EUROPEAN COMMISSION 7th EURATOM

FRAMEWORK PROGRAMME 2007-2013

THEME [Fission-2011-2.3.1]

SILER
Seismic-Initiated events risk mitigation in LEad-cooled Reactors

Grant Agreement N°: 295485

Deliverable title: Development of full scale prototypes of High Damping Rubber Bearings and experimental validation

Work Package	Deliverable number	Lead contractor	Date
4	D4.1	FIP Industriale S.p.A.	

Responsible person details

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Starting date	Due date	Actual date	Delay*	Nature
01/06/2012	30/09/2013	31/03/2014		

Description of the activities:

This report summarizes the activities carried out in Task 4.2 of the SILER project, i.e. the design, manufacturing and testing of full scale prototypes of High Damping Rubber Bearings (HDRB).

SIGNATURES

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1. Introduction

The activities of WP4, Task 4.2, were based on input from WP 2, in particular on Deliverable D2.2, titled "Description of the design of seismic isolator", as well as on continous interaction of the WP Leader FIP Industriale with partners ENEA and NUMERIA, in particular with ENEA. Said interaction was needed for the detailed design of the isolators and for the test planning as well. ENEA was more involved than NUMERIA in task 4.2, because since the beginning of the activities it was decided that the HDRB prototypes to be designed, manufactured and tested would have been related to the ELSY reactor, that was modeled by ENEA.

2. Design of High Damping Rubber Bearings

Amongst the different design layouts of HDRB-based isolation system for ELSY, reported in the Deliverable D2.2-Part 1, the focus within WP 4 was on the 15x15 layout, for a total number of 225 isolators. Table 1 summarises the main input parameters received from WP2 to design the HDRB for ELSY.

Table 1 – Preliminary input data to design HDRB for ELSY.

Horizontal stiffness (kN/mm)	7.4÷8.3
Equivalent viscous damping (%)	10
Maximum vertical load in seismic conditions (kN)	25700
Minimum vertical load in seismic conditions (kN)	-3570
Displacement in seismic conditions at DBE d_{bd} (mm)	≈ 250

It can be noted in Table 1 that the minimum vertical load is tensile.

On the basis of this input, FIP Industriale designed isolators with the geometric and mechanical characteristics reported in Table 2, using the high damping rubber compound developed within task 4.1.

The HDRB has been designed according to EN15129:2009, with additional prescriptions established within SILER project, for example to design the isolators with shear strain at design displacement at DBE not higher than 100 %, in order to guarantee an high safety factor against failure even at BDE. Other additional prescriptions were related to the verification against buckling stability, and to the fiwing methods. As far as the latter is concerned, the mechanical anchorages have been designed to support 100 % of the horizontal load, despite EN 15129 allows to reduce such percentage to 75 % in case non linear dynamic analyses are performed. Furthermore, to take into accout a very high level of BDE, a very high safety coefficient, slighty higher than 3, has been used in the design of anchorage system, aiming at avoiding the failure of anchorages before the failure of the isolators themselves.

The buckling stability under seismic actions has been checked not only according to EN 15129, but also according to the following formulas (given in EN 1337-3):

$$\frac{N_{cr}}{N_{Ed,max}} \geq 1.5$$

where:

- N_{cr} is the buckling load given by:

$$N_{cr} = \frac{G \cdot A_r \cdot S \cdot D'}{T_q}$$

- G is the dynamic shear modulus of the elastomeric compound at shear strain 100 %
- D' is the diameter of the internal steel shims
- S is the shape factor, i.e. the ratio between the effective plan area of a rubber layer to its force-free surface area. For circular isolators S is given by:

$$S = \frac{D'}{4 \cdot t_r}$$

- t_r is the thickness of each rubber layer
- A_r is the reduced effective plan area due to the total maximum displacement at DBE d_{DBE}, that for circular isolators is given by the expression:

$$A_r = \frac{(\varphi - \sin\varphi) \cdot D'}{T_q}$$

where:

$$\varphi = 2 \cdot \arccos\left(\frac{d_{DBE}}{D'}\right)$$

Table 2 – Main characteristics of the HDRB designed for ELSY (identified by the mark SI-H 1350/256).

Diameter	1350 mm
Total rubber thickness	256 mm
Thickness of each rubber layer	16 mm
Shape factor	19.7
Rubber shear modulus	1.4 MPa
Horizontal stiffness (kN/mm) at s.s. 100%	7.82
Vertical stiffness (kN/mm)	5792

Annex I shows the drawing of SI-H 1350/256, including anchorage plates as well as counterplates.

On the basis of said design, and subsequent interaction with FIP Industriale, ENEA carried out linear and non-linear dynamic analyses of ELSY reactor using the SI-H 1350/256 isolators. In particular, the non-linear dynamic analyses using different groups of time-histories related to different design spectrums. Amongst the different set of time histories considered, the maximum displacements were obtained with those corresponding to RG spectrum.

