A hybrid control strategy for the seismic retrofitting of irregular RC buildings

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SUMMARY:
In this paper it is investigated the performance of a hybrid control system for the reduction of the seismic vulnerability of existing reinforced concrete (RC) asymmetric structures with coupled modes. For this kind of structures the purely passive control system is not always able to warrantee an effective response control, due to the modal coupling. To overcome this problem, a hybrid control strategy is proposed which allows the mitigation of the response regardless of the dynamic characteristics of the structure and the seismic input. The control system is made of bidirectional Active Tuned Mass Dampers (ATMD) located in the positions that minimize the structural response. Several multi-storeys structures with different mass eccentricities are considered to demonstrate the effectiveness of the control system. Simulations under natural earthquakes are carried out considering the directionality of the seismic input.

Keywords: Hybrid control, active tuned mass dampers, seismic behaviour, retrofitting, translational and torsional response.

1. INTRODUCTION

It is well known that in earthquake-prone zones good design criteria suggests to build structures that are regular in plan and in elevation. The regularity in plan consists in having a structure that is approximately symmetric along the two principal directions and not too much elongated in order to avoid significant torsional effects which arise when there is an eccentricity between the mass center and the elastic center of the story.

New structures are generally built according to the regularity criteria suggested by Standards and Codes. When the regularity criteria cannot be satisfied, torsionally responsive structures are penalized through the seismic design procedure. Instead, many existing structures were designed and built some decades ago, when seismic protection criteria were not well established and the negative effect of the irregularities in plan and in elevation were not taken into account during the design (De Stefano & Pintucchi, 2008). Therefore, to make safe irregular existing structures, it may be necessary to mitigate the seismic vulnerability adopting a proper retrofit solution.

The retrofitting of existing RC structures it is often carried out increasing the structural strength and varying the stiffness distribution over the building, for example by adding shear walls or other stiffening devices in proper positions. This method can be effective in reducing the seismic response but may modify significantly the structural configuration of existing buildings. In the recent years the base isolation technique began to be applied as a retrofitting solution. It can be effective in limiting the seismic accelerations applied to the superstructure but it cannot be used for every type of existing building and requires proper design of the structural details. A promising retrofitting method may be the addition of viscoelastic bracings or other types of dampers. This solution may work quite well but may require a difficult detailing of the connections, especially for RC buildings.

Hybrid control systems, such as Active Tuned Mass Dampers (ATMDs), may further improve the control system effectiveness. They need a lower actuation power with respect to the purely active systems and have the capability of working as passive systems when power supply is missing. One of the advantages of the hybrid approach is that, unlike the purely passive system (Lin et al., 1999; Singh et al., 2002), it is robust with regards to the uncertainties on the dynamic characteristics of the structure and with regards to the characteristics of the seismic input (Samali & Al-Dawod, 2003). ATMDs may be designed to control both the translational and the torsional response and therefore may be effective for the retrofit of torsionally sensitive structures. Moreover, they can be easily installed on the top of the building and do not require modification of the structural system and difficult detailing of the connections.

In this paper it is exploited the possibility of using an hybrid control system for the reduction of the seismic response of existing RC asymmetric structures. The control system is made of bidirectional ATMDs, properly designed in order to minimize the structural response. Several multi-storeys buildings with different mass eccentricity are considered to demonstrate the effectiveness of the control system. Simulations under natural earthquakes are carried out considering the directionality of the seismic input and different seismic excitations.

2. THE HYBRID CONTROL SYSTEM

2.1. The dynamics of the control system

The hybrid control system considered in this paper is made of Active Tuned Mass Dampers which are control devices consisting of mechanical components such as masses, springs, viscous dampers and actuators. The ATMDs are considered located at the top floor of the structure and each one may move along both the principal directions *x* and *y*.

To obtain the dynamic response, a generic structure is schematized as a simplified system having 3 DOFs for each floor. The total number of DOFs, including those of the ATMD, is $3n + m$ where n is the storeys number and m is the total number of degrees of freedom of the control system.

