

TESTING OF HIGH DAMPING RUBBER BEARINGS AND LEAD RUBBER BEARINGS FOR NUCLEAR POWER PLANTS

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Abstract: The paper describes a wide testing campaign carried out on full scale prototypes of elastomeric isolators – both high damping rubber bearings (HDRB) and lead rubber bearings (LRB) – within the framework of the EC-funded SILER research project. The prototypes tested were designed for two reference nuclear power plants, the ELSY reactor and the MYRRHA reactor. Due to the typical huge masses of NPP, the related isolators often have large sizes. HDRB prototype is circular, with a diameter of 1350 mm; LRB prototype is square, with a side of 1250 mm, and four lead cores. The prototypes were subjected to different tests. One prototype was subjected to a complete type test campaign according to the European Standard EN 15129:2009, as well as to 3-D tests applying contemporarily displacement time-histories in two horizontal axes and vertical load time-history. Failure and post-failure tests were also performed, showing that the isolator, even after failure, is still able to sustain the vertical load and the horizontal displacement.

Introduction

Seismic isolation is the most promising technology to protect nuclear power plants (NPP) from earthquake, because it strongly reduces the horizontal acceleration and gives to the structure a “rigid body” behaviour. Therefore, all the internal most critical components are subjected to the same horizontal acceleration, allowing for a standardized design of the plant independently of the construction site. Seismic isolation is often used in civil structures (buildings, bridges, etc.) in many countries, but its use in NPPs is up to now quite limited, mainly in France [Moussalam *et al.* 2013]. In all the seismically isolated NPP, elastomeric isolators have been used.

Due to the typical huge masses of NPP, the related isolators often have large sizes. This complicates the manufacturing process and the execution of the type tests on full-scale prototypes. Furthermore, for application in NPPs, it is very important to know the behaviour of the isolators beyond the design conditions, thus tests up to failure are needed. Recently tests up to failure were carried out in Italy on reduced scale isolators designed for the IRIS medium size NPP [Bergamo *et al.* 2011].

This paper describes a wide testing campaign carried out on full scale prototypes of elastomeric isolators – both High Damping Rubber Bearings (HDRB) and Lead Rubber Bearings (LRB) – within the framework of the SILER project. The SILER project, presented in another paper [Forni *et al.*, 2015] is an EC-funded cooperative project aimed at studying the risks associated with seismic initiated events in Gen IV Heavy Liquid Metal reactors, and developing adequate protection measures.

The prototypes tested were designed for two reference NPPs studied within the SILER project, the ELSY reactor and the MYRRHA reactor. In the following the design characteristics of the prototypes are shortly described, and the most important test results are reported.

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Isolators prototypes

The HDRB designed for the ELSY reactor was selected as prototype for tests. Due to the requirement of an high stiffness value, of about 8 kN/mm, an elastomer compound with shear modulus of 1.4 MPa, specially developed within the SILER project, was used. Another main design requirement, established within the SILER project, was that the shear strain corresponding to the displacement at the Design Basis Earthquake should not be higher than 100%. Apart the specific requirements of the SILER project, the isolator was designed according to the European Standard on Anti-seismic devices EN 15129 [CEN TC 340, 2009]. The equivalent viscous damping of the elastomer is slightly higher than 10% at 100% shear strain. The prototype has a diameter of 1350 mm, a total rubber thickness of 256 mm, a shape factor of 19.7, an horizontal stiffness of 7.82 kN/mm at 100% shear strain, and a vertical stiffness of 5792 kN/mm.

The LRB selected as prototype for tests is the type A LRB of the isolation system designed for MYRRHA reactor [Forni *et al.* 2015], i.e. the stiffer type placed at the slab corners. The required effective stiffness and equivalent viscous damping were about 15 kN/mm and 25%, respectively. The isolator, designed according to EN 15129 and some specific requirements of the SILER project, is square, with a side of 1250 mm, and 4 lead cores, each with diameter 200 mm. Total rubber thickness is 192 mm. The elastomer compound is a low damping one specially developed within the SILER project, based on natural rubber, with effective dynamic shear modulus $G=1.4$ MPa at shear strain 100% and frequency 0.5 Hz. Figure 1 shows the theoretical bilinear curve of this isolator.