3. Manufacture and Testing of High Damping Rubber Bearings Prototypes

The HDRB designed for ELSY, SI-H 1350/256, was selected as the main type of HDRB full scale prototypes to be manufactured and tested within SILER project.

One of the manufactured prototypes was subjected to a complete testing campaign, comprising not only the Type Tests according to 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 standard type tests). In particular, the horizontal displacement was applied following the displacement time-histories obtained by ENEA as an output of the non linear 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 analyses on the structure.

These complex tests were carried out because in the past some experimental research studies, carried out in USA, have demonstrated that multidirectional tests are more severe than the standard compression-shear tests carried out applying the horizontal displacement along one axis only.

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 DBE and at BDE, the latter defined as 1.5 DBE, 2 DBE, and 2.5 DBE.

Table 3 lists all the tests carried out on the prototype of SI-H 1350/256. Most of the dynamic compression-shear tests according to EN 15129 were carried out at the isolation frequency of 0.571 Hz, that is the isolation frequency of ELSY.

Table 3 – List of tests carried out on SI-H 1350/256

test #	test name	label	main dof		Ampl. or Max.displ. [mm]	max. vel. [mm/s]	freq [Hz]	load shape	cycles [#]	vert load [kN]	notes
1	Compression Stiffness	CS	vert		-	-	-	-	-	11300	Rif. § 8.2.1.2.8 EN15129:2009
2	Horizontal vs. Shear Strain	HS1	long		±13	46	0.571	sine	5	8075	Rif. § 8.2.1.2.2 EN15129:2009
3	Horizontal vs. Shear Strain	HS2	long		±26	92	0.571	sine	5	8075	Rif. § 8.2.1.2.2 EN15129:2009
4	Horizontal vs. Shear Strain	HS3	long		±51	184	0.571	sine	5	8075	Rif. § 8.2.1.2.2 EN15129:2009
5	Horizontal vs. Shear Strain	HS4	long		±128	459	0.571	sine	5	8075	Rif. § 8.2.1.2.2 EN15129:2009
6	Time history at DBE	TH1	bidirectional	long	177	527	-	time history	-	9210	"central" isolator No. 1113, without vertical earthquake, with eccentricity, t.h.RGt3
				lat	117	478	-	time history			
7	Time history at DBE	TH2	tridirectional	long	136	551	-	time history	-	time history (min 999 kN, max 6174 kN)	"corner" isolator No. 1015, without vertical earthquake, with eccentricity, t.h.POLIMI 5
				lat	113	520	-	time history			
8	Time history at BDE (1.5 x DBE)	TH3	tridirectional	long	174	716	-	time history	-	time history (min 477 kN, max 6999 kN)	"corner" isolator No. 1015, without vertical earthquake, with eccentricity, t.h.1.5xPOLIMI 2 (BDE)
				lat	166	695	-	time history			
9	Horizontal vs. Shear Strain	HS5	long		±256	918	0.571	sine	5	8075	Rif. § 8.2.1.2.2 EN15129:2009
10	Time history at BDE (2 x DBE)	TH4	long		249	1052	-	time history	-	time history (min -255 kN, max 4599 kN)	"corner" isolator No. 1001, without vertical earthquake, with eccentricity, t.h.2xPOLIMI 3 (BDE)
11	Horizontal vs. Shear Strain	HS6	long		±384	1378	0.571	sine	3.5	8075	Rif. § 8.2.1.2.2 EN15129:2009
12	Time history at BDE (2.5 x DBE)	TH5	long		389	1704	-	time history	-	time history (min 8340 kN, max 10090 kN)	"central" isolator No. 1113, without vertical earthquake, with eccentricity, t.h.2.5xPOLIMI 1 (BDE)
13	Horizontal vs. Shear Strain	HS7	long		±512	1415	0.440	sine	3.5	8075	Rif. § 8.2.1.2.2 EN15129:2009
14	Horizontal Displacement Capacity	HDC1	long		768	-	-	constant velocity	-	24800	Rif. § 8.2.1.2.7 EN15129:2009; monotonic test up to failure
15	Horizontal vs. Shear Strain	HS8	long		±256	918	0.571	sine	5	8075	repetition of test 9 (HS5) after failure

The most important results of these tests are reported here below.

Figure 1 shows the force vs. displacement graph measured in the compression stiffness test (test 1), and Figure 2 shows the prototye under test.

