

# The use of sliding pendulum isolators for the C.A.S.E. project in L'Aquila

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## Summary

C.A.S.E is the largest base isolation project ever executed in the world. It consists of 185 3-story apartment buildings made with different construction methods, including prefabricated concrete, steel and wood. In total 4600 apartments for approximately 17.000 persons to recover the homeless after the 6<sup>th</sup> April 2009 earthquake in L'Aquila. Each building is erected on a reinforced concrete slab of 18x54x0,5m which is supported by 40 steel columns provided on top with seismic isolators. So in total there are 7400 base isolators in the project. Peculiar aspect of the project is the fact that it has been completed in less than 9 months after the day of the earthquake.

The paper describes the general structural design and the details of the sliding pendulum isolators adopted for the project: design, production, installation and testing.

**Keywords:** Base isolation, Sliding pendulum isolators, Friction coefficient, Energy dissipation

## 1. Introduction

C.A.S.E is the largest base isolation project ever executed in the world. It consists of 185 3-story apartment buildings made with different construction methods, including prefabricated concrete, steel and wood. In total 4600 apartments for approximately 17.000 persons to recover the homeless after the 6<sup>th</sup> April 2009 earthquake in L'Aquila. Each building is erected on a reinforced concrete slab of 18x54x0,5m which is supported by 40 steel columns provided on top with seismic isolators. So in total there are 7400 base isolators in the project. Peculiar aspect of the project is the fact that it has been completed in less than 9 months after the day of the earthquake.

The buildings are located in 19 different sites around L'Aquila as shown in fig. 1

The execution of this project in the foreseen schedule has been a big challenge for all the actors involved: the owner from one side –the Italian government itself represented by the Protezione Civile- and all the suppliers, including the seismic isolators manufacturers.

The author of this paper has been involved with the company by him managed for the supply of more than 2/3 of all the isolators.

In the limited time available for the supply of nearly 5000 isolators (three months) it was necessary to select the technical solution for the isolators, develop the construction drawings, organize the manufacturing, set up a dedicated testing equipment and perform the required tests.

Due to the variety of constructions foreseen on top of the reinforced concrete slabs and the different possible values and distributions of the masses, sliding pendulum isolators immediately appeared to be the best possible solution, granting constant isolation parameters and displacements independently from the location of the masses. With this kind of isolator there was no need to take

into account any torsion movement around the vertical axis, hence minimizing the design displacement of the isolators.

