Numerical Assessment of the Seismic Performance of Sliding Pendulum Isolators

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SUMMARY
The dynamic properties of sliding pendulum isolators employed for the seismic protection of building and structures are governed by the radius of curvature and the coefficient of friction of the sliding surfaces. A major issue concerns the heat generation occurring at the sliding interface during repeated cycles and the effects of the consequent temperature rise on the properties of the sliding materials. Typically, the coefficient of friction reduces with the increasing of temperature causing a deviation of the stiffness and damping characteristics of the isolation unit from their design value.
A finite element model of sliding pendulum isolators is now presented; both its thermal and mechanical outputs have already been validated through comparison with experimental tests.
The aim of this work is to show the potentialities of this design tool in predicting the isolator behaviour during qualification tests according to principal codes (EN 15129 and AASHTO).

Keywords: curved surface sliding isolators; seismic isolation; thermal analysis; frictional heating

1. INTRODUCTION

The Curved Surface Slider (CSS), also known as Friction Pendulum System (FPS) (Zayas et al. 1987, 1990), is today a popular and well-established hardware used for base isolation of buildings and structures against seismic actions. Design and manufacturing of curved surface sliders is regulated in the most updated standards on antiseismic devices worldwide, including the European (EN 15129 2009) and American (AASHTO 2010) codes.
The partner curved surfaces of the isolator usually consists of a convex pad made of a self-lubricant thermoplastic material and a concave steel plate. The sliding properties of the surface materials are key for the performance of the isolation system. The relevant coefficient of friction shall provide dissipation of seismic energy during the earthquake while do not constraint slow service motions induced in the structure e.g. by temperature variations and live loads; also the durability of the materials is fundamental to decide whether the isolator is capable of sustaining high velocities and a large accumulated path of service movements without any deterioration.
In this respect, one of the major issues in the selection of materials for use in CSS is related to the heat generated at the sliding interface of the isolator under large friction forces and high velocities and its effect on the properties of said surface materials.
The specific frictional power generated during sliding depends on the product of the contact stress p, the velocity V , and the coefficient of friction μ. The largest part of this frictional power is converted into heat, resulting in a substantial rise in the temperature at the sliding interface. The coefficient of friction of self-lubricating thermoplastics is temperature-dependent, and it typically decreases as the temperature rises, therefore reducing the damping characteristics of the isolation system (Mosqueda et al. 2004). In addition thermoplastic materials become softer, and their wear resistance and load carrying capacity drop, as their melting temperature is approached, representing a big concern for long term serviceability of the bearing.
A procedure for the preliminary assessment of the materials of the sliding surfaces accounting for their temperature-dependent behaviour has not yet been established. Though several experimental methods have been proposed to evaluate the friction coefficient of candidate materials under a wide range of

pressures, velocities and temperatures through small scale tests (Dolce et al. 2005; Quaglini et al. 2011), the capability of such procedures to reproduce the actual thermal state at the sliding interface of real size isolators and to give a reliable estimate of the coefficient of friction under repeated cycles is questionable. Prototype tests on full scale isolators prescribed in the standards mimic the real operation of the devices and are essential in their qualification process, but are expensive and time consuming, and therefore not indicated at the R&D stage for development and selection of new materials. Additionally, prototype tests provide evaluation of the overall properties of the device but do not allow direct estimation of local variables at the sliding interface, like temperature and pressure, which is a necessary information for the proper design and evaluation of materials' suitability.
An alternative to the experimental approach is represented by numerical investigation. However to date only a very few studies have been published, e.g. Drozdov et al. (2008) investigated in a finite element analysis the heat state of a spherical bearing with a PTFE/steel interface; in this study the energy dissipation was modelled by a constant heat source located at the interface between the PTFE and steel surfaces, and the analysis was restricted to the steady state condition, with no motion between the surfaces.
In this regard a more refined finite element framework for thermal-mechanical analyses of CSS isolators has been very recently developed and validated in experimental tests (Quaglini et al. 2012). Its main characteristics are the use of a complete three dimensional geometry of the isolator, the implementation of recursive subroutines which calculate at each time instant the friction coefficient at the sliding interface based upon the current values of contact stress and temperature, and the coupled thermal-mechanical formulation. The method allows to investigate the thermal state of the isolator, accounting for the stability of the relevant materials under the maximum temperatures produced during sliding, and to predict the effect on the deterioration of the properties of the device, like stiffness and damping.
The aim of this work is to illustrate the potentialities of this numerical framework to be used as a design tool for either performing a preliminary evaluation of the seismic hardware under the severe test conditions required by the standards, and providing fundamental information on the temperature and mechanical variables affecting the materials of the sliding surfaces.

