**Experimental investigation on the temperature rise of double curved surface sliders and its implications on the hysteretic behavior**

**DOI 10.37153/2686-7974-2019-16-189-201**

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**Abstract**

The hysteretic behavior of friction isolators is affected by the variability of the friction coefficient caused by heating phenomena at the sliding interface. The aim of this contribution is to investigate such heating phenomena through a series of full-scale experimental tests on a double curved surface slider. The prototype isolator is equipped with eight thermocouples placed in different points of the isolator, which are embedded in the sliding plate. The probes of the thermocouples are in contact with the stainless steel sheet covering the sliding plate, in such a manner that their measurements are representative of the temperature rise occurring at the sliding interface. By investigating different axial loads and sliding velocities, we discuss the measured temperature rise and its implications on the hysteretic behavior of the prototype isolator. Friction variation is observed in the cyclic response of the isolator, which reduces the energy dissipated per cycle and, consequently, may lead to some underestimations of the displacements occurring during real seismic events if a constant friction coefficient is assumed. The proposed data can be helpful to calibrate sophisticated thermo-mechanical finite element models, which is the object of ongoing research.

*Keywords: Curved surface sliders; Friction pendulum isolators; Heating phenomena; Friction variation; Temperature measurements.*

**1. Introduction**

In the field of passive vibration control, commonly used seismic protection strategies include seismic base isolation (Naeim and Kelly 1999; De Domenico et al. 2018b, 2018c), supplemental energy dissipation (Takewaki 2009; De Domenico and Ricciardi 2019; De Domenico et al. 2019) and tuned mass damper or enhanced variants (De Domenico and Ricciardi 2018a, 2018b, 2018c, 2018d). Curved surface sliders (CSS), also known as friction pendulum isolators, are seismic isolation devices that have been increasingly used as effective earthquake protection strategy of buildings and bridges. The pendulum operating principle is offered by an articulated slider moving along a concave surface, and the restoring capability is due to the curved geometry of the sliding surface itself. The popularity of these devices is mainly due to the large displacement capability, besides the compact shape, especially for improved versions with multiple sliding surfaces like double (Fenz and Constantinou 2006) and triple pendulum system (Sarlis and Constantinou 2013), and the lower thickness in comparison with the elastomeric devices. The imposed natural period of vibration is controlled by the sliding surface radius, thus it is not affected by the supported mass, which results in an ideal coincidence of the center of mass and center of stiffness. The energy dissipation is uniquely dependent upon the tribological properties of the sliding materials. Typical materials employed in practice include Polytetrafluoroethylene (PTFE) composites, Ultra High Molecular Weight Polyethylene (UHMWPE) and Polyammide (PA).

Experimental findings reveal that the friction coefficient of these isolators is far from being constant during an earthquake event (i.e., complying with the Coulomb’s law of friction). In reality, the friction coefficient is variable, and it may be considered as a complex function of axial load, sliding velocity and heating phenomena at the sliding interface, which may lead to significant friction variation. Among the above effects, the primary and most important source of variation of the friction coefficient is the temperature rise arising at the sliding surfaces. Friction-induced temperature rise and consequent variation of the friction coefficient are two interconnected phenomena that affect one another and that, consequently, should be carefully considered to assess the actual hysteretic characteristics of these isolation devices. Nevertheless, experimental investigations focusing on the mutual interaction between mechanical and thermal behavior are very few (Constantinou et al. 2007; Quaglini et al. 2014). Moreover, available experimental results refer to just few excitation scenarios (not exploring the variability of the temperature rise with different sliding velocity and axial loads) and are limited to single CSS. Additional experimental results that correlate the temperature rise at the sliding interface with the corresponding hysteretic behavior are desirable for a proper understanding of the complex thermo-mechanical response of friction isolators.