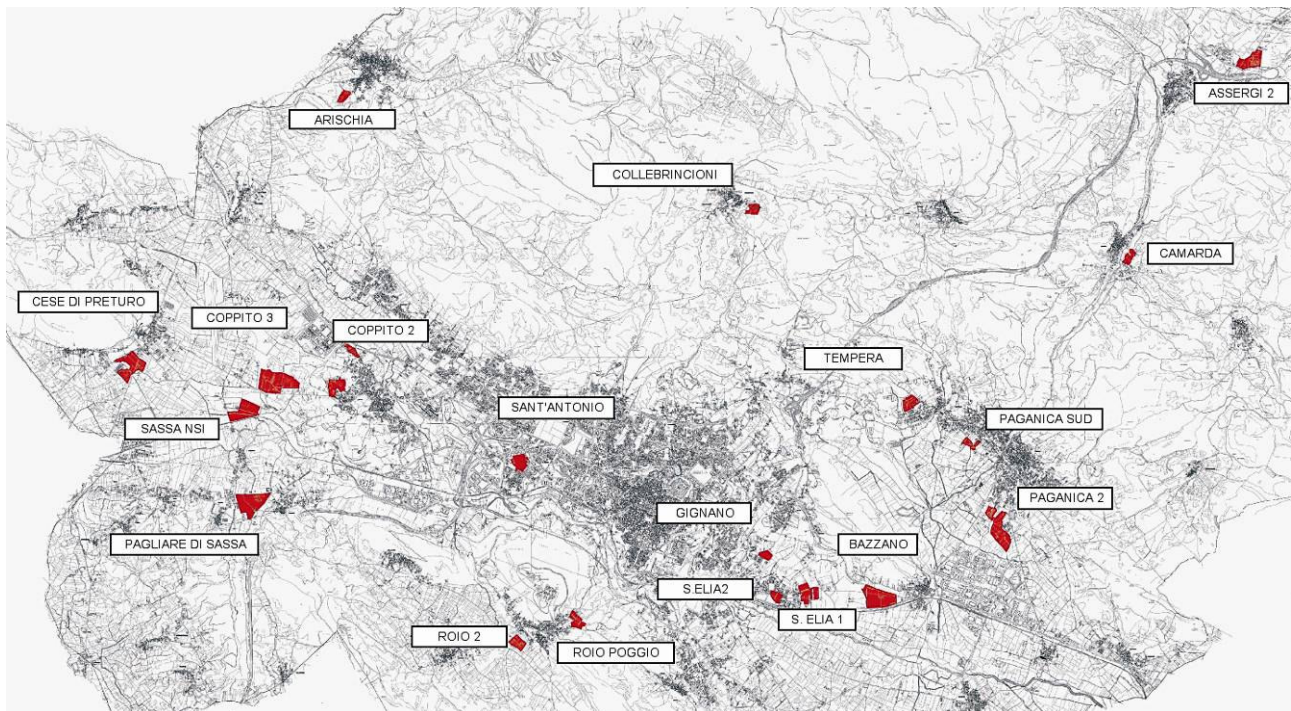


Fig. 1 – The location of the 19 sites around L’Aquila where the 185 buildings of the C.A.S.E. project have been erected

The foreseen isolation parameters, natural period 3,3 s and equivalent viscous damping 20%, required the use of a sliding material with friction coefficient of 3%, slightly different from the materials experienced before by ALGA. The suitable material was found and tested in few days only after the tender award thanks to the co-operation with Politecnico di Milano.

The production could start two weeks after the award of the tender and continued for 12 weeks at the incredible rhythm of 400 isolators per week, with 4 trucks per week reaching the sites of L’Aquila and two teams of specialized workers involved in two shifts for the installation.

The isolators have been designed and tested in accordance with the Italian “Norme Tecniche per le Costruzioni (NTC)” issued in January 2008 but also in accordance with the new European Standard EN 15129, at the time of the tender in formal vote stage, successively approved in August 2009 and published in the following November.

The Standards required the execution of 2 prototype tests and routine test on 5% (EN) or 20% of the isolators (NTC). It was decided to perform the prototype tests and 5% dynamic routine tests at Eucentre and the remaining 15% routine tests on an expressly developed testing machine at ALGA laboratory. In addition several *in situ* dynamic tests has been performed by the client applying dynamic excitations to entire apartment buildings.

## 2. The structural design

### 2.1 General

The structural design of the buildings constitutes the fundamental element that allowed the development of the entire project and is extremely simple in its basic logic: two reinforced concrete plates separated by columns and isolators, the lower one being in contact with the soil and the upper

one with the building (see Fig. 2).



Fig. 2 – The conceptual design of the buildings for the C.A.S.E. project

The plates were designed without knowing the local soil properties, nor the weight and plan distribution of the buildings that had a great variability within the 185 different cases. Therefore, for both aspects conservative assumptions were used, to be verified case by case.

The 2 reinforced concrete slabs are characterized by similar flexural actions induced by gravity. They are both of 500 mm thickness. The total weight to be supported for each building supported by 40 columns was estimated between 30 and 40 MN, so an average weight for each column of 1 MN.

In reality 50% of the buildings were in wood, 30% in prefabricated concrete and 20% in steel.

The design period of vibration of the isolation system was selected in the range of 4 s.

## 2.2 Seismic action

The seismic action and in particular the spectral demands in acceleration and displacement are represented for an event with a 1000 years return period in L'Aquila according to the Italian code, soil category B and E, damping 5% in the following diagrams (see fig. 3)