2. FINITE ELEMENT FRAMEWORK

2.1. Model description

The numerical procedure is illustrated with reference to the analysis of a typical Curved Surfaces Slider with a pair of curved sliding surfaces and a spherical articulation as illustrated in Figure 2.1.

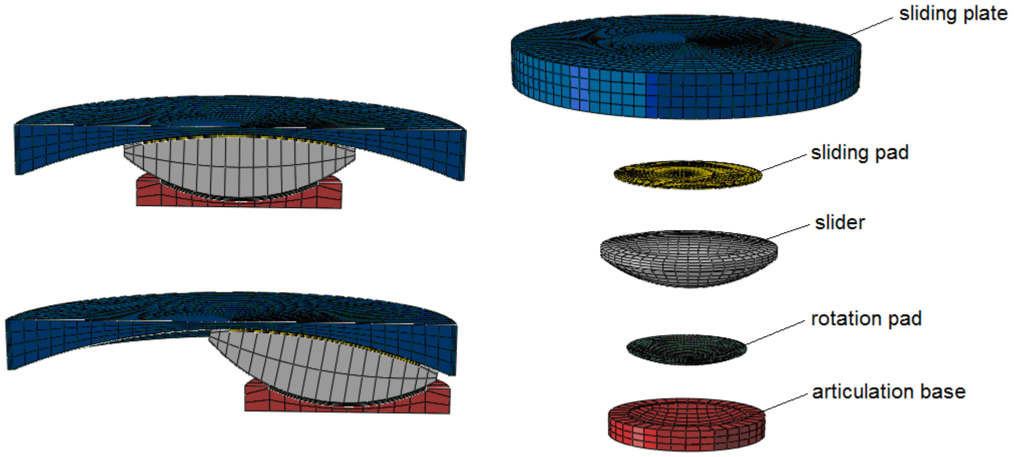

Figure 2.1. Finite element mesh of the CSS unit: typical operation (left) and details of its component parts (right)

The CSS consists of five main component parts: the concave sliding plate, the articulated slider, the basement (or articulation base), and two pads of self-lubricant materials, the first one sliding on the concave sliding plate (the sliding pad) and the second one at the spherical articulation (the rotation pad). The sliding pad is made of a PTFE composite material, with a design friction coefficient of 0.12 at ambient temperature, while the rotation pad consists of a low-friction polymer, additionally lubricated with silicon grease. The sliding plate, the basement and the slider are made of carbon steel, with the curved surfaces of the sliding plate and of the slider rubbing on the pads covered with a thin (2 mm) sheet of polished stainless steel. The relevant physical properties of the materials are listed in Table 2.1.

Table 2.1. Material properties

Material	Elastic Modulus	Conductivity	Specific Heat
	[MPa]	[mW/(mm K)]	[J/(kg K)]
carbon steel	209 000	53.7	$4.9 \cdot 10^5$
stainless steel	196·000	16.0	$5.0 \cdot 10^5$
PTFE composite	800	0.65	$1.1 \cdot 10^6$
low-friction polymer	2 800	0.25	$1.7 \cdot 10^6$

The radii of curvature of the surfaces are 1650 mm for the main sliding surface and 530 mm for the spherical articulation's, respectively.
The CSS design characteristics are listed in Table 2.2.

Table 2.2. CSS design characteristics

Design Vertical Load	N_{Sd}	4500 kN
Design Seismic Displacement	d_{bd}	340 mm
Period	T	2.13 s
Energy Dissipated per Cycle [(1)]	EDC	517 kJ
Effective Stiffness [(1)]	K_{eff}	3375 kN/m
Effective Damping [(1)]	ξ_{eff}	21 %

[(1)] evaluated at Design Seismic Displacement (d_{bd})

A three-dimensional geometrical model of the CSS is created and subdivided in a mesh of three dimensional finite elements (Figure 1). Either linear hexaedrical elements type C3D8T with 8 nodes per element and 4 degrees of freedom at each node (displacements in three directions plus temperature), or linear wedge elements type C3D6T with 6 nodes per element, were used.
The coefficient of friction of PTFE and PTFE composites generally depends on sliding velocity and temperature. Nevertheless, it is generally acknowledged (Constantinou et al. 1990; Dolce et al. 2005; Quaglini et al. 2011) that for such materials the coefficient of friction stabilizes at velocities larger than 50 mm/s; therefore in the model friction was considered dependent on temperature only.
The dependence of the coefficient of friction of the PTFE composite on the temperature developed at the sliding interface was modelled according to the exponential function:

$$\mu = \mu_0 \, exp(-\beta \cdot \theta) \tag{2.1}$$

where μ_0 is the value of the friction coefficient at 0°C, β is a parameter which represents the rate of decrease of friction with temperature, and θ is the temperature. The values $\mu_0 = 0.118$ and $\beta = 0.0027$ °C^{-1} were determined in friction tests performed on 75 mm circular specimens of the PTFE material at temperatures between 20°C and 100°C and extrapolating the reference value μ_0 at 0°C (Quaglini et al. 2011). At the spherical articulation the coefficient of friction of the rotation pad was taken to be 0.005 and the effect of temperature changes was assumed to be negligible.

