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DEVELOPMENT OF A NEW SLIDING PENDULUM FOR SEISMIC ISOLATION OF STRUCTURES

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ABSTRACT

Seismic protection of civil structures is one of the most interesting goals for structural engineers in order to avoid collapses and/or high damages in case of strong earthquakes.
The task of seismic protection systems is to control the structural vibrations, to reduce as much as possible the forces on the structures and to keep them in service or with negligible damages after the seismic events.
Among the seismic protection systems the structural isolation is one of the most used techniques. The basis idea for seismic isolation of structures is to reduce the seismic forces by a suitable selection of the vibration period of the structure accepting a relative displacement of the structure respect to the ground that can be minimized by energy dissipation.
The authors are developing a sliding pendulum seismic isolators with an innovative material for the sliding surface to ensure an optimum capacity of carrying the vertical loads, an high wear resistance to guarantee a long durability of the device in service static conditions, a good energy dissipation by friction in case of earthquake motion and a good resistance to high temperatures that occurs during the dissipation by friction.
This paper describes the design and the tests of the sliding pendulum performed by ALGA S.p.A.

1. INTRODUCTION

The development of the new sliding pendulum has been obtained by a cooperation between ALGA S.p.A and the Department of Politecnico of Milano for the selection of the suitable material for the sliding friction material.
ALGA S.p.A. has designed single and double sliding surfaces devices; the first one for a prototype to be tested in the laboratory at the Eucentre in Pavia and the second one for the “Golden Ears Bridge” project in Canada.
The paper deals with the design of the sliding device, the selection of the optimal material

for the sliding surface, the device tests in service and earthquake conditions in order to evaluate the performances according to the international standard for seismic protection devices.

2. SLIDING PENDULUM DESGN THEORY

2.1 Sliding pendulum theory for single sliding surface

The fundamental parameters for the device design are the following:

- Isolated structure period
- Horizontal stiffness of the device
- Transmitted horizontal force

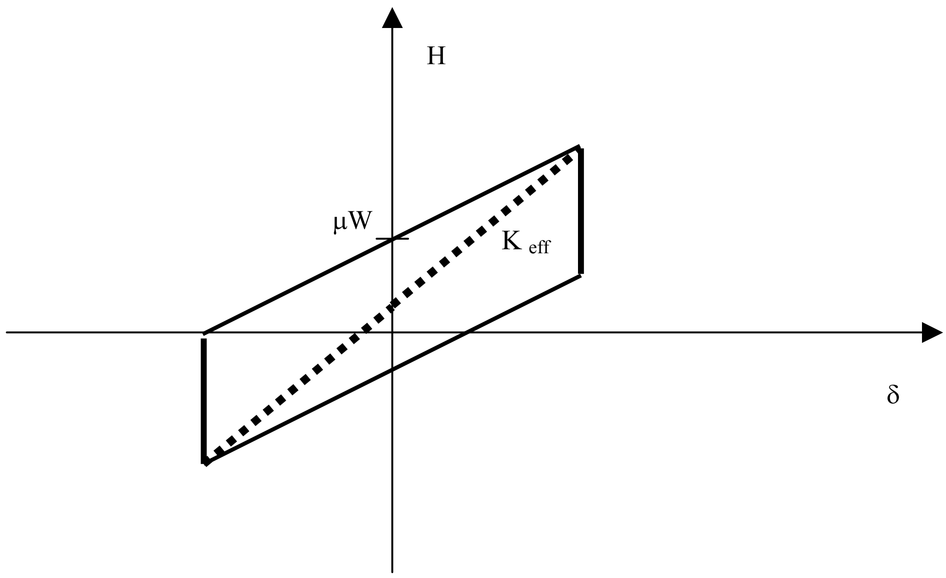
The structural system isolated period is calculated according to the following formula:

$$T = 2\,\pi\,\sqrt{R / g}$$

with:

T = Isolated structure period in second
R = sliding surface curvature radius
g = gravity acceleration

The theoretical response curve is the following:



The significant parameters are::

