

Semi-Active Control of Precast RC Columns under Seismic Action

Nicola Caterino ^{1,2}, Mariacristina Spizzuoco ³

¹ Department of Engineering, University of Napoli Parthenope, Centro Direzionale, isola C4, 80123 Naples

² Construction Technologies Institute, National Research Council (CNR), San Giuliano Milanese, Milan, Italy

³ Department of Structures for Engineering & Architecture, University of Napoli Federico II, Via Claudio 21, 80125 Naples, Italy

nicola.caterino@uniparthenope.it

Abstract. This work is inspired by the idea of dissipating seismic energy at the base of prefabricated RC columns via semi-active (SA) variable dampers exploiting the base rocking. It was performed a wide numerical campaign to investigate the seismic behaviour of a pre-cast RC column with a variable base restraint. The latter is based on the combined use of a hinge, elastic springs, and magnetorheological (MR) dampers remotely controlled according to the instantaneous response of the structural component. The MR devices are driven by a SA control algorithm purposely written to modulate the dissipative capability so as to reduce base bending moment without causing excessive displacement at the top. The proposed strategy results to be really promising, since the base restraint re-laxation, that favours the base moment demand reduction, is accompanied by a high enhancement of the dissipated energy due to rocking that can be even able to reduce top displacement in respect to the “fixed base rotation” conditions.

1. Introduction

The idea of a controlled rocking precast RC column is herein proposed and discussed. It is potentially suitable for seismic retrofit of existing precast RC frame structures where column-to-plinth connection, realized according to outdated technologies, can yield significant rotation in case of severe earth-quakes. However, the proposed technique could also be applied to optimize the lateral response of new structures, where the base joint can be specially designed as to allow - in certain conditions and within given limits – rotations and hence energy dissipation.

The idea of exploiting unavoidable rocking mechanism between assembled precast structural elements to dissipate seismic energy has been explored during the last decades. Most re-search is addressed to enhance seismic capacity of precast RC structures adding energy dissipation systems at the beam-to-column connections [1, 2], less frequently the base connection of columns [3] or cantilever walls [4] have been also involved.

Herein a semi-active (SA) control system based on the application of magnetorheological (MR) devices to realize a time-variant base restraint is investigated. The mechanical proper-ties of such variable base restraint for precast RC columns can be driven in real time by a properly written control logic [5]. The controller has to be programmed to instantaneously calibrate the MR devices installed at the base



of the column in order to reduce the base bending moment, relaxing in selected intervals of time the base restraint. Again, the control logic has to hold the top displacement within acceptable values so as to avoid significant, detrimental second order effects. After the formulation of the above idea, a finite element model of the structure has been carried out so as to develop numerical simulations addressed to optimally calibrate the control logic properly designed for such kind of applications.

2. A variable base restraint for precast rc columns: control algorithm

The special base restraint is schematically shown in figure 1, where the uncontrolled precast RC column, fully restrained at the base, is modelled as a single degree of freedom dynamic system (figure 1(a)), having top mass m , stiffness k_T and inherent damping c_T . In order to control the structural demand, the authors propose to replace the perfectly rigid base restraint with a controllable one that is able to instantaneously become more or less “stiff”, during the motion. figure 1(b) just sketches the materialization of this idea by a smooth hinge, with a rotational spring (of stiffness k_ϕ) and a rotational variable damper whose damping constant c_ϕ can be driven in real time by a control algorithm. The same result can be obtained in practice by mounting two vertical linear springs (k_s) placed at a certain distance (l_s) from the hinge and two vertical SA dampers (c_d) at a distance l_d from the central hinge (figure 1(c)).