2.2. Model validation

Validation of the finite element model was carried out by simulating dynamic tests as prescribed by the standard EN 15129. Details can be found elsewhere (Quaglini et al. 2012).
Mechanical and thermal boundary conditions for the analyses were defined as follows:

1. the CSS unit is subjected to the application of the design vertical load N_{Sd} = 4500 kN uniformly distributed on the upper surface of the sliding plate;
2. the sliding plate is moved horizontally with respect to the basement according to a sinusoidal waveform with constant period (T = 2.13 s);
3. the upper surface of the sliding plate keeps parallel to the lower surface of the basement during its horizontal movement, while vertical movement of the sliding plate as a consequence of the rotation at the spherical articulation the sliding plate is allowed;
4. the reference temperature of the whole model at the beginning of the analysis is θ_0 = 23°C;
5. at the upper and lower surfaces of the CCS unit, temperature holds constant throughout the analysis and equal to the reference temperature θ_0 = 23°C;
6. conductivity heat transmission is allowed at the sliding and rotation surfaces;
7. the lateral surfaces of the isolator are adiabatic (this assumption is reasonable for short time intervals which allow to neglect losses by radiation and convection).

The analyses were performed simulating two tests, carried out at displacement amplitudes of either 85 mm and 170 mm, corresponding to average speeds of 160 mm/s and 320 mm/s, respectively.
The agreement between the thermal and mechanical variables calculated by the finite element model experimental values measured in cyclic tests carried out on a prototype of the CSS unit under the same loading conditions was fairly good, as illustrated in Figures 2.2 and 2.3.

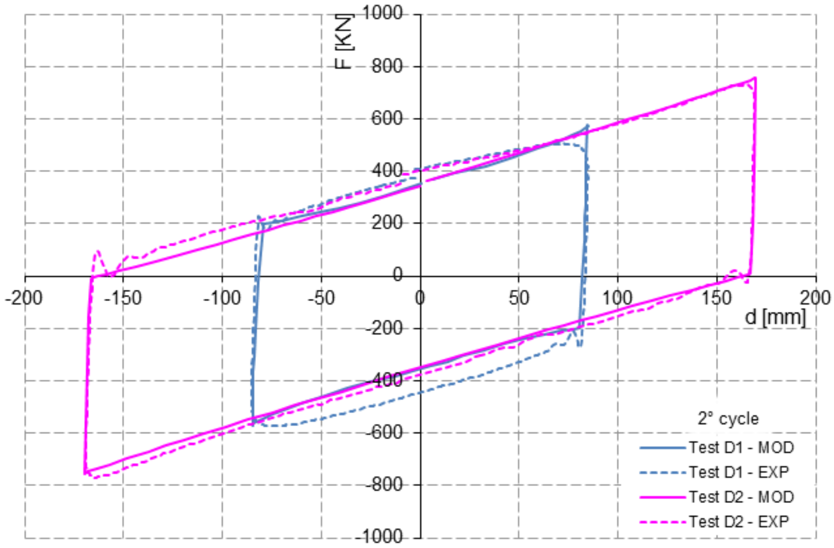

Figure 2.2. Hysteretic load – displacement diagrams of the CSS unit during cycles of horizontal loading at displacement amplitude d = 85 mm (D1) and d = 170 mm (D2) and period T = 2.13 s: comparison between finite element simulations (MOD) and experimental data (EXP)