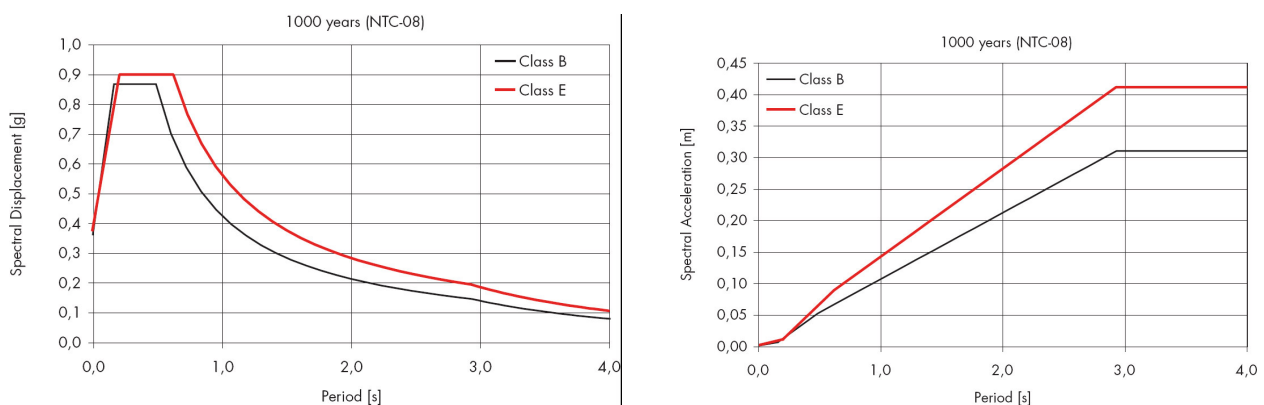


Fig. 3 – Acceleration and displacement spectra of an event with 1000 years return period in L'Aquila according to the Italian code, soil category B and E, damping 5%

It is important to note that the fundamental parameter to be assessed for a proper design of the isolation system is the maximum displacement demand at a period of around 4 s. The spectra derived from the registrations of April 6<sup>th</sup> 2009 show generally displacement demand of less than

120 mm, with one exception for one registration only, for which the demand is close to 250 mm. The code spectra for events with return periods of 1000 years, to be used for the design of the isolation system, have values of about 300 mm for soils type B and 400 mm for soils type E. These values can be significantly reduced in presence of energy dissipation, as a function of an appropriate equivalent damping, according to the  $\eta$  factor:

$$\eta = \sqrt{\frac{10}{5 + \xi}}$$

Where  $\xi$  is the equivalent viscous damping that could be of the order of 10 to 16% for High Damping Rubber Bearings and 20% for sliding pendulum isolators.

### 2.3 The base isolation system

The design and the verification of the isolation system was carried out considering the possibility of adopting two different configurations, characterized by different devices: one based on the use of 12 elastomeric isolators together with 28 free sliding bearings for each plate; the other on the use of 40 sliding pendulum isolators.

Both choices were compatible with the project requirements, in different ways. Actually the smaller dissipation capacity of the system with elastomeric isolators and the fact that it was not possible to avoid some eccentricity of the mass in respect of the barycentre of the isolators brought the displacement demand for this kind of isolators to 360 mm with soil type E. Instead the displacement demand for the sliding pendulum isolators, due to the higher value of the equivalent viscous damping and to the fact that the mass and stiffness barycentres are always coincident thanks to the proportionality between mass and stiffness for this kind of isolators, was limited to 260 mm for the soil type E.

This fact had an impact on the cost of the two possible solutions and oriented the choice to the sliding pendulum isolators for both tenderers.

With this kind of isolators the force corresponding to a displaced position is defined by the following equation:

$$F = Mg\mu + \left(\frac{Mg}{R}\right)d$$

In which  $M$  is the mass,  $g$  the gravity  $R$  the radius of the spherical surface of the sliding pendulum isolators selected as 4,0m,  $\mu$  the friction coefficient selected as 0,03 and  $d$  the displacement.

The least favourable conditions for the verification of the displacement capacity of the isolation system versus the corresponding demand are likely to be those of a rigid and heavy superstructure, i.e. those of a large participating mass and deformations concentrated in the isolation system. With a configuration of this sort, the system global characteristics (40 pieces) resulted to be as follows:

