SEISMIC PROTECTION OF THE SOUTHERN BRANCH OF THE NATIONAL PALACE MUSEUM, TAIWAN

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Abstract

Seismic isolation is of primary importance for strategic facilities to guarantee the continuity of the most important services to people after an earthquake.

On the other hand, it is more and more applied in the protection of historical monuments and museum, with the aim to save inestimable treasures.

The paper describes the seismic isolation of the southern branch of the National Palace Museum of Taibao, Chiayi County, Taiwan, an investment of USD 268 million spread over 70 hectares.

The seismic protection is composed by 210 sliding pendulums with very high vertical load capacity, up to 20.000 kN and able to carry out one meter of movement. All the types of devices have been tested dynamically at high velocity at Eucentre Laboratory of the University of Pavia (Italy) and at UCSD-S.Diego showing the performance in terms of load capacity under different displacement conditions as well as the dissipation properties with different levels of vertical load and displacement.

Keywords: Seismic Protection of museum, Sliding Pendulum, Dynamic Tests

1. INTRODUCTION

The construction of the Southern Branch of the National Palace Museum is a project developed with the aim to drive the cultural, social and economic development of both Northern and Southern regions of Taiwan.

The museum is located at Taibao City in the Chiayi County, Taiwan and the story of the construction begins at the end of 2014 with the approval by the government of the project created by the Taiwan-based firm Artech Inc.

The Southern Branch Museum, originally scheduled for completion in 2008, was later postponed as a result of contractual disputes as well as the Typhoon Morakot, which created a flooding that measured 10.3 meters tall in the foundation. In October 2010, a project revision plan was completed and the building of the Southern Branch Museum was reinitiated to come up to the end of construction by the end of 2015.

The project cost was of USD 268 million spread over 70 hectares (700,000 square meters). The building thought to be diamond-level “green” is both earthquake resistant and flood resistant, thanks to measures taken by the designers to ensure isolation from ground level to protect the building from seismic shocks and also to have flood and drought-resistant capabilities, making it a gold-level "smart" building.

Fig. 1 – The South Palace Museum

Taiwan is situated in a seismically active zone, on the Pacific Ring of Fire, and at the western edge of the Philippine Sea Plate. Geologists have identified 42 active faults on the island, which caused between 1901 and the year 2000 91 major earthquakes, 48 of them resulting in loss of life. Seismic protection of strategic buildings is hence of primary importance. Museums are of course among them, for the inestimable treasures they contain.

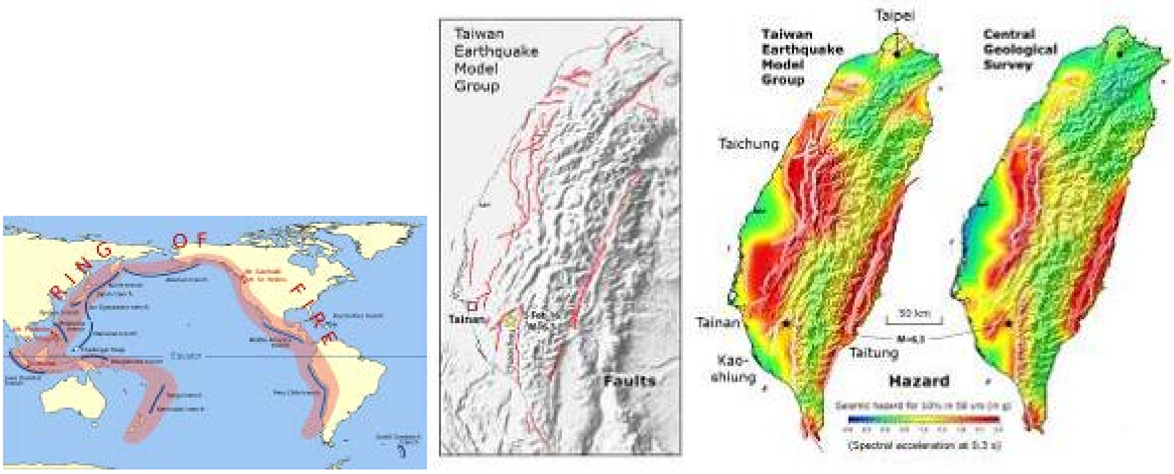


Fig. 2 – Taiwan Seismic Hazard

2. DESCRIPTION OF THE APPLIED ISOLATION SYSTEM

The building of the museum is composed by a structure characterized by strong irregularity. The columns layout has a waved shape as shown in the following picture. The very irregular columns layout makes this structure perfect to be isolated with the sliding pendulum technology.

