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An Innovative Active Control System for The Seismic Retrofit of a Precast R.C. Wall-Bearing Building

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Abstract

Seismic improvement and retrofitting of existing Italian buildings cannot always be an easy problem to solve. In fact, several traditional intervention techniques exist but each one of them is related to practical difficulties in its implementation, since they often involve invasive building activities and inconvenience to the occupants.

With the aim of proposing an innovative solution to the problem, ISAAC has developed, patented and tested an active control technology, already introduced by the ISO 3010:2017 standard as Active Mass Damper (AMD). It consists in the use of inertial forces, generated by the active movement of mobile masses installed on the roof of the building, to counteract its oscillations during the seismic event and to limit the expected damage to structural and non-structural elements. This type of intervention gives the possibility of increasing the seismic and dynamic performance of the building acting only externally, quickly and without causing disturbance to residents.

The system was tested with experimental tests on a shaking table at the EUCENTRE laboratories in Pavia, which allowed the validation of the technology and the development of software and best practices for FEM modelling techniques of the structural behavior considering the AMD system.

The paper presents the case of application of the active control system on a 14-storey residential building with precast reinforced concrete load-bearing wall structure. After a brief description of the construction system of the building, the material investigation campaign and the dynamic identification tests carried out are illustrated.

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Afterwards, the design and analysis method for the retrofit intervention with AMD technology is described, highlighting the achievable seismic performance improvement.

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1. Introduction

A multitude of strategies have been proposed over the years that can be adopted to strengthen structurally deficient buildings enhancing their seismic performance. The selection of the optimal strengthening technique and the level of intervention is a rather complex procedure that is carried out on a case-by-case basis, considering the nature of the structural deficiencies to be addressed and other relevant factors. In this context, “response-control” strategies based on the use of devices that can reduce the seismic demand by altering the dynamic properties of the structure and/or by absorbing part of the earthquake energy, have gained popularity over the past few decades. They are normally grouped in three broad categories, namely passive, semi-active and active devices, based on the fundamental principles governing their behavior and on their overall characteristics.

Active control systems provide protection of a building by generating forces that counterbalance the forces induced by an earthquake. These forces are generated by electro-mechanical or electro-hydraulic actuators based on the feedback response from the structure, and they require a higher power source compared to the semi-active devices. Active vibration control systems are gaining increasing traction because of their flexibility and versatility: De Roeck (2011), Dyke et al. (1996), Moutinho et al. (2011), Xu et al. (2014).

Examples of active control systems for civil engineering applications include active brace systems, active tendon systems, active isolation systems and active mass dampers. Active mass dampers, also referred to as Active Mass Drivers (AMDs) are most relevant for the study presented in this paper and are thus discussed herein.

In particular, the paper presents the case of application of an innovative active control system on a 14-storey residential building. The system has been recently tested on a full-scale shake lab test for checking its efficiency and to support the definition of a FE model-based approach for design scopes.

2. Description of the building

The building was built in 1970 and it is located in Milan. It has a compact and pseudo-square plan, measuring approximately 460 square meters and reaches 45 meters in height with 14 floors above ground (Fig. 1).

The typology of construction adopted was the Balency System: a modular technology widely promoted by the homologous French company in the Seventies in some parts of Italian territory. It consists in the assembly of special precast r.c. panels which define both the load-bearing structure and the internal partition of the apartments (Fig. 2a).

Two kinds of panels exist: vertical loading panels carrying only the load from floor slab and lateral resistant panels, which are able to counter act also the lateral forces, like wind and seismic forces. The first type has not any kind of connections between each other and with the slab below them: the stability is insured by the friction action from the carried load. On the other hand, the lateral resistant panels have special welded-connections in two couples of edge metallic bars which restore the mechanical continuity of the vertical walls (Fig. 2b).

All kind of panels have rebars anchored in the concrete slab cast in place (Fig. 2c), so the boundary condition of panels at the bottom and top edges are out-of-plane hinges.

The structure of the building has an inherent complexity due its huge articulation and the FE model has considered every kind of detail in order to simulate accurately the static and dynamic behaviour of the building. For this aim, experimental campaigns have been executed on the structure; in particular, geometry and structural relief, investigations on materials and dynamic identification tests.

