Semi passive antiseismic devices for systems and components of strategic infrastructures

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SUMMARY:
New semi-passive anti seismic devices made by of steel, marble or ceramic for seismic protection of systems and components of strategic infrastructures have been developed at the ENEA C.R. Casaccia Research Center of Roma, Italy. As the devices are blocked in normal conditions and unblocked by a Seismic Early Warning (SEW) triggering signal, they have been named "semi passive". A complete seismic qualification campaign of an electrical cabinet for nuclear plants, protected by the new semi passive devices has been performed. Displacement data during the qualification tests have been acquired by means of a new, high-resolution, motion-capture system called 3DVision. The 3DVision system is able to track the 3D motion of several selected points of the structures in terms of displacement, using a constellation of high-resolution Infrared Cameras to measure accurate 3-D positions of hundreds of markers placed on the cabinet during the seismic qualification tests.

Keywords: Semi-passive devices, shared experiments, seismic, vibrations, qualification tests.

1. INTRODUCTION

This paper describes the use of semi-passive anti seismic devices "Earlyprot" made of steel, marble or ceramic for seismic protection of equipment for strategic infrastructures and cultural heritage assets. They are very low stiffness sliding-rolling devices provided with dissipative cables; the number of cables can be variable allowing to calibrate the energy dissipation according to the dynamic parameters of the nuclear component to be protected and the energy content of the floor spectra during the seismic qualification tests. The seismic isolators Earlyprot are also useful for isolation of statues, museum techs, delicate instruments for hospital and control centers. The devices can be configured as passive or semi-passive: the former provide a permanent base isolation action, the latter means they are blocked in normal conditions and unblocked by a Seismic Early Warning (SEW) triggering signal, therefore they have been named "semi passive" (De Canio, 2008). The first requirement for any device, component or system essential for the safety, either for strategic infrastructures and cultural heritage, is related to its qualification process comprehensive of design, prototyping, manufacturing, installation, operative life and decommissioning. A crucial phase of this process is the prototyping/qualification looping, where large research infrastructures need to perform the type tests according to national and international specifications. In Italy, the main research infrastructures for qualification tests are available at the UTTMAT-QUAL (Qualification of Components and Systems) laboratory located at the ENEA Casaccia Research Center of Rome, where large facilities are located for Climatic, Electro Magnetic, Shock, Vibration and Seismic qualification tests. Two shaking tables are available for three axial seismic experiments, reproducing the real stress-strain field in the structures due to the dynamic loads induced by wind, traffic and earthquakes. The seismic activities are principally devoted to the experimental studies of innovative systems for seismic protection of civil, industrial, and historical buildings, together with tests of sub-structures and scaled mock-ups to evaluate their dynamic behavior, the isolation/dissipation performance of anti-seismic devices and the collapse mechanisms of structural macro elements of monumental buildings.

Table 1.1. Test facilities at ENEA C.R. Casaccia laboratories

	Table 1 (Master)	Table 2 (Child)	Shaker 1	Shaker 2
Table size	4m x 4m	2m x 2m	1.5m x 1.5m	0.6m x 0.6m
Degree of Freedom	6DOF	6DOF	1DOF	1DOF
Frequency range	0-50 Hz	0-100 Hz	5-2000 Hz	5-200 Hz
Acceleration	3g peak	5g peak	125g (0-peak)	100g(0-peak)
Velocity	0.5 m/s (0-peak)	1 m/s (0-peak)	2 m/s (0-peak)	1.2 m/s (0-peak)
Displacement	0.25 m (0-peak)	0.30 m (0-peak)	0.025m (peak-peak)	0.025m (peak-peak)
Mass/Force G.C. height	10ton 1m g. c. height	1 ton 1m g. c. height	145 KN Force 1m g. c. height	27 KN Force 1m g. c. height

The seismic qualification of an electrical cabinet for nuclear power plants (NPP), provided by the seismic isolators Earlyprot, have been carried out according to IEEE 344-2004. The seismic qualification has been preceded by the dynamic characterization of the devices and the cabinet. Beside the traditional sensors (accelerometers, LVDT, strain gauges) used during the qualification tests, the displacement data have been acquired by a new, high resolution 3-D optical movement detection and analysis tool. Its purpose is to track the absolute coordinates of several selected points of the structures during the dynamic tests of natural (earthquake) and artificial (mechanical) induced vibrations. This system uses twelve high resolution Infrared Cameras to measure accurate 3-D positions of hundred markers placed on the structure during the seismic tests. The innovative monitoring technique allows measuring 3 axial absolute displacements x(t), y(t), z(t) with easy and fast test set-up, high accuracy and the possibility to link the 3D-motion time histories of the tracked markers with CAD drawings of the structure and validate the FE models in real time experimental data assimilation (Mongelli et al. 2010). The new monitoring system have been tested during several shaking table experiments for the dynamic characterization of structures and components before the seismic qualification tests of systems and components for mechanical, transportation and nuclear industry.

