Design, Full-scale Testing and CE Certification of Anti-seismic Devices According to the New European Norm EN 15129: Curved Surface Sliders

C. Mendez Galindo, T. Spuler, G. Moor & F. Stirnimann
Mageba SA, Bulach, Switzerland

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SUMMARY:

The increasing need for safer bridges and buildings in Europe has stimulated the development of the first European specifications for the design, manufacturing, and testing of anti-seismic devices, the European norm EN 15129. Among the great variety of anti-seismic devices, seismic isolators such as curved surface sliders (CSS), also called pendulum isolators, have found wide application in bridge and building structures. In order to reach the CE Certification according to EN 15129, a complete testing campaign has been carried out as specified by the European norm. Despite the demanding testing requirements in the new European norm, the results proved that the proposed design of the isolators successfully fulfilled the performance required for the CE Certification.

Keywords: seismic isolation, curved surface sliders, pendulum isolators, full-scale testing, EN15129

1. INTRODUCTION

Although Europe is not as seismically active as other parts of the world, the design of critical structures to withstand the effects of earthquakes continues to gain importance on the continent. This was underlined by the publication of the new European Norm for Anti-seismic Devices, EN 15129 on August 2010. This norm regulates the design, production and testing of most existing types of anti-seismic devices, and crucially, also allows the development of new devices, as long as they fulfil the established performance criteria. From August 2011, only manufacturers certified to supply seismic devices with the CE label will be able to provide these devices in Europe (CEN 2009). This is a significant development for the bridge industry in Europe, due to the critical role bridges play as lifelines in the aftermath of an earthquake – enabling access for emergency services and the evacuation of the affected population. The cost associated with repair or replacement of damaged bridges is likely to be small compared with the economic impact caused by disruption to traffic after an earthquake and during the long reconstruction phase. In order to assure functionality of bridges, they must be designed to safely withstand the devastating forces of seismic ground movements. Past earthquakes have served as full-scale tests and the often tragic results have forced engineers to reconsider design principles and philosophies. Recent earthquakes have repeatedly demonstrated, for example, that during an earthquake, adjacent spans of multi-span bridges often vibrate out-of-phase, causing significant damage to the structures (Moor et al. 2011).

2. SEISMIC ISOLATION

The need for safer bridges has stimulated the adoption of a common earthquake protection strategy which has seen conventional bearings being replaced by seismic isolation devices. An isolation system placed between the bridge superstructure and its supporting substructure is generally capable of increasing both flexibility and energy dissipation. Flexibility in the horizontal plane will lower the frequency of the bridge, decreasing earthquake-induced acceleration, while the energy-dissipating capacity of the seismic isolators will considerably reduce the damaging energy exerted to the bridge piers. Moreover, when isolation bearings are installed on the top of a bridge's piers, the lateral force from the superstructure during a seismic event can be distributed among all piers, avoiding the concentration of lateral forces at specific locations (Mendez et al. 2009). Seismic isolation systems provide an alternative to conventional earthquake resistance design such as strengthening of structural elements, and have the potential for significantly reducing seismic risk without compromising safety, reliability, and economy of bridge structures. Together with the adoption of new performance-based design criteria, this has resulted in seismic isolation technologies already becoming the preferred option for many structural engineers. The main objective of a seismic isolation system is to increase the natural period of a structure. However, instead of elongating the period to high values, an adequate seismic design emphasizes increased energy dissipation capability and distribution of lateral forces to as many substructures as possible.

Seismic isolators provide the structure with enough flexibility so the natural period of the structure differentiates as much as possible from the natural period of the earthquake, as shown in Figure 1. This prevents the occurrence of resonance, which could lead to severe damage or even collapse of the structures. An effective seismic isolation system shall provide effective performance under all service loads, vertical and horizontal, shall be as effective as conventional structural bearings. Additionally, it shall provide enough horizontal flexibility in order to reach the target natural period for the isolated structure. Another important requirement of an effective isolation system is ensuring re-centering capabilities, even after a severe earthquake, so that no residual displacements could disrupt the serviceability of the structure. Finally, it shall also provide an adequate level of energy dissipation; mainly through high ratios of damping (Figure 2), in order to control the displacements that otherwise could damage other structural elements.