Effective stiffness secant to the design displacement

$$K_{eff} = 14,615kN / m$$

Corresponding period of vibration of the isolation system

$$T = 2\pi \sqrt{\frac{M}{K_{eff}}} = 3,29s$$

Corresponding equivalent viscous damping

$$\xi = \frac{2\mu Mg}{\pi K_{eff} d} = 0,201 = 20,1\%$$

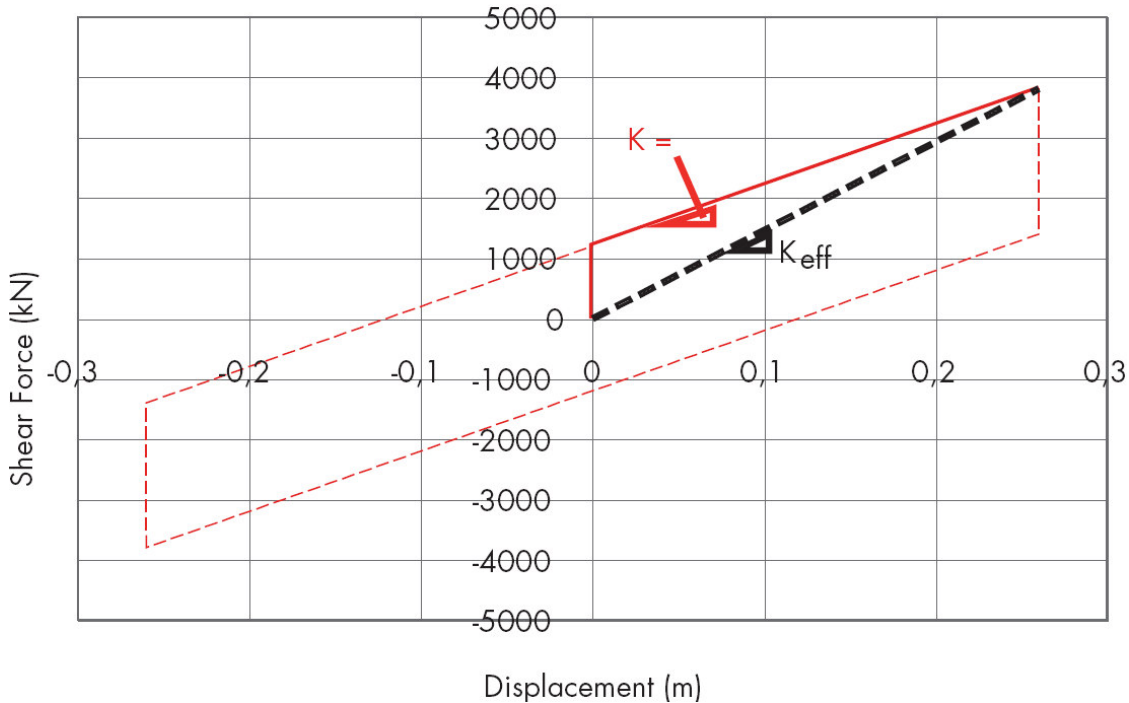


Fig. 4 – Force – displacement response of a system of 40 sliding pendulum isolators and heavy superstructure

### 3. The isolators

#### 3.1 General features

Sliding pendulum isolators have been invented in the U.S.A in 1985. The patent expired in 2005 and from that date a few European manufacturers started developing their solutions.

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

The basic scheme of a sliding pendulum is shown in fig. 5 (Single Sliding Pendulum SSP). The main component (marked with A) is a couple of mating spherical surfaces sliding one on the other and having the double function: to dissipate energy through friction and to generate the re-centring force thanks to the action of the gravity. The relative rotations required by the sliding on the spherical surface as well as the relative structural rotation are allowed by the spherical hinge (marked with B). Disregarding the friction the movement between the two main surfaces corresponds to the movement of a pendulum with period T equal to:

$$T = 2\pi \sqrt{\frac{R}{g}}$$

being R the radius of the surfaces. 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 C.A.S.E. project.

An evolution of the above feature is the Double Sliding Pendulum (DSP), having two spherical surfaces and a spherical articulation between them (see fig.6). In certain cases the intermediate spherical articulation may be missing and the relative rotation is taken by sliding of the main sliding surface. This solution however generates higher parasitic moments due to rotation and practically can be adopted only if the friction coefficient is very low (say  $\leq 0,03$ )