SA MR dampers are considered as smart devices within the proposed control system: when a low value is imposed to the base damping, the base restraint is less ‘stiff’, so that the structure’s restraint is able to relax by converting its potential energy into kinetic energy, and the bending moment at the base is reduced. A direct consequence of controlling the demand of base bending stress could be an increase of top displacement demand; therefore, the SA base control system is thought to reduce base stress, by restraining the increase of top displacements within certain limits to control second order effects. A specific bang-bang control algorithm is formulated by the authors [5] to instantaneously decide the system’s base configuration: it switches back and forth from an “OFF” state (intensity of current $i = i_{\min}$, i.e. the minimum current set to be given to the dampers) to an “ON” state ($i = i_{\max}$, i.e. the maximum assumed value for the current) according to a logic aiming to control both the base stress and the top displacement. Therefore, the control algorithm is so formulated:

$$\begin{aligned}
 \text{a) if } |\sigma(t)| < \sigma_{lim} & \rightarrow i(t) = i_{max} \\
 \text{b) if } |\sigma(t)| \geq \sigma_{lim} \text{ and } |x(t)| < x_{lim} & \rightarrow i(t) = 0 \\
 \text{c) if } |\sigma(t)| \geq \sigma_{lim} \text{ and } |x(t)| \geq x_{lim} \text{ and } x(t) \cdot \dot{x}(t) > 0 & \rightarrow i(t) = i_{max} \\
 \text{d) if } |\sigma(t)| \geq \sigma_{lim} \text{ and } |x(t)| \geq x_{lim} \text{ and } x(t) \cdot \dot{x}(t) \leq 0 & \rightarrow i(t) = 0
 \end{aligned} \tag{1}$$

where $\sigma(t)$, $x(t)$ and $\dot{x}(t)$ are respectively the value of stress at the base, top displacement and top velocity at the instant of time t .

In other words, the controller keeps ‘stiffer’ the base restraint until the stress exceeds the limit value σ_{lim} (expression a) of eq. (1)), whereas ‘relaxes’ it (“OFF” state of the dampers) when this limit is overpassed and the displacement falls within the limit of acceptability x_{lim} (expression b) of eq. (1)). When both stress and displacement are beyond the respective threshold values, the controller switches “ON” the dampers if the displacement is going towards a larger value (so trying to damp or invert the displacement’s trend; expression c) of eq. (1)), otherwise it switches “OFF” the MR devices to make them collaborating to both stress and displacement reduction. Figure 2 schematically describes the above defined logic: the decision of the controller (switch “ON” or switch “OFF”) depends on the occurrence of each of the four possible combinations regarding the value of base stress and top displacement. The application of the proposed control algorithm requires the definition of rational criteria to optimally calibrate the parameters involved in (i_{\min} , i_{\max} , σ_{lim} and x_{lim}). An effective calibration procedure has been proposed by the authors in Caterino et al. [6].

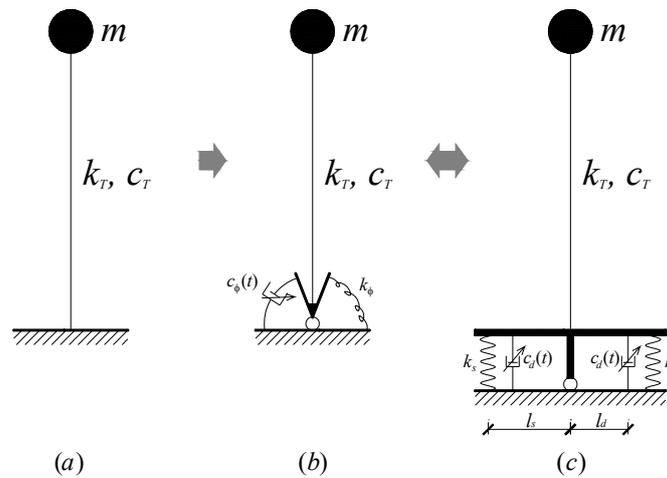


Figure 1. Basic idea of SA control of a precast RC column via MR dampers

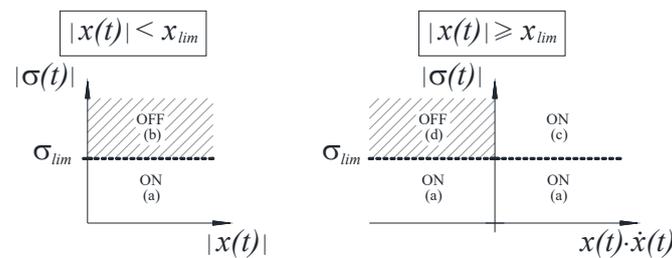


Figure 2. The logic behind the controller (symbols refer to eq. (1))