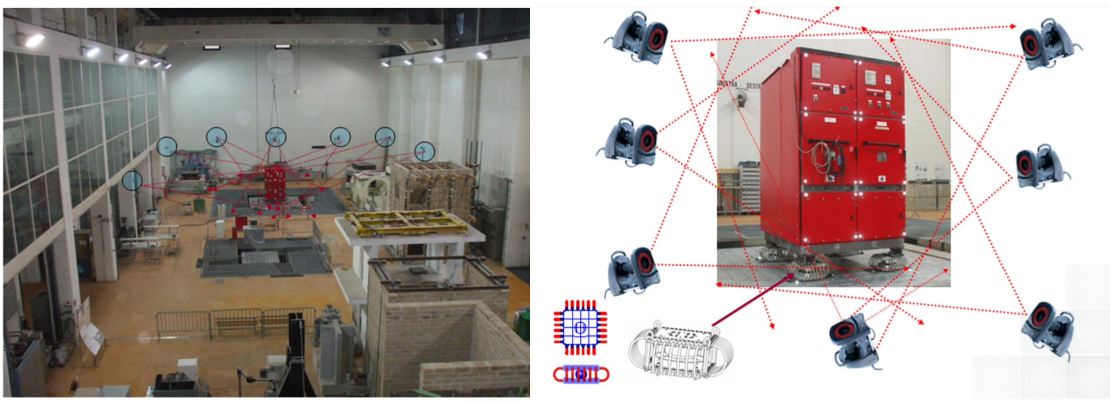

Figure 1. Qualification tests of the electrical cabinet according to IEEE-344-2004: position of the 3D_VISION system cameras to detect the motion of the markers.

The possibility to synchronize visible and infrared cameras allows the remote participation and control of the shaking table tests in a networking configuration of distributed experiments. The following figure shows the conceptual structure of this networking configuration within the virtual framework DySCo (structural Dynamic, numerical Simulation, qualification tests and vibration Control).

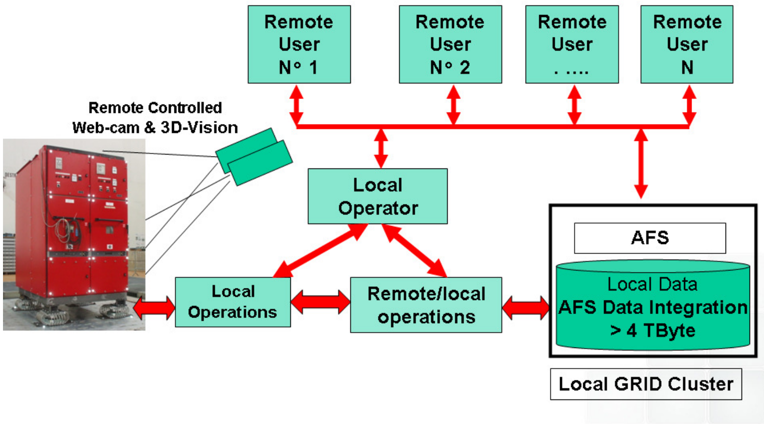

Figure 2. Remote participation in a networking configuration of shared experiment.

As the experimentation goes on, remote users have the possibility to interact step by step with the operator. The connection to DySCo is provided by the ENEA grid of numerical computation, the results are shared in real time via Internet among the partners of the experiment.
It is also possible, using the ENEA-GRID remote access tools, to use specific software available in the system, after authentication and permissions request to administrators of the GRID. In this way remote users can submit in ENEA-GRID numerical simulation and computation, accessing to ENEA software and hardware resources. A wide group of services on the CRESCO computing system (AFS access tools, Videoconference system, Ticket and trouble system, Java document manager and a complete How-to to the GRID) completes the offer of this website (Roselli et al. 2010). One of the objectives is also to implement the process of vibration and seismic qualification for nuclear components and systems. The remote control allows the customer to immediately analyse the results together with the ENEA scientists and visualize where the problem for a non-qualification notify is. The figure 3 shows the images shared during the qualification tests of the class 1-E cabinet for nuclear plant. The assimilation of the marker's displacements in the FEM allows the validation of the numerical model for successive qualification by analysis of cabinets of the same family.

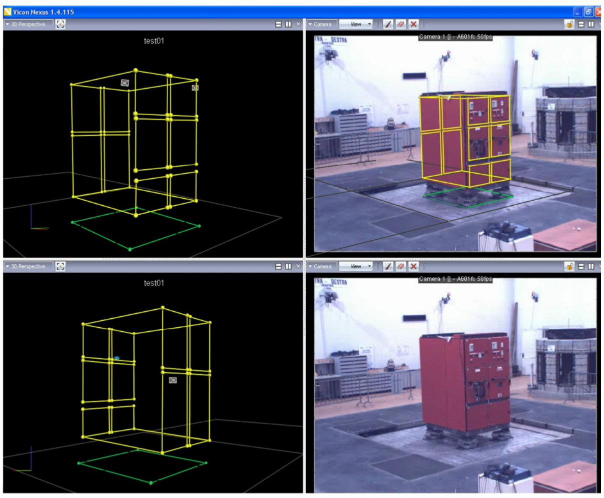

Figure 3. Remote shared images and data during the qualification tests of the electrical cabinet. Assimilation of the marker's displacements during the shaking table tests allows the validation of the numerical model