The aim of this contribution is to complement the previous experimental studies by considering a more general testing scenario. In this work, a double (not single) CSS is tested under different monodirectional excitations (including five sliding velocities and two levels of vertical load) at the laboratory CERISI of the University of Messina, Italy. In line with previous experimental campaigns, temperature measurements are obtained through eight thermocouples embedded into the upper plate of the device, at a certain depth below the sliding interface. The mechanical and thermal response of this device is monitored experimentally. The recorded force-displacement curves and the thermocouple registrations are useful to calibrate new thermo-mechanical models (for instance, based on finite elements) or to validate existing analytical/numerical models available in the literature (Lomiento et al. 2013, 2013b; Kumar et al. 2015; De Domenico et al. 2018a; Gandelli et al. 2018; Furinghetti et al. 2019) against experimental findings.

**2. Fundamentals of the hysteretic behavior of friction isolators**

We here recall the basics of the mechanical behavior of friction isolators focusing the attention on the frictional performance. A sketch of a double curved surface slider (DCSS) is shown in

Figure along with a schematic diagram of the corresponding force-displacement response. The device consists of a slider (typically made of steel), whose external surfaces are convex and equipped with two pads of a specific sliding material. The most widely used sliding materials are polytetrafluoroethylene (PTFE), PTFE-based composites enhanced with fillers, or self-lubricating polymers with high-bearing capacity such as ultra-high-molecular-weight polyethylene (UHMWPE). Above and below the slider there are two steel plates, whose internal surfaces are concave with the same curvature radius as the inner pads and are covered by a sheet of polished stainless steel (typically 2.5 mm thick).

When the slider departs from the original (equilibrium) position, the sliding motion along with the curvature of the surfaces give rise to a resisting force *F*. In particular, the mechanical behavior of the device is controlled by two main characteristics: 1) the curvature radius *R* of the two opposed pairs of curved surfaces (one concave and one convex); 2) the tribological properties of the sliding materials at the interface. Indeed, the curvature radius *R* affects the re-centering properties of the device according to the pendulum principle (re-centering force *F*r), in relationship with the value of the axial load *N* (i.e., the gravity load of the supported mass) and the entity of the displacement magnitude *u*. On the other hand, the frictional force *F*f arises due to the sliding motion and is ideally independent on the value of the displacement, but mainly related to the friction coefficient ** and to the signum of the sliding velocity *v*. The mathematical model describing the idealized bilinear hysteretic behavior shown in

Figure is the following (Zayas et al. 1990)

 (1)

where *W* is the applied vertical load acting on the device, represents the restoring stiffness and is the signum function. According to Eq. (1) that assumes a constant friction coefficient, the frictional force is  depending on whether the sliding velocity is positive or negative, respectively. Therefore, the bilinear hysteretic behaviour of the device stems from the sum of two contributions, the restoring force *F*r and the frictional force *F*f.

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Figure 1. Sketch of a double curved surface slider (left) and schematic force-displacement response (right)

In contrast to the assumption of constant friction coefficient underlying Eq. (1), the value of ** evolves during a real seismic event as observed in experiments. In order to highlight the real variability of the friction coefficient due to different effects, the restoring force *F*r can be subtracted by experimental measures of the total force of the device *F*, and the resulting friction force (evolving during the test) can be divided by the vertical load *W* to obtain the value of **. Relevant results obtained at the CALTRANS SRMD laboratory at the University of California San Diego are depicted in Figure 2 for two different testing pressures, namely 15 MPa and 30 MPa.

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Figure 2. Variability of the friction coefficient with pressure, velocity and cyclic effects (from Lomiento et al. 2012)

The Coulomb friction model would lead to a rectangular friction coefficient-displacement cycle, whereas the experimental loop departs significantly from this idealized rectangular shape. The main sources of variability of the friction coefficients are ascribed to the following aspects:

1. *Breakaway effects* due to the transitions between the static and dynamic values of the friction coefficients that occur at the beginning of motion and at each motion reversal;
2. *Pressure effects* as the friction coefficient decreases with increasing vertical loads; for instance, the two values of applied pressures lead to friction coefficients of around 0.08 (for *p*=15MPa) and 0.05 (for *p*=30MPa);
3. *Velocity effects* as the friction coefficient is related to the velocity of motion; it decreases with reduction of speed and this can be observed before the motion reversals by inspection of the rounded shape of the cycle near the attainment of the peak displacement values, wherein the velocity decreases down to zero;
4. *Cycling effects* as the friction coefficient decreases with repetition of cycles; this is due to heating phenomena arising at the sliding interface that induce temperature rise and friction variation. This work is mainly focused on the cycling effects, which are significant especially for high-velocity tests and for high contact pressures.