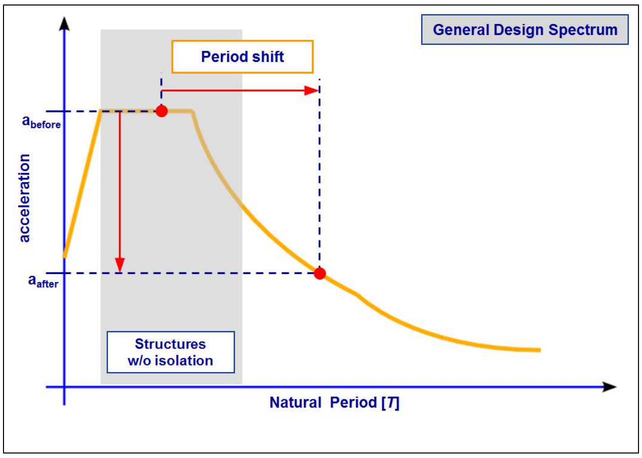


Figure 1. Reduction of acceleration by seismic isolation

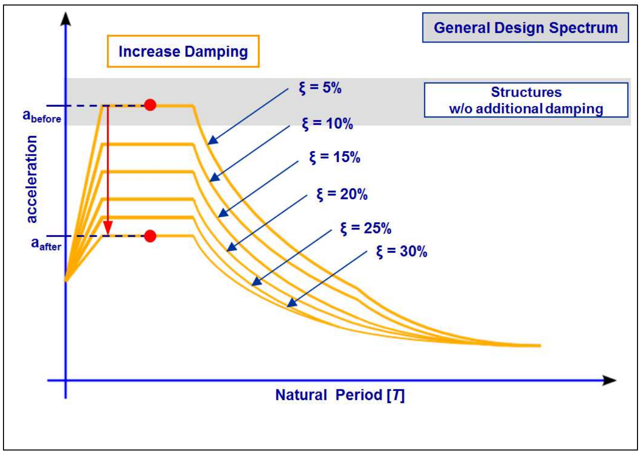
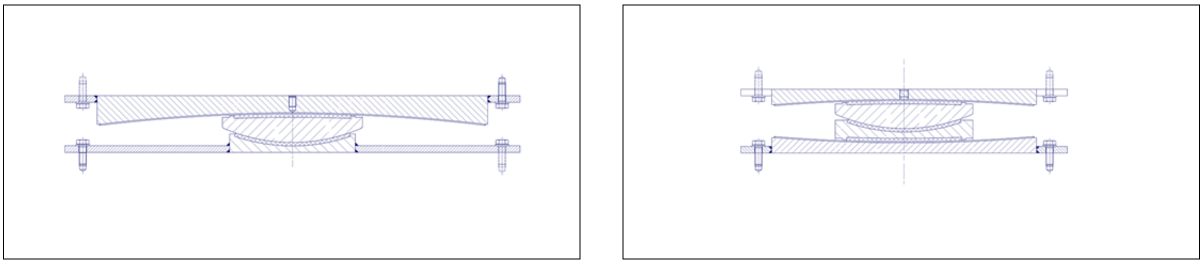
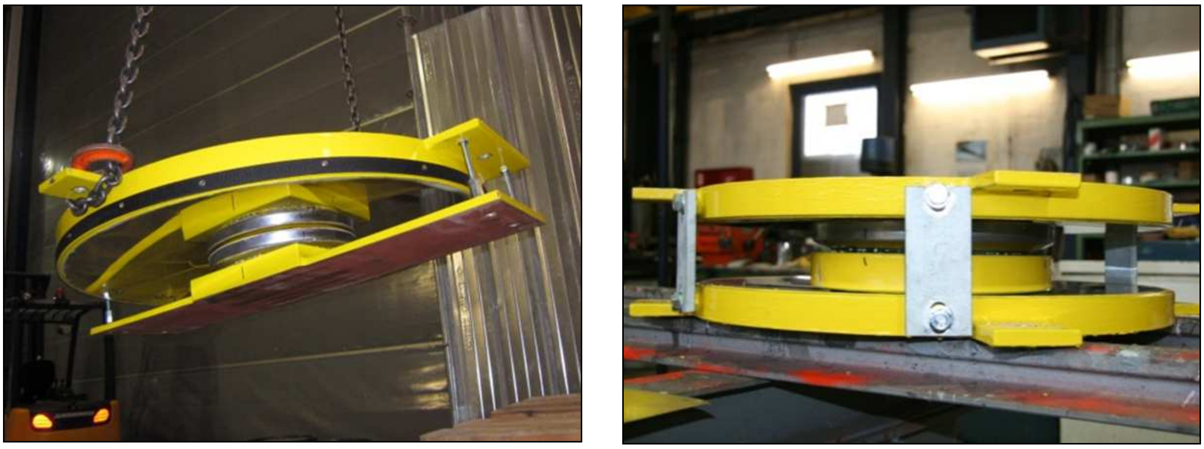