2. SEISMIC CHARACTERIZATION OF EARLYPROT DEVICES BY SHAKING TABLE TESTS.

The cabinet was seismically protected by the isolators EARLYPROT. They are sliding-rolling

(pendulum type) devices provided by dissipating cables limiting the displacements (see Fig. 4).
The characterization tests of the isolators were performed by the following sequence of tests:

- pull-release tests for the evaluation of stiffness and damping coefficients with two configuration of masses (34KN and 17 KN), and different number of dissipating cables (36, 32, 24, 16, 8, 0)
- X and Y axes sine sweep tests: (0.2g_0.05-5Hz), (0.3g_0.05-5Hz), (0.25g_0.0-2Hz)
- X and Y axes sine tests: Acc (g)=0.1, 0.2, 0.25, 0.3, 0.5, 0.7 ; Hz= 0.2, 0.25, 0.3, 0.5, 0.7, 2.0

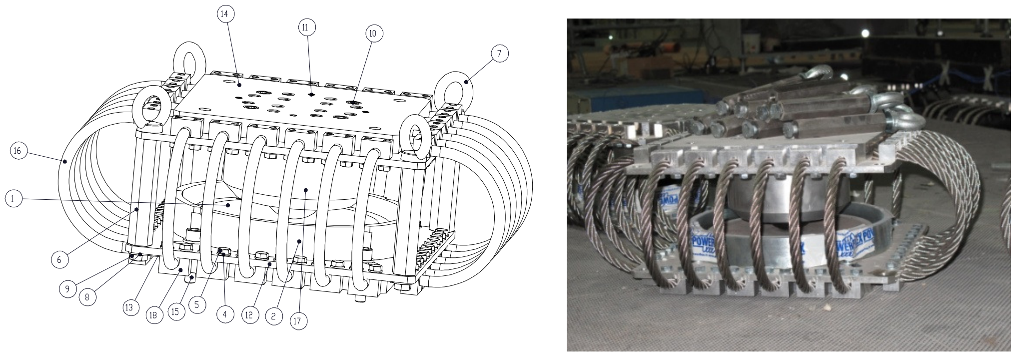

Figure 4. Semi passive seismic isolator EARLYPROT, blocked in normal condition and activated by an early warning triggering signal.

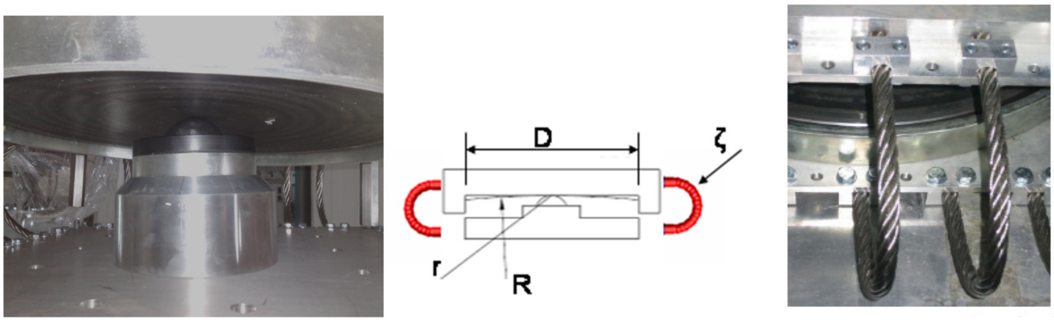

Figure 5. Semi passive seismic isolator EARLYPROT: details of the rolling sphere and dissipative cables

The dynamics of the device is controlled by the following dimensional parameters: R= Radius of the sliding/rolling surface; D= max oscillation of the device (Peak to Peak); ζ = non dimensional dissipation of the cable, the total dissipation coefficient is given by the total number of cables. The relationship between dimensional parameters and mechanical characteristics of the device is:

$$K = \frac{m \cdot g}{R}; T = 2 \cdot \pi \sqrt{\frac{m}{K}} = 2 \cdot \pi \sqrt{\frac{R}{g}} ; \qquad C_{eq} = 2 \cdot \pi \cdot \frac{\mu}{\mu + D/R} \quad (1.1)$$

K = stiffness; T = fundamental period; C_{eq}= equivalent damping proportional to the area of the hysteretic cycle (see Fig. 6); μ = damping coefficient.