- μ = dynamic friction coefficient

- δ = horizontal displacement
- W = design vertical load
- K = device horizontal stiffness = W / R
- K_{eff} = effective device horizontal stiffness = H / δ = (μ + 1)W / R
- H = horizontal load given by the device = μ W+ K δ
- T_{eff} = effective isolated structure period

$$T_{eff} = 2\pi\sqrt{W / (g \times K_{eff})}$$

- ξ_{eff} = effective damping of the isolation system

$$\xi_{eff} = 2 \left[\mu / (\mu + \delta / R) \right] / \pi$$

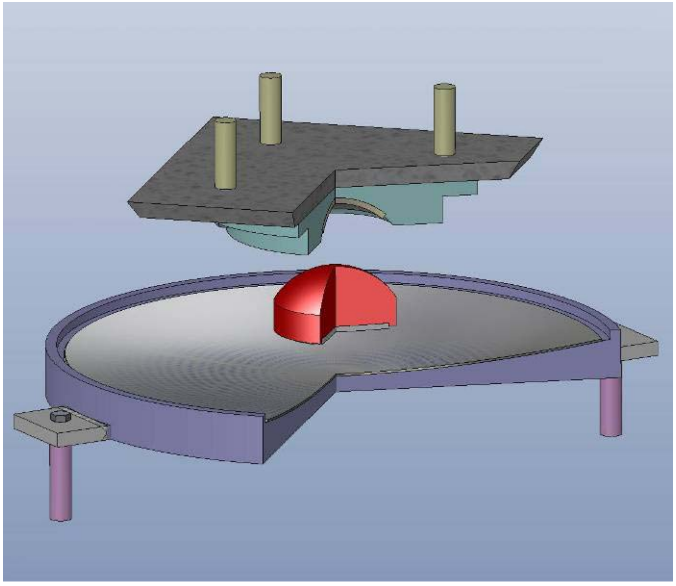


Figure 1 Open view of the single surface sliding pendulum

The single surface pendulum prototype is basically composed by the following components:

- base plate (see the figure 2), this plate is fixed to the structure at one side and has a concave surface on the other side to allow the bearing rotation. The concave rotation surface is realized by inserting in the base plate a disk of a innovative sliding material, called Xlide, patented by ALGA to minimize the friction due to the rotation. In practise the sliding pendulum allows the structure rotations as a spherical bearing with a reduced friction respect to the "Standard" bearing with PTFE surfaces

- median plate that at one side is convex and in contact with the rotation surface and at the other contains the special friction material that in service allow the slow movements and in case of dynamic fast motion due to the earthquake dissipated the energy by friction.
- sliding plate (see the figure 3) that is concave and allow the bearing movement; the suitable selection of the radius of the concave surface gives the isolation period according to the theory previously shown

Figure 2 Base plate of the single surface sliding pendulum

Figure 3 Sliding plate of the single surface sliding pendulum, the sliding surface is in stainless steel and appears like a mirror

2.2 Sliding pendulum theory for double sliding surfaces

The double sliding surfaces pendulum consists of a combined bearing (see the figure 4) where the rotation occurs on an internal surfaces while the translation happens on two concave surfaces. By a suitable combination of the sliding surfaces radius and the two sliding materials one can optimize the device response curve according to the theory of the paper (Fenzand et al.)by varying the stiffness and energy dissipation. In practice the device designer can activate firstly one sliding surface and only after a certain movement allows the motion on the second sliding surfaces obtaining a bilinear response curve. In the sliding pendulum designed by ALGA S.p.A. for for the “Golden Ears Bridge” project in Canada the aim is to have a device with a response curve equal to the one of a single sliding surface by using a double sliding surfaces in order to equally distribute the movement on the two surfaces minimizing the plan dimension of the bearings; being in fact the horizontal movement quite large (1.2 meter) the plan dimension of a single sliding surface pendulum is not compatible with the structure dimension.