Based on these experimental observations, the frictional force *F*f entering Eq. should be considered as a complex function of vertical load, sliding velocity and temperature rise at the sliding interface as follows

 (2)

Such a model can only be calibrated based on extensive experimental data that investigate the temperature rise at the sliding interface for different vertical loads and sliding velocities. The present experimental work aims to provide a series of test results (temperature measurements and force-displacement loops) for a full-scale DCSS prototype that can be helpful to develop such complex models of friction variability.

**3. Full-scale prototype of double curved surface slider**

A full-scale prototype of double curved surface slider has been tested at the laboratory CERISI of the University of Messina, Italy (see Figure 3), whose main geometrical and mechanical characteristics are summarized in (Failla et al. 2015).

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Figure 3. Photograph of the laboratory CERISI, University of Messina, Italy

Table 1. Geometrical data of the analysed double curved surface slider

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| **Geometric dimension** | **symbol (ref. to Figure 1)** | **Length [mm]** |
| Radius of the steel plate | *A* | 765/2 = 382.5 |
| Radius of the slider | *a* | 415/2 = 206.5 |
| Radius of curvature | *R* | 3216/2 = 1608 |
| Height of the slider | *h* | 95 |
| Thickness of the pads | *t*pad | 8 |

The main geometrical properties of the device are listed in Table 1. The sliding material is UHMWPE. Before the tests, the upper plate of the DCSS prototype is CNC machined to create a set of holes that allow the installation of eight thermocouples according to the drawings and photographs in Figure 4.

J-type thermocouples are used with conductors having dimensions 1/0.3 mm, tolerance in accordance with IEC 584 Class 2 and temperature range from -60°C to +350°C. The eight thermocouples are labeled from 0 to 7, which corresponds to the numbers of channels (CH) used for the acquisition of the temperature registrations.

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Figure 4. Preparation of the DCSS prototype with eight thermocouples embedded into the upper plate

As shown in Figure 4, the thermocouples are embedded into the upper plate of the DCSS prototype and then special care has been taken in order to allow their conductors to come out from the device via two properly realized routes. The device is then installed in the testing equipment as can be seen in the photographs of Figure 5. The two routes through which the conductors pass are deep enough to prevent breakage of the wires when the upper plate is in contact with the overlying girder steel beam of the testing equipment and subject to the vertical load.

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Figure 5. Installation of the DCSS prototype into the testing equipment, with thermocouple wires coming out from the two routes realized in the upper plate

The testing protocol, listed in Table 2, comprises two bearing pressures (15 and 30 MPa) and five different sliding velocities in the range 10 mm/s – 400 mm/s. In particular, the tests 1-10 consists of a sinusoidal displacement input of the form  where  is the frequency and  the maximum displacement. These tests have a maximum velocity  and an average velocity over a cycle . These tests have allowed us to investigate the heating phenomena for different testing scenarios ranging from small contact pressures in conjunction with slow sliding motion up to more severe excitations associated with higher contact pressured in combination with higher sliding velocities. It is reasonably expected that the temperature rise is more pronounced for the latter testing conditions, as the heat flux *q* (power dissipated per unit area) can be ideally expressed by the following formula (Lomiento et al. 2013b; De Domenico et al. 2018a)

 (3)

thus increasing linearly with the vertical load *W* and the sliding velocity *v*. In Table 2 we have also included two very slow tests, named S1 and S2, wherein the maximum displacement is  and a constant velocity  is imposed through a triangular wave form, according to the UNI EN15129:2009 standards (CEN TC 340 2009). These tests are useful to investigate the breakaway effects at the beginning of motion (cf. again Figure 2) and are included in the experimental campaign to check whether the heating phenomena are present in such testing conditions with extremely slow sliding motion.