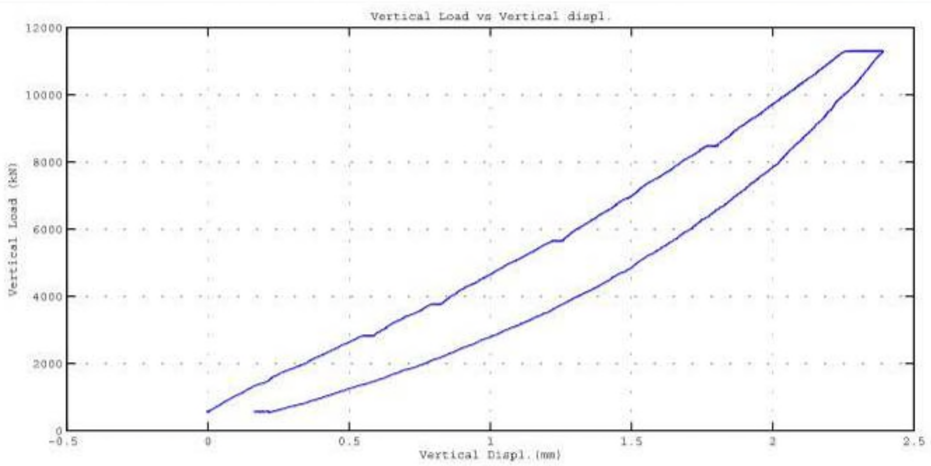


Figure 1 – Force vs. displacement graph of compression stiffness test.

Figure 2 – The isolator under compression stiffness test.

Figures 3 and 4 show the force vs. displacement graphs (respectively for all cycles and for the 3rd cycle only) obtained 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 (Test 9), 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 and the equivalent viscous damping is 12.8 % (Figure 4). This result is fully within the tolerances admitted by the standard: in effects, the nominal value of the dynamic shear modulus is 1.4 MPa at 100 % shear strain.

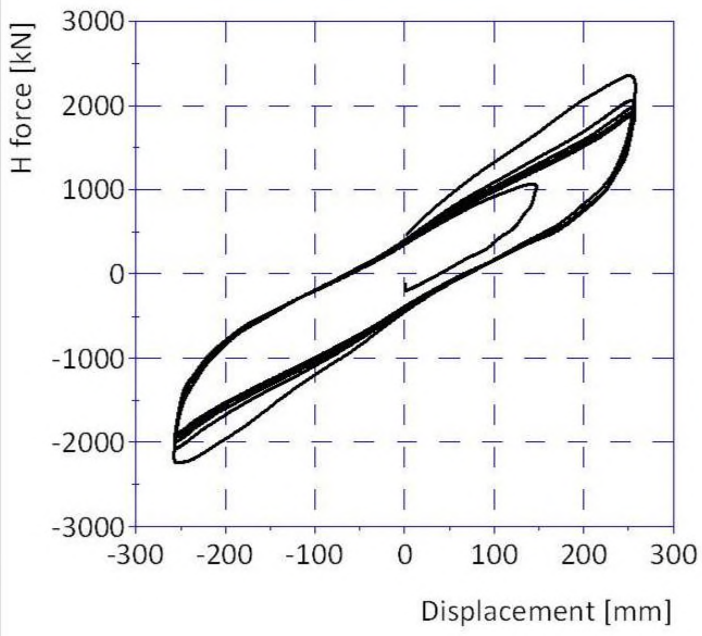


Figure 3 – Result of dynamic test at 100 % s.s. on isolator SI-H 1350/256.

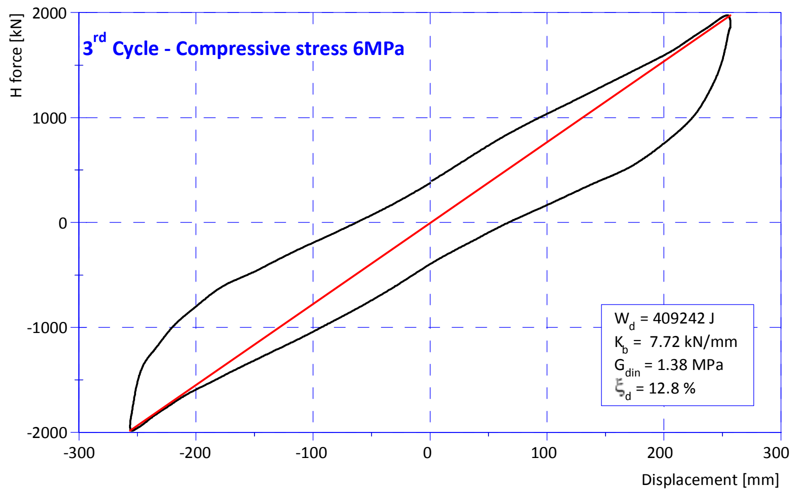


Figure 4 – Result of dynamic test at 100 % s.s. on isolator SI-H 1350/256 – third cycle.

Figure 5 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.