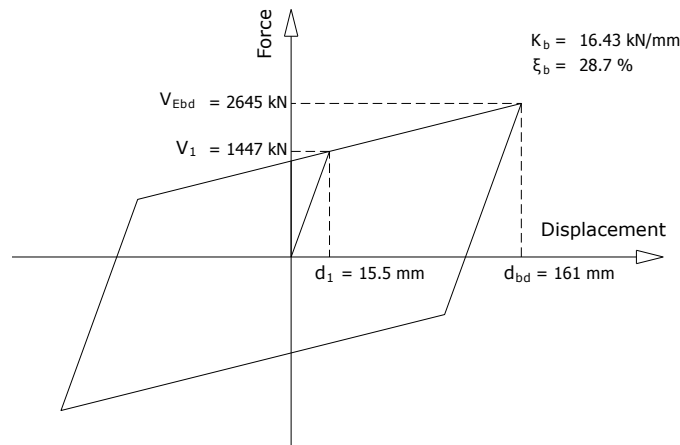


Figure 1. Bilinear curve at DBE of LRB prototype.

Testing protocol

One HDRB prototype was subjected to a complete testing campaign, at the Caltrans/UCSD Seismic Response Modification Devices test facility [Seible *et al.*, 2000]. The testing protocol comprises not only the Type Tests required by the European Standard EN 15129, but bidirectional and tridirectional time-history tests as well. Bidirectional tests are tests in which a constant vertical load is applied, and contemporarily the horizontal displacement is applied along two orthogonal axes instead of one only (as in most of the type tests). In particular, the horizontal displacement was applied following the displacement time-histories obtained as an output of the non linear dynamic analyses on the structure, on some of the isolators. Similarly, in tridirectional tests, horizontal displacement time histories were applied along two orthogonal axes, and the vertical load time history was applied as well: i.e., instead of keeping constant the vertical load, the variation of the vertical load during the earthquake was considered, using the output of the non linear dynamic analyses on the structure.

The bidirectional and tridirectional tests carried out in SILER project made use of horizontal displacement and vertical load time-histories calculated under different accelerograms both

at Design Basis Earthquake (DBE) and at BDE (Beyond Design Earthquake), the latter alternatively defined as 1.5 DBE, 2 DBE, and 2.5 DBE.

Table 1 lists all the tests carried out on the HDRB prototype. Most of the dynamic compression-shear tests according to EN 15129 were carried out at the frequency of 0.571Hz, that is the design isolation frequency of ELSY. Type Tests according to EN 15129 and bidirectional and tridirectional tests were alternated, in order to follow the order of increasing maximum horizontal displacement (shear strain), to avoid scragging effects. The last test (#16) is a repetition of the test at 100 % shear strain after failure of the isolator in previous test (#15), in order to check the behaviour of the isolator even after failure.

Table 1. List of tests carried out on HDRB prototype at Caltrans/UCSD SRMD Test Facility.

test #	test name	main dof		ampl. or max.displ. [mm]	freq [Hz]	load shape	cycles [#]	vert load [kN]
1	Compression Stiffness	vert		-	-	-	-	11300
2	Horizontal vs. Shear Strain	long		±13	0.571	sine	5	8075
3	Horizontal vs. Shear Strain	long		±26	0.571	sine	5	8075
4	Horizontal vs. Shear Strain	long		±51	0.571	sine	5	8075
5	Horizontal vs. Shear Strain	long		±128	0.571	sine	5	8075
6	Time history at DBE	bidirectional	long	177	-	time history	-	9210
			lat	117	-	time history		
7	Time history at DBE	tridirectional	long	136	-	time history	-	time history (min 999 kN, max 6174 kN)
			lat	113	-	time history		
8	Time history at BDE (1.5 x DBE)	tridirectional	long	174	-	time history	-	time history (min 477 kN, max 6999 kN)
			lat	166	-	time history		
9	Horizontal vs. Shear Strain	long		±256	0.571	sine	5	8075
10	Time history at BDE (2 x DBE)	long		249	-	time history	-	time history (min -255 kN, max 4599 kN)
11	Horizontal vs. Shear Strain	long		±384	0.571	sine	3.5	8075
12	Time history at BDE (2.5 x DBE)	long		389	-	time history	-	time history (min 8340 kN, max 10090 kN)
13	Horizontal vs. Shear Strain	long		±512	0.440	sine	3.5	8075
14	Horizontal Displacement Capacity	long		768	-	constant velocity	-	24800
15	Horizontal vs. Shear Strain	long		±256	0.57	sine	5	8075

Two LRB prototypes were subjected to preliminary combined compression-shear tests in the static testing rig of FIP Industriale Laboratory, up to the limits of the testing rig in terms of horizontal force (2000 kN), under a vertical load equivalent to an average pressure of 6 MPa, according to EN 15129:2009. These preliminary tests allowed to measure the bilinear behaviour of LRBs and check it in comparison with the theoretical bilinear curve. Further dynamic tests according to EN 15129 are underway, and will be presented elsewhere.