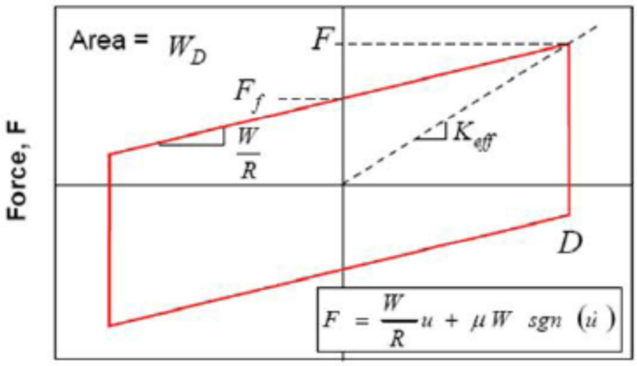

Figure 6. Hysteretic cycle for sliding/rolling device

Three devices of different diameter have tested D = 0.2m 0.4m 0.5 m with six configurations of damping depending on the number of cables per size of the device and two values of the vertical loads: W1= 17 KN and W2 = 34 KN. The table 2.1 contains the test identification of the pull-release tests with two masses of 17 and 24 KN weight and different number of dissipative cables for each side of the 0.4m Diameter isolator (200mm max displacement).

Table 2.1. Test facilities at ENEA C.R. Casaccia laboratories

N° of Cables each side	9	8	6	4
Load W1=34 KN test id	1C	4C	5C	8C
Load W2=17 KN test id	2C	3C	6C	7C

Table 2.2. Dimensional parameters of the devices EARLYPROT

D = diameter	0.2 m	0.4 m	0.5 m
R = pendulum radus	2 m	2 m	2 m
N= Number of cables	36, 32, 24, 10, 8, 0	36, 32, 24, 10, 8, 0	36, 32, 24, 10, 8, 0
W1, W2 = vertical loads	17 KN, 34 KN	17 KN, 34 KN	17 KN, 34 KN
T = period	2.83 sec (0.36 Hz)	2.83 sec (0.36 Hz)	2.83 sec (0.36 Hz)
K=W/R	8.4 KN/m, 1.69 KN/m	8.4 KN/m, 1.69 KN/m	8.4 KN/m,1 .69 KN/m
K_{eq} = equiv. stiffness	9.3 KN/m, 18.7 KN/m	5.1 KN/m, 10.2 KN/m	7.6 KN/m, 15.3 KN/m
C_{eq} = equiv. damping	15%	15%	15%

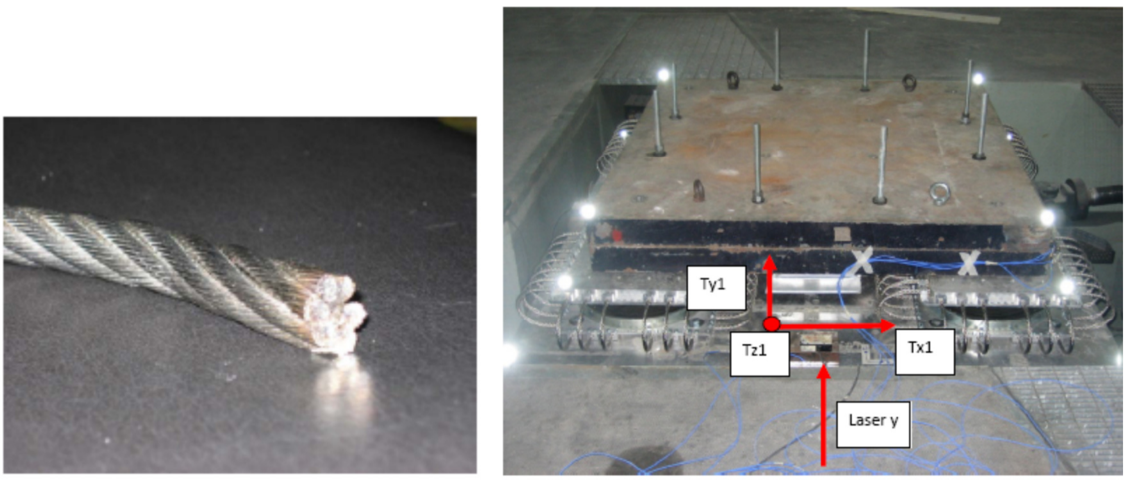

Figure 7. Dissipative cables and test set-up for the characterization of the devices, sensors for accelerations (Accelerometers) and displacements (laser and markers)

Displacement signals have been detected by means of a laser sensor and markers of the 3D_vision system, accelerometers have also installed for acceleration data. Figure 8 shows the displacement data recorded by the 3DVision motion capture system during the pull-release tests of the D=0.4m device with 17 KN weight: a) 6_cables/side, b) 0_cable/side.