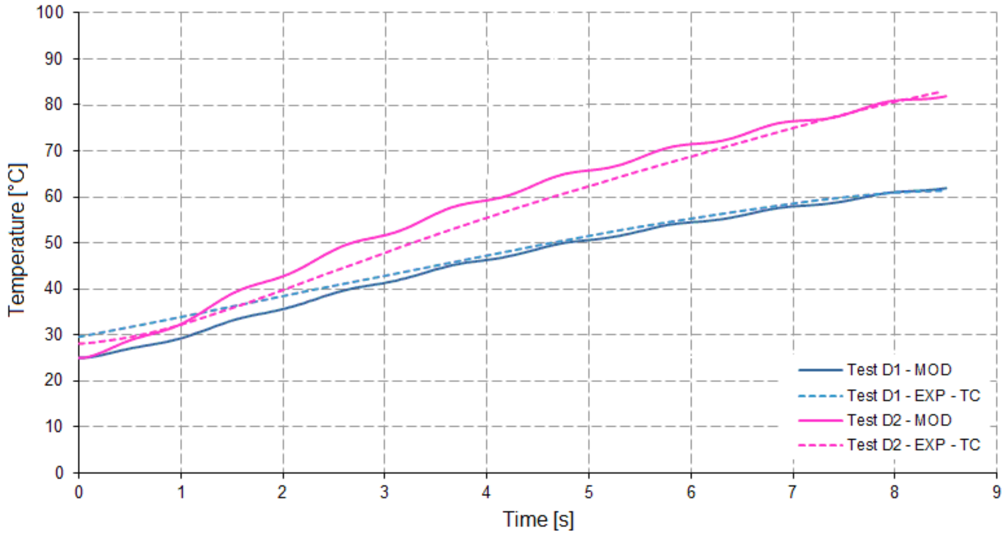

Figure 2.3. Peak temperature on the back of the stainless steel sliding surface during horizontal loading at displacement amplitude d = 85 mm (D1) and d = 170 mm (D2): comparison between finite element simulations (MOD) and thermocouple measurements (EXP)

3. SEISMIC PERFORMANCE ANALYSES

Analyses were conducted with the developed finite element formulation reproducing the tests conditions of two among the most popular standards on antiseismic devices, the European norm EN 15129 and the North-American AASHTO 2010 code. The CSS unit described in Section 2 and already used for validation was employed as the study case.

The European standard test conditions and requirements for the seismic performance of sliding isolators are defined in chapter 8.3 of EN 15129. During 3 cycles of loading at 0.25, 0.5 and 1.0 times the design displacement d_{bd}, at the natural period of the isolator, the effective stiffness K_{eff} (which is defined as the ratio between the force attained at the maximum displacement, and the maximum displacement itself) and the Energy Dissipated per Cycle (*EDC*) in each of the three cycles shall deviate no more than 15% from the relevant design value. Tests parameters for the study case are listed in Table 3.1.

Table 3.1. Test parameters according to EN 15129 standard

Test	Vertical Load	Displacement	Period	Velocity	Cycles
	[kN]	[mm]	[s]	[mm/s]	[-]
D1	4500	85	2.13	160	3
D2	4500	170	2.13	319	3
D3	4500	340	2.13	638	3

The AASHTO code recommends that during 20 cycles of loading at the design displacement d_{bd} the variations of the effective stiffness and the *EDC* shall be less than 20% and 30% respectively with respect to the peak values at the first cycle. Tests parameters for the study case are listed in Table 3.2.

Table 3.2. Test parameters according to AASHTO standard

Test	Vertical Load	Displacement	Period	Velocity	Cycles
	[kN]	[mm]	[s]	[mm/s]	[-]
D4	4500	340	2.13	638	20

From each analysis both the global response of the isolator, represented by the load – displacement curve, and local variables at the sliding interface were computed.

4. RESULTS

4.1. Simulations according to EN 15129

Figure 4.1 reports the load - displacement hysteretic curves of the CSS unit calculated in the numerical tests D1, D2 and D3 (left) and the plots of the average temperature attained on the surface of the sliding pad during the 3 cycles of each test (right). In each tests, increasing the number of cycles produces both a decrease in the resisting force and an increase in the surface temperature, and both effects become more evident at higher velocities.