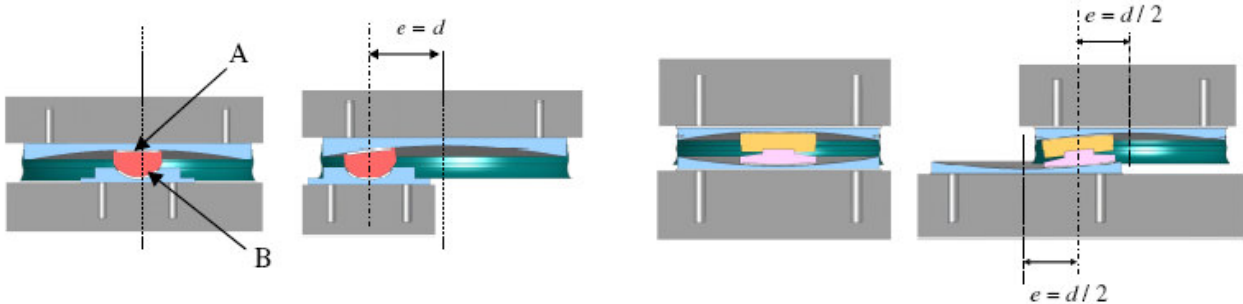


Figure 5. Single Sliding Pendulum (SSP). A: main sliding surfaces; B: spherical hinge;  $e$ : eccentricity;  $d$ : displacement between superstructure and base  
 Figure 6. Double Sliding Pendulum (DSP).  $e$ : eccentricity;  $d$ : displacement between superstructure and base

This solution (DSP) allows to halve the displacement of the resultant for the superstructure and the infrastructure and reduces the overall dimensions of the device.

For the C.A.S.E. project ALGA selected the SSP solution

The behaviour of the sliding pendulum isolator is determined by the properties of the main sliding surfaces: their radius of curvature and the friction coefficient. In particular the static friction coefficient determines the necessary force to start the movement and is the fundamental parameter to design the isolator, its fixing and the adjacent structure; the dynamic friction is the mechanism through which the energy is dissipated. The choice of the dynamic friction shall be done considering many factors: as higher is the coefficient of friction as higher is the energy dissipated but higher also the heat generated and lower the re-centring capability of the device

### 3.2 Sliding material

At the state of the art in 2005 the sliding surfaces in the sliding pendulum isolators were made mating a metallic surface in stainless steel or chromium plated and a plastic material, normally PolyTetraFluorEthylene (PTFE) or their composite materials. The behaviour of the PTFE-stainless steel or chromium surfaces has been widely studied by many authors and is well known. However the use of PTFE for these application is not optimal for the following reasons:

Very low friction coefficient, 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

In addition to that, composite materials based on PTFE after severe dynamic tests showed some time separation of particles due to the deterioration of the binder for the effect of heat.

The use of synthetic materials based on PoliEthylene (PE) or Ultra High Molecular Weight PoliEthylene (UHMWPE) represented an improvement in comparison with PTFE but also in this case the reduction of bearing capacity due to the heating strongly limit their performance

To overcome these inconveniences ALGA started developing new sliding materials that could better fit the purposes of the sliding pendulum, appointing Politecnico di Milano and their specialists (Prof. Carlo Poggi, Prof. Virginio Quaglini and Ing. Charlotte Tavecchio) to execute a research program in

this sense. The research program started in year 2006 and as a partial result two new materials based on thermoplastic synthetic resins were found to fit in a very good way the requirements of the sliding pendulum isolators:

**XLIDE MTF.** This material is suitable to provide a dynamic friction of 6% and its behaviour is well described in the paper mentioned in the references as [2]

**HOTSLIDE:** This is the material utilized for the C.A.S.E project and its properties are described here below.

An important testing campaign has been performed on the HOTSLIDE material to verify all its mechanical and physical characteristics to assess its suitability not only for the use in sliding pendulum isolators but also for standard structural bearings subjected to high temperatures or to important wear problems. For the latter purpose HOTSLIDE has been provided with dimples and lubricating grease.

The tests have been executed partly in Politecnico di Milano utilizing the equipment shown in Fig. 3 and partly at ALGA laboratory. For the purpose of this paper we limit to show the main results obtained for the application in sliding pendulum isolators in general and for the C.A.S.E. project in particular. For this application has been used undimpled, unlubricated HOTSLIDE mated with a stainless steel surface of X5CrNiMo1712 with mirror finish (roughness  $R_z < 1 \mu\text{m}$ ).