Figure 2. Reduction of acceleration by additional damping



(a) (b)

Figure 3. Section view of an isolator Pendulum Mono (a), and Pendulum Duplo (b)



(a) (b)

Figure 4. Test samples of an isolator Pendulum Mono (a), and Pendulum Duplo (b)

3. CURVED SURFACE SLIDERS

3.1. Description and working principle

Curved Surface Sliders (Pendulum Isolators) are based on the working principle of a pendulum. The isolators allow the horizontal displacement of the structure, while providing the necessary natural period shifting required by the seismic isolation system. Once activated by an earthquake, the isolators will allow the virtual decoupling of the supported structure from the ground. At the same time, the restoring force due to gravity will bring it back toward the centre position. This principle allows the structural engineer to reach desired periods without having to consider the supported mass. The performance of the device mainly depends on the radius of curvature and the coefficient of friction. Under normal service conditions, Pendulum isolators are designed to transmit vertical forces to the bridge sub-structure. In case of an earthquake, lateral flexibility is achieved through the sliding of a rocking element along the primary curved surface. One of the key parameters in the design of this isolators is the radius of curvature of this surface. Energy dissipation is produced by the dynamic friction between the sliding stainless steel surface and a sliding material. Finally, the re-centering function is given by the combination of gravity and geometry of the isolator construction (Fig. 3a-3b).

3.2. Pendulum Mono Isolator

Pendulum Mono isolators (Fig. 4a) consist of three basic elements: A primary curved sliding surface, whose radius of curvature determines the oscillation period of the isolator, a steel rocking element equipped with a sliding material called *RoboSlide*, which slides along the primary curved surface, and a fixed steel plate especially designed to allow the rotations induced by the horizontal displacement of the isolators. The size of the primary sliding surface depends on the maximum design displacement.

