. The materials B (full marks) and CF (empty marks) tested in the same day are compared in the two figures. The continuous lines indicate the highest and lowest values of recorded temperature (thermocouple 1 and 5, respectively), the solid lines represent material B, while the dashed line stands for material CF. The temperature ranges from 13°C to 184°C, in the left graph and from 15°C to 185°C, in the right graph. It is evident as the velocity affects the behaviour of the materials in terms of temperature: the temperature increases with increasing velocity up to the value of 393 mm/s and after it decreases, probably due to the fact that at the higher velocities the sliding time was not long enough to develop a large amount of heat. In both cases it is noticeable a very small difference between the two materials.

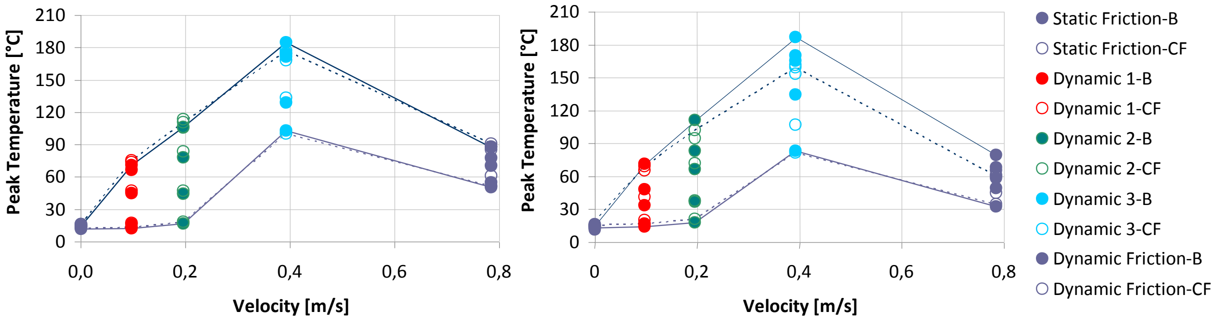

Figure 3.10. Peak Temperature vs Velocity, CAR77-1-L-SLIDE B and CAR77-3-L-SLIDE CF (left), CAR77-2-L-SLIDE B and CAR77-4-L-SLIDE CF (right)

5. CONCLUDING REMARKS

The tribological properties of the sliding interfaces are of major importance for the proper response of sliding devices, but a relatively limited number studies is available on the frictional behavior of engineering plastics investigating the influence of pressure and sliding velocity replicating service parameters typical of seismic devices.

In the present endeavor, results are illustrated of an experimental campaign carried out at the bearing Tester System of the EUCENTRE TREES Lab of Pavia (Italy), on 2 full scale devices equipped with 2 different versions of a newly developed material. A proper experimental protocol has been defined, with the objective of characterizing all the response quantities of interest, with a focus on the dependence of the frictional properties of the sliding material on the operating conditions of a seismic device (i.e. vertical load, pressure, velocity, temperature).

The sliding material installed in the tested device has been developed to respond to high dissipation requirements, for which reason particular attention has been devoted to the thermal behaviour during the tests. It has been observed a certain degree of stability of response to repeated cycles, relatively low idle time necessary to restore the initial device temperature and significant dependence of the friction coefficient on both velocity and vertical load.

As a general trend, the response quantities appear to be much more sensitive to the vertical load rather than to the velocity. This is quite relevant from the point of view of the structural response, since the axial load variation during the seismic motion may be very important (as well documented e.g. in Elnashai and Papazoglou, 1997, Ambraseys and Douglas, 2000, Calvi et al., 2004). The fact that the information about the dependence of the friction coefficient to the vertical pressure is in general not available to the designer and that the dependence of the restoring stiffness to the vertical load is generally not modeled may constitute an important issue in the design process of structures isolated with CSS devices.

While for most of the quantities the dependence on the vertical load is evident, the breakaway friction coefficient is apparently more sensitive to the velocity, for both materials, likely due to the different acceleration experiences during the tests at different velocities and same peak displacement.

The most evident effect of the velocity consists in the development of significant heating during the test, due to the large frictional properties of the sliding materials. Concerning the heating behaviour of both the materials, it has been noticed an important increase with the velocity up a value of 393 mm/s, followed by a decrease for larger values, attributable to the fact that at higher velocities the sliding time was not long enough to develop a large amount of heat. The relatively low idle time necessary to restore the initial device temperature after each test, despite the very high temperature reached during the test, is mainly due to the heat dissipation provided by the full scale steel device, and means that i. the device is able to ensure an important heat dissipation, and ii. the significant temperature increase may influence only the instantaneous response of the material, without important delayed effects.

The L-SLIDE B shows sligthly higher values than the L-SLIDE CF in almost all the response quantities and a sligthly larger sensitivity to the velocity in the thermal response. However, globally, the differences between the two materials are not relevant.

Differences could be searched for in the durability and in the wear endurance of the two materials, which however were not investigated within the present work and may constitute a further development, together with the study of the effects of ageing and exposure to environmental agents.

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