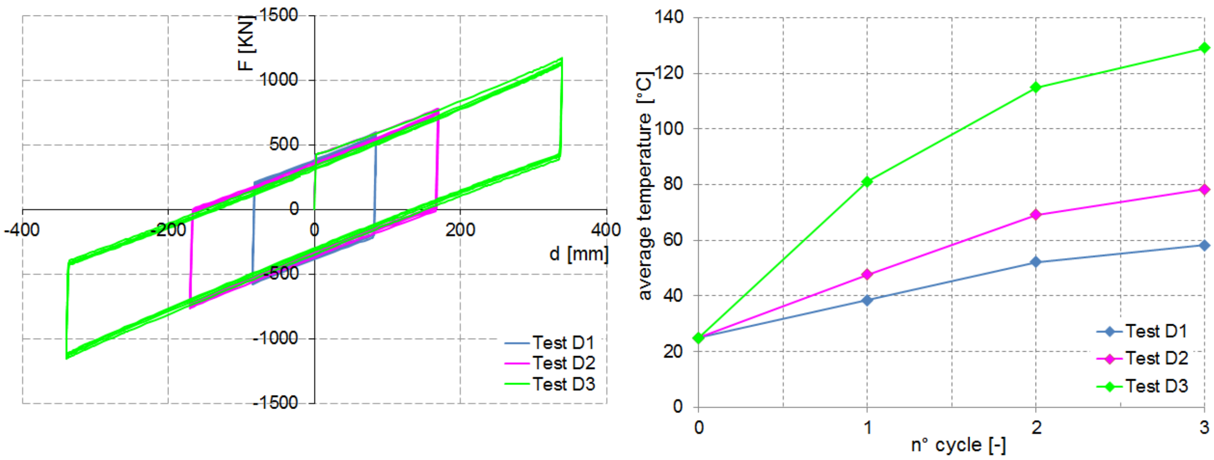

Figure 4.1. Load – displacement diagrams and cycle histories of average temperature on the surface of the sliding pad of the CSS unit during test D1, D2 and D3

From the hysteretic loops the Energy Dissipated per Cycle (*EDC*) and the effective stiffness (K_{eff}) of the CSS unit were calculated.

Figures 4.2 reports the values of both parameters during repeated cycles in Test D1, D2 and D3 and the relevant ranges of acceptability according to EN15129 (maximum change from the design value less than 15%).

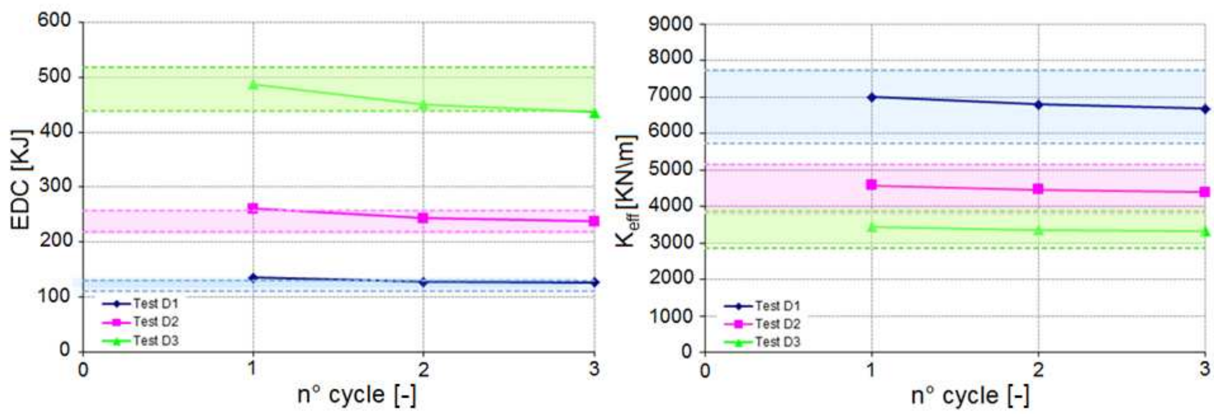

Figure 4.2. Change of Energy Dissipated per Cycle (*EDC)* and Effective Stiffness (K_{eff}) during repeated cycles at different speeds and range of acceptability (colored strips) according to EN 15129

The Energy Dissipated per Cycle and effective stiffness of the isolator decline from the first cycle to the subsequent ones. However the variations from the relevant design values are lower than 15% and the standard requirement is fulfilled.

Figure 4.3 illustrates the temperature on the rubbing surface of the sliding pad at each cycle during Tests D1, D2 and D3. Temperature increases during motion as effect of frictional heating, as expected,

and exhibits a not uniform profile on the surface, with higher values close to the perimeter of the pad and lower values at the centre. Peak values as high as 106°C in Test D1, 169°C in Test D2 and 221°C in Test D3 respectively, were determined at the edges of the pad surface perpendicularly to the direction of sliding.
The contact stress *p* on the rubbing surface of the sliding pad, as shown in Figure 4.4, resembles the temperature pattern of Figure 4.3. Pressure increases from the centre of the pad towards the perimeter, where larger values are produced due to the combined effect of the Hertz pressure distribution, curvature of the sliding surfaces and load eccentricities. At the maximum displacement amplitude, peak values as high as 60 MPa were produced.