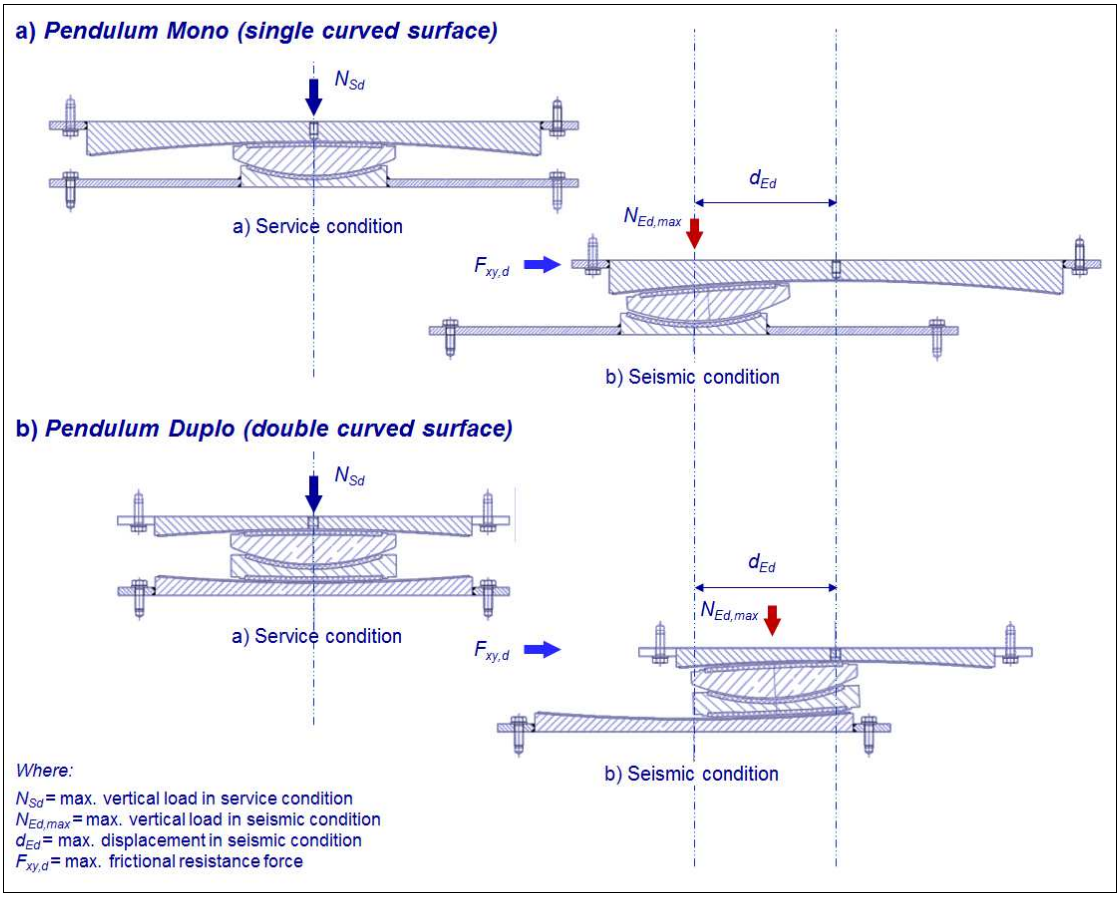


Figure 5. Working principle of Pendulum isolators

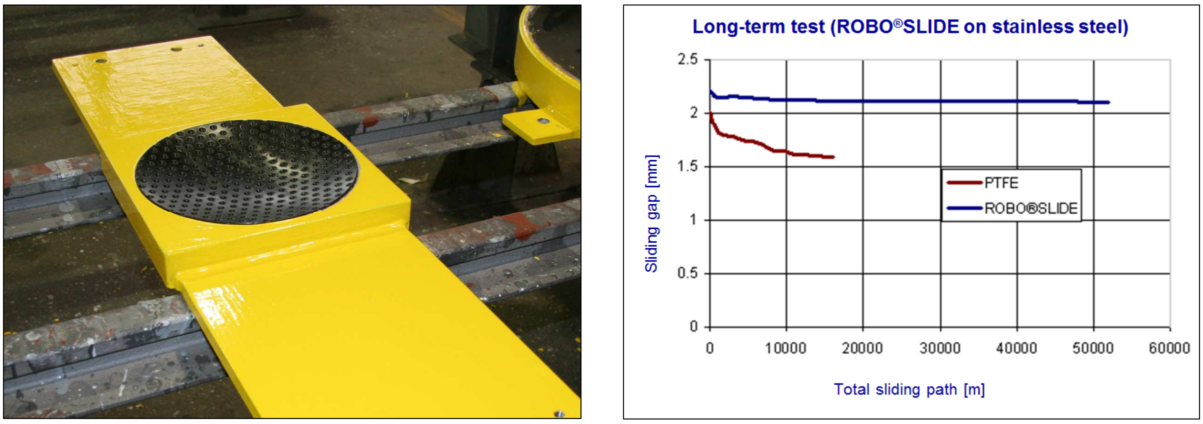
3.3. Pendulum Duplo Isolator

Pendulum Duplo isolators (Fig. 4b) include two primary curved sliding surfaces. This allows higher horizontal displacements to be facilitated with smaller bearing dimensions. These isolators include a rocking component equipped with an articulation element that allows high rotations (Fig. 5).

3.4. RoboSlide sliding material

RoboSlide is a special sliding material made of modified, ultra-high molecular polyethylene with reduced abrasion resistance and increased bearing capacity, adapted for seismic isolators in bridge and building construction. The sliding material is equipped with a durable, almost frictionless sliding surface ensured by the addition of grease pockets and a powerful lubricant (Fig. 6a). Isolators equipped with *RoboSlide* are suitable for all types of construction. In addition to effective physical properties such as low wear and high compressive strength, the *RoboSlide* sliding material retains its properties at low temperatures down to -50°C. *RoboSlide* has high resistance to aggressive chemicals and the effects of high-energy radiation. Additionally, it has high formability, making it easier to accommodate irregularities in the supporting structure and flatness deviations. Wear and local overstressing are therefore less likely.

Extensive static load and sliding friction tests have been carried out by the independent material testing laboratory of the University of Stuttgart (MPA) in accordance with the test program for heavy-duty sliding materials of the Deutsches Institut für Bautechnik (DIBt, German Institute for Constructional Engineering). The tests clearly showed that the sliding friction values are within the range of EN 1337 both at low temperatures and low stresses, and had clearly fallen short at higher stresses ($\mu < 0.02$). After sliding for a total of 50km the *RoboSlide* sliding disc showed practically no signs of wear. This equates to much more than double the durability of a bearing with PTFE (Fig. 6b).



(a) (b)

Figure 6. RoboSlide installed below rocking component (a) and long-term test results (b)

4. TESTING

The first testing of seismic isolation systems in accordance with EN 15129 has been recently carried out, at the European Centre for Training and Research in Earthquake Engineering (EUCENTRE) in Pavia, Italy. The full-scale "Type Testing" of two curved surface slider isolators was carried out by specialist manufacturer Mageba SA, and all tests achieved positive results, paving the way for certification with the CE label, verifying conformance with the applicable norm.