It is worth noting that the sinusoidal displacement has been imposed along the *x\_test* axis for all tests except for test #5 that has been carried along the *y\_test* axis (cf. left-hand side of Figure 4). This is important to interpret the temperature measurements of the eight thermocouples in relationship with their position in plan, since the thermocouples 4-5-6-7 are aligned with the *x\_test* axis, whereas the thermocouples 4-3-0 are aligned with the *y\_test* axis.

Table 2. Testing protocol of the DCSS prototype

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| --- | --- | --- | --- | --- | --- | --- | --- |
| **Test #** | ***u*max [mm]** | ***W* [kN]** | ***p* [MPa]** | ***v*max [mm/s]** | ***v*av [mm/s]** | **cycles [#]** | ***f*0 [Hz]** |
| 1 | 300 | 2178 | 15 | 10 | 6.4 | 3 | 0.0053 |
| 2 | 300 | 2178 | 15 | 40 | 25.5 | 3 | 0.0212 |
| 3 | 300 | 2178 | 15 | 100 | 63.7 | 3 | 0.0531 |
| 4 | 300 | 2178 | 15 | 200 | 127.3 | 3 | 0.1061 |
| 5 | 300 | 2178 | 15 | 400 | 254.6 | 3 | 0.2122 |
| 6 | 300 | 4357 | 30 | 10 | 6.4 | 3 | 0.0053 |
| 7 | 300 | 4357 | 30 | 40 | 25.5 | 3 | 0.0212 |
| 8 | 300 | 4357 | 30 | 100 | 63.7 | 3 | 0.0531 |
| 9 | 300 | 4357 | 30 | 200 | 127.3 | 3 | 0.1061 |
| 10 | 300 | 4357 | 30 | 400 | 254.6 | 3 | 0.2122 |
| S1 | 6 | 2178 | 15\* | 0.1† | 0.1† | 1 | 0.0027 |
| S2 | 6 | 4357 | 30\* | 0.1† | 0.1† | 1 | 0.0027 |

\* the bearing pressure is kept for 1 h before imposing the horizontal displacement

† triangular wave (constant velocity)

**4. Results and discussion**

For the sake of brevity, only a limited set of results of the testing protocol listed in Table 2 are here presented and discussed. In particular, tests #2 and #7 (corresponding to maximum sliding velocities of 40 mm/s) have been selected as representative situations in which the heating phenomena are not pronounced, therefore the modest temperature rise does not lead to a significant friction variation. On the other hand, tests #5 and #8, associated with higher sliding velocities, do produce a friction variation owing to the heating phenomena occurring at the sliding interface.

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Figure 6. Force-displacement loops of the DCSS prototype for test #2 (left) and test #7 (right)

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Figure 7. Temperature measurements of the eight thermocouples for test #2 (top) and test #7 (bottom)

The force-displacement loops of the tests #2 and #7 are shown in Figure 6. As can be seen, the three cycles are almost superimposed to one another, with no significant difference between the first and third loop. This indicates that the friction coefficient is not affected by the temperature rise occurring in these tests and is quite stable during repetition of cycles (i.e., no considerable cycling effects take place). The corresponding temperature values of the eight thermocouples are shown in Figure 7 for both tests #2 and #7. It is observed that the maximum temperature measured during the test #2 does not exceed 35 °C while the maximum temperature for test #7 is slightly higher than 42 °C. The higher temperature in test #7 in comparison with test #2 (at the same maximum sliding velocity) is due to the higher contact pressure (*p*=30MPa in test #7 versus *p*=15MPa), which corresponds to a doubled heat flux, cf. again Eq. (3). However, there is a contemporaneous mechanism of “thermal control of friction”, which makes the corresponding temperature rise not scaled proportionally with the heat flux (Ettles 1986).