3. Calibration of the SA controller: a case study

The calibration procedure proposed by Caterino et al. [6] is herein applied with reference to a specific case study, to provide the optimal choice of values to be assigned to the parameters involved in the control algorithm. The first step is generating a finite element model of the structure to be examined, able to reproduce both fixed base (FB) and SA controlled configurations. With reference to a given seismic input, the structural response in the FB and passive cases has been determined. Then a small number of SA numerical simulations has been performed in order to single out the optimal configuration of the controller able to achieve the maximum reduction of base stress while not causing increasing of top displacement in respect to the FB case.

3.1. Case study

The case study structure is a central column of a real precast RC structure (figure 3). The reference real structure is a precast RC structure having plan dimensions 20 m × 30 m, and a double slope covering. The columns are 5.7 m tall, with a uniform square cross section of dimensions 0.55 m × 0.55 m. The mass acting at the top of a central column is the sum of the masses of the covering elements relative to a half span at each side of the column and is equal to 25.7 tons.

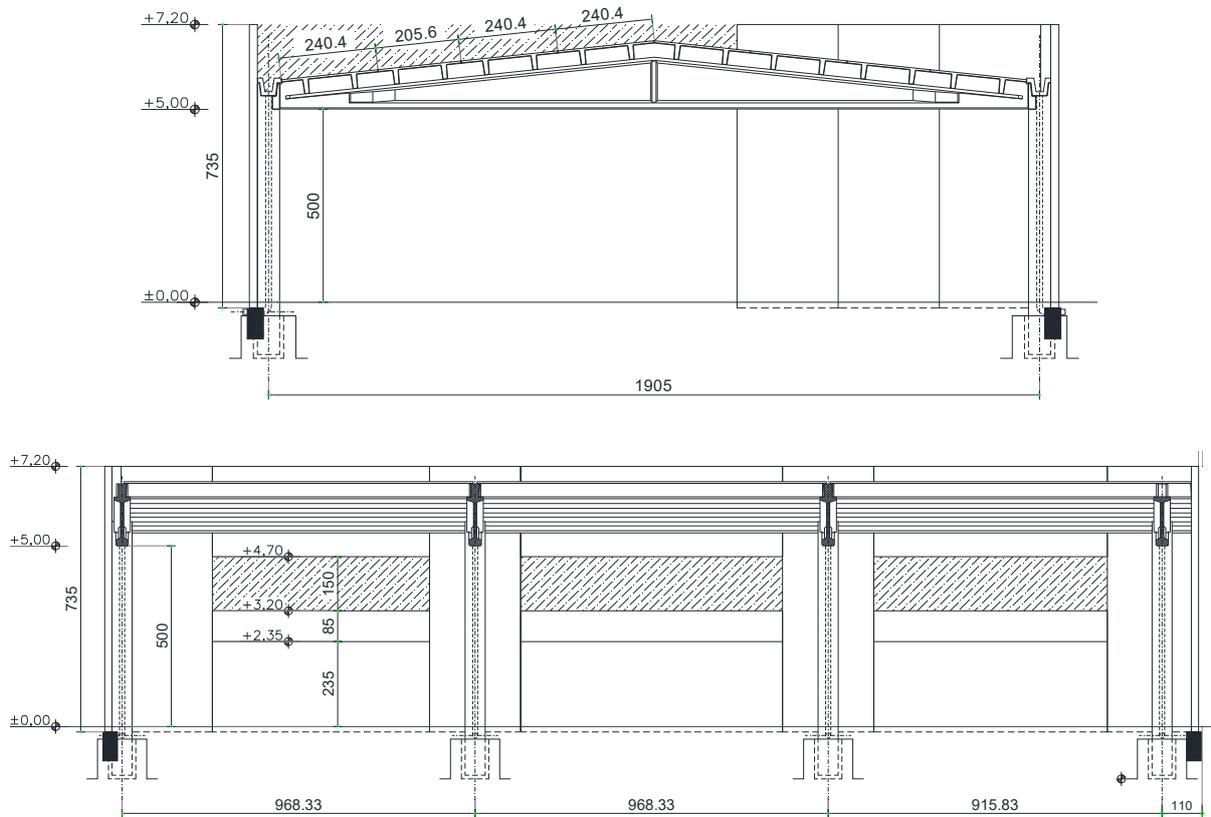


Figure 3. Case study structure

The base of the model is highly stiff and is supported in the middle by a cylindrical steel hinge. On both sides of the base, one cylindrical spring and one MR damper are installed. The assembly “elastic springs + SA MR dampers”, placed in parallel at the base of the tower, just represents the smart base restraint herein proposed to control the dynamic behavior of the structure. The registration of the Campano Lucano (Italy) earthquake (figure 4) has been adopted for the numerical analyses (code of the seismic record 290ya, magnitude 6.9, fault distance 32 km, date 23/11/1980, station ID ST96).

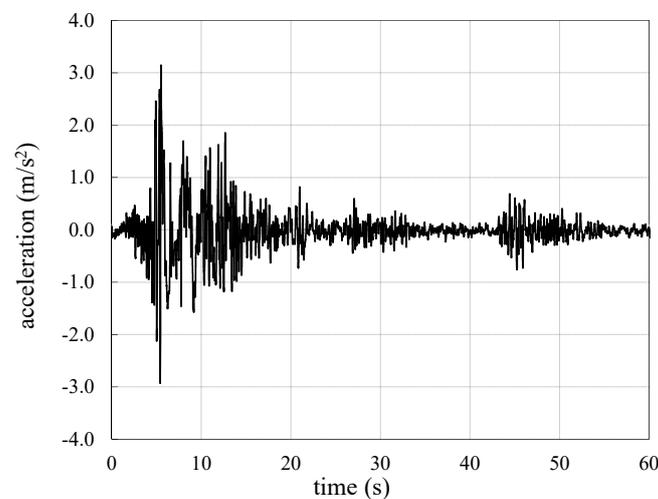