4.1. Testing protocol

Pendulum isolators are designed and manufactured according to European Standard EN 15129 and with European Technical Approval ETA-08/0115. Isolators are marked with the CE mark of conformity, which confirms that they satisfy all requirements of this Standard and Approval, without exception. Pendulum isolators are also tested according to EN 15129 described in Table 1.

Table 1. CSS Full-scale tests required by the European Norm for Anti-seismic Devices EN 15129

Type of Testing	Required Tests	No. of Complete Cycles
"Type" Tests	1. Load bearing capacity	-
	2. Frictional resistance force under service conditions	1
	3. Static coefficient of friction	-
	4. Service	20
	5. Benchmark	3
	6, 7 and 8. Dynamic 1, 2 and 3	3
	9. Integrity of overlay	3
	10. Seismic	3
	11. Bi-directional	3
	12. Property verification	3
	13. Ageing test	3
"Factory Production Control" Tests	1. Load bearing capacity	-
	2. Frictional resistance force under service conditions	1
	3. Sliding isolation test with 3 cycles	3

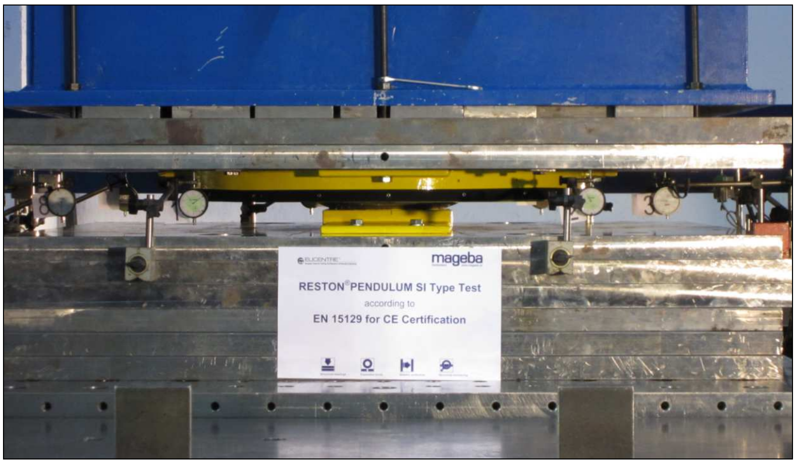


Figure 7. Pendulum Mono isolator during “Type” testing at EUCENTRE

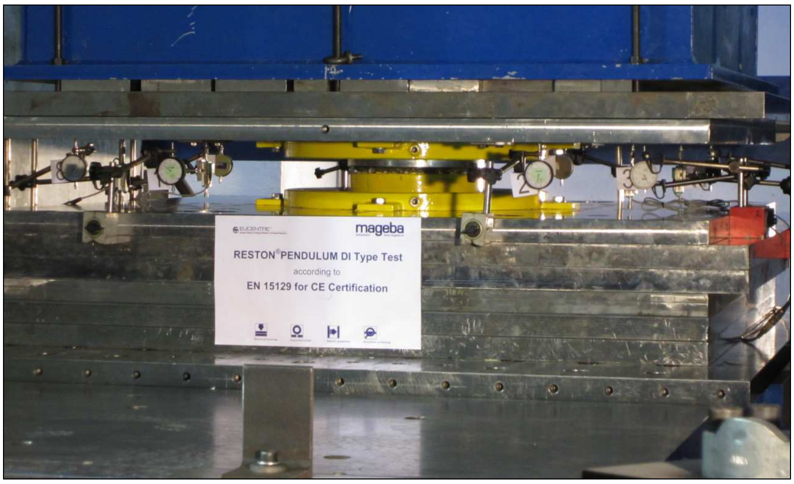


Figure 8. Pendulum Duplo isolator during “Type” testing at EUCENTRE

4.2. Curved surface sliders performance

The “Type” tests indicated in Table 1 have been performed in full-scale Pendulum isolators. Two different types of device were tested: two Mono isolators with a single curved sliding surface, and two Duplo isolators which have two curved sliding surfaces (Figs 7 and 8). Both types of isolators were designed to withstand the same dynamic demands: a maximum vertical design force of 4,000kN and a maximum horizontal displacement of 259mm, and were designed with a radius of curvature of 3.6m.

The four full-scale curved surface sliders were subjected to 15 tests, of which 11 involved dynamic conditions. Each isolator underwent a total of 48 cycles during the whole testing campaign. The load bearing capacity test indicated in the norm requires a load of up to twice the maximum vertical force, which in the case of the curved surface sliders reached 8,000kN. Due to the importance of friction in this type of device, a test for frictional resistance force under service conditions was performed on the isolators, as well as a long-term friction test (up to 10,000m) of sliding material samples.