The geometry relief detected two kinds of walls in terms of structural thickness: 150 mm thickness for walls that carry out both vertical and horizontal loads and 100 mm thickness for walls that carry out only vertical loads.

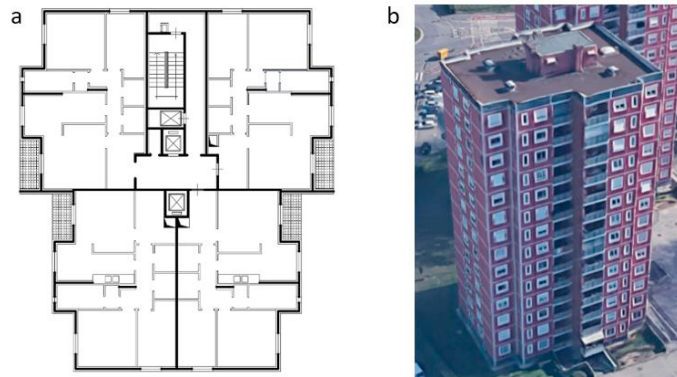


Fig. 1. a) typical plan and b) view of the building.

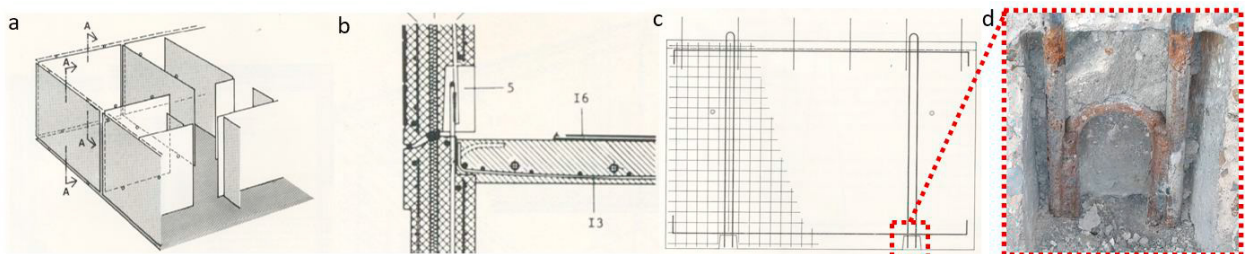


Fig. 2. Drawings of details of the structural system Balency: a) static scheme; b) connection detail of panels to the floor slab; c) and d) connection detail of laterals resistant panels, rebar $\Phi 18$.

Horizontal decks are made up of cast in situ slabs with structural 14 cm thick-ness, in static configuration of simple support on the walls. About the material characterization, compression tests on concrete and steel specimens taken from some structural elements have been performed in specialized laboratory. The mean of the cylindric compression strength was 31.2 MPa for the concrete, and the mean yielding strength of rebars was 472 MPa.

3. Preliminary dynamic identification test

The preliminary dynamic identification test on structures is always the first step in the design process of intervention with active control system. The knowledge of the real dynamic behaviour of structures has a crucial importance in the definition of the FE model, because managing a model fitting the experimental data insure the truthful prediction of the design. Typically, OMA (Operation Modal Analysis) and EMA (Experimental Modal Analysis) can be performed on an existing structure with the aim of identify its modal parameters, like frequency, deformed shape and viscous damping. At this date, only OMA has been executed, but it has been enough to preliminary identify the estimations of those parameter in order to get a predictive FE model.

A total of 14 accelerometric sensors have been placed in strategic points on the facades and on the roof of the building, in order to catch its first principal vibration modes, and the data have been continuously acquired and saved into dataset of ten minutes for six days.

At this point, for each dataset has been evaluated the peaks and RMS acceleration, in order to exclude the data where the vibrations are too low or high for a correct assessment of the structural properties. After that, the “optimal” dataset has been manipulated using the PolyMAX algorithm, under the hypothesis of white noise input. The algorithm evaluates the dynamic model which better match the Fourier Transform of the Auto and Cross Correlations computed from the time history data recorded from the vibrations of the structure due to ambient excitations. This is it possible thanks to the analytical solution of the Non-Linear Least Square problem applied to the basic formulation of a transfer function. The results obtained are the stability diagrams for each dataset (Fig. 3), allow-ing the evaluation of natural frequencies (Table 1). Then the unscaled mode-shapes of the building have been obtained by using the Frequency Domain Decomposition technique for the extrapolation of the three singular matrices U , S and V from the Power

Spectral Density matrix. This operation based on a Singular Value Decomposition, obtained from the recorder acceleration output of the building.