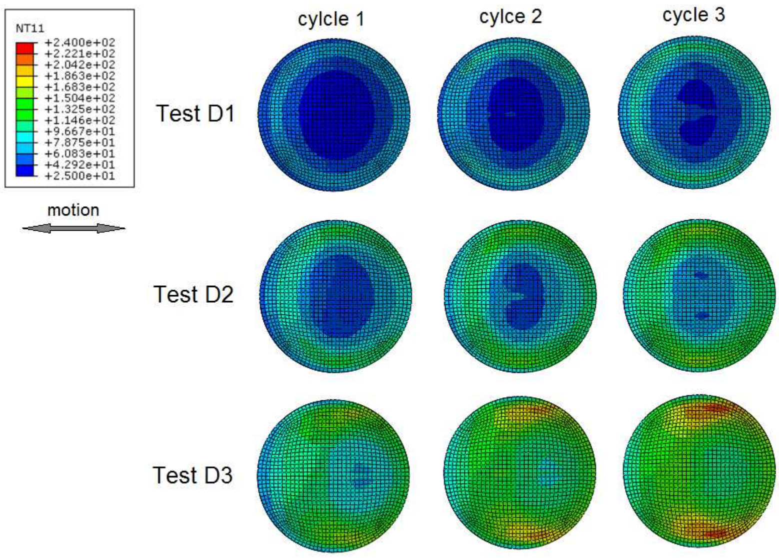

Figure 4.3. Temperature profiles on the surface of the sliding pad during Tests D1, D2 and D3 (values in °C)

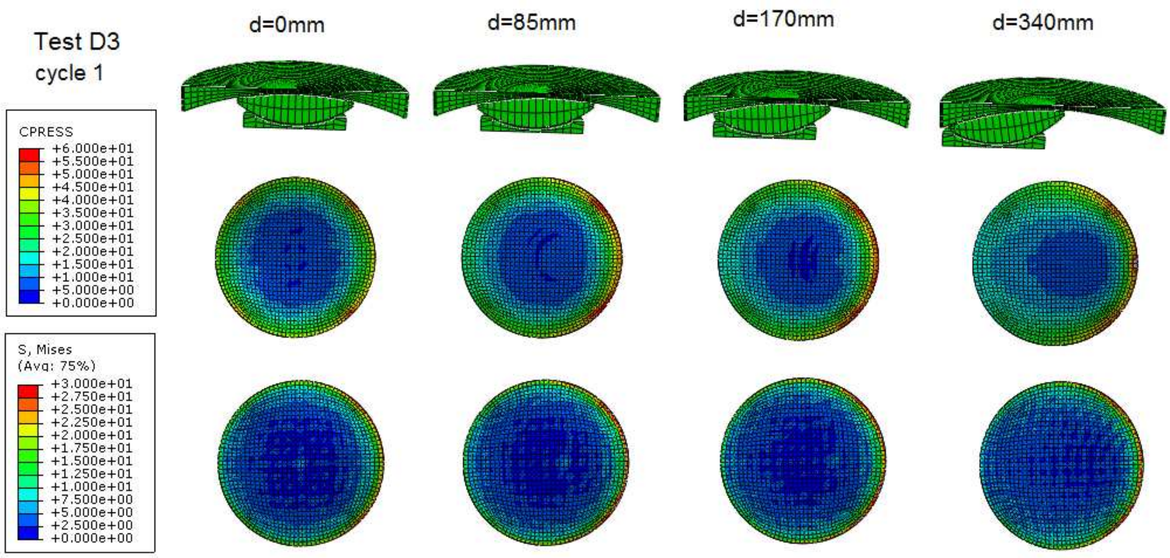

Figure 4.4. Distribution of contact (CPRESS) and Von Mises (S. Mises) stresses on the surface of the polymeric pad during the first cycle of Test D3 (values in MPa)

4.2. Simulation according to AASHTO code

Figure 4.5 plots the average and the maximum temperature values calculated on the surface of the sliding pad during the 20 cycles of the test according to AASHTO code (Test D4).

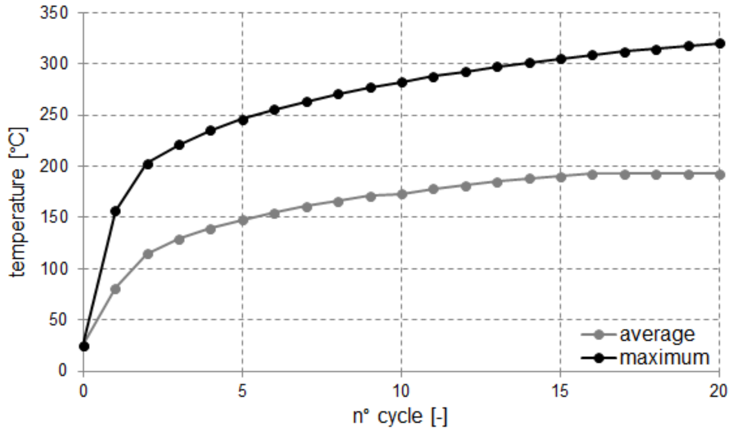

Figure 4.5. Average and maximum temperature histories on the surface of the sliding pad during Test D4 according to AASHTO