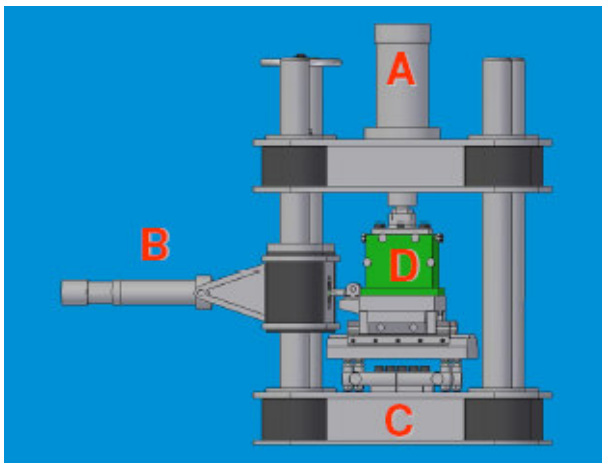


Figure 7. Testing equipment for the friction coefficient at Politecnico di Milano: A-actuator to apply the contact pressure; B horizontal actuator; C – load cells; D controlled temperature chamber

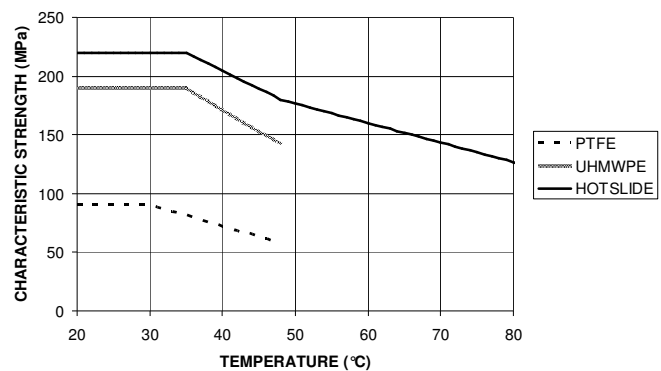


Figure 8. Compared compressive strength of different sliding materials at high temperatures

The tests were conducted on circular sheets of 75 mm diameter, 6,7 mm thickness recessed for 4,5 mm in a steel backing plate. The mating surface was a sheet of austenitic steel in accordance with EN 1337-2. The test program consisted of cycles of movement at different sliding velocities, either at constant velocity or with a sinusoidal profile. The contact pressure was 57 MPa and the temperature  $21 \pm 1^\circ\text{C}$ .

In non seismic conditions, at 0,5 mm/ velocity Hoslide showed a dynamic friction  $\mu_{\text{dyn}} = 0,30$  and a static friction  $\mu_{\text{st}} = 0,37$  at breakaway.

In seismic conditions, at average velocities varying between 40 and 100 mm/s and peak velocity up to 157 mm/s, for all the 40 sliding cycles foreseen the dynamic friction  $\mu_{\text{dyn}}$  was always included between 0,025 and 0,30 showing a very good constancy and meeting the design requirements (0,30) and the variation tolerance foreseen by the Italian Code NTC 2008 ( $\pm 25\%$ ).

An other series of tests aimed to verify the characteristic compressive strength at various temperatures. The evaluation of the compressive strength has been executed in accordance with

CUAP 03.01/35 [3]. The compressive strength is very high, starting from 220 MPa at ambient temperature and remaining considerably higher than other materials even at 80°C. The comparison of the compressive strength for HOTSLIDE and other materials, PTFE and UHMWPE is shown in figure 4

### 3.3 Production

The production of the isolators have been a great challenge. The award of the contracts was primarily based on the delivery time proposed by the manufacturer but the penalty in case of delay was extremely high in order to prevent excessively optimistic declarations. Being ALGA awarded two contracts the client did not accept to add the foreseen delivery times Therefore ALGA had to organize to produce the isolators for the 2 contract in parallel in order to avoid a penalty that could raise up to 70.000 € per day of delay.