The very high seismic demand is the reason of the release of a huge quantity of seismic energy. This energy could cause high values of forces and moments transmitted to the foundations if a seismic isolation system is not adopted. The need of dissipating a so important quantity of energy moved the designer to adopt a seismic isolation system using sliding pendulums.

In order to not increase too much the shear force on the columns, a 3% dynamic friction coefficient and a radius of 3962 mm have been chosen.

Sliding pendulum with vertical load capacity up to 20000 kN and ±500 mm of displacement were designed, produced and tested by Alga according to the designer specifications. The Figure 4 shows the sliding pendulum installed along with its behavior characteristic curve.

The main figures of the device installed are shown in the table here below:

Table 1 – Main Figures of the Isolators

Device	Quantity	Vertical Force [kN]	Displacement [mm]
PS 20000/1000	5	20000	±500
PS 12500/1000	17	12500	±500
PS 10000/1000	60	10000	±500
PS 6500/1000	83	6500	±500
PS 4000/1000	45	4000	±500

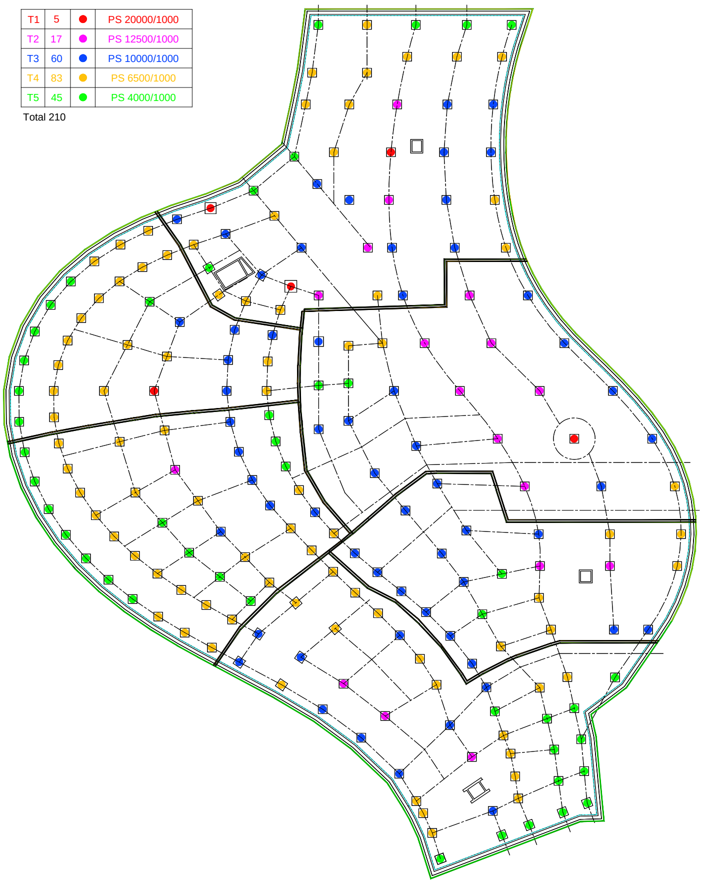


Fig. 3 – South Palace Sliding Pendulum layout

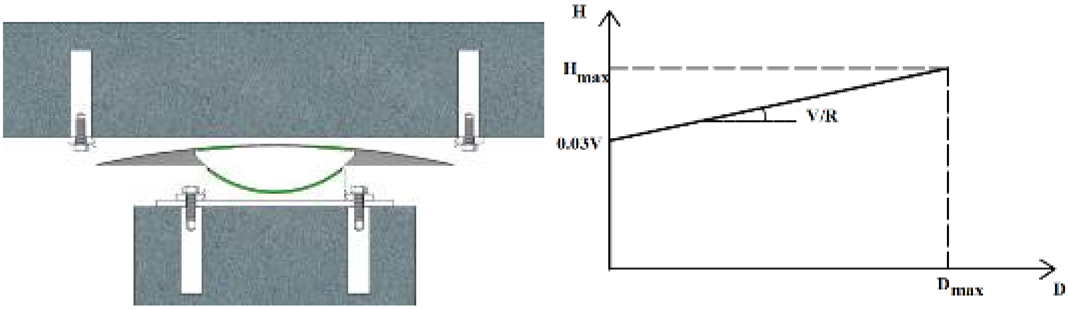
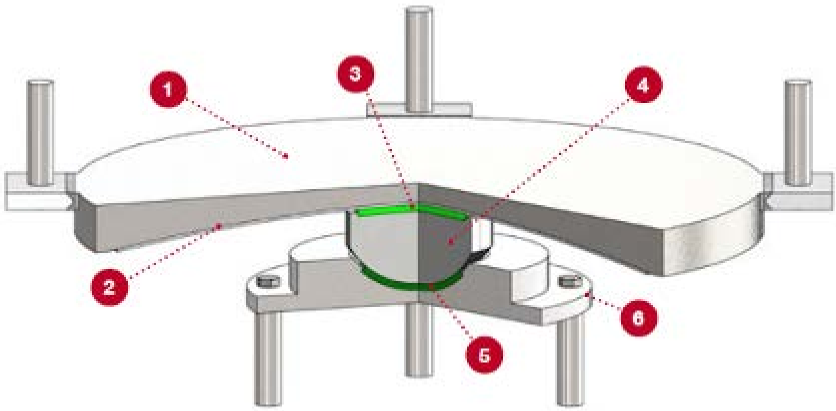


Fig. 4 – Sliding pendulum typical section and behavior law

Sliding pendulums with one primary sliding surface have been installed in the columns of the museum. Pendulum are composed of three steel plates: sliding plate (pos. 1 in Fig. 5), median spherical plate (pos. 4 in Fig. 5), base plate (pos. 6 in Fig. 5) separated by two sliding surfaces. There are two types of sliding surfaces: the first one is the main (primary) spherical sliding surface (pos. 3 in Fig. 5) equipped with a high performance sliding material called "Hotslide" coupled with stainless steel. The second one is the secondary spherical sliding surface (pos. 5 in Fig. 5) equipped with lubricated sliding material coupled with a chromium plated steel surface with the aim of compensating the rotation of the spherical internal plate induced by the displacement of the sliding plate.

The basic scheme of a sliding pendulum is shown here below in Fig. 5



1. Top sliding plate
2. Primary sliding surface
3. HOTSLIDE Sliding material
4. Median plate
5. Secondary sliding surface
6. Bottom plate

Fig. 5 – Single sliding pendulum typical section

The scope of the primary sliding surface is to develop the horizontal reaction of the isolator and hence to define the behavior law of the device. The horizontal reaction is obtained by two different effects which collaborate in the seismic isolation system to protect the building from the earthquake.

The first effect is the curvature radius of the sliding plate which allows the device to develop a horizontal force increasing with the displacement creating the "pendulum" effect. This is mainly responsible of the period shift of the isolated structure and of the re-centering capacity of the isolation system.

The second one is the friction developed by the liner during the movement. The friction induces an energy dissipation and hence damping which decreases further the shear force on the columns of the isolated structure.

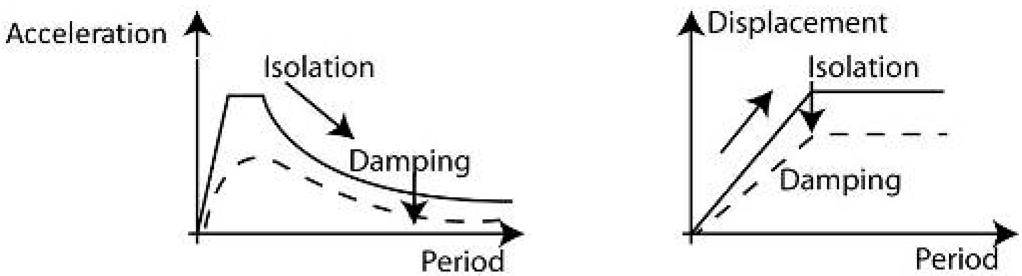


Fig. 6 – Period shift and damping effect of the isolation system with sliding pendulum

As it is well known, sliding pendulum isolators utilize the physical law of the pendulum to act as a harmonic oscillator placed between the structure and the foundation suitable to increase the natural period of the structure.