Test results

Some of the test results are presented in the following.

Figure 2 shows the HDRB under testing in the Caltrans/UCSD SRMD Test Facility. Figure 3 shows the force vs. displacement cycles measured in the compression-shear dynamic test at the design fundamental frequency (0.571 Hz) and at 100 % shear strain, carried out according to EN 15129, under a constant vertical load equivalent to an average compression stress of 6 MPa. The dynamic shear modulus measured on the third cycle of said test is 1.38 MPa (- 1% of the nominal value of 1.4 MPa) and the equivalent viscous damping is 12.8 %.



Figure 2. The HDRB prototype under compression stiffness test.

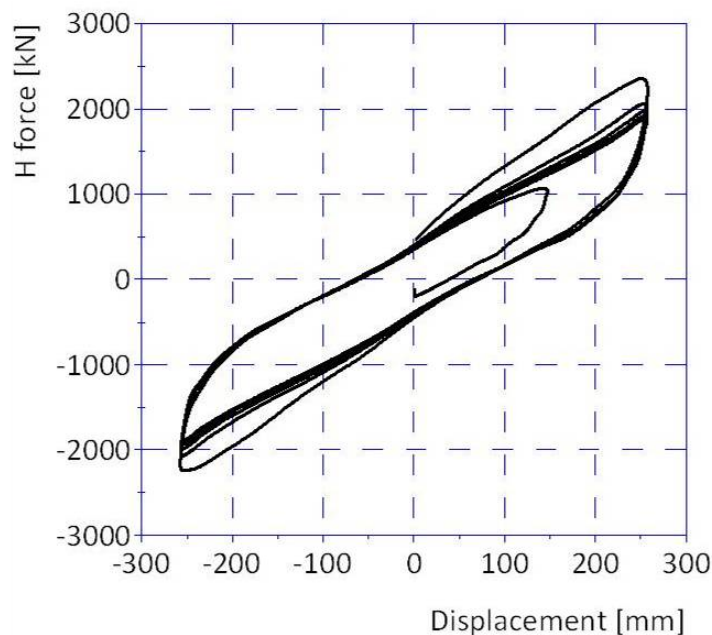


Figure 3. Result of dynamic test at 100 % s.s. on HDRB prototype.

Figure 4 shows the horizontal displacement time histories applied simultaneously along two orthogonal axes (longitudinal and lateral), under constant vertical load (9210 kN), and the corresponding measured force vs. displacement hysteretic cycles (test 6). Said displacement time histories are the output of a non linear analysis at DBE using as input the horizontal accelerograms' couple named "RGt3" (one of the reference accelerograms of the SILER project), on an isolator in the central part of the structure. It is evident in such displacement time histories that the peak displacement in longitudinal direction is higher than in lateral direction.