Figure 4. Selected seismic input

3.2. Numerical model

A finite element model has been generated in Matlab environment to simulate the dynamic behavior of the case study structure. It consists in 37 elements: 36 elements simulate the column with uniform cross section ($55 \text{ cm} \times 55 \text{ cm}$), while the last element (37th) is more rigid and represents the connection of the top of the column to the structural covering. The part of the double slope covering acting on the considered column is simulated by a concentrated mass at the top of the column. Such mass is added in the global mass matrix at the translational degree of freedom at the top of the tower.

The base support has been modelled as in figure 5, that is by a rotational spring k_{spring} and a Maxwell element (representing the MR dampers) working in parallel. The value for k_{spring} ($2.1 \times 10^7 \text{ Nm/rad}$) can be easily derived from the stiffness of the two linear springs and their distance from the center of rotation (hinge).

The Maxwell element, as known, consists of a spring $k_{Maxwell}$ and a linear viscous damper $c_{Maxwell}$ in series. The controllable part of this device is represented by the constant $c_{Maxwell}$, while $k_{Maxwell}$ has been simply assumed high enough ($3 \times 10^8 \text{ Nm/rad}$) so as to behave like a rigid link. Two different values of $c_{Maxwell}$ (c_{on} , c_{off}) have been determined so as to reproduce the dissipative capability of MR dampers respectively in the “ON” and “OFF” states. These two opposite configurations of the MR dampers are assumed to be those of the experimental campaign cited above, respectively corresponding to $i=i_{min}=0 \text{ A}$ and $i=i_{max}=1 \text{ A}$. The MR dampers considered to calibrate the Maxwell device properties are those adopted in Caterino et al. [6]. The values of c_{on} , c_{off} have been calibrated as follows: $c_{on}=1 \times 10^{10} \text{ Nms/rad}$ and $c_{off}=2 \times 10^6 \text{ Nms/rad}$.