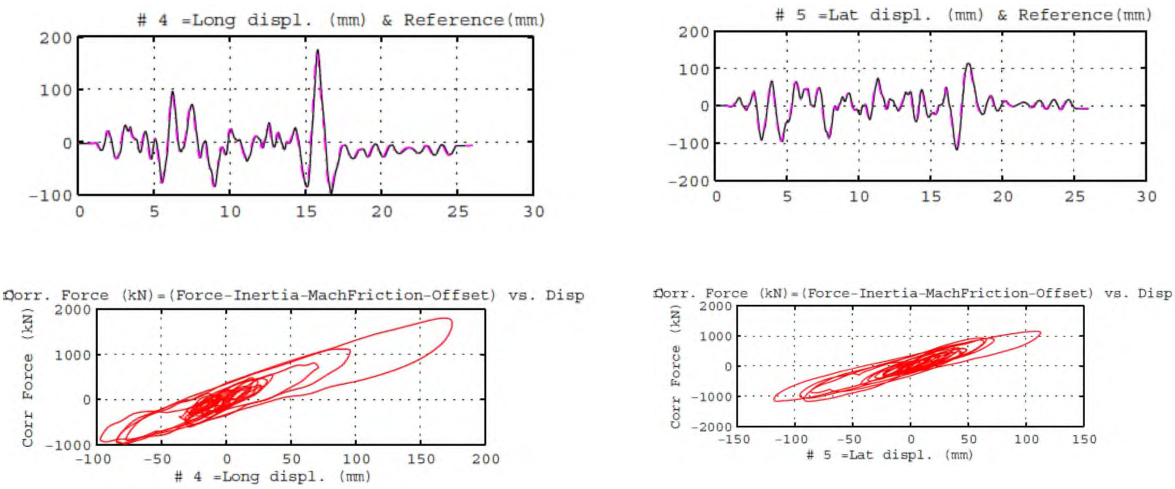


Figure 5 – Input (above) and results (below) of bidirectional time-history test (test 6) on isolator SI-H 1350/256, at DBE with time-history named “RGt3”.

Figure 6 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 7 shows the force vs. displacement hysteretic cycles measured in such test.

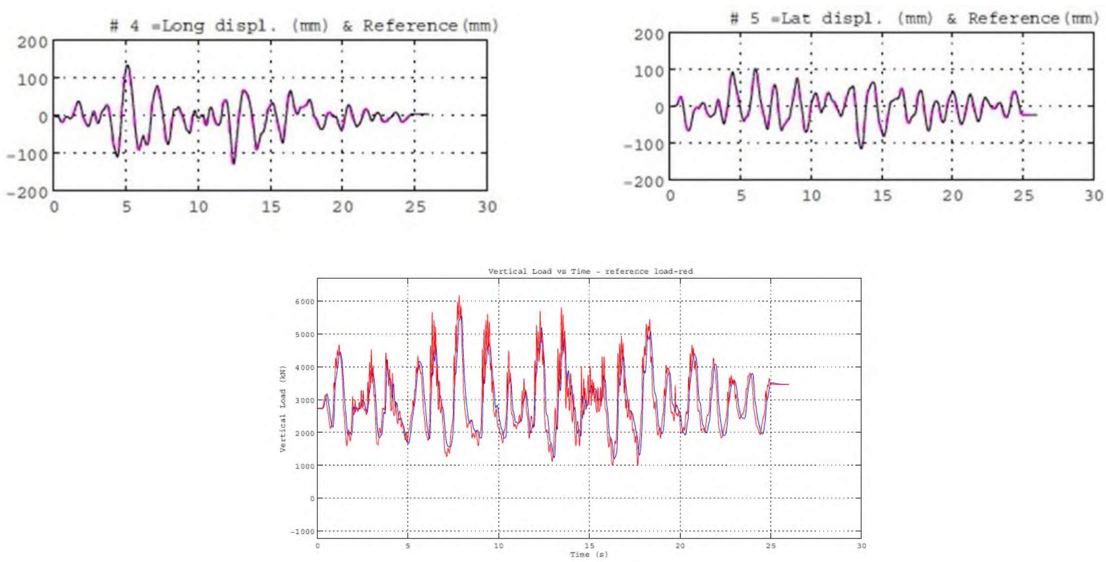


Figure 6 – Horizontal displacement input (above) and vertical load input (below) of tridirectional time-history test (test 7) on isolator SI-H 1350/256, at DBE with time-history named “Polimi 5”.

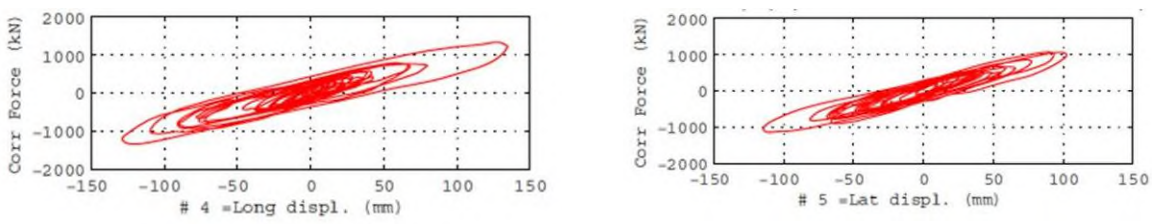


Figure 7 – Horizontal force vs. displacement graphs measured in longitudinal (left) and lateral (right) directions during the tridirectional time-history test (test 7) on isolator SI-H 1350/256, at DBE with time-history named “Polimi 5”.