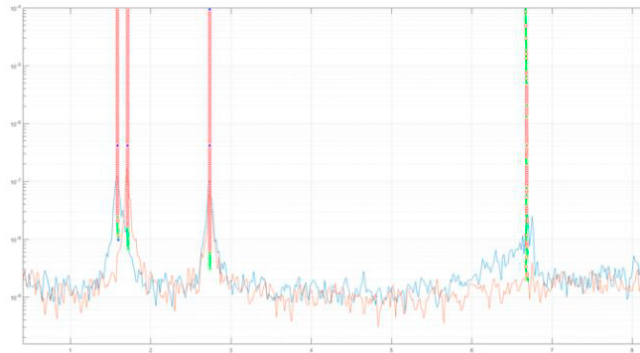


Fig. 3. Stability diagram of one dataset.

4. Elaboration of the FE model

4.1. Modeling technique

The FE model considered beam elements representing the structural walls in their exact positions and with their effective dimensions.

In fact, rigid links connecting the beams have been created both at the bottom and top of the deck to define the width of the walls. Furthermore, links with non-linear properties have been modelled for the simulation of the mono-lateral stiffness and strength of connections of the structural elements, following the information collected from the preliminary investigations. Non-linear elements have also been inserted within adjacent walls, in order to take into account contacts and frictions between adjacent walls, due to their mutual collaboration along vertical interfaces.

As for the internal walls carrying only gravitational loads, they were simply modelled with beam elements with hinges at the bottom end.

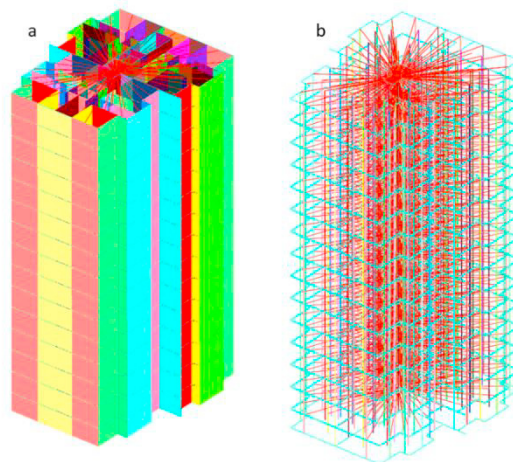


Fig. 4. a) global FE model in its solid view and b) in its wireframe view modelled in Straus7.

A further modelling feature is the insertion of rigid links in the horizontal plane for the simulation of the concrete deck slab. These rigid links essentially connect all the top ends of the beams representing the structural walls (Fig. 4).

A complex FE model has been developed, consisting in 20791 nodes, 13523 beams and 17722 links. Nevertheless, it was well manageable by the power of the new 64-bit solver of Straus7 software, and thanks to its full versatility. In fact, by means of the API tool, it was possible to customize and speed up the management of the numerical outputs according to every type of need.

4.2. Model updating

Regarding the calibration of the stiffness of the elements schematizing the vertical joints, a linear model was developed, used for determining the vibration modes of the structure. The calibration of the value of the shear stiffness of the connecting elements between the various rigid links systems allowed to obtain a satisfactory correspondence with the natural vibration modes determined experimentally by OMA analysis (Table 1).

The determined stiffness value, therefore, was assumed as an initial condition for the non-linear analysis.

Table 1. Experimental and numerical modal frequencies.

Mode	Experimental (Hz)	Numerical (Hz)	Difference (%)
1 – Flexural Dir.X	1.58	1.56	-1
2 – Flexural Dir.Y	1.71	1.76	-3
1 – Torsional	2.73	2.48	-9
4 – Flexural Dir.X	6.68	5.17	-22

5. The active control system of the seismic response of structures

5.1. Working principle of the active control system

A novel active control system for the protection of structures against the effects of earthquake was recently proposed Rosti et al. (2022). According to ISO 3010:2017, the active control system is classified as Active Mass Damper (AMD) and it consists of an innovative inertial system used as Active Vibration Control device. Differently from other AMDs, this system is a modular and non-invasive solution for the retrofit of existing buildings that do not require the ad hoc design of the device for each different building, like typical AMDs and TMDs.