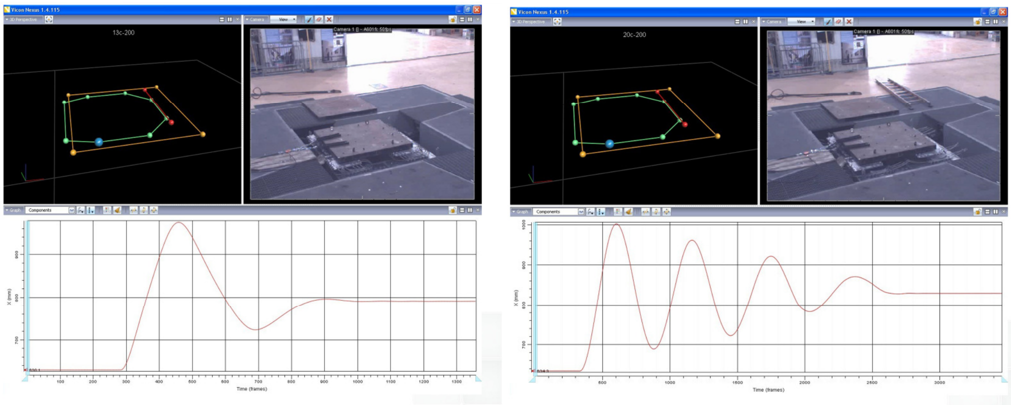

Figure 8. Pull-release test: Device=400 mm, W=17 KN, A0=200 mm ; a.) N= 6 cables/side, b.) N=0 cables

The figures 9-a,b,c,d,e,f represent the displacements recorded by the 3D_vision motion capture system during the pull-release tests of the semi passive devices EARLYPROT with 34 KN load at different number of dissipating cables, starting with the test 1C (9_cables/side, e.g. 36 total) up to test 12C (0_cables). The devices with 2_cables/side = 8 cables are recentering as well the 0_cables.

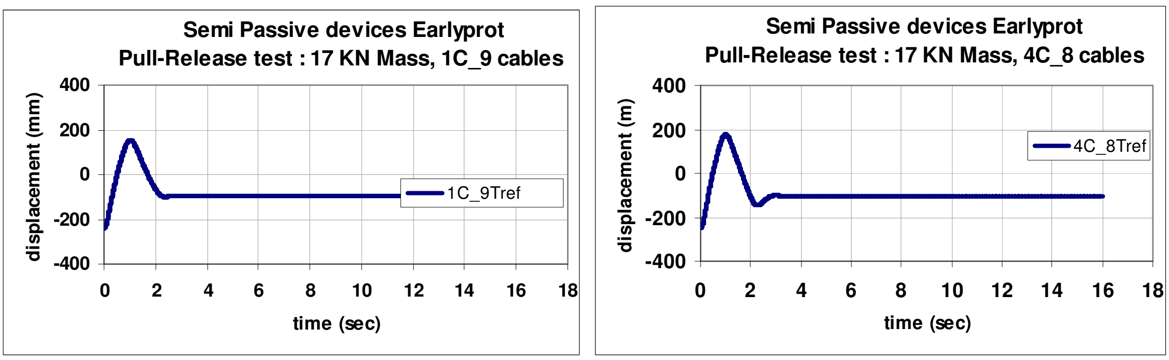

Figure 9-a,b. a) Test 1C, W=34 KN, 9_cables/ side; b) Test 4C W=34 KN, 8_cables/side

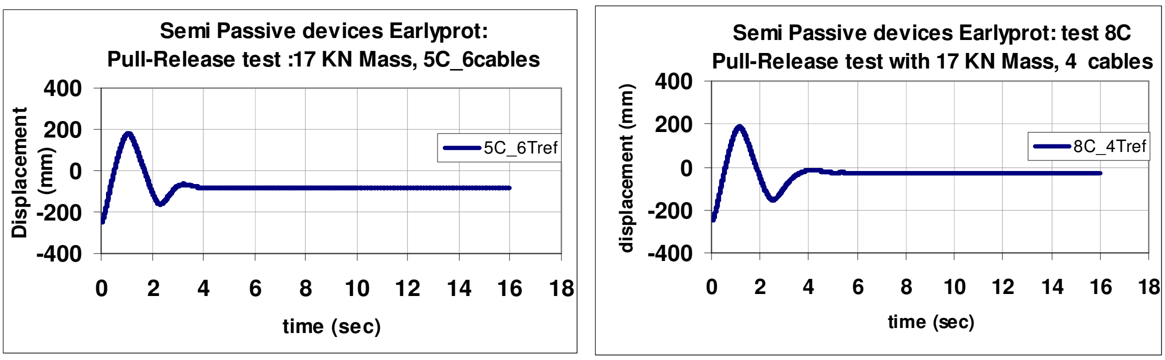

Figure 9-c,d. c) Test 5C W=34 KN, 6_cables/side; d) Test 8C W=34 KN, 4_cables/side