Disregarding the friction, the movement between the two main surfaces corresponds to the movement of a pendulum with period T equal to:

$$T = 2\pi\sqrt{\frac{R}{g}} \quad (1)$$

R being the equivalent radius of the device.
If the friction component to the horizontal force is also considered, the effective period T_{eff} is then calculated as:

$$T_{eff} = 2\pi \sqrt{\frac{V_D}{K_{eff}\, g}} \quad (2)$$

With K_{eff} the effective stiffness of the sliding pendulum for the design displacement:

$$K_{eff} = \frac{V_D}{R} + \mu \frac{V_D}{D_D} \quad (3)$$

In the expressions (2) and (3) V_D is the dead vertical load and D_D is the design displacement.

Table 2 – Main Figures of the Isolation System

Device	Quantity	Vertical Dead Load V_D [kN]	Design Seismic Displacement D_D [mm]	Effective Stiffness K_{eff} [kN/mm]	Period T [sec]	Effective Period T_{eff} [sec]	Effective Damping ξ_{eff} [%]
PS 20000/1000	5	11772	±350	3.98	3.99	3.45	16
PS 12500/1000	17	7848	±350	2.65	3.99	3.45	16
PS 10000/1000	60	6377	±350	2.16	3.99	3.45	16
PS 6500/1000	83	4415	±350	1.49	3.99	3.45	16
PS 4000/1000	45	2698	±350	0.91	3.99	3.45	16

The period is independent from the isolated mass with great advantage for the isolation of building with not perfectly known mass distribution like in the South Palace building.

The behavior of the sliding pendulum isolator is determined by the properties of the main sliding surfaces: their radius of curvature and the friction coefficients. In particular the static friction coefficient determines the necessary force to start the movement. The dynamic friction is the mechanism through which the energy is dissipated.

The choice of the dynamic friction shall be done considering many factors: the higher is the coefficient of friction, the higher is the energy dissipated but the higher is also the heat generated and the lower is the re-centering capability of the device.

The most important aspect of an isolation system composed by sliding pendulum is the fact that the stiffness is linearly dependent on the vertical load applied, which is actually the weight of the structure. Hence the centre of mass and the centre of stiffness are always automatically coincident. This is a great benefit for the structure since it avoids to have torsional modes of vibration in the building and then additional displacement due to the geometry of the isolation layout caused by an imposed rotation.

The sliding surfaces of the sliding pendulum isolators are obtained mating a metallic surface in stainless steel or chromium plated and a plastic material, normally PolyTetraFluorEthylene (PTFE) or their composite materials.

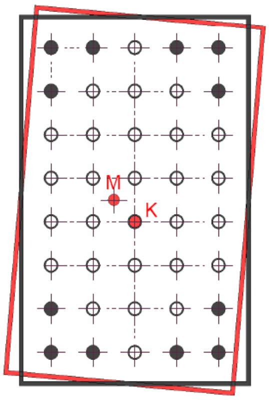


Fig. 7 – Additional displacement caused by rotational modes of vibration

The behavior of the PTFE-stainless steel or chromium surfaces has been widely studied by many authors and it is well known. However, the use of classical not filled virgin PTFE for these application is not optimal for the following reasons:

- Very low friction coefficient especially when used lubricated, not suitable to get great energy dissipation
- Further reduction of the friction coefficient due to the heat generated by the energy dissipation
- Great reduction of the bearing capacity due to the heating

To overcome these inconveniences ALGA developed, in collaboration with Politecnico di Milano, a special sliding material that could better fit the purposes of the sliding pendulum.

An important testing campaign has been performed on the polyamide-based sliding material called HOTSLIDE to verify all its mechanical and physical characteristics and to assess its suitability for the use in sliding pendulum isolators where high temperatures play an important role on the design of the device, both in terms of compressive and wear resistance.