The purpose of the AMD is to generate inertial forces that "counteract" the movement of the building by reducing the amplitude of oscillation and, consequently, the earthquake-induced forces experienced by the structural elements. The magnitude of the inertial forces to be generated is calculated in real time by the control algorithm, based on the accelerometric readings of sensors installed at certain locations across the structure. Ideally, the AMD is to be installed on the roof of a building, with one or more devices acting in at least two orthogonal directions to reach the desired three-dimensional performance (optimal arrangement is determined on a case-by-case basis).

The active control system comprises four main subsystems: sensors, controller, actuators and power system. The sensors are elements which provide the feedback needed for the control. They are installed on the structure to measure system response variables, such as displacements, velocities and accelerations. The sensors can also be used to perform tasks such as structural health monitoring, by allowing the dynamic identification of the structure during its life cycle.

The controller is the core of the system because it implements the vibrating control algorithm. It produces actuation signals by a feedback function of sensor measurements and defines the inertial mass displacement in time. Many types of control exist in the literature. The "Sky-Hook", a direct velocity feedback control, was chosen for its performance and robustness.

The algorithm defines a control force proportional to the relative velocity of the roof of the building $v_{rel,roof}$ through a constant G (Gain), and this force is produced by the acting actuator used to move the inertial mass (Eq. 1):

$$F_c = -G \cdot v_{rel,roof} \quad (1)$$

The Gain has to be properly tuned, in order to ensure performance and stability of the system in any working conditions. The system is connected to an Uninterruptible Power Supply (UPS) able to power all the electronic systems in case of a blackout. The battery installed into the UPS can generate up to 3kW and provides power to the AMD, in absence of external current, for at least 24 hours. The mobile mass generates the inertia force through the movements imparted by the actuator. It can be hydraulic or electric, depending on its construction technology.

Two kinds of AMD are considered in this work: an AMD with hydraulic actuator (first prototype, called I-Pro 1) and an AMD with electric actuator (new generation, called Electro-Pro 20x, used in the design project).

5.2. FE modeling approach for the simulation of structures with the active control system

The first prototype of the control system (I-Pro 1) was designed, produced and preliminary tested at the Politecnico di Milano, Italy (for more details see Rosti et al. (2022)). Subsequently, dynamic experimental test on twin full-scale r.c. buildings has been carried out on the shaking table of the Eucentre laboratory in Pavia, Italy, (Rebecchi et al. (2022)). The dynamic experimental test investigated not only the performance of the AMD equipped on the building, but it also checked the efficiency of the whole active control system: the acquisition and processing of data, the stability of the control algorithm, and the elaboration of signals.

For this reason, the experimental results have been used as benchmark to tune a structural model developed with a commercial FEM software (Midas Gen), for the simulation of the dynamic behaviour of the building equipped with active control system, Rebecchi and Bussini (2021). Understanding the best practice to model the AMD with its control algorithms is the key to manage the design of retrofit of buildings with active control systems.

Regarding the simulation of the AMD, it worth to be noted that it is an active response control system and its behaviour is determined by specific algorithms and control logic. However, if some hypotheses about the mechanics of its behaviour are respected during its operativity (like the maximum stroke available and the maximum velocity that the mobile mass can undergoes) the device can be approximated with a simple non-linear dashpot with a cut-off on the maximum force deliverable. In fact, the control force delivered is the product of the relative velocity of the roof of the structure measured at the installation point and a damping constant, like the constitutive law of a viscous damper (Eq. 1). In particular, the damping constant c of the damper constitutive law coincides with the G parameter of the control algorithm of the AMD. In Rebecchi and Bussini (2021) it was shown that this approximation may be adopted, and the behaviour of the device was simulated with one non-linear dashpots assigned to the top level of the structure (Fig. 5).

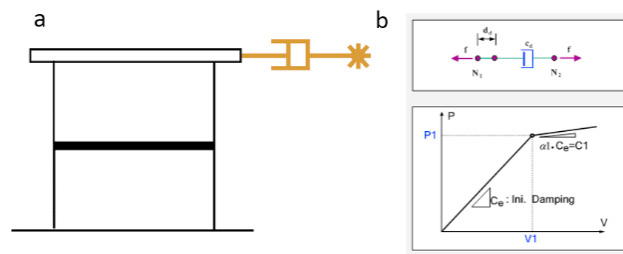


Fig. 5. a) idealization of the AMD with a viscous damper element at the top (sky-hook approach); b) constitutive law of the links.