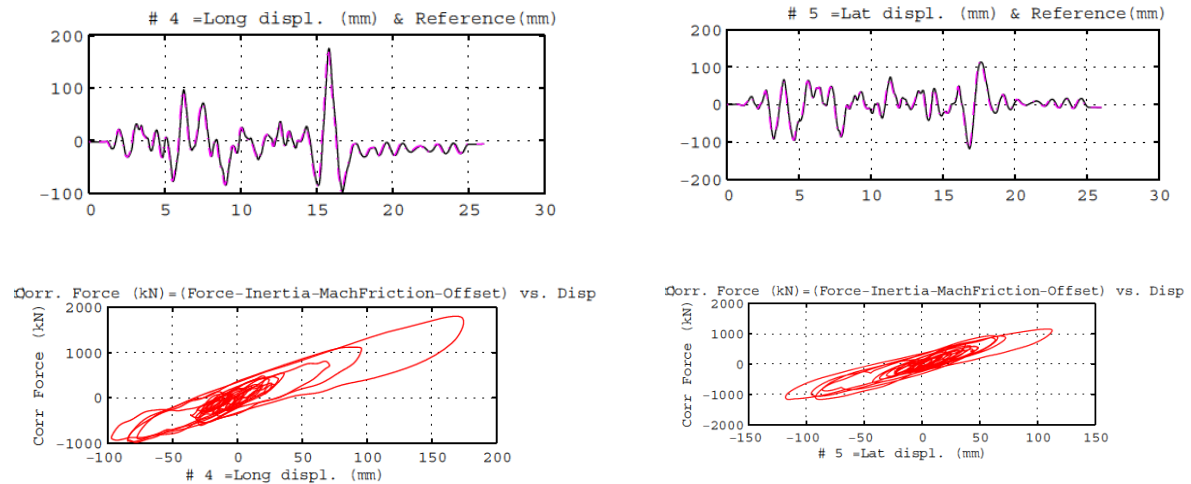


Figure 4 – Input (above) and results (below) of bidirectional time-history test (test 6) on HDRB prototype, at DBE with time-history named "RGt3".

Figure 5 shows the horizontal displacement time histories applied simultaneously along two orthogonal axes (longitudinal and lateral), and the vertical load time history applied (test 7). Said time histories are the output of a non linear analysis at DBE using as input the horizontal accelerograms' couple named "Polimi 5" (one of the reference accelerograms of the SILER project), on an isolator on a corner of the structure. Figure 6 shows the force vs. displacement hysteretic cycles measured in such test.

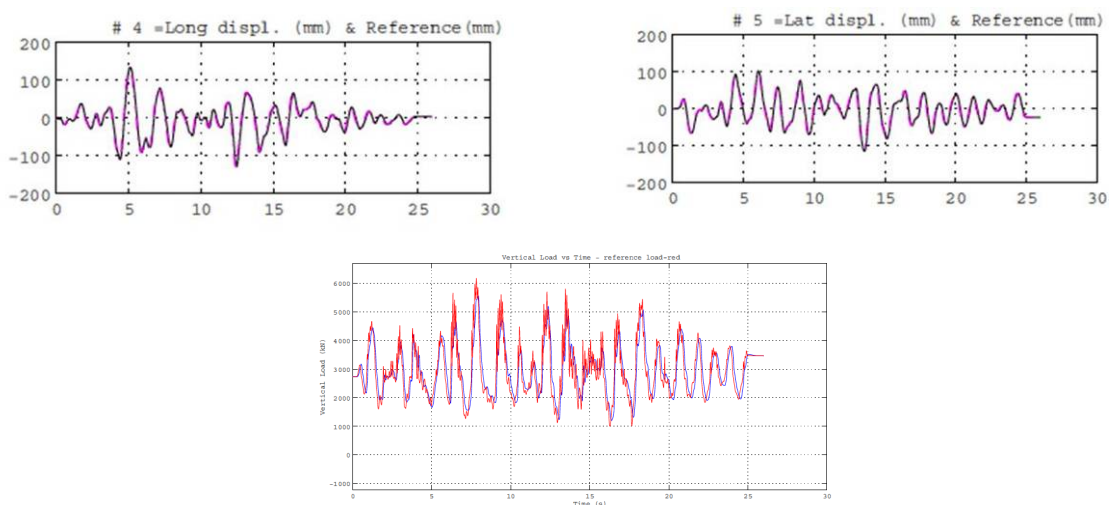


Figure 5 – Horizontal displacement input (above) and vertical load input (below) of tridirectional time-history test (test 7) on HDRB prototype, at DBE with time-history named "Polimi 5".

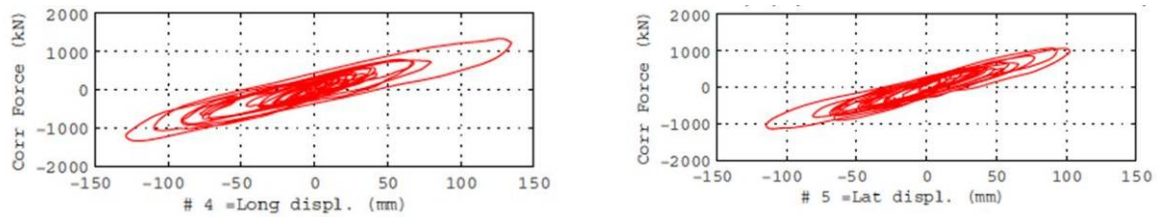


Figure 6 – Horizontal force vs. displacement graphs measured in longitudinal (left) and lateral (right) directions during the tridirectional time-history test (test 7) on HDRB prototype, at DBE with time-history named “Polimi 5”.