The equations of motion of a multiple degrees of freedom (MDOF) linear system can be written as:

$$\mathbf{M}\ddot{\mathbf{q}}(t)+\mathbf{C}\dot{\mathbf{q}}(t)+\mathbf{K}\mathbf{q}(t)=\mathbf{P}(t)+\mathbf{B}_0(t) \tag{2.1}$$

where $\mathbf{q}(t)$ is the vector of generalized displacements of the system, having dimension $3n + m$, $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the mass, damping and stiffness matrices of the system, respectively, $\mathbf{P}(t)$ is the vector of the external loading that in the case of seismic excitation is $\mathbf{P}(t)=-\mathbf{M}\{\mathbf{1}\}\cdot\ddot{\mathbf{q}}(t)$, $\mathbf{u}(t)$ is the vector of the control forces, $\mathbf{B_0}$ is a convenient collocation matrix and dots denote time derivative.

The state space formulation of the equation of motion of the actively controlled system may be derived from Eqn. 2.1 as follows:

$$\dot{\mathbf{z}}=\mathbf{A}\mathbf{z}+\mathbf{B}\mathbf{u}+\mathbf{H}\mathbf{f} \tag{2.2}$$

where $\mathbf{z}=\{\mathbf{q}\ \dot{\mathbf{q}}\}^T$ is the state vector, $\mathbf{A}$ is the system matrix, $\mathbf{B}$ and $\mathbf{H}$ are the location matrices for the vectors $\mathbf{u}(t)$ and $\mathbf{P}(t)$, respectively.

Owing to the common availability of accelerometers as monitoring sensors, tracking of the state by means of a state observer using only acceleration measurements is here considered. The output, $\mathbf{y}$, thus results in a linear combination of generalized nodal accelerations, $\mathbf{y}=\mathbf{C_a}\ddot{\mathbf{q}}$, where $\mathbf{C_a}$ is a convenient matrix that selects the monitored DOFs.

The output can be rewritten in terms of state vector and control forces:

$$\mathbf{y} = \mathbf{Cz} + \mathbf{Du} + \mathbf{Hf} + \mathbf{v} \tag{2.3}$$

where v is the vector of measurement noise and:

$$\begin{aligned} \mathbf{C} &= -\mathbf{C_a}\left[\mathbf{M_s}^{\text{-}\mathbf{1}}\mathbf{K_s} \quad \mathbf{M_s}^{\text{-}\mathbf{1}}\mathbf{C_s}\right] \\ \mathbf{D} &= \mathbf{C_a}\mathbf{M_s}^{\text{-}\mathbf{1}}\mathbf{B_0} \end{aligned} \tag{2.4}$$

The linear optimal control algorithm is used for the problem at hand. The linear quadratic performance index can be written as:

$$J = \int_0^t \left(\mathbf{z^T Q z} + \mathbf{u^T R u}\right) \tag{2.5}$$

where **Q** and **R** are the weighting matrices of the state vector and the control forces vector respectively. By application of the classic LQR algorithm the optimal gain matrix **K**, which allows minimizing the performance index J in Eqn. 2.5, is computed and the feedback is calculated as $\mathbf{u} = -\mathbf{Kz}$.

2.2. The design of the control system

The design of the hybrid control system, for any given structure, consists of 2 phases:
- choice of the parameters of the passive devices such as mass, stiffness and damping;
- calibration of the parameters of the active control system.

In the first step of the design process, many possible ATMDs' configurations made of 3 ATMDs are considered. The choice of 3 ATMD is due to the necessity of controlling separately the translational and torsional responses since in the case of irregular structures the torsional response is usually significant and the use of a single ATMD may not lead to the desired mitigation of the response. In the selected configuration, one ATMD is expected to control the first two translational modal responses along the *x* and *y* directions while the other two ATMDs are expected to control the torsional response.

The total mass of the ATMDs, M_{ATMDs}, is set equal to a conveniently small percentage of the first modal mass of the building M_S, e.g. $\mu = M_{ATMDs}/M_S$ where μ is the total mass ratio of the ATMDs. The total mass ratio μ is distributed as follows: a mass ratio μ_c is assigned to the central mass and the remaining mass ratio $\mu_l = \mu - \mu_c$ is assigned to the lateral masses.