5.3. Configuration of the active control system

The AMD with electric actuator (Electro-Pro 20x) has been considered for the design of seismic retrofit of the building. It shares the same working principles of the hydraulic one (I-Pro 1) described in the previous section: data acquisition, data processing and control logic of the algorithm. The main difference between the two systems can be found properly in the machines which generates the control forces.

Electro-Pro 20x is made of a linear synchronous motor consisting of a magnetic stator and a linear forcer able to develop a maximum force of 20 kN. Both the stroke and the mobile mass can be optimized to best fit the dynamic requirements of the structures. Typically, the total length varies between to 1 m to 3 m, and the mobile mass can be assembled by modular steel plates from a minimum of 250 kg up to 1000 kg (Fig. 6a).

Thanks to its small size and low weight, Electro-Pro 20x can easily fit several practical requirements regards its installation on existing structures. Furthermore, the modularity of the system allows the design of suitable configuration to achieve the goals of the retrofit project.

For the retrofit design, n°8 AMDs have been considered and the configuration of system on the roof top of the building is displayed in Fig. 6b. The mobile parts have a weight of 1000 kg and the strokes of the machines are 2 meters. The AMDs are supported by couple of steel beam and concrete pier caps for not directly graving over the floor slab of the roof. Anchor bolts and mechanical dowels insure the rigid connections of the AMDs and the support structures.

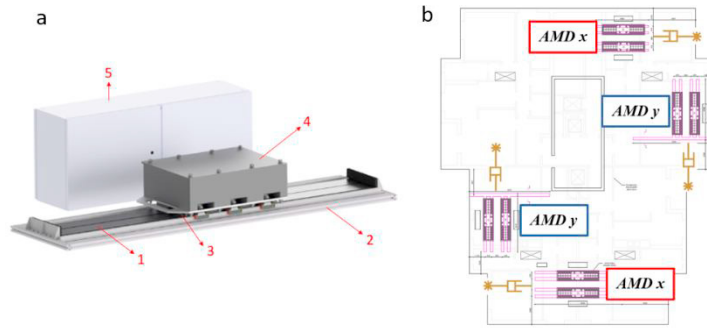


Fig. 6. a) Electro Pro 20x: 1) permanent magnets, 2) basement for the anchor to sub-structure, 3) linear forcer, 4) mobile mass; 5) machine box including drivers, power system and other electrical components; b) configuration of the installation on the roof of the AMD system with ideal dashpot elements considered in the FE model.

6. Seismic analysis and results

6.1. Setup of the FE model and dynamic analysis

Following the approach described in section 5.2, the FE model has been modified by inserting 4 damper elements (one for each installation point) at the last floor of the building, as for design project (Fig. 6b). The damper elements have been connected with cut-off bars elements in order to take into account the maximum force deliverable by a couple of AMD (2x20 kN). The c constant of damper, which represents the control gain G of the control algorithm, has been tuned in order to optimize the performance of the AMDs and to get the better results in terms of structural behaviour of the building in the seismic conditions. In particular, the iteration procedure led to consider a gain of 1.1 kNs/mm for AMDs in X direction and a gain of 0.6 kNs/mm for the AMDs in Y direction.

A total of 12 non-linear transient dynamic analyses were carried out: n°3 analyses relative to the scenario before retrofit and n°3 analyses after retrofit (with AMDs), each one for Life Safety and Damage Limit State. So, n°2 sets of n°3 couples of natural accelerograms (for both horizontal direction) have been selected from Rexel-Web database for the simulation of the seismic hazard of site location (Milan, PGA_{SLV} 0.049g).

6.2. Results of analysis

The analysis of the structure without active control system stated that the most critical vulnerabilities are the connections between the vertical panels in terms of shear actions. No relevant problems have been found for flexural action on the structural elements. In Fig. 7 are displayed the distribution of failures in the connection link for both situations investigated: building controlled and not-controlled. Without AMDs the amount of fails at SLV is 4850 (84% of the total); this number has been reduced to 2642 (46% of the total) thanks to the additional damping effect of the active control system. So, the relative reduction in terms of shear connection fail after the retrofit project is 38%.