Figure 7 shows a view in the horizontal plan of the displacement time-histories applied simultaneously along two orthogonal axes (X and Y), the vertical load time history applied simultaneously as well, and the corresponding measured force vs. displacement hysteretic cycles. The input for this test is the output of a non linear analysis at BDE=1.5 DBE, using as input the accelerogram named “POLIMI 2” within the SILER project, on an isolator at a corner of the structure (test 8).

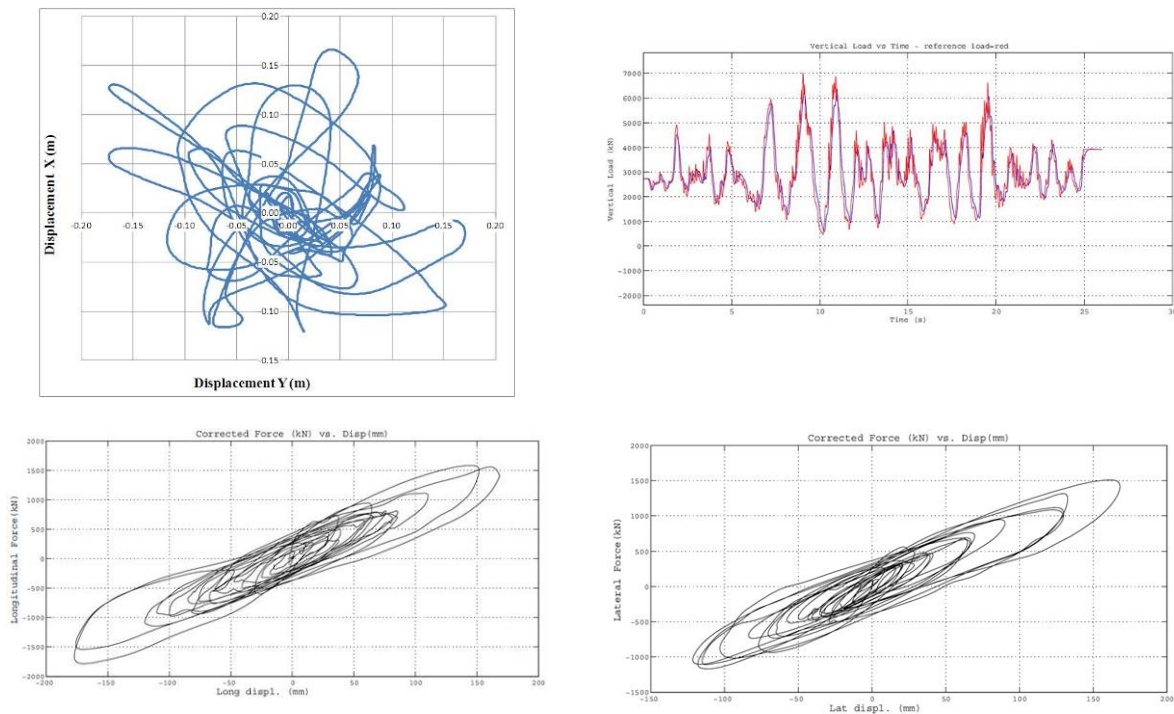


Figure 7 – Input (above) and result (below) of tridirectional time-history test on HDRB prototype, at BDE=1.5 DBE, with time-history named “Polimi 2” (test 8).

All the bidirectional and tridirectional tests were satisfactory, the isolator behaviour was as expected in both horizontal directions. For earthquakes at BDE levels higher than 1.5 DBE it was not possible to do bidirectional or tridirectional tests, due to testing rig limitations. Thus, the time history tests at such levels were carried out in one horizontal direction only, the longitudinal direction, while simultaneously apply the vertical load time-history.

Figure 8 shows the results of the test 12, whose input were the results of the non linear analyses corresponding to a BDE level equal to 2.5 DBE with time history "Polimi1", in terms of force vs. displacement curve. Despite the high level of input, the isolator showed no sign of damage.