Hotslide is in fact a special sliding material polyamide based which has the property to be able to resist to a high pressure level, more than 2 times than PTFE, especially suitable for high temperatures, both due to environment conditions and to heating due to energy dissipation. Many tests performed with Politecnico di Milano show the good resistance of the sliding material at different temperatures.

Fig. 8 – Special sliding material “Hotslide”

As well, Hotslide has very good resistance to wear. This is also shown by long term friction tests performed at Politecnico di Milano up to 10 km of accumulated path. During this test a very small degradation of the Hotslide special sliding material has been observed.

Fig. 9 – Special sliding material "Hotslide" after wear test

Fig. 10 and Fig. 11 show different phases of installation of the sliding pendulum for the South Palace Museum.

Fig. 10 – Installation of the sliding pendulum before casting the concrete slab

Fig. 11 – General view of the installed sliding pendulum

3. THE PERFORMED TESTS ON FULL SCALE SLIDING PENDULUM

All the devices have been tested full scale at Eucentre laboratory in Pavia (Italy) and at University of California – S.Diego (UCSD).

Eucentre is the European centre for training and research in earthquake engineering and its laboratory is specifically dedicated to test on seismic devices or for seismic protection.

All the tests were performed on full scale devices. According to the designer specifications tests at different levels of displacement at the design velocities were performed. In particular tests at velocities typical of the service situation, like the case of wind and braking, and dynamic tests with a different number of fully reversed cycles at different seismic displacement at velocity of 550 mm/s were performed.

The biggest device has been tested at UCSD according to the testing protocol shown in Table 3:

Table 3 – Testing Protocol for PS 20000/1000

devices	Aps 20000/1000-T1(Prototype Test)							
test#	test name	label	Ampl. [m]	max vel [m/s]	freq [Hz]	load shape	vert load [kN]	cycles [#]
1	Wind and braking	WB	±0.006	0.005	0.208	triangular	17500	20
2	Seismic	S1	±0.150	0.240	0.254	sine	12000	3
3	Seismic	S1	±0.250	0.390	0.248	sine	12000	3
4	Seismic	S1	±0.350	0.550	0.250	sine	12000	3
5	Seismic	S1	±0.450	0.550	0.194	sine	12000	3
6	Seismic-2	S2	±0.350	0.550	0.250	sine	12000	3
7	Seismic Performance Verification	SP	±0.350	0.550	0.250	sine	12000	4+4+2
8	Stability	ST	±0.500	0.550	0.194	sine	17000	3
9	Stability	ST	±0.500	0.550	0.194	sine	4000	3

Fig. 12 and Fig. 13 show the sliding pendulum installed in the testing machine and some test phases.