Figure 8 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).

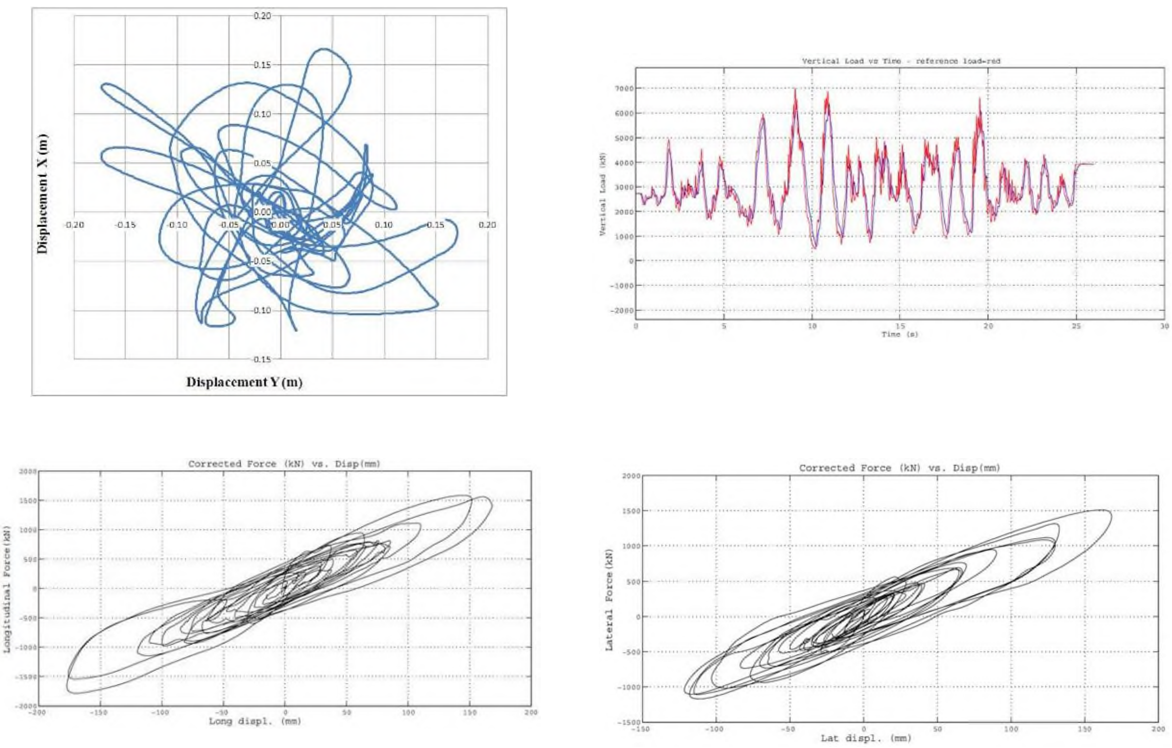


Figure 8 – Input (above) and result (below) of tridirectional time-history test on isolator SI-H 1350/256, at BDE=1.5 DBE, with time-history named “Polimi 2” (test 8).

All the bidirectional and tridirectional tests were satisfactory, the isolator behaviour was as expected in both horizontal directions. For earthquakes at BDE level 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 level were carried out in one horizontal direction only, the longitudinal direction, while simultaneously apply the vertical load time-history.

Figure 9 shows the vertical load time history corresponding to a BDE level equal to 2.5 DBE, with time history “Polimi 1” (test 12). In particular, the red curve is the reference time history obtained as output in the non linear analyses, while the blu curve is the time history really applied during the tests. While in test 8 the two curves are very close (see Figure 8, above right), in such test the testing rig was not able to follow perfectly the reference time history, and the applied vertical load varied more than in the reference curve, thus resulting in a more severe test. Figure 10 shows the results of such test in terms of force vs. displacement curve. Despite the high level of earthquake, the isolator showed no sign of damage.