Figure 9 shows the same force vs. displacement curve of Figure 8 in comparison with that of test 7 (DBE, time history “Polimi 5”) in longitudinal direction. It is worth noting that no evidence of hardening is visible, as often happens with high damping compounds, despite the high shear strain reached in test 12. Conversely, there is some reduction in the equivalent stiffness, that is positive in order to reduce forces at BDE.

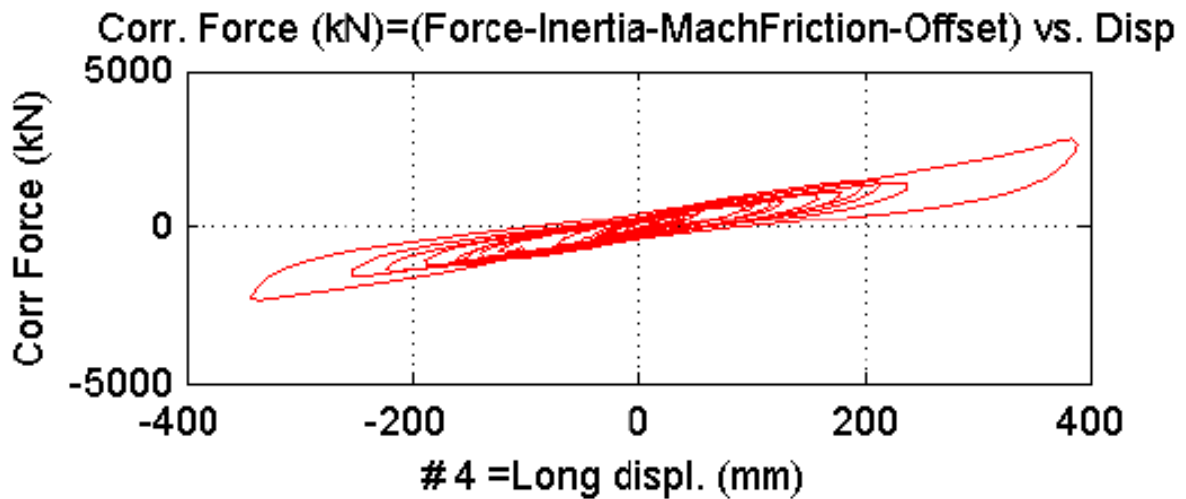


Figure 8 – Horizontal force vs. displacement measured in test 12, at BDE=2.5 DBE, with time-history named “Polimi 1”.