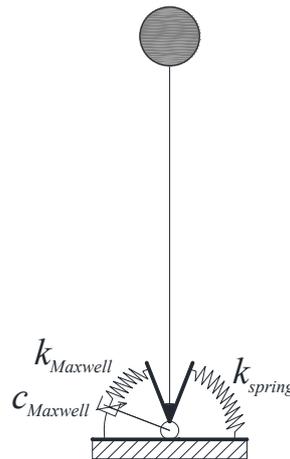


Figure 5. Representation of the base restraint within the FE model of the SA controlled structure.

3.3. Numerical simulations

A limited number of numerical analyses have been performed with reference to the above FEM model in SA configuration. Each of them corresponds to a selected combinations of stress (σ_{lim}) and displacement (x_{lim}) limits. The constrained optimization of the controller has been performed according to the condition aiming to achieve the greatest reduction of the base stress (objective function) and, at the same time, a top displacement (constraint function) no higher than that in uncontrolled FB conditions:

$$\min(\sigma_{max} / \sigma_{max, FB}) \quad \text{subject to} \quad x_{max} / x_{max, FB} \leq 1 \quad (2)$$

Its result is to assume, for σ_{lim} and x_{lim} , values respectively around $0.1\sigma_{max,FB}$ and $0.5x_{max,FB}$, leading to significant reduction of both base stress and top displacement, due to a sharp increase of dissipated energy due to a larger rocking of the base. According to the criterion defined in the condition above, the optimal configuration of the control algorithm corresponds to the case $(\sigma_{lim}, x_{lim}) = (3 \text{ MPa}, 10 \text{ mm})$: it leads to the maximum response reduction (about 48%) in base stress, without increasing the displacement in respect to the FB case. The following figures 6 to 9 show the time history response of the structure in FB configuration, in Passive ON and Passive OFF configurations, and when semi-actively controlled with the above parameters $(\sigma_{lim}, x_{lim}) = (3 \text{ MPa}, 10 \text{ mm})$. The results are also summarized in table 1. The reason behind the performance exhibited by the controller calibrated with $(\sigma_{lim}, x_{lim}) = (3 \text{ MPa}, 10 \text{ mm})$ is the significant number of instants where the rotations of the base are larger, so to determine a higher dissipation of energy.

Table 1. Maximum base stress and top displacement in the analysed configurations.

Setting	Base stress [MPa]	Top displacement [mm]
FB	34.07	35.56
Passive ON	30.66	49.50
Passive OFF	13.00	104.31
Optimal SA	17.89	34.67