The calibration of the optimal parameters of the tuned mass dampers may be carried out using an analytical solution proposed in the literature. According to Warburton (Warburton, 1982), the stiffness of the tuned mass dampers is computed as follows:

$$k_{ATMD,i} = m_{ATMD,i}\alpha_{opt,i}^2\omega_{S,k}^2 \tag{2.6}$$

where $\alpha_{opt,i} = \sqrt{(1+\mu_i/2)}/1+\mu_i$ is the optimal tuning ratio, $\mu_i = \mu_c$ or $\mu_i = \mu_l$ is the mass ratio of the i-*th* tuned mass damper. The stiffness of the central tuned mass damper is computed using the first two flexural circular frequencies $\omega_{S,k} = \omega_{S,1}$ or $\omega_{S,k} = \omega_{S,2}$ and the stiffness of the eccentric tuned mass dampers are computed using the first torsional circular frequency $\omega_{S,k} = \omega_{S,3}$. The damping coefficient of the *i-th* ATMD is computed using the following expression:

$$c_{ATMDi} = 2m_{ATMDi}\gamma_{opt,i}\alpha_{opt,i}\omega_{S,k} \tag{2.7}$$

where $\gamma_{opt,i} = \sqrt{\mu_i(1+3\mu_i/4)/(1+\mu_i)(1+\mu_i/2)}$ is the optimal damping ratio. In Eqn. 2.7, the circular frequencies of the flexural modes $\omega_{S,k} = \omega_{S,1}$ or $\omega_{S,k} = \omega_{S,2}$ are used for the central TMD while the circular frequency of the torsional mode $\omega_{S,k} = \omega_{S,3}$ is used for the eccentric TMDs.

Once the optimal parameters of the passive devices are set, the calibration of the weight matrices **R** and **Q** applied to the control forces and the state vector in the LQR performance index, Eqn. 2.5, is carried out (Venanzi et al., 2011; Venanzi & Materazzi, 2012). The matrices R and Q are defined as follows:

$$\mathbf{R} = 10^{-\varphi_1}\cdot\mathbf{I}_1 \qquad \mathbf{Q} = \mathbf{\Phi}\cdot\mathbf{I}_2 \qquad \mathbf{\Phi} = diag\left[1,...,1,\varphi_2,...,\varphi_4\right] \tag{2.8}$$

where $\mathbf{I_1}$ (m x m) and $\mathbf{I_2}$ ($6n$ + $2m$ x $6n$ x $2m$) are identity matrices, $\mathbf{\Phi}$ is a matrix which stores at the proper positions the coefficients of the state vector. In particular the coefficients are: φ_1 exponent of the coefficient that multiplies matrix **R**; φ_2: weighting coefficient of the structural rotations in matrix **Q**; φ_3: weighting coefficients of the ATMDs' displacements in matrix **Q**; φ_4: weighting coefficients of the ATMDs' velocities in matrix **Q**. The calibration of the coefficients may be carried out both with an optimization procedure and with parametric analyses.

3. NUMERICAL ANALYSES

3.1. Description of the case studies

To study the performance of the hybrid control system, an irregular RC building is considered. The cross-sectional shape of the structure is represented in Fig. 3.1. Although in the literature the coupled lateral-torsional response of irregular building is usually studied with reference to rectangular structures with non coincident mass and elastic centers, in this study a L-shaped building is considered. This allows to take into account, in addition to the coupling between the modes, the problem of the best positioning of the actuators, that in structures with recesses and protrusions is not always straightforward.