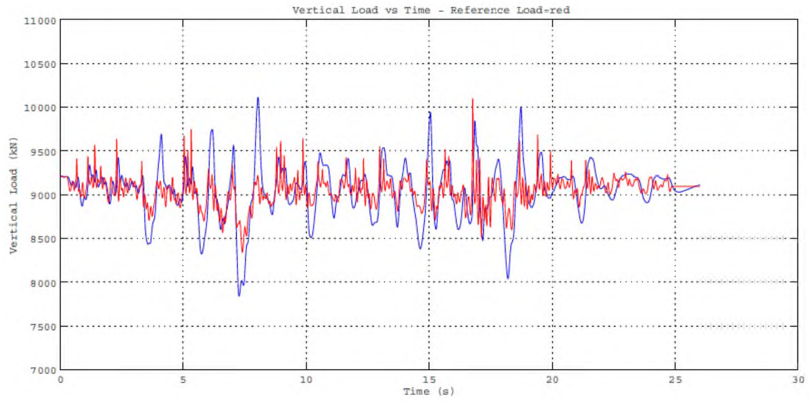


Figure 9 – Vertical load time history applied on the isolator during test 12, at BDE=2.5 DBE, with time-history named “Polimi 1”.

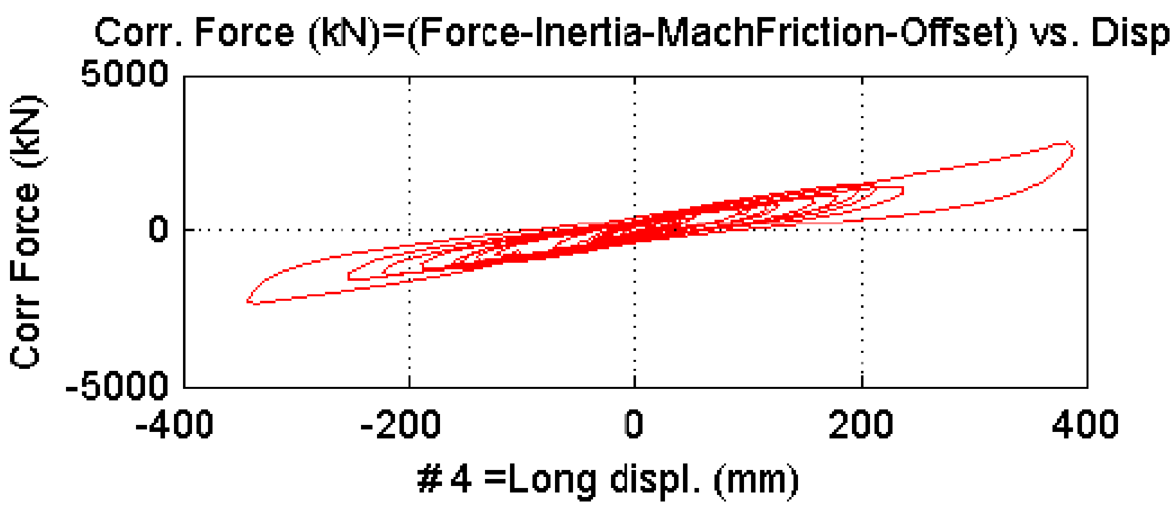


Figure 10 – Horizontal force vs. displacement measured in test 12, at BDE=2.5 DBE, with time-history named “Polimi 1”.

After the sinusoidal dynamic test at amplitude of ± 512 mm, corresponding to a shear strain of 200 %, the horizontal displacement capacity test – i.e. failure test – was carried out, applying the displacement according to the curve showed in Figure 11, instead of increasing it monotonically up to failure. The failure was visible in the prototype slightly before reaching the maximum displacement of 768 mm (corresponding to a shear strain of 300 %), but is not evident in the measured force vs. displacement graph (Figure 12), in which the force continues to increase.

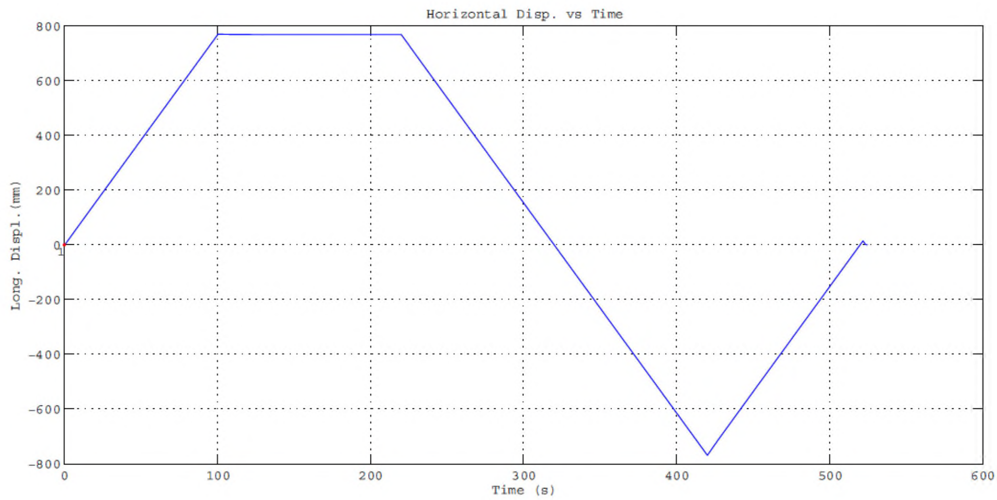


Figure 11 – Input of horizontal displacement capacity test (test 14).