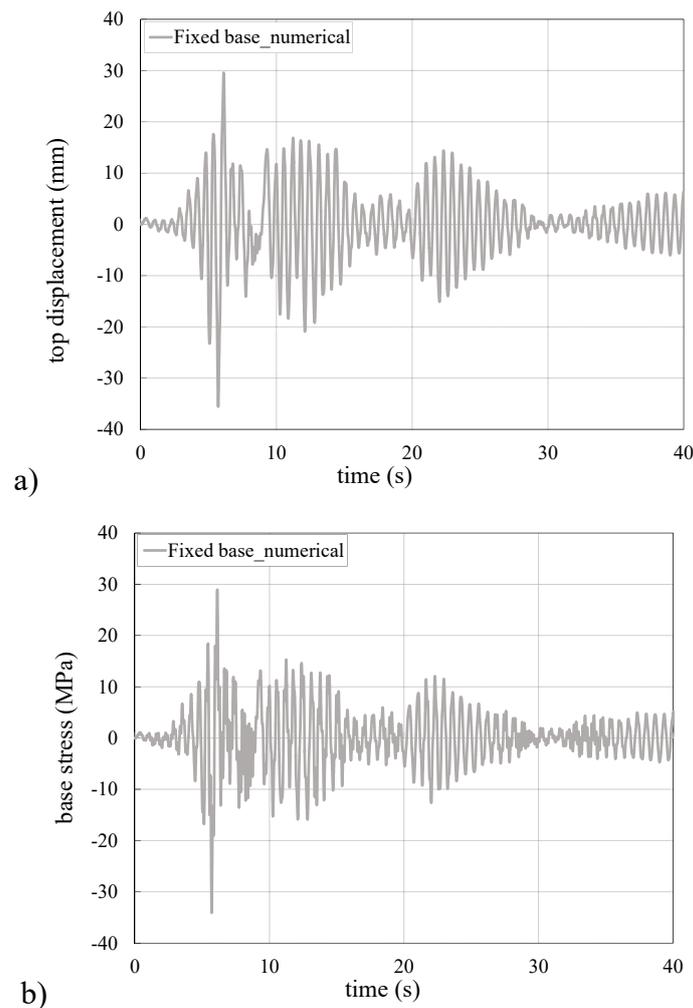


Figure 6. a), b) Fixed base configuration (FB)

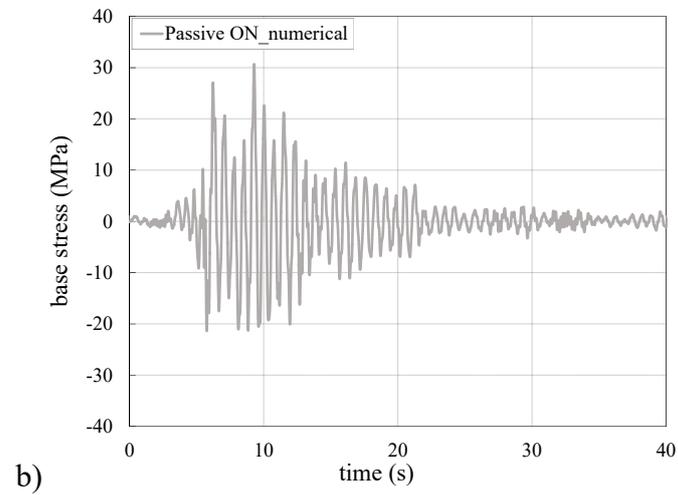
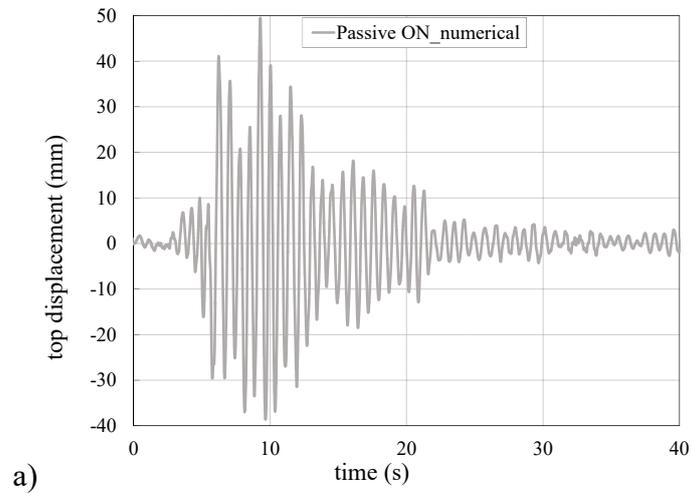
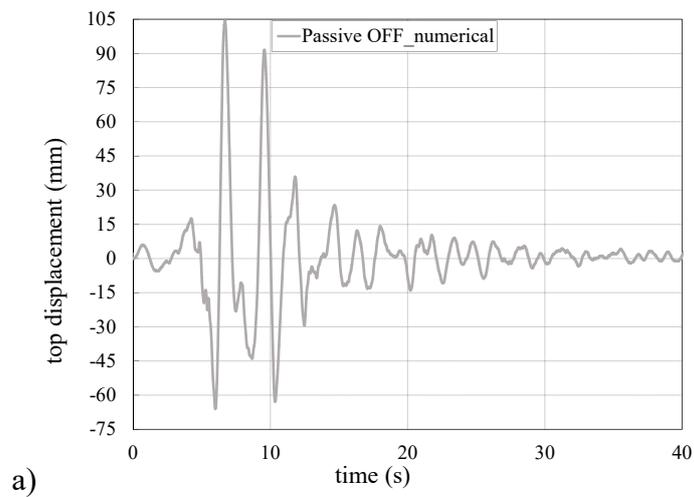
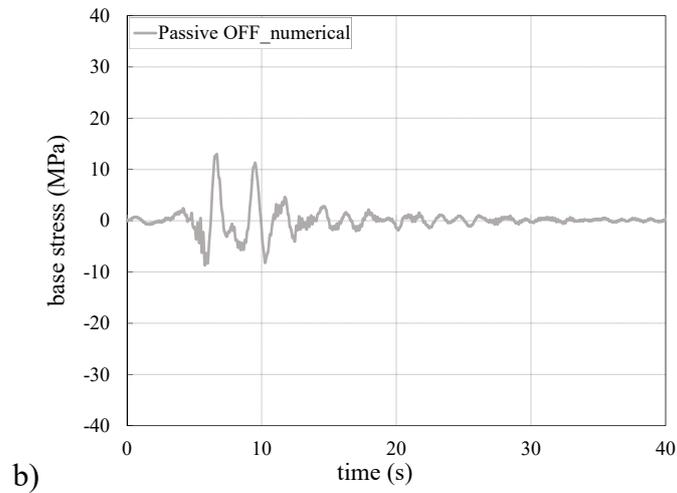