By inspection of the different temperature measurements of the eight channels (CH #0- CH #7), it can be noted that the highest temperature value occurs at the CH #5. The thermocouple 5 is indeed placed along the *x\_test* axis and is probably the one associated with the more frequent sliding activity. Interestingly, the fluctuations of temperature are of short duration and therefore the corresponding temperature rise is called *flash temperature* in the relevant literature (Stachowiak and Batchelor 2005).

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Figure 8. Force-displacement loops of the DCSS prototype for test #5 (left) and test #8 (right)

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Figure 9. Temperature measurements of the eight thermocouples for test #5 (top) and test #8 (bottom)

Friction variation is instead observed in more severe testing excitations. In Figure 8 we show the force-displacement loops corresponding to test #5 and test #8. Especially for test #5, it is seen that the loops are narrowing after repetition of cycles, which is due to the friction variation induced by the temperature rise.

By examining the corresponding temperature measurements for the two tests shown in Figure 9, peak temperature values of around 70 °C in test #5 (with maximum sliding velocity of 400 mm/s) are obtained. Once again, the thermocouple associated with the highest value of the temperature is CH #5. However, in contrast to other tests performed along the *x\_test* axis, in the test #5 the thermocouple CH #6 is associated with higher temperature values than the other tests. A possible justification is due to the fact that the sliding motion in test #5 is directed along the *y\_test* axis, therefore the thermocouple CH #6 is placed along the peripheral part of the slider, where the highest values of the contact pressure take place. This is in line with trends of contact pressures identified in finite element analysis (De Domenico et al. 2018a), as well as in experimental tests through the aid of pressure-sensitive films placed between the sliding pad and the stainless steel sheet (Furinghetti et al. 2019). Moreover, the thermocouple CH #6 is crossed when the displacement of the device is zero and the corresponding velocity is maximum, therefore a large amount of heat flux (as a combination of pressure and velocity) is transferred. By observing the bottom part of Figure 9, the maximum temperature is slightly lower than 60 °C in test #8 (with maximum sliding velocity of 100 mm/s). This fact, in combination with the previous results obtained in tests #2 and #7, indicates that the considered sliding material (UHMWPE) does not provide relevant friction variations for temperature rise up to T=45°C. A summary of the maximum temperature rises (with respect to the initial value of temperature at the beginning of the test) measured by the eight channels (eight thermocouples) in the considered tests #2, #5, #7, #8 is reported in Table 3.

Table 3. Maximum temperature increase measured by the eight thermocouples in the tests #2, #5, #7, #8

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| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Test #** | **CH0 [°C]** | **CH1 [°C]** | **CH2 [°C]** | **CH3 [°C]** | **CH4 [°C]** | **CH5 [°C]\*** | **CH6 [°C]** | **CH7 [°C]** |
| 2 | 18.1 | 18.7 | 21.2 | 20.9 | 18.6 | 20.8 | 17.4 | 13.7 |
| 5 | 44.8 | 45.5 | 49.0 | 48.6 | 35.1 | 54.8 | 50.1 | 46.3 |
| 7 | 20.8 | 23.3 | 26.5 | 25.7 | 24.6 | 26.4 | 23.1 | 19.1 |
| 8 | 33.4 | 35.1 | 39.7 | 38.8 | 33.5 | 39.0 | 34.0 | 29.1 |

\* thermocouple associated with the highest temperature

A specific proposal of analytical or numerical model accounting for the friction variation due to the heating phenomena is beyond the scope of the present contribution. We limit ourselves to point out the main consequences of the friction variation occurring in more sever tests (like #5 and #8) in terms of the main hysteretic parameters, namely the energy dissipated per cycle (*EDC*), and the dynamic friction coefficient per cycle  computed as

 (4)

wherein the average maximum displacement  is equal to , with  and  the maximum (positive) and minimum (negative) displacement in each cycle. Finally, the average maximum force  is calculated as