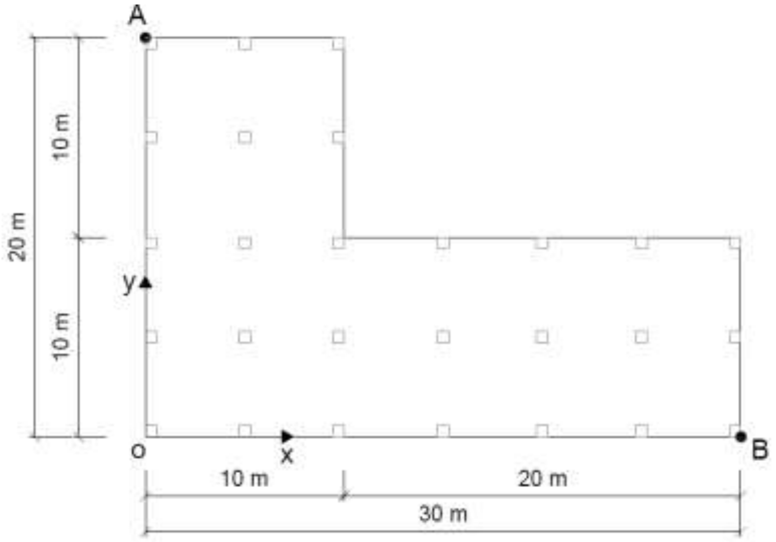

Figure 3.1. Schematic representation of the generic plan of the irregular building.

The supporting structure is made of RC beams and columns. The column size is 0.5 x 0.5 m and they are equally spaced along the two principal directions every 5 meters. The stiffness centres at each floor have coordinates (X_{CK}; Y_{CK}) = (12.77 m; 7.77 m).

In order to evaluate the influence of the mass eccentricity on the performance of the controlled system the mass and stiffness distributions are varied and the structures summarized in Table 3.1 are considered. Structure no.1 is the one in which the mass is considered uniformly distributed over the floors and the position of the elastic center corresponds to the uniform distribution of columns along both the directions *x* and *y*. In Structure no.2 the eccentricity of 3.50 m to the mass center is assigned at 45° with respect to the principal axes. In Structures no.3 and no. 4 the eccentricity of 3.50 m to the mass center is assigned along the *x* axis and *y* axis respectively.

Table 3.1. Coordinates of the elastic and mass centers for the analysed structures

	Description	Coordinates C_K (m)	Coordinates C_M (m)
Structure no.1	Small mass center eccentricity (0.38 m)	12.77 – 7.77	12.50 – 7.50
Structure no.2	Mass center eccentricity at 45° (3.50 m)	12.77 – 7.77	10.00 – 5.00
Structure no.3	Mass center eccentricity along x (3.50 m)	12.77 – 7.77	9.00 – 7.50
Structure no.4	Mass center eccentricity along y (3.50 m)	12.77 – 7.77	12.50 – 4.00

The modal characteristics of the structures are reported in Table 3.2. The modal damping ratio is the 5% of the critical for every mode.

Table 3.2. Modal characteristics of the analysed structures

	Mode	Structure no.1	Structure no.2	Structure no.3	Structure no.4
Natural Period (s)	1	0.584	0.636	0.645	0.637
	2	0.564	0.574	0.564	0.583
	3	0.497	0.473	0.476	0.465
Modal mass (t)	1	1.033e3	2.359e3	1.408e3	1.535e3
	2	1.038e3	1.954e3	1.038e3	1.038e3
	3	1.081e5	5.585e3	3.848e3	3.294e3
Participating mass ratio - Dir. x (%)	1	0.0	23.5	0.0	56.1
	2	82.0	43.9	82.7	0.6
	3	0.0	15.3	0.0	25.9
Participating mass ratio - Dir. y (%)	1	82.6	36.3	60.7	0.5
	2	0.0	37.5	0.0	81.7
	3	0.0	8.5	21.7	0.0
Participating mass ratio - Rotation z (%)	1	44.7	4.7	1.3	4.1
	2	15.9	6.3	19.4	45.1
	3	21.6	71.2	61.4	32.9

A simplified dynamic system with 3 DOFs for each floor is used for the analyses. The coupling between the modes is considered for each structure trough the non-zero off-diagonal terms of the stiffness matrix **K**. The mass matrix **M** is diagonal and collects the translational masses and the rotational moments of inertia of the floors. The simplified dynamic system is considered centered in correspondence of the mass centers of the floors, therefore both the stiffness and mass matrices are computed with respect to the mass centers.