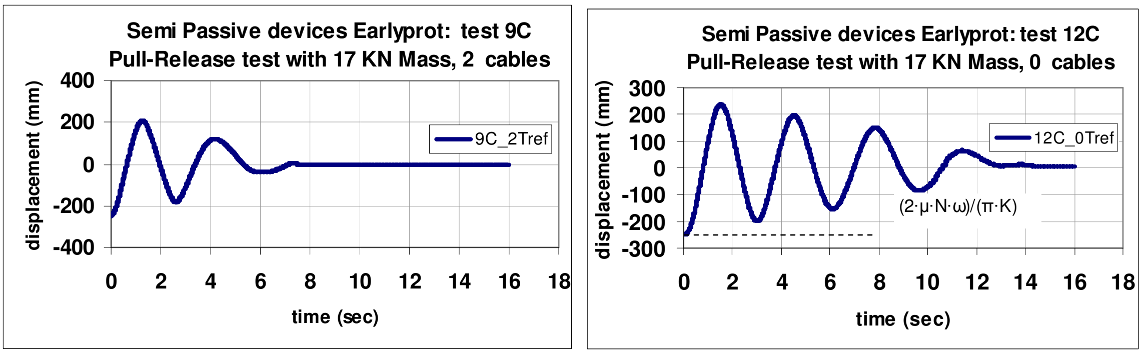

Figure 9-e,f. e) Test 9C W=34 KN, 2_cables/ side; f) test 12C W=34 KN, 0_cables

The logarithmic decrements after each cycle are not constant: the equivalent damping spans from =64% (36 cables) to =9.0% (0 cables) with a nonlinear dependency to the number of cables. Beside the pull over tests, up to 48 shock, sine sweep and fixed frequency tests have been carried out along X and Y axes to characterize the devices. The sine and sweep tests are useful for the evaluation of the hysteretic cycles of the devices. The graphs in figure 11 are the hysteretic cycles during the sine test at (0.5Hz, 0.2g), (0.4Hz, 0.3g) and (0.5Hz, 0.3g), (0.4 Hz, 0.1g), (0.7 Hz, 0.25g); at low displacements, there is constant dissipation value of 3% compatible with the numerical calculation and no hardening effect. The stiffness of the device increase with the displacements as shown in figure 12 where the dissipative cables have hardening effect at high displacements.

3. SEISMIC QUALIFICATION OF THE CLASS 1-E CABINET.

The seismic qualification test sequence for the electrical cabinet provided by seismic isolators was:

1. Verification of the document compliance
2. Fastening of the cabinet on the 4m x 4m shaking table
3. Application of 3 accelerometers on the shaking table, 3 accelerometers on the top and 3 accelerometers on the point selected by the previous FEM analysis
4. Application of 40 markers at the edges of each section to achieve displacements by means of the 3DVision motion capture system
5. According to IEEE Std 344-2004, search of the principal resonance frequencies along X,Y Z axis with the following sinusoidal sweep in frequency: Freq.=0.-0.13Hz, D=50mm; Freq.=1-33Hz, Acc.=0.2g,(g=9.81ms-2); sweep rate=1oct/min
6. To achieve the relative importance of the non-linear effects of the sliding isolators, the resonance search has been conducted also with the following sinusoidal sweep test: Freq.= 0-0.13, d=25mm; Hz=1.4-33Hz, Acc=0.2g; Sweep rate =1 oct/min
7. Initial functional test in normal working condition: powering 220V/50Hz, verification of VBF functionality, leave the cabinet in operative mode
8. Application of the acceleration time history along X axis with TRS ≥ RRS at 2% damping, (ref. figure A1/ “High RRS, ZPA=0.5g , according to IEEE Std 693-2005, Par. A.1.2.2.2)
9. Examination of the full functional availability of the unit during the seismic test by activation of the breaking circuit at the test time t when the Arias intensity Ia(t) is 50% of Ia(∞)
10. Reiteration for 5 times the phases 7-8-9
11. Reiteration of the 5 times sequence of phases 7-8-9 along the Y axis
12. Reiteration of the 5 times sequence of phases 7-8-9 along the Z axis
13. Reiteration of the test for the SSI earthquake along X, Y and Z axis

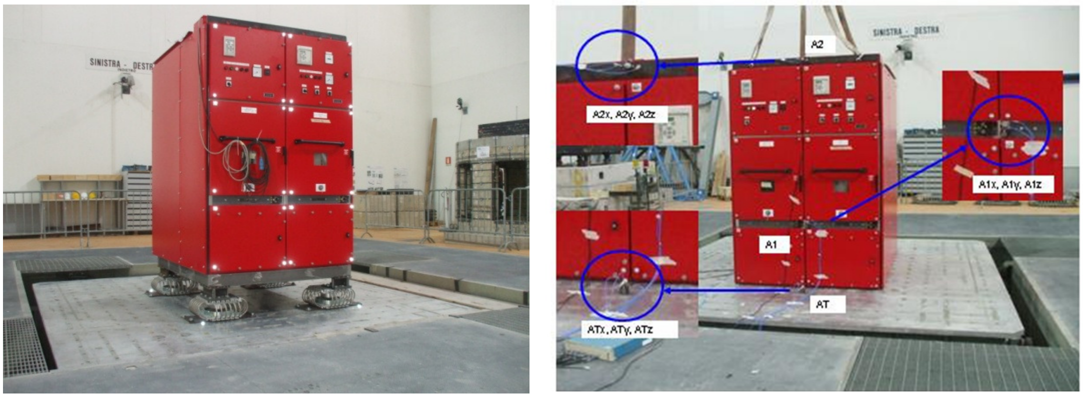

Figure 10-a,b. Seismic qualification of the class 1-E electrical cabinet a.) base isolation; b.) fixed base.