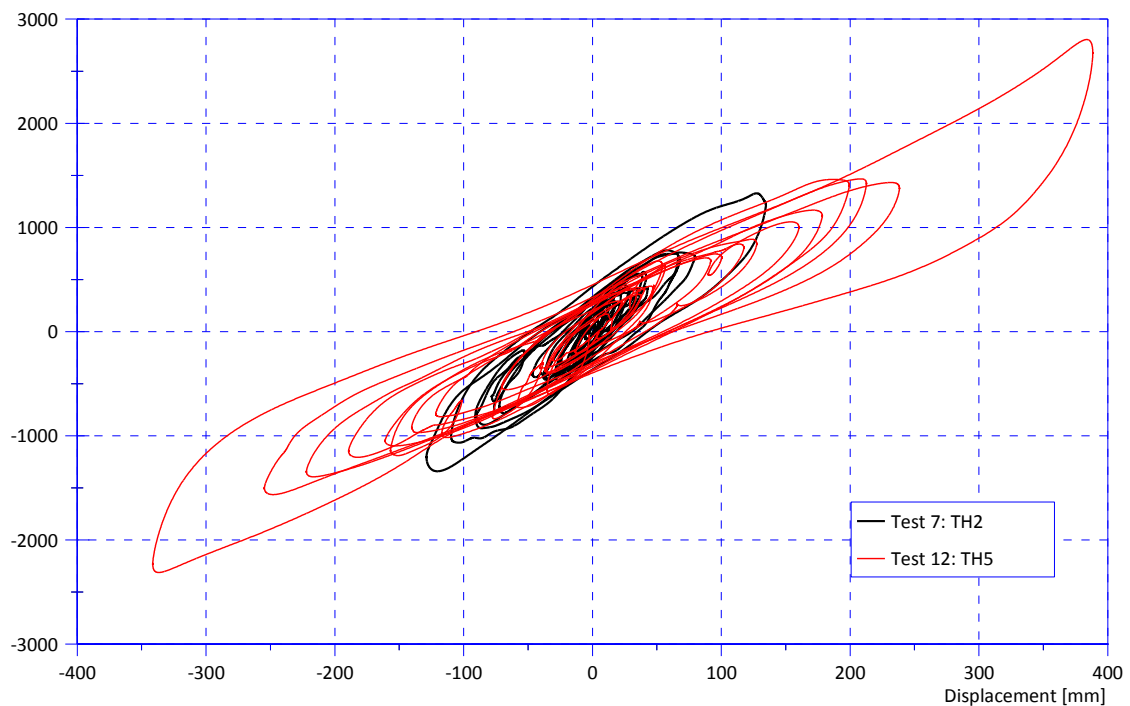


Figure 9 – Comparison of horizontal force vs. displacement measured in tests 7 (DBE) and 12 (BDE=2.5 DBE)

After the sinusoidal dynamic test at amplitude of ± 512 mm, the horizontal displacement capacity test – i.e. failure test – was carried out, applying the displacement according to the curve showed in Figure 10, instead of increasing it monotonically up to failure. The failure was visible in the prototype slightly before reaching the maximum displacement of 768 mm, but is not evident in the measured force vs. displacement graph (Figure 11), in which the force continues to increase.

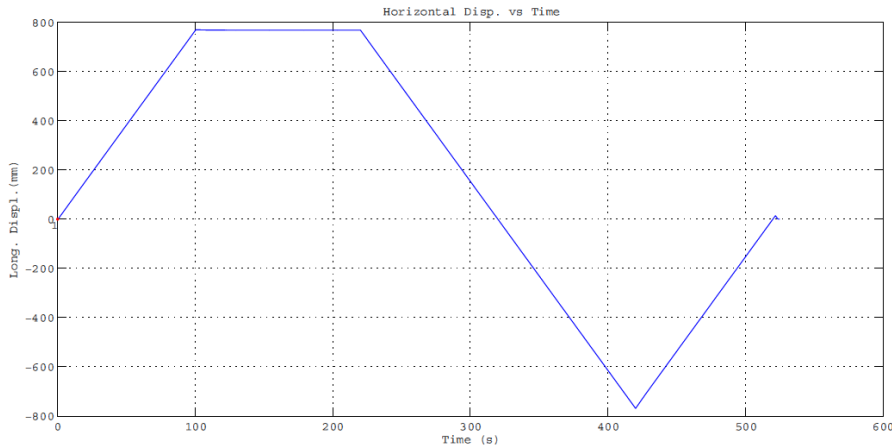


Figure 10 – Input of horizontal displacement capacity test (test 14).

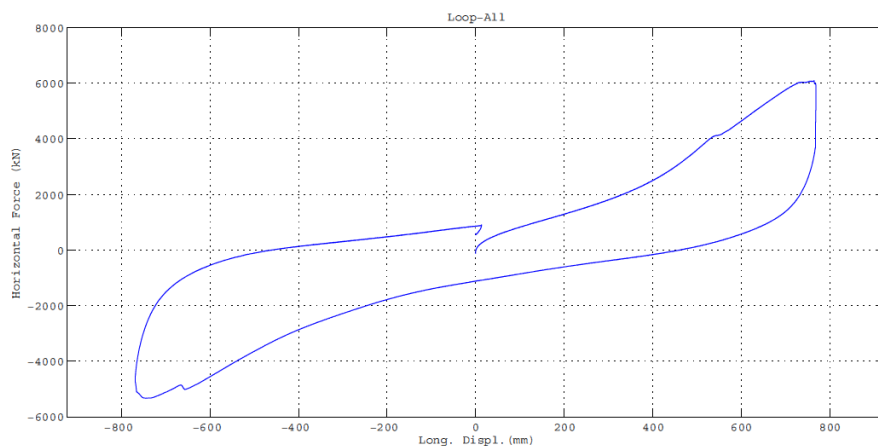


Figure 11 – Horizontal force vs. displacement measured in test 14.

After the failure test, a test at 100 % shear strain was carried out, to check the behaviour of the isolator after failure, simulating the effects of an aftershock that could follow a Beyond Design Earthquake that has deformed the isolator up to its failure.