To obtain the coupled stiffness matrices of the structures the following steps are carried out:
1. for each structure a finite element model with the desired mass and stiffness distribution, i.e. mass eccentricity, is built;
2. the flexibility matrix **F** is computed from the finite element model trough static analysis (the terms of the flexibility matrix F_{ij} are the displacements in the *x* or *y* direction and the torsional rotations at the center of mass of the *i*-th floor due to a unit horizontal force in the *x* or *y* direction or unit torsional moment at the center of mass of the *j*-th floor);
3. the flexibility matrix of each structure is inverted to obtain the stiffness matrix **K**.

3.2. The control system

The design of the control system is made following the steps summarized in Section 2.2.

The preliminary choice of the best number and position of the ATMDs can be carried out through an optimization procedure or a trial and error procedure. The last type of procedure was adopted in this work. The chosen control system is made of 3 bidirectional ATMDs located over the top floor at coordinates (referred to the elastic center):

- ATMD 1: x = -7.5 m; y = 5.0 m ;
- ATMD 2: x = 0.0 m; y = 0.0 m;
- ATMD 3: x = 7.5 m; y = -5.0 m.

The choice of a configuration with 3 ATMD, in which the control system is symmetric with respect to the elastic center of the top floor C_K, proved to be the most effective in controlling the 3D response of the selected irregular building. The ATMD no. 2, the one located in correspondence of the elastic center of the structure, is expected to mitigate the first two translational modal responses along the *x* and *y* directions while the external ATMDs, no. 1 and 3, are expected to control mainly the torsional response.

The total mass ratio is $\mu = 5\%$, the mass ratio of the ATMD no.2 is $\mu_c = 4\%$ and the total mass ratio of the lateral masses no. 1 and 3 is $\mu_l = 1\%$. The tuning parameters, obtained as specified in Section 2.2, are shown in Table 3.3.

Table 3.3. Tuning parameters of the passive TMDs

	TMD no.	Structure no.1	Structure no.2	Structure no.3	Structure no.4
Mass (t)	1-3	5.19	9.77	5.19	5.18
	2	41.32	94.36	41.52	61.40
Stiffness x (KN/m)	1-3	0.83e3	2.15e3	1.13e3	1.15e3
	2	4.83e3	1.06e4	4.85e3	4.54e3
Stiffness y (KN/m)	1-3	0.83e3	2.15e3	1.13e3	1.15e3
	2	4.51e3	8.69e3	3.72e3	3.80e3
Damping x (KN s/m)	1-3	4.06	7.51	4.06	3.93
	2	88.04	197.60	88.49	85.58
Damping y (KN s/m)	1-3	4.06	7.51	4.06	3.93
	2	85.08	178.48	77.46	78.31

The coefficients of the weight matrices **R** and **Q** of the control forces and the state vector of the LQR performance index are chosen through a parametric analysis, in order to respect the limitations on the maximum ATMDs' strokes (s_{max} = 1.0 m) and the maximum control forces (F_{max} = 1000 KN).

3.3. Analyses and results

The horizontal acceleration records of the Friuli (1976, Italy), El Centro (1940, USA) and Kokaeli (1999, Turkey) earthquakes are used for the analyses in order to verify the efficiency of the control system.

In Fig. 3.2 are shown the time histories of the base accelerations used for the analyses. In order to allow a comparison, the selected accelerograms have similar peak ground accelerations (PGAs). In particular, the El Centro time history has a PGA of 0.318 g, the Friuli accelerogram has a PGA of 0.314 g and the Kokaeli accelerogram has a PGA of 0.349 g.

In Table 3.4 are summarized the maximum displacements obtained using the Friuli accelerogram applied at 45° with respect to the reference axes. The displacements are the combination of the displacements along the *x* and *y* axes at points A and B (Fig. 3.1) at the 5th story.