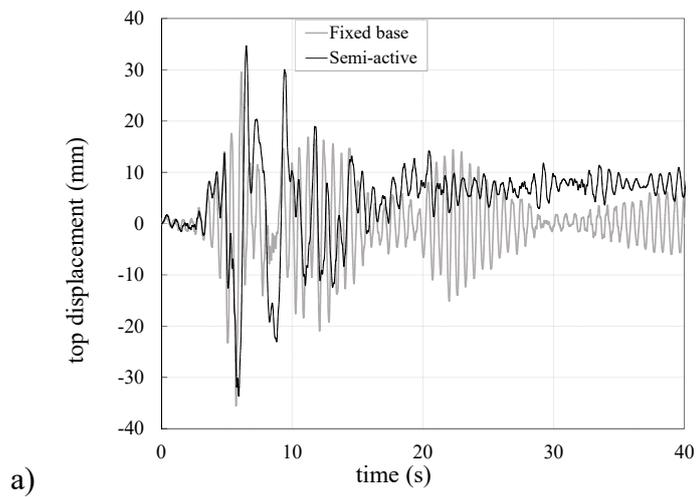
Figure 7. a), b) Passive ON configuration.



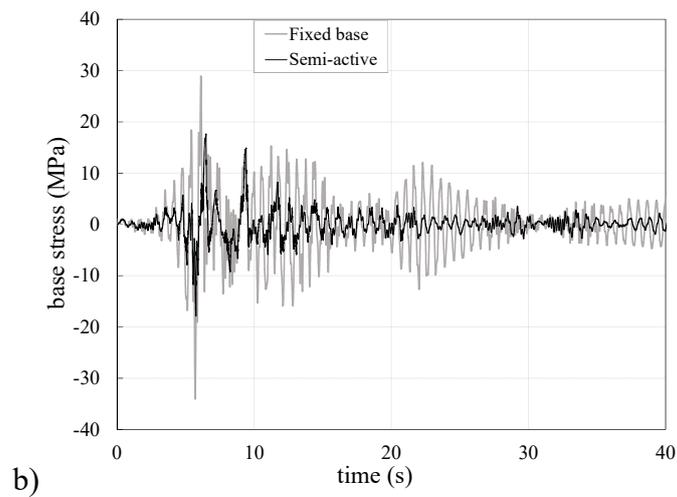


b)

Figure 8. a), b) Passive OFF configuration



a)



b)