Both average and maximum temperature increase very fast in the first cycles, and then the rate becomes smaller. After 15 cycles the average temperature seems to approach an asymptotic value, while the maximum one still increases with a constant rate. It shall be noted that the peak temperature is more than 1.5 times larger than the average one, e.g. 320°C vs 195°C at the twentieth cycle.
This large increase in temperature has substantial effects on the load – displacement characteristics of the isolator, as shown in Figure 4.6 where the changes of *EDC* and K_{eff} during the 20 cycles of the test is illustrated. Nevertheless, for the CSS unit analyzed in the case study the standard requirements on the maximum allowable change in stiffness an damping properties are still fulfilled.

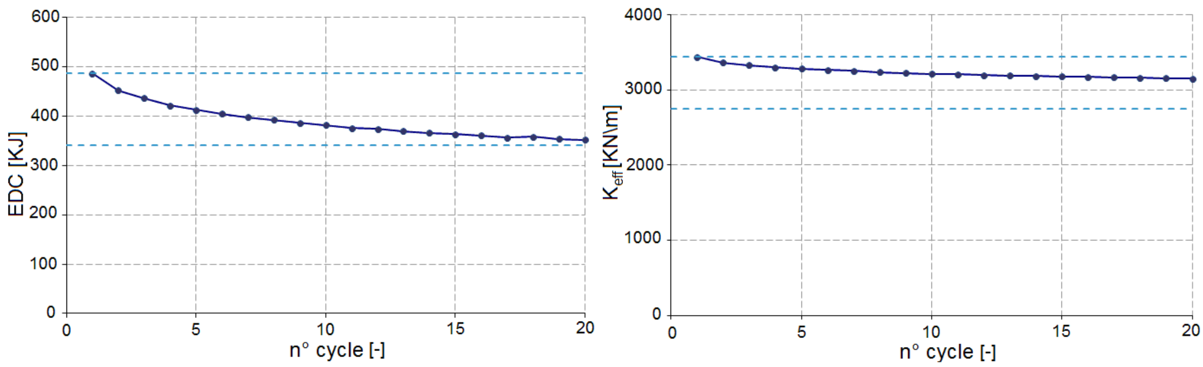

Figure 4.6. Change of Energy Dissipated per Cycle (*EDC)* and effective stiffness (K_{eff}) during repeated cycles and range of acceptability according to AASHTO

Excessive temperature rise has adverse effects not only on the coefficient of friction, but also on the stiffness and strength of the thermoplastic material, which softens at temperatures approaching its melting point. Figure 4.7 illustrates the temperature profiles through the thickness of the sliding pad calculated at three distinct positions, chosen in accordance with the temperature and pressure patterns reported in Figure 4.3.
The peak temperature is developed close to the edge of the pad, perpendicularly to the direction of sliding (point A), where larger contact pressures are produced. In the central region of the pad (point B), where the contact pressure is lower, the local temperature is substantially less than the average value over the whole surface.

The large increase in temperature occurring in the first three cycles is restricted to a thin layer of material, approximately 1 mm thick, and the heat developed at the sliding interface takes a large number of cycles to extend to the underlying material. Therefore a small number of cycles even at high seismic velocities is likely not to represent an issue for the mechanical strength of the pad. However the sliding pad is usually mechanically recessed into the steel backing plate for approximately half of its thickness, and in case of prolonged seismic excitation the melting temperature can be approached within a material thickness on the order of this protrusion; in this case the lateral flow of the material is no more prevented and can seriously endanger the load bearing capability of the isolation unit.