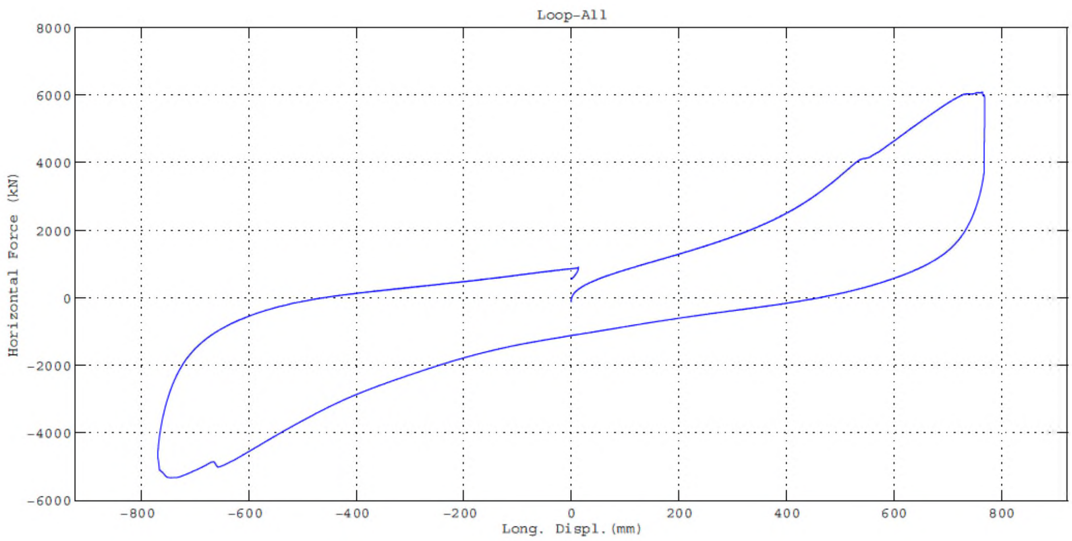


Figure 12 – Horizontal force vs. displacement measured in test 14.

After the failure test, a quasi-static compression-shear test at 100 % shear strain was carried out, in order to check the behaviour of the isolator even after failure. Figure 13 shows the force vs. displacement graph measured in this 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.