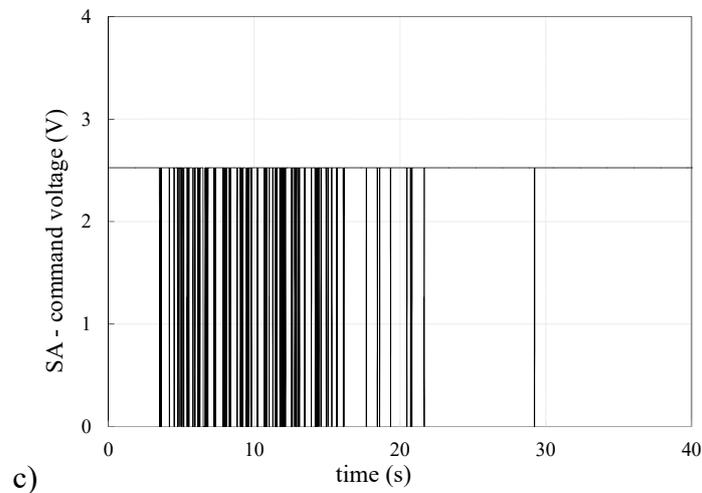


Figure 9. a), b), c) Fixed base versus Optimal SA configuration, and command voltage as given by the algorithm

4. Conclusions

The idea to instantaneously remote control base stiffness and damping of a precast RC column to mitigate structural demand due to strong earthquakes has been discussed herein. The reduction of stiffness at the base restraint itself would imply reduction of base bending moment, but at the cost of a significant, undesired increase of displacement demand at the top of the column. This is no longer true when the change of stiffness is accompanied by a change of damping too. The greater rocking of the base can be not so harmful for displacement demand if it is coupled with a significant dissipation of energy. This is the main concept achieved by the authors and confirmed by the simulations above described. The semi-active control via magnetorheological dampers proposed for precast RC column is based on a 2-parameters control algorithm. The optimal couple of values (σ_{lim} , x_{lim}) for such parameters has been found according to a specific calibration procedure. In particular, these limit values for base stress and top displacement result to be respectively about 10% and 50% of the corresponding peak response values registered in the fixed base conditions. The so calibrated control system allowed high reduction of base stress that results to be roughly halved in respect to the “fixed base” case, without increasing the top displacement response. The issue of recentering the system after the excitation is under study, it will be one of the focuses of the future developments of this work.

Acknowledgment

The research activity has been partially funded by the University of Naples “Parthenope” with a grant within the call “support for individual research for the 2015–17 period” issued by rector decree No. 953-954/2016, partially by the RELUIS research project funded by the Italian department for civil protection. The above supports are gratefully acknowledged.

References

- [1] H. A. Spieth, D. Arnold, M. Davies, J. B. Mander, and A. J. Carr, “Seismic performance of post-tensioned precast concrete beam to column connections with supplementary energy dissipation,” *004 NZSEE Conference*, 2004.
- [2] A. G. Murahidy, H. A. Spieth, A. J. Carr, and J. B. Mander, “Design, construction and dynamic testing of a post-tensioned precast reinforced concrete frame building with rocking beam-column connections and ADAS elements,” *004 NZSEE Conference*, 2004.
- [3] L. Lu, X. Liu, J. Chen, and X. Lu, “Seismic performance of a controlled rocking reinforced concrete frame,” *Advances in Structural Engineering*, Early view (published on line), 2016.

- [4] A. Belleri, M. J. Schoettler, J. I. Restrepo, and R. B. Fleischman, "Dynamic behavior of rocking and hybrid cantilever walls in a precast concrete building," *ACI Structural Journal*, vol. 111(3), pp. 661-672, 2014.
- [5] N. Caterino, "Semi-active control of a wind turbine via magnetorheological dampers," *Journal of Sound and Vibration*, vol. 345, pp. 1-17, doi:10.1016/j.jsv.2015.01.022, 2015.
- [6] N. Caterino, C. T. Georgakis, M. Spizzuoco, and A. Occhiuzzi, "Design and calibration of a semi-active control logic to mitigate structural vibrations in wind turbines," *Smart Structures and Systems*, vol. 18(1), doi: <http://dx.doi.org/10.12989/sss.2016.18.1.000>, 2016.