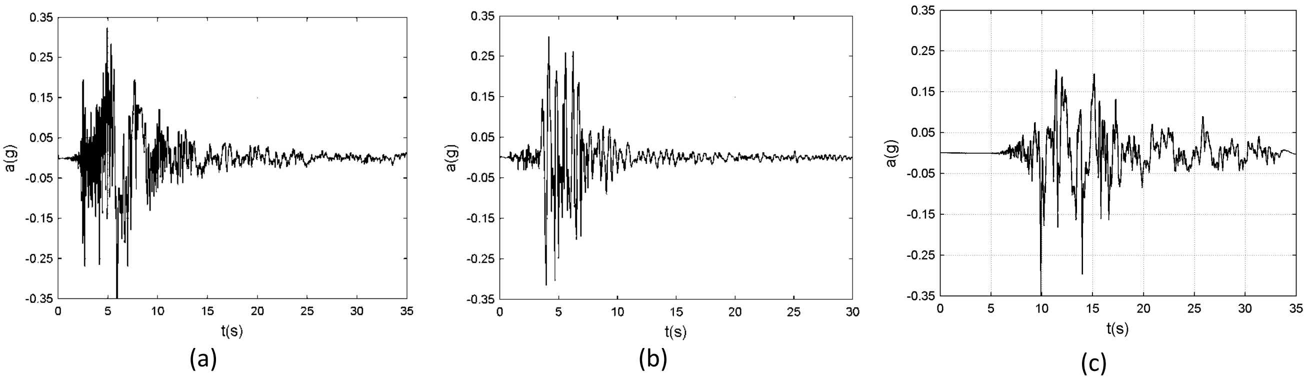

Figure 3.2. Accelerograms used for the analyses: Friuli (a); El Centro (b); Kokaeli (c).

Table 3.4. Maximum displacements (in cm) at points A and B obtained for the Friuli earthquake applied at 45° with respect to the reference axes.

	Structure no.1	Structure no.2	Structure no.3	Structure no.4
Uncontrolled point A	7.87	8.85	13.15	8.30
Uncontrolled point B	9.96	11.22	8.02	15.31
Passively controlled point A	6.13	6.65	9.56	6.43
Passively controlled point B	6.56	7.57	6.44	10.50
Hybridly controlled point A	1.83	3.53	4.83	2.85
Hybridly controlled point B	1.89	3.92	3.17	5.98

It can be observed that in all the cases the hybrid control is very effective in reducing the structural response. The reduction strongly depends on the point considered to compute the displacements and on the magnitude and direction of the mass eccentricity.

In Fig. 3.3 are represented the time histories of the absolute displacements of the elastic center C_K at the top floor of the Structure no.1 obtained with the Friuli seismic ground acceleration applied to the structure at 45° with respect to the reference axes and the time history of the interstory drift time history at the point A between the 2nd and the 3rd story. In particular, in Fig. 3.3a-3.3c are shown the displacements in direction *x*, *y* and the rotations and in Fig. 3.3d the interstory drift for the uncontrolled structure, the purely passively controlled structure and the hybridly controlled structure.

The plots in Fig. 3.3 show the efficiency of the controlled system in reducing the structural response. In may also be observed the important contribution of the active control in mitigating the structural response, especially the rotations, with respect to the purely passive control.

The effect of the directionality of the seismic excitation on the performance of the control system is also considered. With this goal, parametric analyses are carried out varying the direction of application of the seismic input.