The markers positioned at the FEM nodal points are evident in the Fig.10-a, the position of the accelerometers is represented in Fig.10-b: a1= three axial accelerometers at the base table, a2 = three axial accelerometers at measurement point 1, a2= three axial accelerometers at the top of the cabinet. The time histories for the seismic qualification have been defined according to the IEEE 693-2005. They are compatible with the Required Response Spectrum RRS at page 32 figure A1 High required response spectrum HRRS in the frequency range 0.5-33 Hz – 0.5g ZPA, curve 2% damping.

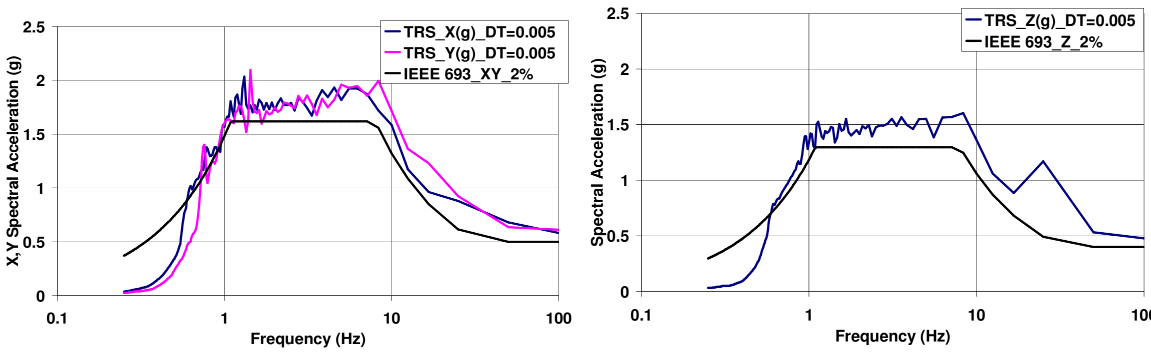

Figure 11-a,b. a.) Superposition of TRS and RRS along X, Y axes; b.)Superposition of TRS and RRS along Z axis

The acceleration time histories at the base and at the top of the cabinet during the qualification tests with base isolation are shown in the figures 16-a, 16-b, 16-c. The comparison between the top and base accelerations evidence the efficacy of the base isolation by means of the devices Earlyprot. However there is no isolation along the Z axis as shown in the figure 16-c. On the other end, even if the devices was provided with 9_cables/side, at the end of the test the cabinet was recentered due to the effect of the vertical component of the motion to reduce the friction damping forces.