The sliding isolation tests are among the most important for curved surface sliders, since they test key parameters such as maximum design displacement and maximum design velocity. EN 15129 specifies ten different sliding isolation tests. These include a service test at a vertical load of 4,000kN, and a number of further tests such as seismic, dynamic, bi-directional, benchmark, property verification and integrity of overlay, at maximum displacement of 259mm and velocities of up to 0.275m/s, as indicated in Table 2 (EUCENTRE, 2011).

Table 2. Summary of “Type” tests conducted on two full-scale Pendulum Mono and Pendulum Duplo samples

Parameter	Units	Value
Maximum displacement	mm	259
Maximum vertical load	kN	8,000
Frequencies	Hz	0.0042 – 0.169
Velocities	m/s	0.05-0.275
Total No. cycles	-	192

4.2.1. Load bearing capacity

According to the European norm for anti-seismic devices, the samples must be tested up to twice the maximum design load for service conditions. Such requirements lead to isolators highly capable of withstanding compression forces exceeding significantly design values.

4.2.2. Isolation characteristics

The main purpose of the isolation characteristics tests (tests 4 to 13 in Table 1) is to ensure that the isolators’ performance is in agreement with the design values defined in advance by the structural engineer. Such values generally have a tolerance of +/- 10% in terms of restoring stiffness between successive cycles, and +/- 5% tolerance between the restoring stiffness of the upper and lower portions of the cycles. In terms of restoring force tolerance among cycles, as well as for the lateral force for each of the three cycles, the norm requires +/- 15% of the design value. The norm also requires that the energy dissipated by cycle (EDC) by test samples is no less than 85% of the design value at the adjusted maximum target displacement. Finally, it is also required that the restoring stiffness among the test samples does not vary more than +/-15%. The results from the restoring stiffness between successive cycles at seismic test are shown in Figure 9 for the test samples of Pendulum Mono, and Figure 10 for the test samples of Pendulum Duplo. The red shaded area is the graphic representation of the maximum tolerance for the variations between values. The results clearly show that the variation of the restoring stiffness among the different cycles is well within the tolerance required by the norm.

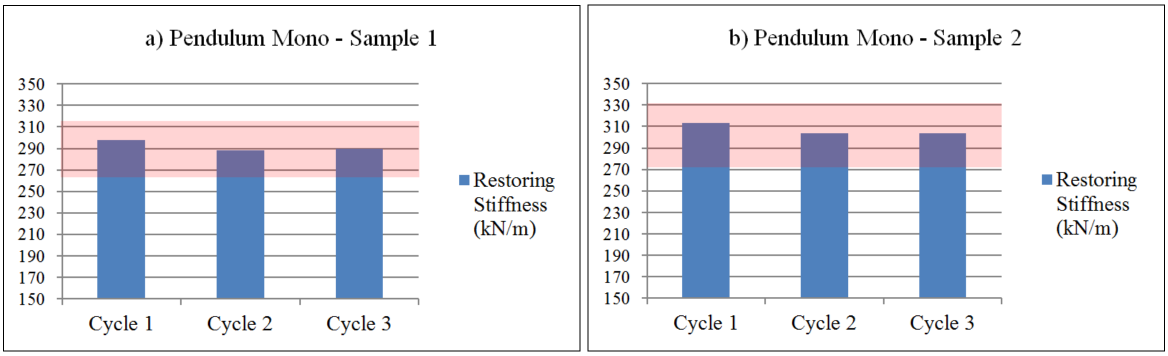


Figure 9. Restoring stiffness of the two samples of Pendulum Mono

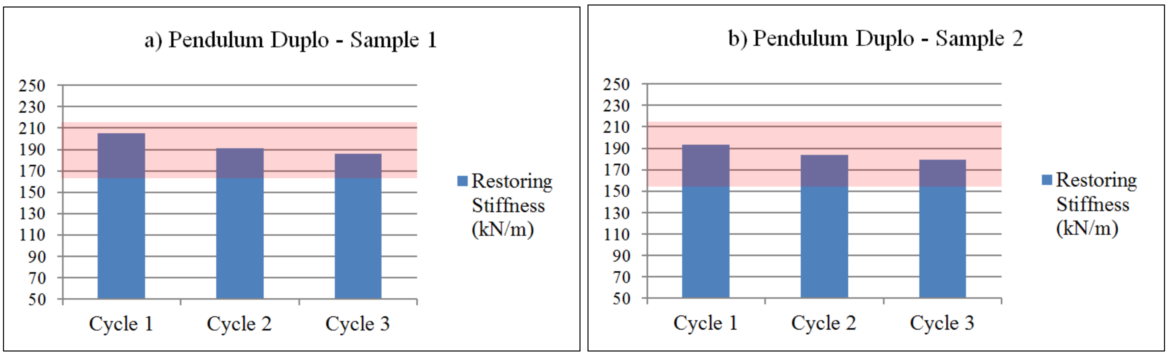


Figure 10. Restoring stiffness of the two samples of Pendulum Duplo

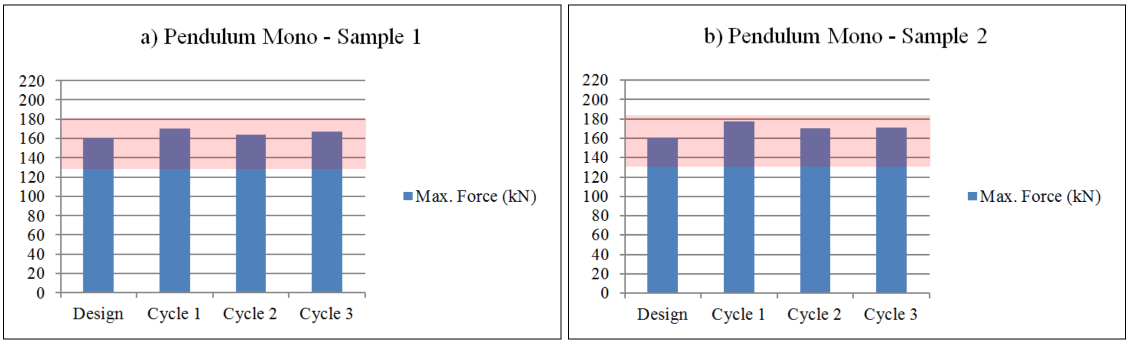


Figure 11. Maximum lateral force for the two samples of Pendulum Mono

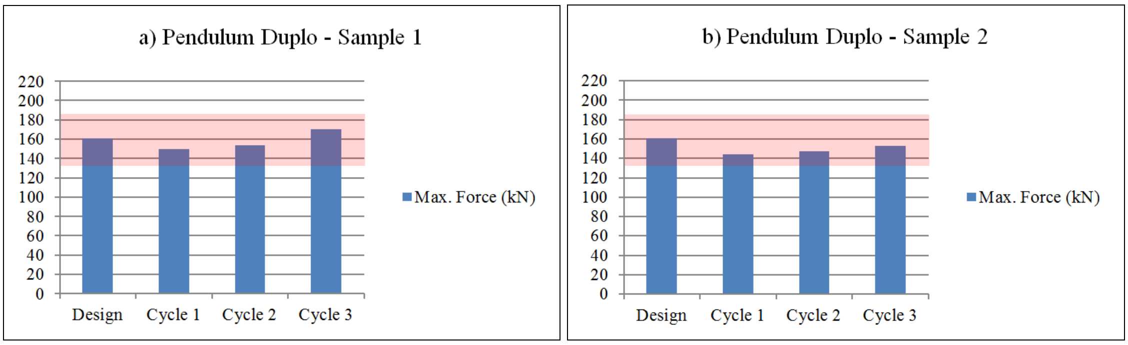


Figure 12. Maximum lateral force for the two samples of Pendulum Duplo

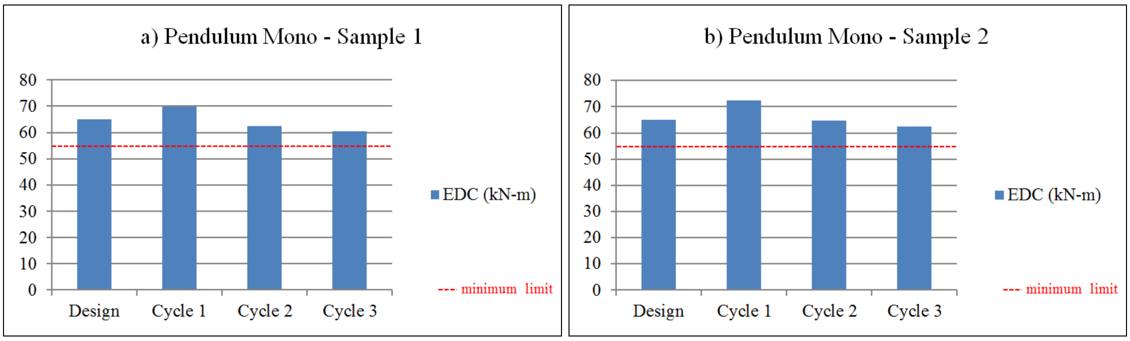


Figure 13. Energy dissipated by cycle for the two samples of Pendulum Mono

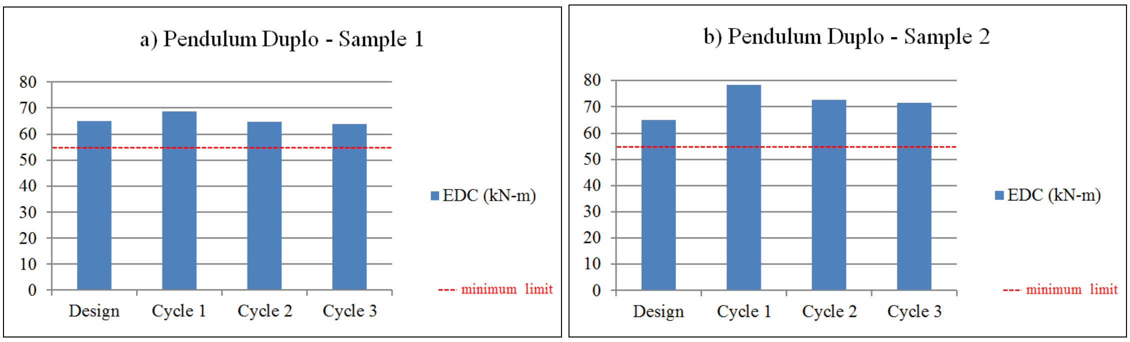
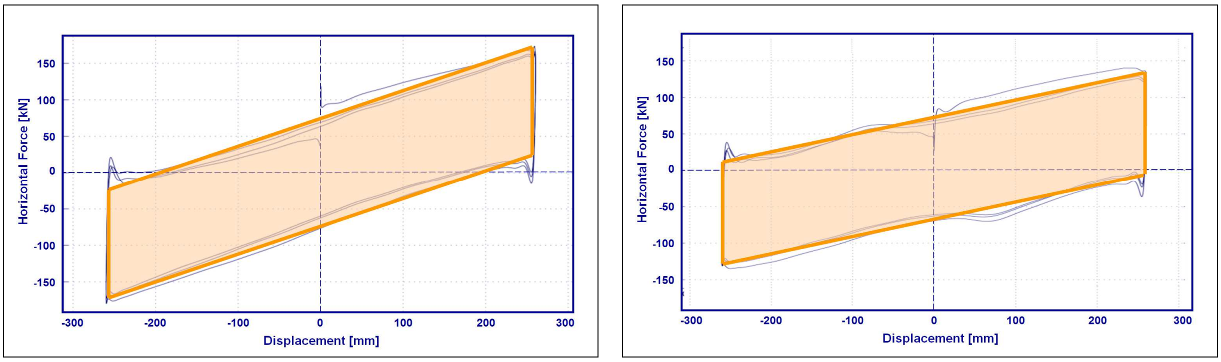


Figure 14. Energy dissipated by cycle for the two samples of Pendulum Duplo

The maximum lateral forces for each of the cycles in both types of isolator are shown in Figure 11 and Figure 12. The red shaded area in the figures is a graphical representation of the tolerance given by the norm. The results clearly show that the maximum lateral forces are all within the allowable limits and prove to be in accordance with the design values.



(a) (b)

Figure 15. Hysteresis of isolators Pendulum Mono (a) and Pendulum Duplo (b)

Another important value in order to evaluate the compliance with the norm is the energy dissipated by cycle. The results of the EDC in each test sample are shown in Figures 13 and 14. In this particular case, as indicated at the beginning of the section, where the minimum variation of EDC in each cycles should not be less than 85% of the design value of EDC.

Finally, an ageing test with three full cycles was carried out on the same isolators in which the *RoboSlide* material had been artificially aged at a temperature of 70°C for 14 days. All the testing was supervised by an independent surveillance body which is responsible for the verification of the compliance with the requirements of EN 15129. Figures 15a and 15b show two force-displacement plots recorded from the three-cycle seismic tests performed in the two samples of Pendulum Mono and two samples of Pendulum Duplo (EUCENTRE, 2011).

5. CONCLUSIONS

All of the testing was successfully completed; the testing of the four curved surface sliders resulted in damping values of up to 30% and energy dissipated per cycle of up to 78kN-m. This proved an effective performance in terms of displacement, load bearing capacity, stiffness and energy dissipation. Additionally, the full-scale testing proves that *RoboSlide* sliding material can fulfil the required coefficient of friction. The results confirmed that all of the tested seismic isolators fulfil the strict standards established by the European norm EN 15129.

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