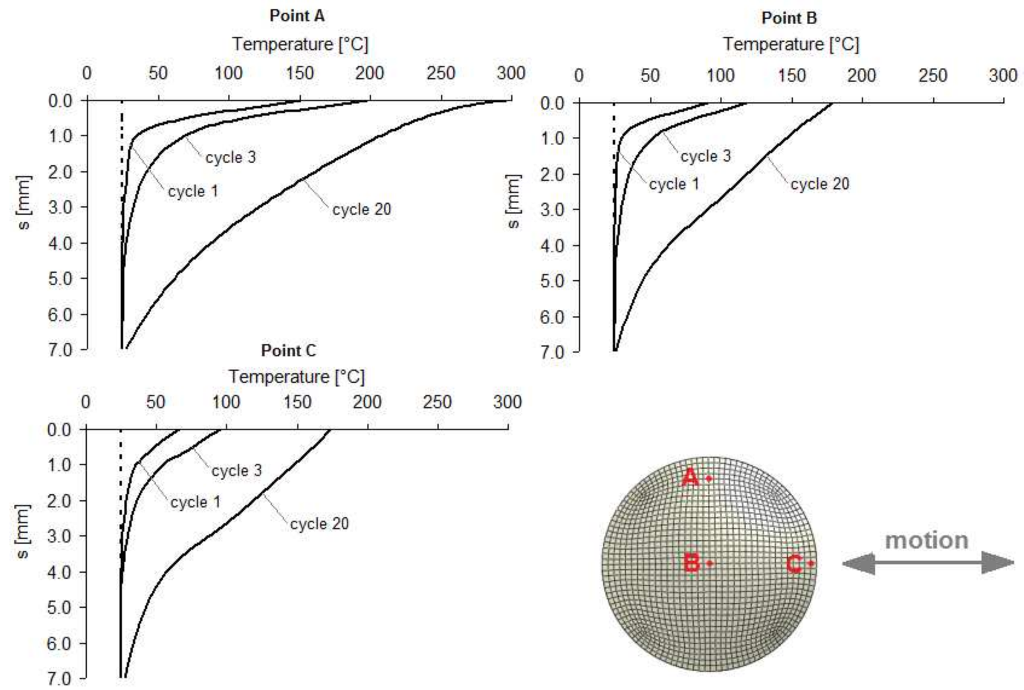

Figure 4.7. Temperature profiles though the thickness of the sliding pad during 20 cycles of motion in correspondence of positions marked as A, B, C

5. CONCLUSIONS

This paper aims at illustrating by means of a study case the potentialities of the thermal-mechanical finite element formulation of Curved Surface Slider units previously developed by the Authors (Quaglini et al. 2012).

The basic feature of the formulation is the implementation of a mathematical law relating the coefficient of friction to the values of the local variables at the sliding interface like contact pressure, velocity and temperature.

The formulation can be used either as a design tool to perform a preliminary evaluation of the seismic hardware under the test conditions required by the standards, and for preliminary assessment of the suitability of the self-lubricating materials, providing fundamental information on the temperature and mechanical variables affecting the materials of the sliding surfaces.

The Authors believe that the finite element formulation presented in this study can represent a reliable contribution to the design of antiseismic hardware, assisting in the selection of self-lubricant materials accounting for their temperature-dependent characteristics.

REFERENCES

AASHTO 2010. Guide Specifications for Seismic Isolation Design, 3rd Edition. Washington DC: American Association of State Highway and Transportation Officials.

EN 15129 2009. Antiseismic Devices. Brussels: Comité Européen de Normalisation (CEN).

Constantinou, M.C., Mokha, A.S. and Reinhhorn, A.M. (1990). Teflon bearings in base isolation. II: Modelling. *ASCE Journal Structural Enginering* **116:2**,455–472.

Fenz, D.M. and Constantinou, M.C. (2006). Behaviour of the double concave friction pendulum bearing. *Earthquake Engineering and Structural Dynamics* **35:11**,1653–1675.

Dolce, M., Cardone, D. and Croatto, F. (2005). Frictional behavior of steel-PTFE interfaces for seismic isolation. *Bulletin of Earthquake Engineering* **3:1**,75-99.

Mosqueda, G., Whittaker, A.S. and Fenves, G.L. (2004) Characterization and modeling of Friction Pendulum Bearings subjected to multiple components of excitation. *ASCE Journal of Structural Engineering* **130:3**,433-442.

Quaglini, V., Dubini, P. and Poggi, C. (2012). Experimental as-sessment of sliding materials for seismic isolation systems. *Bulletin of Earthquake Engineering* **10:2**,717-740.

Quaglini, V., Vitali, M., Motta, R., Ferroni, D. and Dubini, P. (2011). Assessment of heat generation in sliding pendulum isolators. *IABSE-IASS London Symposium* “*Taller, Longer, Lighter meeting growing demand with limited resources*”. **Proceedings volume**: 1-8 (text on CD-rom).

Quaglini, V., Bocciarelli, M., Gandelli, E. and Dubini, P. (2012). Thermal-mechanical behavior of curved surface sliding isolators. *ASCE Journal of Engineering Mechanics* (submitted).