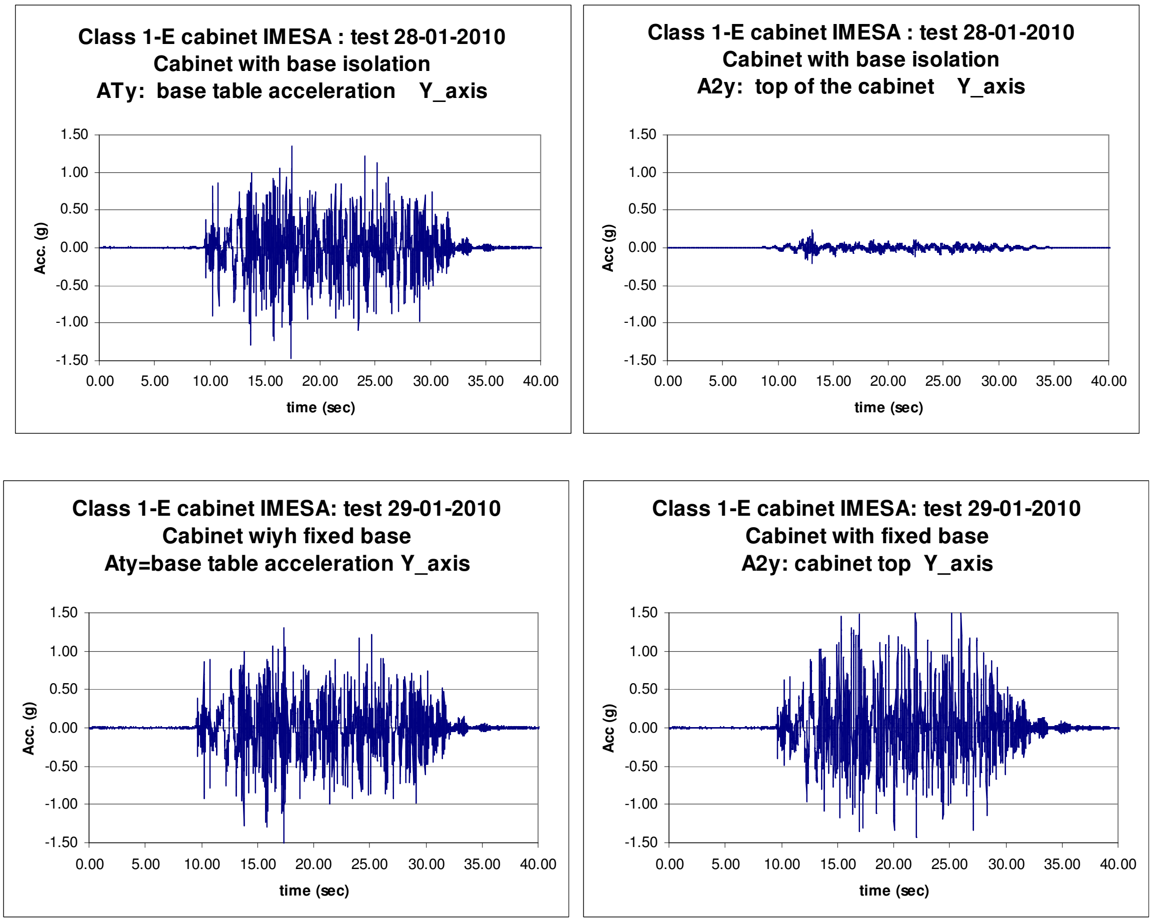

Figure 12. Acceleration time history at the base table and at the top of the cabinet during the qualification tests with base isolation and fixed base.

In figure 13-a and 13-b are the Frequency Response Spectra FRF along Y axis during the qualification of the cabinet with base isolation and with fixed base. Reference channel =ATy (accelerations at the base table along Y); the response channels are A1y= first level of the cabinet and A2y= top of the cabinet. The modal damping have been evaluated at -3dB of the FRF peaks.

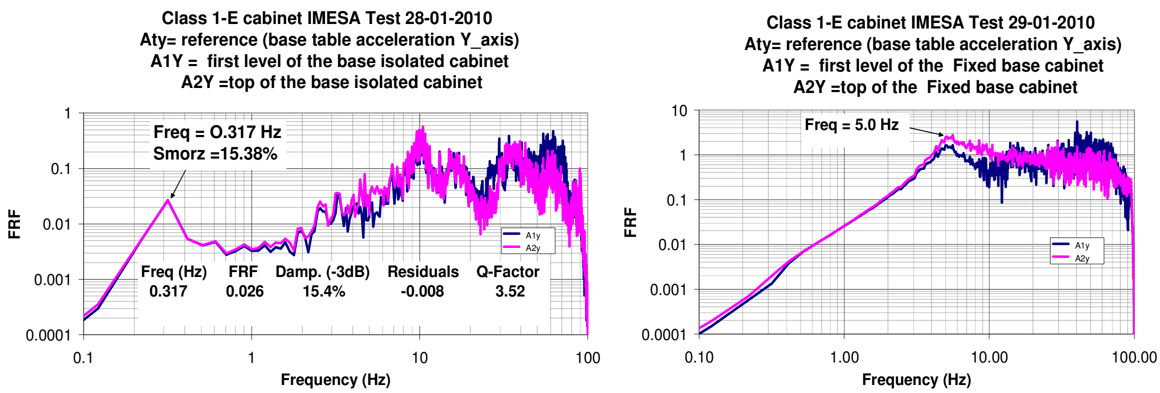

Figure 13. Modal damping evaluated at -3dB of the peak of the Frequency Response Function (FRF)

3. CONCLUSIONS

The seismic qualification tests of a class 1-E electrical cabinet provided by the anti-seismic devices Earlyprot in fully passive configuration was illustrated. The Earlyprot devices are part of the sliding/rolling family of seismic isolators, they are made by steel/ceramic or marble and are provided with dissipative cables to calibrate the energy dissipation according to characteristics of the object to be seismically isolated. The devices can be fully passive or semi-passive, the semi-passive configuration is blocked in normal conditions and unblocked by a seismic early warning (SEW) triggering signal. Beside the seismic isolation of components of nuclear plants, they are also useful for isolation of statues, museum techs, delicate instruments of hospital and control centers. The qualification of the cabinet was preceded by a series of pre-qualification characterization tests. The use of an innovative 3D-vision motion capture for direct monitoring the displacements of hundreds of points of the structure during the dynamic tests allowed the assimilation of the displacements data in the FEM numerical model for its reliable validation. The availability of this monitoring technique is useful for the displacement based approach in structural analysis. The 3D_vision data and images can be easily shared in the distributed experiments within a network of laboratories this was done by the virtual framework DySCo. The results of pre-qualification tests for the dynamic characterization of the cabinet with and without base isolation and the results of the two seismic qualification campaigns of the cabinet with base isolation and the with fixed base was compared.

AKCNOWLEDGEMENTS

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