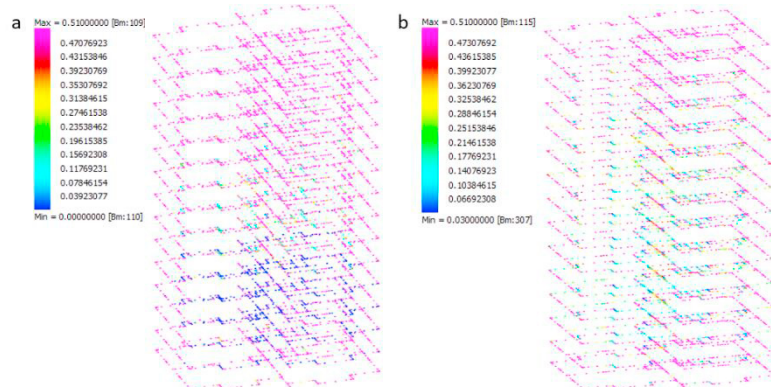


Fig. 7. Comparison of the shear rate in the connection links for structure without control a) and with control b).

A measure of the effect of supplemental damping from the active control system is shown in Fig. 8, where a comparison between the displacement history of a node in the last floor of building with and without AMD for one of the analyses performed at Damage Limit State is displayed. A maximum reduction of 43% has been recorded.

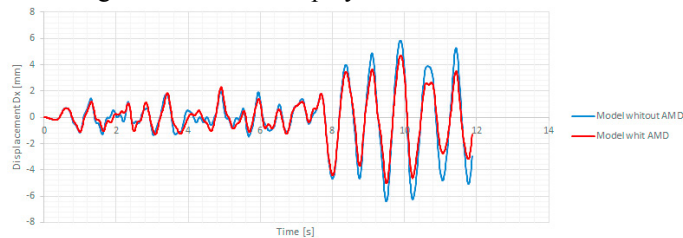


Fig. 8. Comparison of roof displacement history between controlled and non-controlled structure for one of the analyses performed at SLD.

6.3. Performance of the AMDs

The electric motor of the AMDs can move the mobile mass up to a velocity of 5 m/s and with an acceleration of 7 g. However, the AMDs have mechanical limits in their working conditions that must be checked after the numerical situation. If these kinematic limits are over crossed, the control force could noticeably decrease and the system could lose its efficiency.

For that reason, the design process must consider an additional analysis where the control force is processed in order to derive the acceleration and velocity of the mobile mass, and the amplitude of the motion during the design earthquake shakes. Using an internal software specifically developed, it has been possible to predict the mechanical performance of the machines, insuring the correct behaviour of the system. Fig. 9 shows the history of force, velocity and displacements of the mobile mass vs. time for the most significant machine of the system and for most significant analysis carried out. Since all the limits have been respected by the real actuator (green line), the AMDs will correctly behave during the earthquake shake and can deliver the expected control force, leading the dynamic improvement designed.

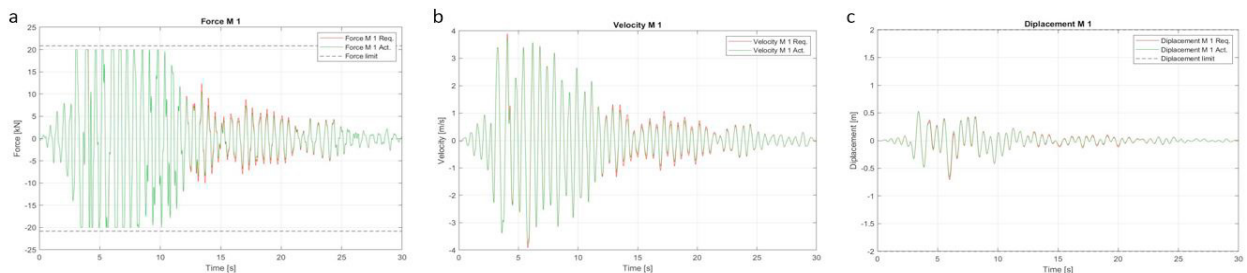


Fig. 9. Performance diagrams of one of the 8 machines installed for SLV analysis: a) control force, b) velocity of mobile mass, c) displacements of mobile mass. Red line: ideal behaviour; green line: real behaviour.

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