Figure 12 shows the force vs. displacement graph measured in said last test (test 15) in comparison with test 9, i.e. the dynamic test at the same amplitude of 256 mm corresponding to 100 % shear strain. Of course the isolator in test 15 shows a much lower stiffness than in test 9, but it is still able to keep the vertical load and offer a certain horizontal stiffness and energy dissipation.

This result show that the HDRB isolators designed for SILER project, even after failure - corresponding to a BDE larger than 2.5 times the DBE - can support the vertical load and can sustain aftershocks as well, offering some energy dissipation and displacement control.

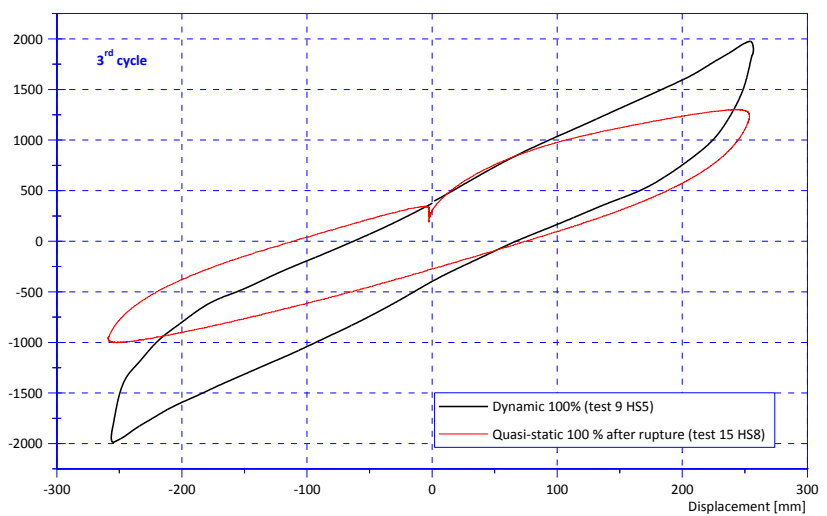


Figure 12 – Comparison of horizontal force vs. displacement measured in tests 9 and 15.

Figure 13 shows one of the LRB prototypes under test in the static testing rig of FIP Industriale Laboratory. Figure 14 shows that the experimental behaviour is fully in agreement with the expected theoretical behaviour.



Figure 13. LRB prototype under testing.

Conclusions

The test results show the reliability of large size elastomeric isolators designed for applications in NPP. In particular, the experimental behaviour in real dynamic conditions, reproducing the effects of earthquake in two or three directions, both at DBE and BDE up to 2.5 times the DBE, was fully satisfactory. The post-failure test showed that the isolator, even after failure, is still able to sustain the vertical load and to offer horizontal stiffness and energy dissipation to control the horizontal displacements.

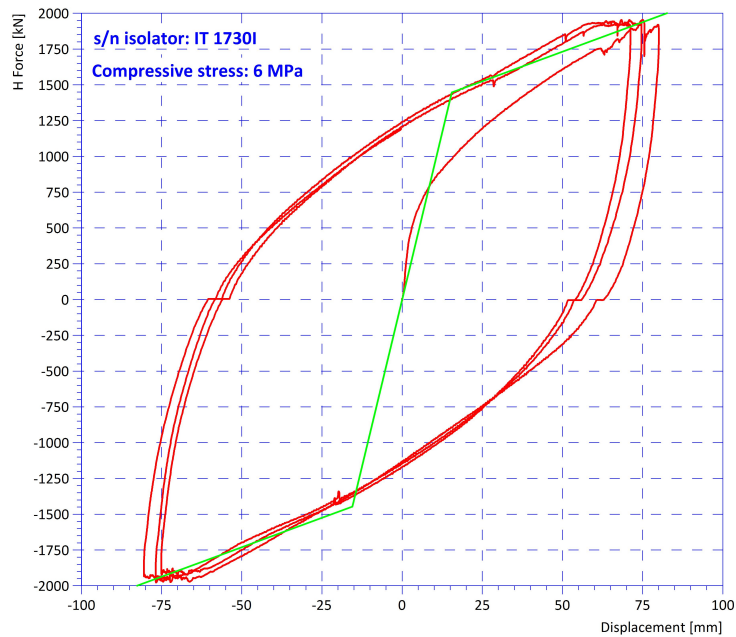


Figure 14. Comparison of theoretical (green) and experimental (red) force vs. displacement curve for LRB prototype.

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