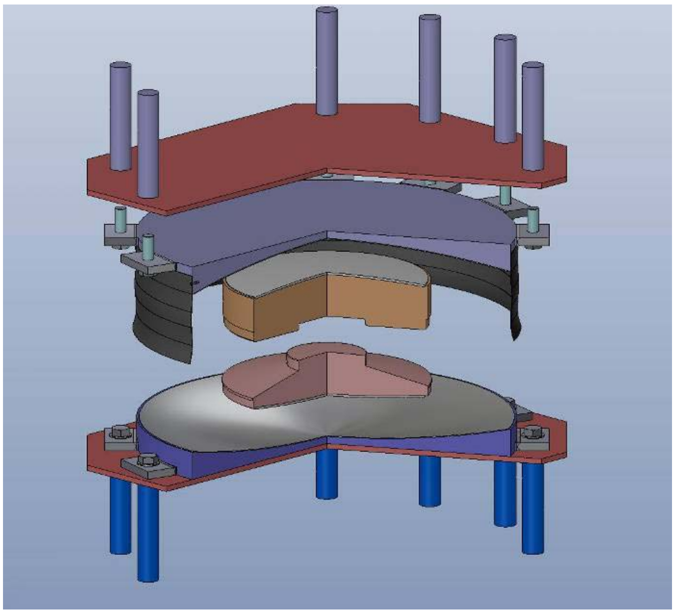


Figure 4 Open view of the double surface sliding pendulum

With reference to the theory showed in the previous section if the motion occurs simultaneously on both surfaces the double sliding surfaces pendulum acts as a single surface device, this condition occurs when:

- $\mu_1 = \mu_2$ the coefficient of friction on the two surfaces are equal
- $R_1 = R_2$ the radius of each sliding surface so it is equal for the two surfaces are equal
- $h_1 = h_2$ where h is the distance between the sliding surface and the bearing center of rotation, so the condition is that the distance for the two sliding surfaces is the same

I the two previous conditions are reached the effective radius of the double surface pendulum is:

$$R_e = R_1 - h_1 + R_2 - h_2$$

The double surfaces pendulum prototype is basically composed by the following components:

- sliding plates that are concave and allow the bearing movement; the suitable selection of the radius of the concave surfaces give the isolation period according to the theory previously shown
- internal median plates, they must transmit the vertical load and allow the bearing rotations. In order to transmit the vertical load spherical steel surfaces are used while the rotation and the internal transmission of horizontal loads are given by a spherical contact between the two plates one embedded into the other

3. SLIDING MATERIAL SELECTION

The research activity for the selection of the suitable material for the sliding surface has been conducted with the Department Structural Engineering of the Politecnico of Milano, the goal is to obtain a material with a controlled and stable friction coefficient with high wear resistance and stable at the operating temperature when dynamic loads with consequent energy dissipation are applied. The results of the research projected a set of candidate material with a dynamic friction coefficient range from 2 to 6 per cent and compression resistance above 100 Mpa. The dynamic friction coefficient was calculated by a special machine constructed at the Politecnico of Milano; this tools if the one normally used for the test of PTFE material according to the norm EN1337-2 and the Politecnico laboratory is a European Notified body for PTFE testing.

4. ALGA DESIGNED SLIDING PENDULUM

ALGA designed two typology of sliding pendulum, one with single sliding surface and the other with double sliding surfaces.

The first one is a device prototype to be installed for the seismic isolation of a relatively light building and the main properties are:
- vertical load in static condition = 1000 kN
- vertical load in earthquake condition = 800 kN
- maximum horizontal movement = +- 300 mm

The second one is a device to be installed for the seismic isolation of a bridge in Canada and the main properties are:

- vertical load range in earthquake condition from 5000 kN to 19500 kN
- maximum horizontal movement = +- 600 mm

The total number of the devices for the project is 70 devices.

5. SLIDING PENDULUM PERFORMANCE TESTS

The tests of the single curvature sliding pendulum were performed at the EUCENTRE in Pavia. The results here shown are the ones of the initial test campaign on the device, the tests are still in progress with the final aim of the full qualification of the device according to the requirements of the draft of the European code prEN 15129 regarding the seismic protection devices. Some tests at high velocity with full stroke movement are still in progress also because the test machine is new and needs to be calibrated and controlled to perform fast test where the horizontal motion has to be controlled in parallel with the vertical one that occurs due to the curved profile of the sliding pendulum device.
The already performed tests are the following:

1) Load Bearing capacity test

W = design vertical load ULS = 1000 kN

Static Test:

- vertical load = 2 W = 2000 kN

2)- Frictional résistance force test

- vertical load = W = 1000 kN applied for 30 minutes
- velocity = < 1 mm/sec for 1 minute