Of course, with such a great deterrent, the production has been completed ahead schedule, supplying 4000 isolators in the first 10 weeks from the order and the remaining ones in the following 4 weeks

Some phases of the production that reached a peak of over 100 isolators per day are shown in Figures 9 and 10

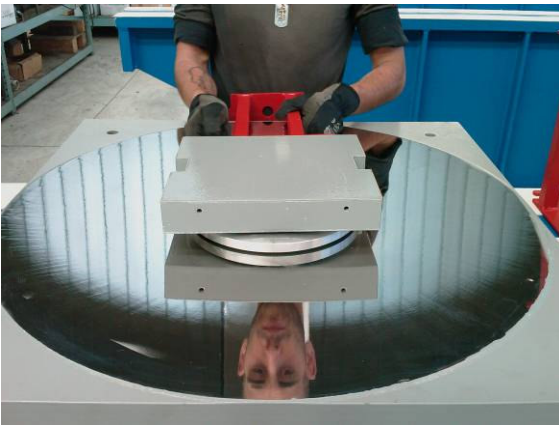


Figure 9 – Assembling of a sliding pendulum isolator



Figure 10 – The assembling line reached a peak of over 100 isolators per day

According to the design data given with the tender the isolators had the following characteristics:

- Radius of the spherical sliding surface 4000 mm
- Friction coefficient of the sliding material  $0,03 \pm 25\%$
- Design displacement at collapse limit state (SLC)  $\pm 260$  mm
- Equivalent viscous damping 20%
- Effective period 3,32 s

### 3.4 Testing

The only applicable Standard in Italy at the time of award of the tenders was the Norme Tecniche per le Costruzioni (NTC 2008). However the European Standard EN 15129 was in the phase of formal vote and has been approved on 18 August 2009, will be formally applicable on 1 August 2010 and compulsory on 1 August 2011.

The Client decided to fulfil the requirements of both Standards, considering that the European Standard, the most updated and advanced in the world, could not be ignored.

Both standards require the execution of tests on two prototypes and the execution of routine tests on 5% of the production (EN 15129) or 20% (NTC 2008), so it was decided by the Client to perform 2 + 2 prototype tests and routine test on 5% of the isolators according to EN 15129 plus 15% according to NTC 2008. In the following tables the tests required by both standards are listed

TEST TYPE	V (kN)	D (mm)	F (Hz)	v (mm/s)	Cycles
Settlement test	2000	0			1
Load bearing capacity	4000	0			1
Frictional resistance force test	2000	6		0,1	Ramp
Service condition test	2000	±25	0,05	5	20
Benchmark test	2000	±260	0,096	50	3
Dynamic test D1	2000	±65	1,0	260	3
Dynamic test D2	2000	±130	0,5	260	3
Dynamic test D3	2000	±260	0,25	260	3
Seismic test E1	1250	±260	0,25	260	3
Seismic test E2	3000	±260	0,25	260	3
Bidirectional test B1	3000	±260	0,25	260	3
Bidirectional test B2 (rot. 90°)	3000	±260	0,25	260	3
Property verification P2	3000	±260	0,25	260	3
After aging test P3	3000	±260	0,096	50	3

Table 1 – Prototypes test required by the EN 15129. Evidenced in grey the routine test required on 5% of the production

TEST TYPE	V (kN)	D (mm)	F (Hz)	v (mm/s)	Cycles
Static evaluation of the friction coefficient	1250	25			3
	2000	25			3
	3000	25			3
Dynamic evaluation of the friction coefficient	1250	±260	0,175	182	3
	2000	±260	0,25	260	3
	3000	±260	0,325	338	3
Dynamic test with 10 cycles at design displacement	1250	±260			10
	2000	±260	0,25	260	10
	3000	±260			10

Table 2 – Prototypes test required by the NTC 2008. Evidenced in grey the routine test required on 20% of the production

Dynamically testing the sliding pendulum isolators implies the dynamic control on two axes and the only available facility in Europe at the time of the tender was Eucentre. However the very large amount of tests required by the NTC 2008, implying 980 units to be tested in 3 months for Alga only, was not compatible with the testing capacity of Eucentre. So Alga was forced to develop his own facility, upgrading the already owned equipments.

The special testing equipment, shown in Figure 11 consists of a steel frame resisting to the vertical load, a vertical actuator with 5000 kN capacity and two horizontal actuators with 200 kN capacity each and 1300 mm stroke. The vertical actuator is connected to a series of accumulators partially filled with nitrogen. The pressure of the oil of the vertical actuator is set up to the necessary value to obtain the required vertical load. The accumulators can compensate little displacements of the piston of the vertical actuator with a minimum variation of pressure. So the vertical load could be kept constant within a tolerance of ±2% with the vertical movements given by the sliding pendulum moving horizontally. With this system the power required is minimized and the entire oil flow available can be utilized by the horizontal actuators. The horizontal actuators were connected to a pump giving an oil flow up to 600 l/min at 210 bar so providing a maximum velocity of 500 mm/s.