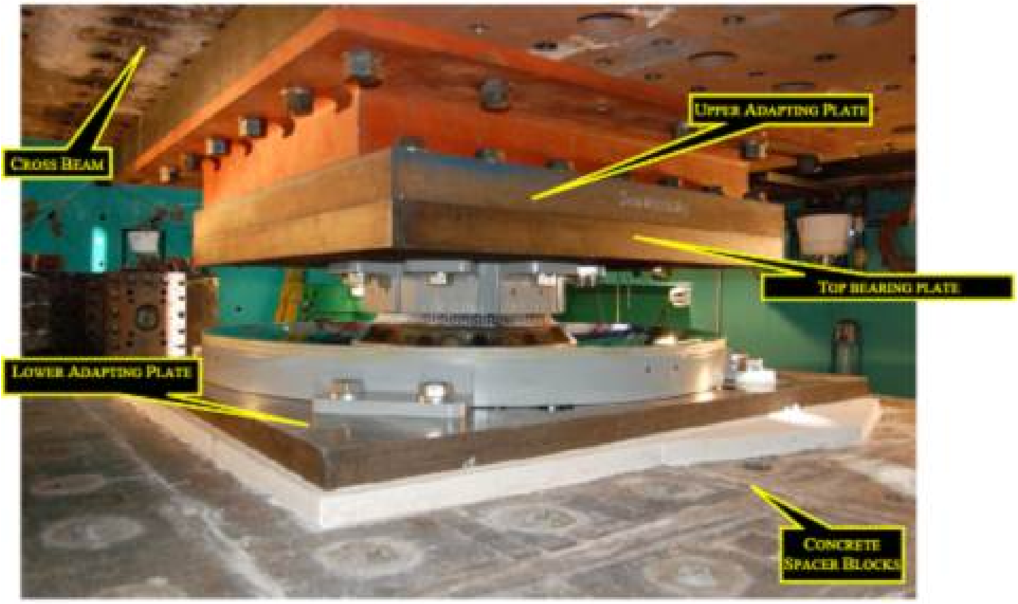


Fig. 12: Test performed on the sliding pendulum at UCSD

Fig. 13 – Test performed on the sliding pendulum at Eucentre Laboratory

The most severe test performed on the prototypes foresaw ten fully reversed cycles at displacement equal to the design displacement of 350 mm at a velocity of 550 mm/s, applying a vertical load of 12000 kN (Test #7). As well, two tests for checking the stability have been performed with three fully reversed cycles at displacement equal to the maximum test displacement of 500 mm at a velocity of 550 mm/s, applying a vertical load up to 17000 kN. The aim of all the prototype tests was to demonstrate the suitability of the supplied sliding pendulums to respect the designer specifications in terms of vertical capacity, horizontal force and displacement and in terms of effective stiffness and energy dissipated per cycle (EDC).

The force displacement plot for the test 4 at the seismic displacement of 350 mm is shown in Fig. 14 while Fig. 15 shows the result for the Seismic Performance Verification Test (# 7).