3) - Dynamic tests

W = maximum vertical load in seismic condition = 1000 kN
D_{bd} = maximum horizontal displacement = 300 mm. In the test here show the horizontal displacement is variable due to test machine vertical displacement control that is still under assessment
v_{ed} = test velocity variable from 5 to = 150 mm/sec

Table 1 – Summary ALGAPEND device dynamic tests

Type of the test	Test run	Displacement (mm)	Peak velocity v (mm(s)	Number of cycles
Service	S	6	5	1
Benchmark	P1	25	25	20
Dynamic 1	D1	150	50	5
Dynamic 2	D2	150	60	3
Dynamic 3	D3	100	100	3
Dynamic 4	D4	100	110	3
Dynamic 5	D5	60	120	3
Dynamic 6	D6	60	150	40

Figure 5 Test machine of the EUCENTRE in Pavia

Figure 6 ALGAPEND device installed in the test machine

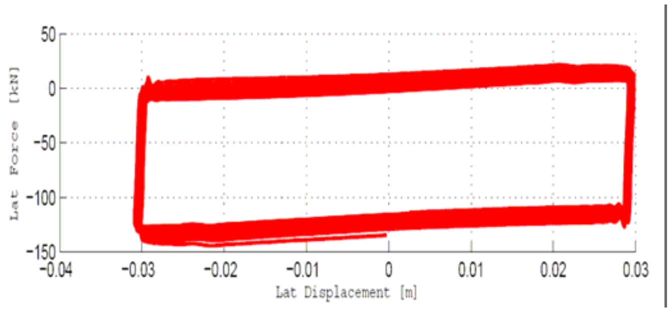


Figure 7. Test P1 see the table 1

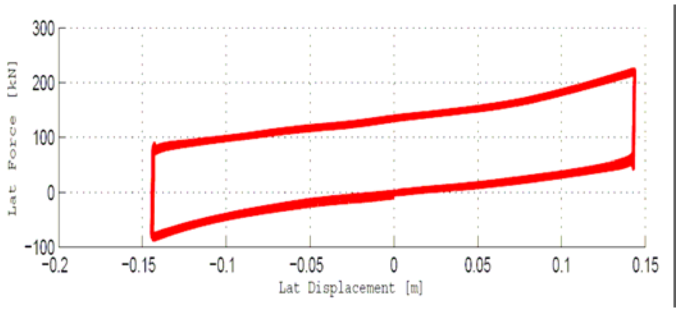


Figure 8. Test D1 see the table 1

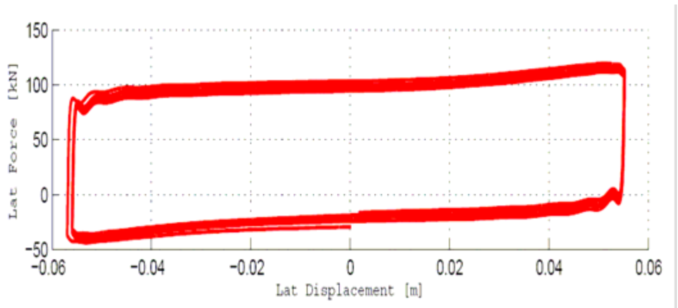


Figure 9. Test D5 see the table 1

The results of the tests confirmed the theoretical design parameters; the dynamic coefficient of friction is about 6 per cent and the equivalent viscous damping about per 29 cent for a displacement of 150 mm.

At the end of the tests the device was opened and no damage occurred on the sliding surface, in the following picture the comparison between the sliding surface before and after tests is shown:

Figure 10 Comparison between the sliding surface before tests (left side) and at the end of test campaign (right side); no damage occurred and no evidence of deformation due to temperature effect due to the energy dissipation by friction.

5. CONCLUSIONS

The results here shown are promising, the device are shown very high stability with no degradation after severe motions and energy dissipation, very good agreement with the theoretical predicted response. At the end of the tests, the device “core” the sliding material disk does not shown any particular damage and is capable to support other dynamic tests, it means in practise that the device can survive to many severe earthquakes with no significant maintenance.

The future tests will complete the device performances evaluation also by measuring the friction surface temperature in order to define the temperature increase at each dynamic cycle.

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