 (5)

wherein  and  denote the maximum (positive) and minimum (negative) force in each cycle. Corresponding values of *EDC*,  and  for the tests #5 and #8 are listed in Table 4, from which we note that the friction variation in test #5 leads to a reduction of 12.7% in terms of *EDC* and in terms of  by comparing the first and third cycle. Similarly, the friction variation in test #8 leads to a reduction of 8.1% in terms of *EDC* and in terms of  by comparing the first and third cycle. Moreover, we verify the variation of  and  with respect to the mean value obtained from the three cycles by computing the variation values for the *i*th cycle as follows:

 (6)

with . From the values reported in Table 4 we notice that the DCSS prototype provided friction variations below ±8% of the mean value. The presented results are useful for the calibration of a numerical model, which is the object of ongoing research.

Table 4. Hysteretic parameters corresponding to two tests with friction variation

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| --- | --- | --- | --- | --- | --- | --- |
| **Test №** | **cycle n.** | ***EDC* [kJ]** | ******dyn **[%]** | ******dyn **[%]** | ***Fav* [kN]** | ***F\_av* [%]** |
| 5 | 1 | 256.73 | 10.06 | +7.84 | 415.3 | +5.20 |
| 2 | 233.41 | 9.15 | -1.92 | 390.0 | -1.22 |
| 3 | 223.75 | 8.78 | -5.92 | 379.1 | -3.98 |
| 8 | 1 | 333.96 | 6.42 | +4.67 | 671.6 | +1.87 |
| 2 | 316.39 | 6.09 | -0.83 | 656.7 | -0.38 |
| 3 | 306.74 | 5.90 | -3.84 | 649.4 | -1.49 |

**5. Conclusions**

This paper has focused on the temperature rise of friction isolators, with particular emphasis on a double curved surface slider prototype that has been analyzed through full-scale experimental tests at the laboratory CERISI of the University of Messina, Italy. The device has been equipped with eight J-type thermocouples installed just below the stainless steel sheet in order to capture the temperature rise at the sliding interface. The thermocouples are placed on specific holes realized by a numerical control machine on the upper plate of the device. Five values of sliding velocities (in the range 10 mm/s - 400 mm/s) and two values of contact pressures (15 MPa and 30 MPa) have been considered, in order to explore different thermo-mechanical responses of the DCSS prototype under a series of testing scenarios.

The results presented in this paper confirms that the temperature rise T and the consequent cycling effects are significant for the performance of full-scale friction isolators. However, the sliding material of the DCSS prototype used in the present experimental campaign, namely UHMWPE, is not significantly affected by temperature rise up to T=45 °C, at least for the tests conducted in this experimental campaign. Values of peak temperature of around 70°C have led to a certain reduction of the force-displacement loops, with a consequent reduction of the *EDC* and of the friction coefficient of a bit more than 12% when comparing the third cycle with the first cycle under imposed sinusoidal displacement tests. In contrast, in tests involving slower sliding velocities or less severe combinations of sliding velocities and contact pressures, associated with temperature rise T in the range from 25°C to 45 °C, no friction variation has been observed and the force-displacement loops are quite similar during repetition of cycles.

In the authors’ opinion, the experimental findings of the present campaign can be useful to calibrate analytical models (like phenomenological models) that account for the friction variation via variables that are only indirectly related to the temperature rise (Lomiento et al. 2013b; Gandelli et al. 2018; Furinghetti et al. 2019). Additionally, the punctual temperature measurements of the eight thermocouples may be important to calibrate and validate more sophisticated thermo-mechanical coupled finite element models that explicitly solve the thermal problem and the mechanical problem in an interconnected manner (Pantuso et al. 2000; Quaglini et al. 2014; De Domenico et al. 2018a), which is left for future research work.

**6. Acknowledgments**

This work was supported by the Ministry of Education, University and Research in Italy (MIUR) under the Research Project of National Interest (PRIN2015) “Experimental techniques for the characterization of the effective performances of trabecular morphology structures realized in additive manufacturing”.

The first two authors would like to express their gratitude to the company FIP MEC for providing the DCSS prototype used for the present experimental campaign.

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