Fig. 11 – Dynamic testing equipment for sliding pendulum isolators at ALGA laboratory

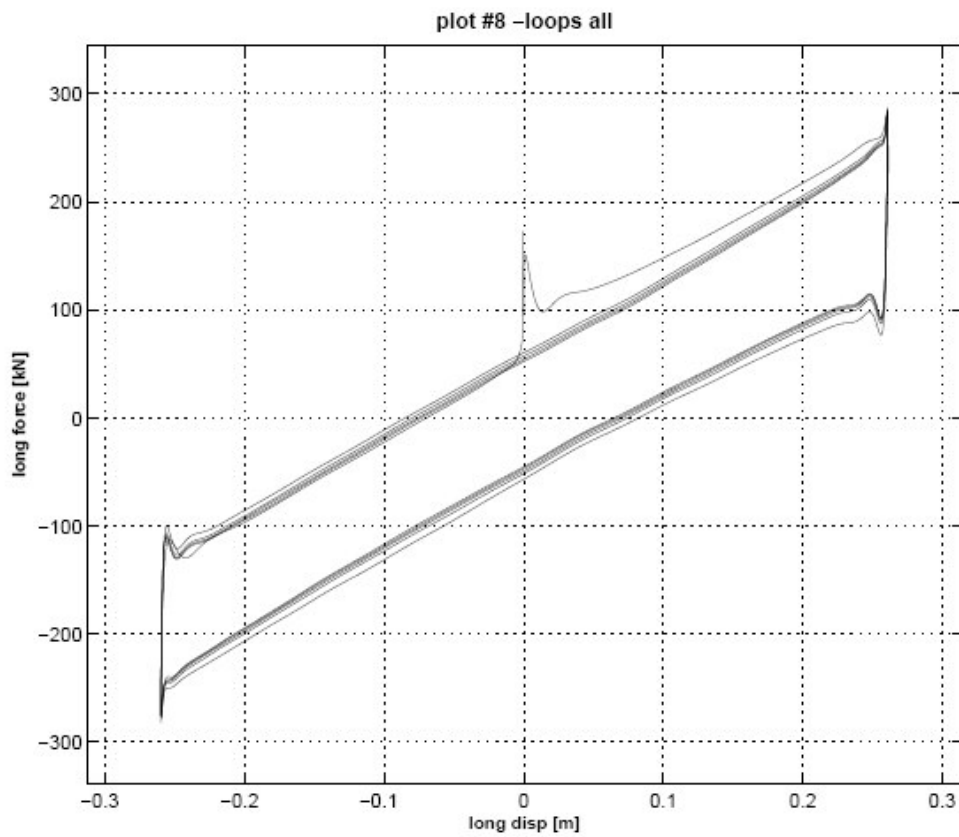


Figure 12 – Typical test result of the sliding pendulum isolators under the following conditions: Vertical load 2850 kN; Amplitude  $\pm 260$  mm; Test frequency 0,16 Hz; Peak velocity 260 mm/s. The average friction value is 0,034

With this equipment it was possible to perform a dynamic test in 20 minutes only, including the time required to install and disinstall the isolator.

In Figure 12 is shown one typical plot of a dynamic test.

In addition to the 980 acceptance and the 4 qualification tests executed in Eucentre and Alga laboratories, some field test has been performed applying to an entire building dynamic horizontal load. The load has been applied utilizing actuators reacting on a steel frame anchored to the steel columns in the basement of the building as shown in Figure 9. The pumping system was able to move the buildings at a maximum velocity of 100 mm/s

All the tests performed could confirm the suitability of the isolators and the correct choice of the sliding material



Figure 13 – The reaction frames applied to a building for the execution of the *in situ* dynamic test

#### 4. Conclusions

The C.A.S.E. project has been a great challenge and its success was possible thanks to the collaboration of all partners involved.

In particular in the field of the base isolation it represents the largest project ever executed in the world.

The very wide amount of tests performed on the sliding material, on complete isolators and in situ, showed the reliability of the system and the stability of the results.

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