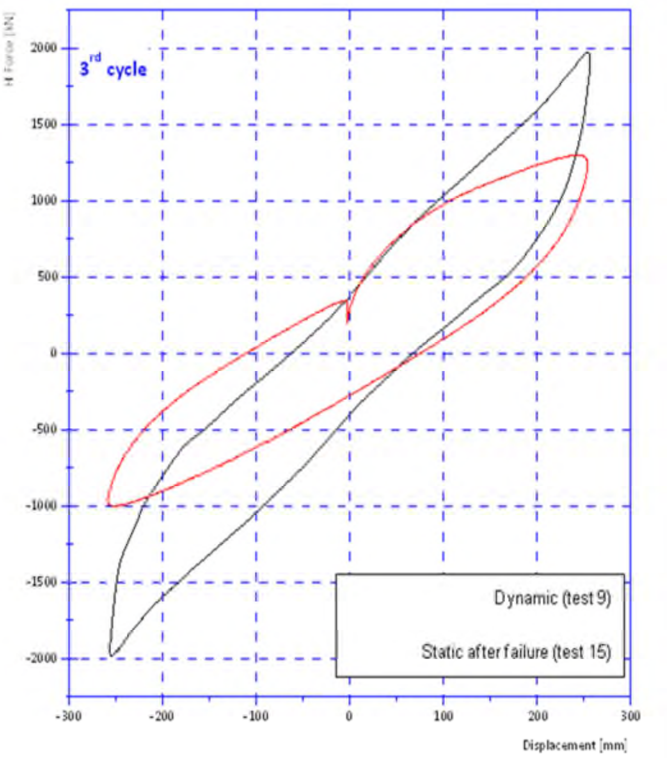
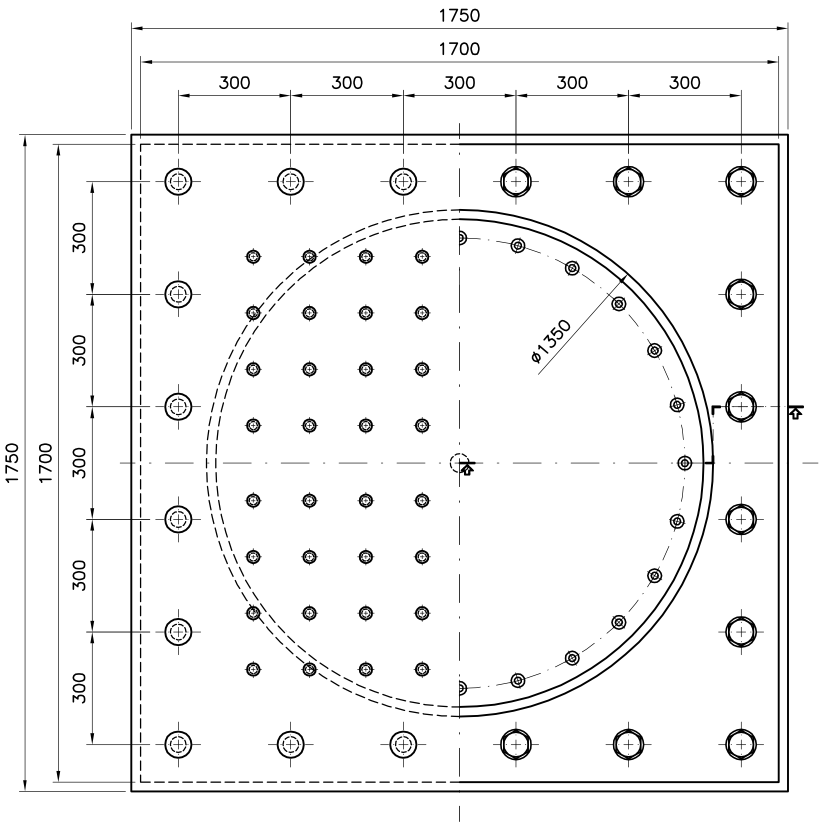
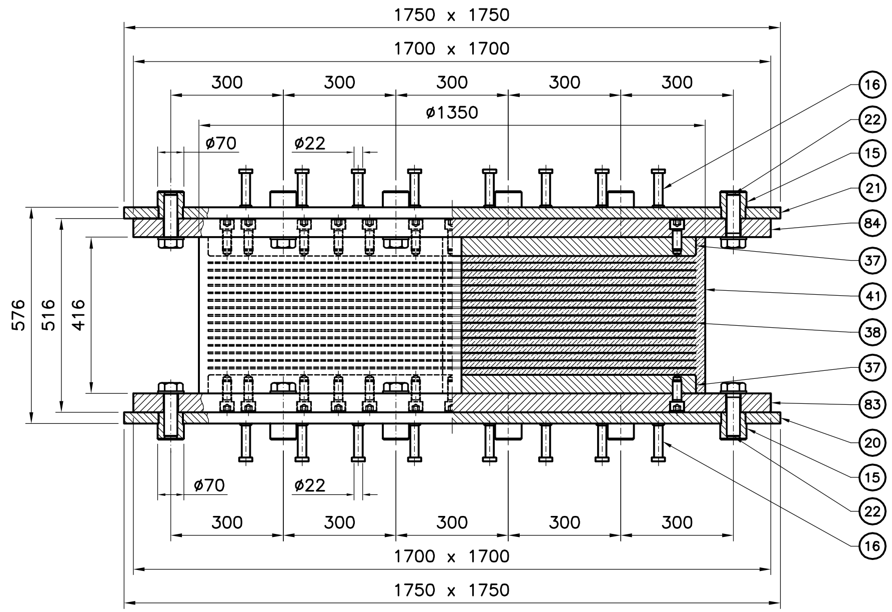


Figure 13 – Comparison of horizontal force vs. displacement measured in tests 9 and 15.

ANNEX I

DRAWING OF SI-H 1350/256





POS.	QUANT.	DESCRIPTION – DIMENSIONS	MATERIAL	CODE	REV.
84	1	Upper anchor plate	S355JR EN 10025		
83	1	Lower anchor plate	S355JR EN 10025		
41		Vulcanized rubber	G_{din}=1.4 MPa		
38		Reinforcing plate	S355JR EN 10025		
37	2	Vulcanized plate	S355JR EN 10025		
22	40	Bolt	Grade 8.8 EN 20898		
21	1	Upper counterplate	S275JR EN 10025		
20	1	Lower counterplate	S275JR EN 10025		
16	128	Shear connector	Fe 37–K DIN 17100		
15	40	Anchor dowel	1 C40 TQ+T EN 10083		

FIP INDUSTRIALE S.p.A. Via Scapacchio' Selvazzano D. (PD)

WEIGHT – Kg: 5700 | SCALE: 1:10

TITLE: Elastomeric Isolator series SI

	DRAWN	APPROVED
DATE	01/10/13	01/10/13
BY	PC	MGC

ITEM IDENTIFICATION: SI–H 1350/256

DRAWING N°: 1A39019 | REV.: 0

REV	DATE	DESCRIPTION	BY

REVISION

FIP – UNI A2 – 594x420