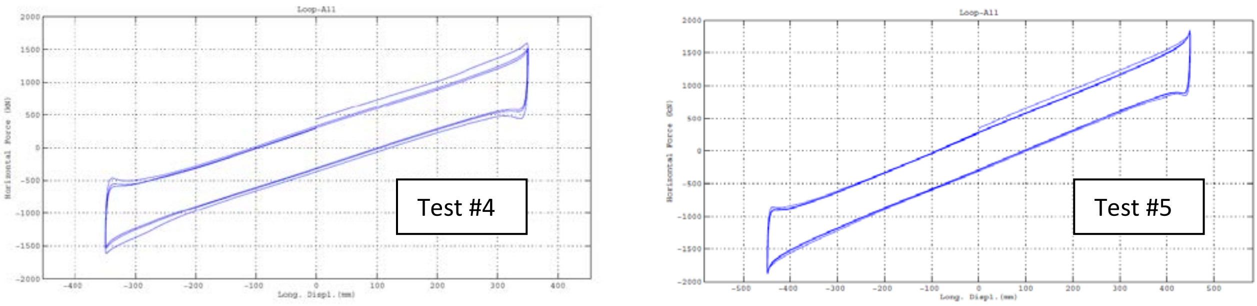


Fig. 14 – Force-Displacement loop for tests 4 and 5

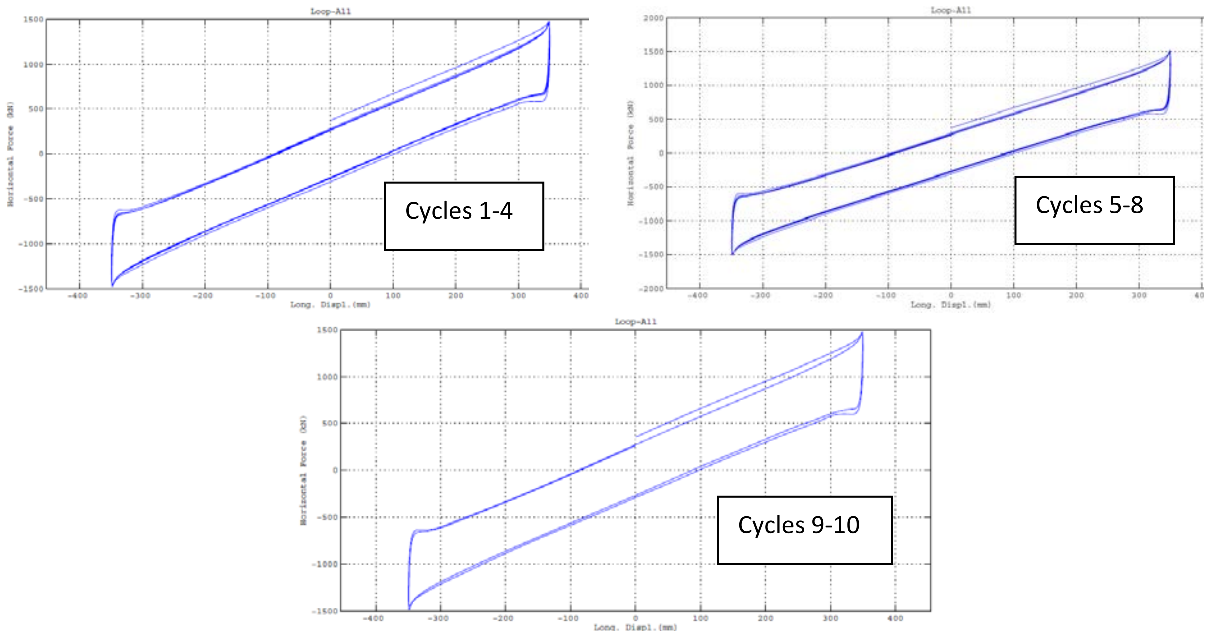


Fig. 15 – Force-Displacement loop for test 7

The result of the tests showed very good behavior of the sliding pendulums used for the isolation system of the South Palace Museum in terms of stability of the response, stiffness developed and damping capacity, for different levels of displacement and when subjected to repeated cycles.
The Hotslide sliding material showed very good behavior in terms of resistance and wearing even after the severe testing program, not showing any sign of damage of loss of bearing capacity and the friction coefficient showed stable values during all the cycles.
The sliding surface was inspected after the test and no sign of damages has been detected.

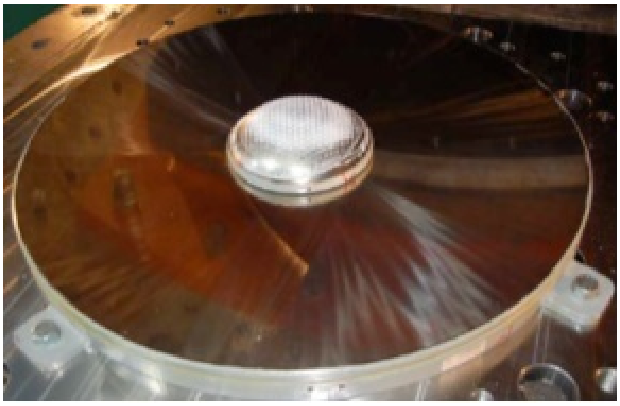


Fig. 16 – Sliding Pendulum after test

4. CONCLUSIONS

The paper describes the seismic isolation of the southern branch of the National Palace Museum of Taibao, Chiayi County, Taiwan, an investment of USD 268 million spread over 70 hectares.

The seismic protection is composed by 210 sliding pendulums with very high vertical load capacity, up to 20.000 kN and able to carry out one meter of movement. All the types of devices have been tested dynamically at high velocity at Eucentre Laboratory of the University of Pavia (Italy) and at UCSD-S.Diego showing the performance in terms of load capacity under different displacement conditions as well as the dissipation properties with different levels of vertical load and displacement.

The sliding pendulums equipped with special sliding material allow to dissipate seismic energy protecting in this way the museum and all historical contents.

Tests on full scale friction pendulums were performed at Eucentre laboratory and at UCSD according to the designer specifications and the test results presented in the paper demonstrate the suitability of the supplied devices for the application on the southern branch of the National Palace Museum in Taiwan.

5. References

[1] Taiwan National Palace Museum website: http://www.npm.gov.tw.

[2] M. Constantinou, A. Mokha, A. Reinhorn, Teflon bearings in base isolation II (1990): Modeling, Journal of Structural Engineering, Vol. 116, No. 2, pp. 455-474.

[3] American Association of State Highway and Transportation Officials (AASHTO) (2010), Guide Specification for Seismic Isolation Design, Washington D. C.

[4] European Committee for Standardization (CEN) (2004), Eurocode 8: Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings