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

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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. 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 for the most common type of elastomeric isolator: lead rubber bearings (LRB). Two full-scale sample isolators have been design to withstand high horizontal forces and displacements. This paper presents a detailed description of the whole testing campaign, as well as a summary of the performance of the two isolators during the specified static and dynamic tests. 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, lead rubber bearings, elastomeric 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 OF BRIDGES

Bridge bearings have historically been one of the most vulnerable components in resisting earthquakes. Steel bearings in particular have performed poorly and have been damaged by relatively minor seismic shaking (Ruiz et al., 2005). Among the great variety of seismic isolation systems, lead-rubber bearings (LRB) have found wide application in bridge structures (Moehle, 1999). This is due to their simplicity and the combined isolation-energy dissipation function in a single compact unit.

By using hydraulic jacks, the superstructure of the bridge can be lifted to remove the original bearings, easily replacing them with suitable LRB bearings. In practice, isolated bridges with LRB bearings have been proven to perform effectively reducing the bridge seismic response during earthquake shaking. The Thjorsa River Bridge in Iceland survived two major earthquakes of moment magnitudes (Mw) 6.6 and 6.5 without serious damage and was open for traffic immediately after the earthquakes as reported by Bessason and Haflidason (Bessasson, 2004). LRB bearings of isolated bridges, due to their inherent flexibility, can be subjected to large shear deformations in the event of great earthquake ground motions. According to experimental test results, LRB bearings experience significant hardening behavior beyond certain high shear strain levels due to geometric effect (Turkington et al., 1989). Seismic isolation systems provide an alternative to conventional earthquake resistance design, and have the potential for significantly reducing seismic risk without compromising safety, reliability, and economy of bridge structures (Pan et al., 2005). Furthermore, with the adoption of new performance-based design criteria, seismic isolation technologies will be the choice of more structural engineers because they offer economical alternatives to traditional earthquake protection measures (Mendez, 2008).

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 2. 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. 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 3), in order to control the displacements that otherwise could damage other structural elements.

3. LEAD RUBBER BEARINGS

Many innovative devices and systems are being developed for the purpose of seismic isolation of bridges (Moehle, 1999). One of the most widely adopted isolation system is the lead-rubber bearing (LRB) shown in Fig. 1. This type of elastomeric bearing protects the bridge from the destructive effects of earthquake ground motions increasing the structure fundamental period beyond the energy-containing periods of earthquakes and also by dissipation of seismic energy through the additional hysteretic damping due to yielding of the lead plug (DesRoches, 2004). Under normal conditions, LRB bearings behave like regular bearings. The isolation device is characterized by a high initial stiffness provided by the lead plug inserted in the bearing to avoid undesirable displacements under service requirements, wind action and minor earthquakes. However, the shear stiffness decreases favorably for moderate levels of deformation, allowing the isolator to uncouple the bridge from the damaging action of earthquake ground motions. Therefore, the seismic damage the structure acquires is drastically minimized through the reduction of the seismic inertial loads (Bessasson, 2004).

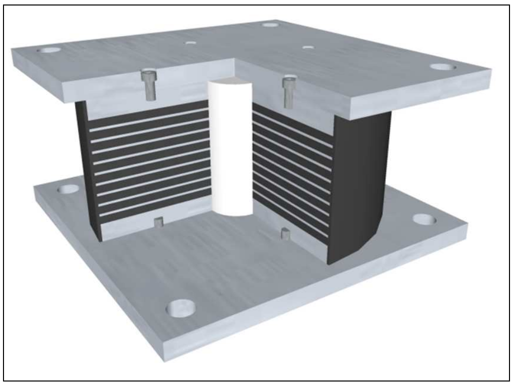

Figure 1. Section view of an elastomeric isolator type LRB

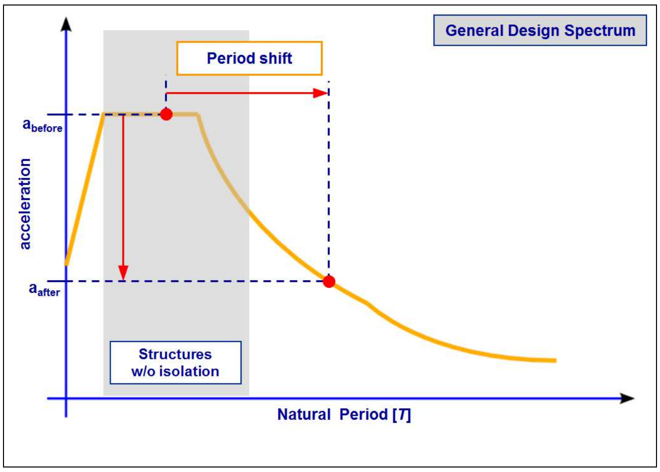

Figure 2. Reduction of acceleration by seismic isolation

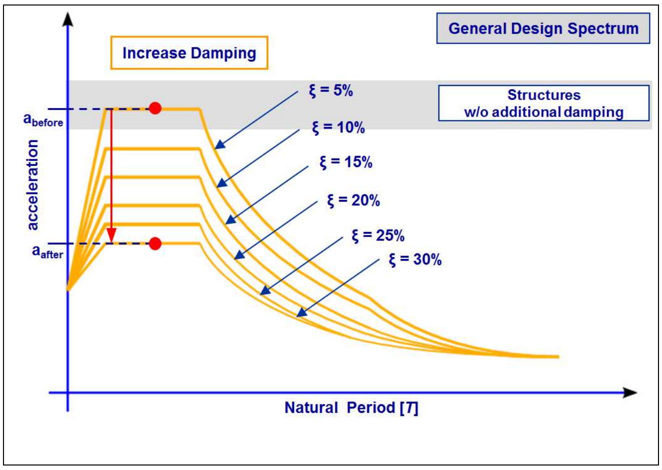

Figure 3. Reduction of acceleration by additional damping

Bridges are ideal candidates for the adoption of base isolation technology due to the facility of installation, inspection and maintenance of isolation devices. Although seismic isolation is an effective technology for improving the seismic performance of a bridge, there are certain limitations on its usage. Seismic isolation improves the performance of a bridge under earthquake loading partially by increasing the fundamental vibration period. Thus the vibration period of a bridge is moved away from the high-energy seismic ground period and seismic energy transfer to the structure is minimized. Therefore , the usage of seismic isolation on soft or weak soil conditions, where high period ground motion is dominant, reduces the benefits offered by the technology (Turkington et al., 1989).

The seismic isolation system has a relatively high vibration period compared to a conventional structure. Due to the principle of dynamic resonance, a larger difference between the dynamic vibration frequencies of the isolation system and the superstructure results in a minimized seismic energy transfer to the superstructure. Therefore, seismic isolation is most effective in relatively rigid structural systems and will provide limited benefits for highly flexible bridges.

Another consideration is related to the large deformations that may occur in the seismic base-isolation bearings during a major seismic event, which causes large displacements in a deck (Pan et al., 2005). This may result in an increased possibility of collision between deck and abutments. Damping is crucial to minimize the seismic energy flow to the superstructure and to limit the horizontal displacements of the bearings (Mendez, 2008). The lead plug deforms plastically at a predetermined flow stress and thus dissipates energy through hysteretic damping.

3.1. Description

LRBs consist of alternate layers of rubber and vulcanized reinforcement steel plates of limited thickness and a central lead core. They can dissipate energy up to 30% damping due to the high damping capacity of the lead core. It is fabricated with the rubber vulcanised directly to the top and bottom connection plates. The bearing can also be supplied with additional anchor plates, allowing easier replacement of the bearing. LRBs are made from natural rubber (NR) with a central lead plug and it has great energy absorption capability. LRBs have found wide application in bridge structures. LRBs provide a high level of damping of up to 30%.

3.2. Working principle

LRBs work on the principle of seismic isolation and limit the energy transferred from the ground to the structure in order to protect it. The rubber/steel laminated isolator is designed to carry the weight of the structure and make the post-yield elasticity available. The rubber provides the isolation and the re-centering. The lead core deforms plastically under shear deformations, while dissipating energy through heat.

3.3. LRB analytical model

LRB bearings have been represented using a number of analytical models, from the simplicity of the equivalent linear model composed of the effective stiffness and equivalent damping ratio formulated by Huang (Huang et al., 1996) to the sophisticated finite element formulation developed by Salomon (Salomon et al., 1999). However, the most extensively adopted model for dynamic analysis of seismic isolated structures is the bilinear idealization for the force-displacement hysteretic loop (Ali et al., 1995). Due to its simplicity and accuracy to identify the force-displacement relationship of the isolation devices, LRB bearing supports can be represented by the bilinear force-displacement hysteresis loop given in Fig. 4. The principal parameters that characterize the model are the pre-yield stiffness K_1, corresponding to the combined stiffness of the rubber bearing and the lead plug, the stiffness of the rubber K_2 and the yield force of the lead plug Q_d. The value of Q_d is influenced primarily by the characteristics of the lead plug, but it is important to take into account that in areas of cold temperatures, natural rubber will cause significant increment of F_1 values.

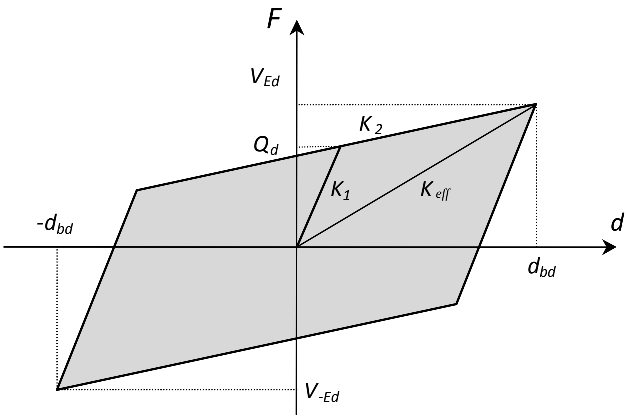

Figure 4. Bilinear analytical model of LRB bearing

4. TESTING

The first testing of seismic isolation systems in accordance with EN 15129 has recently been carried out, at the European Centre for Training and Research in Earthquake Engineering (EUCENTRE) in Pavia, Italy. The full-scale “Type Testing” of two lead rubber bearings 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 (Fig. 5).

Table 1. LRB 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. Compression capacity	-
	2. Compression stiffness	-
	3-7, 9. Dependence of horizontal cycling characteristics	18
	8. One-side horizontal stiffness	-
	10-12. Frequency	9
	13. Temperature	-
	14. Repeated cycling	10
	15. Horizontal displacement capacity	-
"Factory Production Control" Tests	1. Compression stiffness	-
	2. Dependence of horizontal cycling characteristics	18
	3. Horizontal stiffness under one-side ramp loading.	-

4.1. Testing protocol

LRB isolators are designed and manufactured in accordance with EN 15129 and with EN 1337. In order to obtain CE certification, it was necessary to pass the full-scale tests indicated in Table 1 (CEN 2009).

4.1.1. Compression capacity

The main objective of this test is to confirm that the elastomeric isolator, in this case the LRB, is able to withstand the maximum vertical load under service conditions. During the testing it is required to carry out a visual inspection in order to ensure that no visible defects are appearing. In the case of the two samples, such maximum vertical load was 3,450 kN and was applied to the isolator for a period of 3 minutes. Before reaching the maximum value, the load is reached during a period of 10 minutes. Fig. 6 shows the isolator equipped with measurement devices in order to evaluate the vertical displacements due to the compression load.

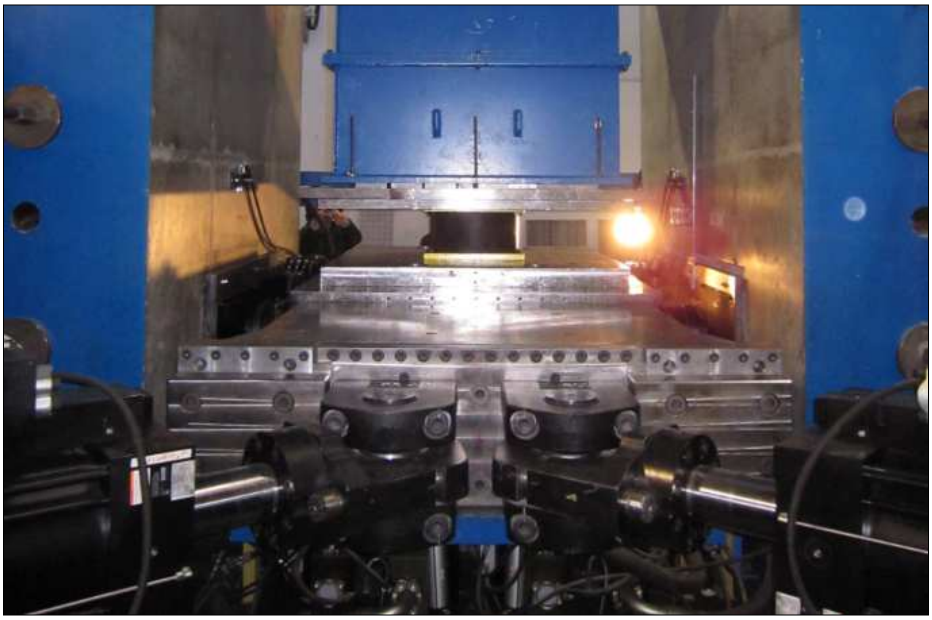

Figure 5. LRB installed at bearing testing machine at EUCENTRE

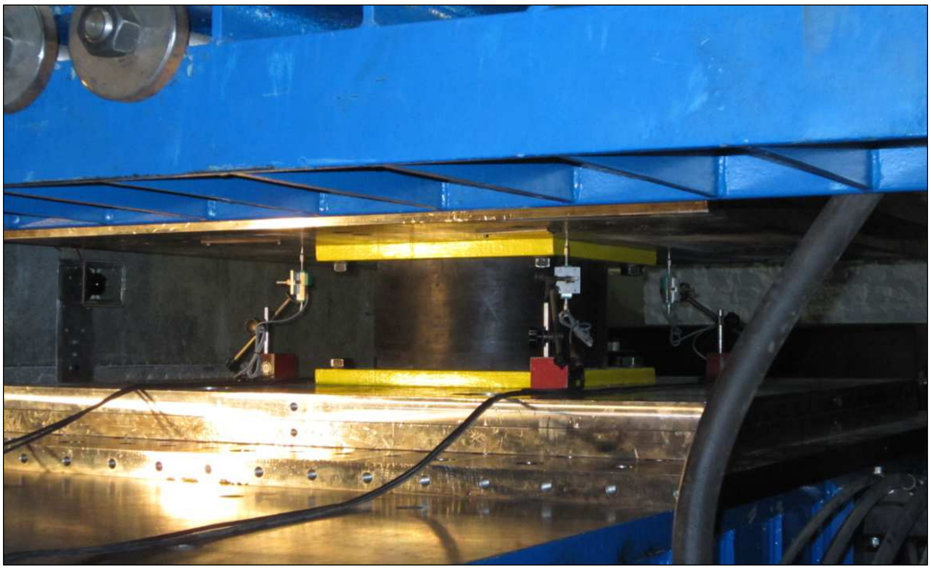

Figure 6. LRB during compression testing at EUCENTRE

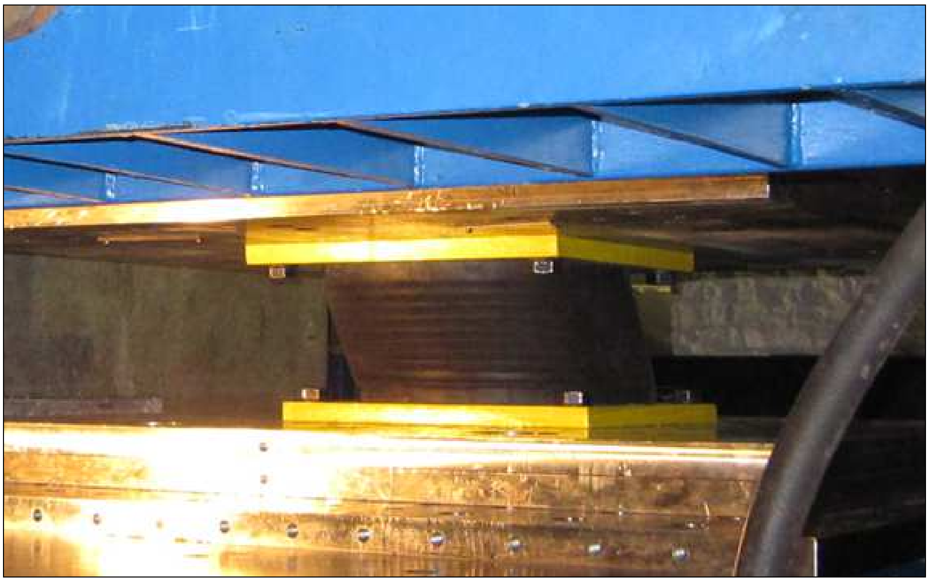

Figure 7. LRB during horizontal cyclic characteristic test at EUCENTRE

4.1.2. Compression stiffness

This test is performed by a loading ramp applied at a constant loading rate which is mainly aim to register static information of the LRB. As for the compression capacity, the load is reached in a period of 10 minutes. For seismic information, this load has to be applied in one second. Once the value of the compression stiffness is recorded, this value will be the base for the performance of the Factory Production Control tests required by the norm. The production units to be tested must show the same value of compression stiffness, with a tolerance of +/- 30%.

4.1.3. Horizontal characteristics under cyclic deformation

These test were particularly demanding on the lead rubber bearings, as the whole series of tests represented a total of 18 complete cycles at a frequency of 0.5 Hz and at different shear strains: +/- 5%, +/- 10%, +/- 20%, +/- 50%, +/- 100% and +/- 150% (Fig. 7). In terms of lead rubber bearings, the aim of these tests is to record mainly two values, the horizontal stiffness and the characteristic strength. These values are then compared from cycle to cycle and among shear strains, in order to verify that both dynamic characteristics remain stable during all cyclic tests. The tolerance in the analysis of the horizontal stiffness and characteristic strength is 20% of the design value.

4.1.4. Horizontal stiffness under one-sided ramp loading
As for the value recorded during the compression stiffness tests, the horizontal stiffness recoded form this test will serve as a value base for the verification of the Factory Production Control Tests. This test must be performed just after the cyclic test with the closest horizontal displacement.

4.1.5. Variation of horizontal characteristics with frequency
The main objective of these tests is to evaluate the effect of frequency particularly on the horizontal stiffness and characteristic strength of the isolators. In order to reach a solid evaluation, tests are performed at different frequencies: 0.1, 0.5 and 2.0 Hz. As for the tests for the horizontal characteristics under cyclic deformation, the values will be compared among cycles and frequencies, in order to verify that the influence of the variation of frequency does not lead to variation higher than +/- 20% of the design value.

4.1.6. Dependence of horizontal characteristics on repeated cycling
This tests aims to evaluate the effects of the repeated cycling on the horizontal characteristics of the isolator. Same as for the previous tests, the most important parameters to verify are the horizontal stiffness and the characteristic strength. There are basically three parameters that need to be considered in the evaluation of these tests, the first is the ratio between the minimum and the maximum horizontal stiffness measured between the second and tenth cycle. Such Ratio must remain higher than 0.7. This also applies to the value of characteristic strength, where 0.7 is also the minimum acceptable ratio. Additionally, a third consideration includes the horizontal stiffness at the first cycle, which has to be compared with the last cycle. The ratio between the last two values must be higher than 0.6.

4.1.7 Lateral capacity
The purpose of the horizontal displacement capacity is to verify that the isolator is able to reach the maximum displacement, without showing any sign of damage or defects. Such displacement is an amplified value of the design displacement of the isolator, as this value has to be multiplied by two factors: 1.15 and 1.5. This leads to a significantly large horizontal displacement that has to be maintained for 2 minutes during which visual inspection has to be carried out in order to ensure that there are no signs of failure or cracks wider than 2 mm.

4.1.8 Summary of testing
The lead rubber bearing isolators each had a diameter of 500mm and a total height of 286mm, and they were designed for a maximum displacement of 250mm and a maximum vertical load of 3,450kN (Fig. 8).

The samples were subjected to 14 different tests, most of them including dynamic conditions, with a total of 37 cycles, and with frequency and amplitude varying from one test to the next. The frequency ranged from 0.1Hz to 2Hz, while the amplitude varied from ±7mm to ±250mm. The velocities reached during the testing also varied, from as little as 0.02m/s to as much as 1.63m/s, as shown in Table 2. Each isolator was also subjected to two compression tests, with loading gradually increasing up to the maximum value of 3,450kN. For all dynamic testing, including simultaneous vertical compression, the vertical pressure of 6MPa represented a vertical load on the samples of 1,131kN. Finally, a hysteretic loop of elastomeric isolators built based on test results and bilinear model is shown in Fig. 9.

Table 2. Summary of "Type" tests conducted on two full-scale LRB samples

Parameter	Units	Value
Maximum displacement	mm	250
Vertical loads	kN	1,150 - 3,450
Frequencies	Hz	0.1 - 2.0
Velocities	m/s	0.02 - 1.634
Total No. cycles	-	74

Figure 8. LRB after manufacturing and marked by surveillance body

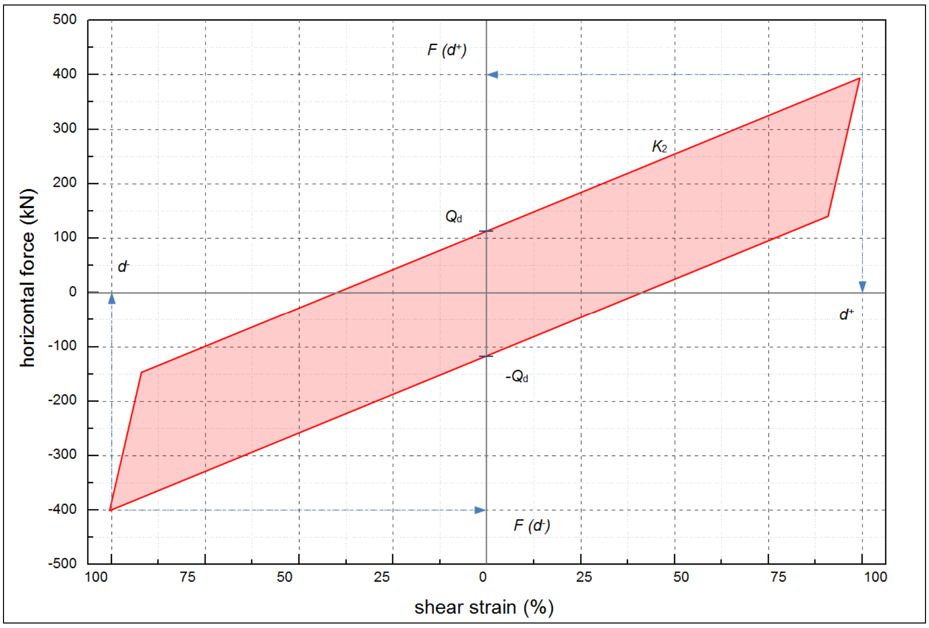

Figure 9. Hysteresis of elastomeric isolators built based on test results and bilinear model

5. CONCLUSIONS

All of the testing carried out was completed successfully; the lead rubber bearing testing resulted in damping values of up to 25% and energy dissipated per cycle of up to 115kNm. The isolator showed an effective performance in terms of displacement, load bearing capacity, stiffness and energy dissipation. The results confirmed that the two full-scale elastomeric isolators fulfil the strict standards established by the European norm EN 15129.

REFERENCES

Bessason, B., and Haflidason, E.: Recorded and numerical strong motion response of a base-isolated bridge, *Earthquake Spectra*, **Vol. 20**, No. 2, pp. 309-332, 2004.

DesRoches, R., Choi, E., Leon, R. T., Dyke, S. J., and Aschheim, M.: Seismic response of multiple span steel bridges in central and southeastern United States. I: As built, *Journal of Bridge Engineering* ASCE, **Vol. 9**, No. 5, pp. 464-472, 2004.

EUCENTRE: Characterization Tests on mageba LASTO®LRB C-500-160 according to European Standard EN 15129:2010 for Anti-seismic Devices, *Technical Report*, EUCENTRE, February 2011.

European Standard EN 15129:2010 for Anti-seismic Devices, European Committee for Standardization, November 2010.

Huang, J. S., and Chiou, J. M.: An equivalent linear model of lead-rubber seismic isolation bearings, *Engineering Structures*, **Vol. 18**, No. 7, pp. 528-536, 1996.

Mendez Galindo Carlos, Hayashikawa T. and Ruiz Julian F. D.: Seismic damage due to curvature effect on curved highway viaducts, *Proceedings of the 14th World Conference on Earthquake Engineering*, IAEE, Beijing, China, October 12-18, 2008.

Mendez Galindo C., Hayashikawa T. and Ruiz Julian F. D.: Seismic performance of isolated curved steel viaducts under level II earthquakes, *Journal of Structural Engineering*, JSCE. **Vol. 55A**, pp. 699-708, March 2009.

Moehle, J. P., and Eberhard, M. O.: Chapter 34: Earthquake damage to bridges. In: Chen, W. F., and Duan, editors. *Bridge Engineering Handbook*, Boca Raton, CRC Press, 1999.

Moor G., Mendez Galindo C., O'suillebhain C.: Measuring Up, *Bridge Design & Engineering*, Bridgeweb.com, **Issue no. 63**, pp. 54-55, June, 2011.

Pan, P., Zamfirescu, D., Nakashima, M., Nakayasu, N., and Kashiwa, H.: Base-isolation design practice in Japan: Introduction to the post-Kobe approach, *Journal of Earthquake Engineering*, **Vol. 9**, No. 1, pp. 147-171, 2005.

Ruiz Julian, D.: Seismic performance of isolated curved highway viaducts equipped with unseating prevention cable restrainers, *Doctoral Dissertation*, Graduate School of Engineering, Hokkaido University, Japan. December 2005.

Salomon, O., Oller, S., and Barbat, A.: Finite element analysis of base isolated buildings subjected to earthquake loads, *International Journal for Numerical Methods in Engineering*, **Vol. 46**, pp. 1741-1761, 1999.

Turkington, D. H., Carr, A. J., Cooke, N., and Moss, P.J.: Seismic design of bridges on lead-rubber bearings, *Journal of Structural Engineering*, ASCE, **Vol. 115**, No. 12, pp. 3000-3016, 1989.