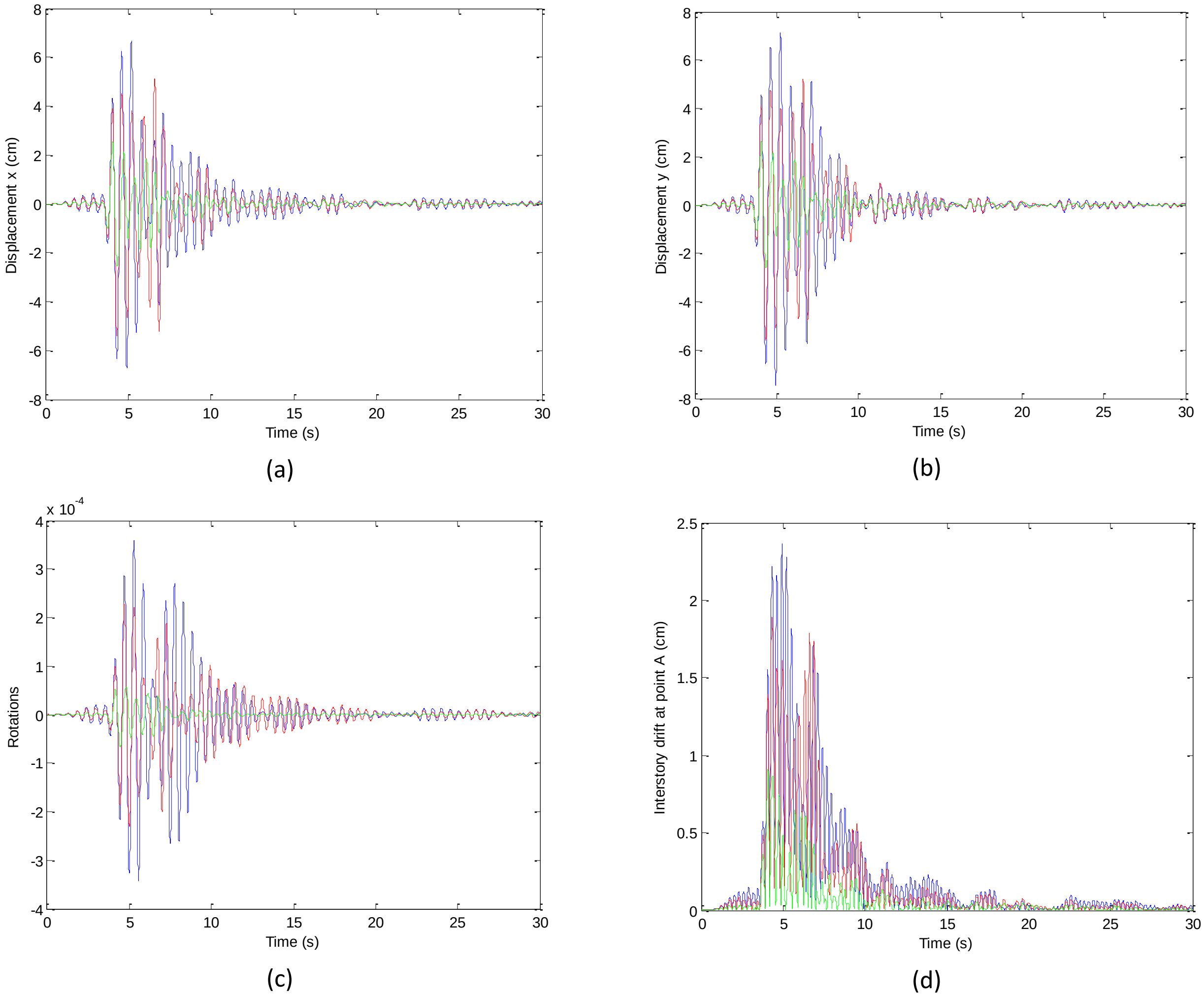

Figure 3.3. Time history of the displacements of the elastic center at the top of the structure no.1 along *x* (a), *y* (b) and rotations (c) and time history of the interstory drift of point A at the top of the building obtained for the uncontrolled, passively controlled and hybridly controlled systems.

Results are presented in terms of relative differences between the maximum interstory drifts obtained for the controlled and uncontrolled structure with reference to the points A and B shown in Fig. 3.1. In particular, the following indices are defined:

$$J_{int,pass}\Big|_A = \frac{\max \delta_{unc,A} - \max \delta_{pass,A}}{\max \delta_{unc,A}} \; ; \; J_{int,hyb}\Big|_A = \frac{\max \delta_{unc,A} - \max \delta_{hyb,A}}{\max \delta_{unc,A}} \qquad (3.1\text{-}3.2)$$

$$J_{int,pass}\Big|_A = \frac{\max \delta_{unc,A} - \max \delta_{pass,A}}{\max \delta_{unc,A}} \; ; \; J_{int,hyb}\Big|_A = \frac{\max \delta_{unc,A} - \max \delta_{hyb,A}}{\max \delta_{unc,A}} \qquad (3.3\text{-}3.4)$$

where $\max \delta_{unc,A}$, $\max \delta_{pass,A}$, $\max \delta_{hyb,A}$, $\max \delta_{unc,B}$, $\max \delta_{pass,B}$, $\max \delta_{hyb,B}$ are the interstory drifts of the points A and B between the 4th and 5th story obtained for the uncontrolled structure, the passively controlled structure and the hybridly controlled structure. All the indices are expressed as percentage values.

In Tables 3.5-3.7 are presented the results in terms of the indices defined in Eqns. 3.1-3.4 obtained using the Friuli earthquake applied in direction *x*, at 45° from the reference axes and in direction *y*. The indices on the hybrid response are obtained considering φ_1=7.5 (Eqn. 2.8).

Table 3.5. Performance indices for the Friuli earthquake applied in direction *x*

	Structure no.1	Structure no.2	Structure no.3	Structure no.4
$J_{int,pass}\|_A$	21	45	18	28
$J_{int,pass}\|_B$	19	35	36	39
$J_{int,hyb}\|_A$	62	68	60	70
$J_{int,hyb}\|_B$	61	66	66	69

Table 3.6. Performance indices for the Friuli earthquake applied at 45° from the *x* axis

	Structure no.1	Structure no.2	Structure no.3	Structure no.4
$J_{int,pass}\|_A$	20	25	27	23
$J_{int,pass}\|_B$	24	33	36	33
$J_{int,hyb}\|_A$	61	60	64	64
$J_{int,hyb}\|_B$	64	65	66	62

Table 3.7. Performance indices for the Friuli earthquake applied in direction *y*

	Structure no.1	Structure no.2	Structure no.3	Structure no.4
$J_{int,pass}\|_A$	22	36	38	25
$J_{int,pass}\|_B$	28	36	36	27
$J_{int,hyb}\|_A$	62	68	72	66
$J_{int,hyb}\|_B$	66	66	66	60

The results of Tables 3.5-3.7 show that the response reduction obtained by the purely passive system strongly depend on the magnitude and the direction of the mass eccentricity while the response reduction obtained by the hybrid system is almost similar for all the analyzed structures. For the structure with small mass eccentricity (Structure no.1) the influence of the earthquake direction on the response reduction of the passively controlled system is limited while for the structures with high mass eccentricity the influence of the earthquake direction on the response reduction is significant. Its influence on the response reduction of the hybridly controlled system is negligible.

In order to study the effect of the type of seismic excitation on the effectiveness of the control system, the analyses are repeated using the Friuli, the El Centro and the Kokaeli accelerograms. The comparison between the results in terms of performance indices are summarized in Table 3.8. To allow a proper comparison, results are obtained using, for each analysis, the exponent φ_1 of the terms of the matrix **R** that allows the achievement of the imposed limit on the control force. In Table 3.8 are also shown the maximum strokes and the maximum control forces obtained in the three cases.

The different response reductions obtained with the different accelerograms can be ascribed to the mistuning of the passive control system due to the different seismic excitations. Moreover the different response reductions obtained by the hybridly controlled system can be ascribed mainly to the different choice of the parameters of the LQR algorithm corresponding to the imposition of the limits on the strokes and the control forces.

Table 3.8. Performance indices for Structure no.2 and for different earthquakes applied in direction 45°

	$J_{int,pass}\|_A$	$J_{int,pass}\|_B$	$J_{int,hyb}\|_A$	$J_{int,hyb}\|_B$	Max stroke (m)	Max control force (KN)
Friuli	25	33	73	77	0.45	972
El Centro	26	30	70	71	0.39	980
Kokaeli	15	32	50	52	0.32	986

3. CONCLUSIONS

In this paper the performance of an hybrid control system for the seismic retrofit of irregular reinforced concrete buildings is investigated. The control system is made of Active Tuned Mass Dampers (ATMDs) that may limit the translational and torsional responses. For an irregular structure with coupled modes, the purely passive control system, although properly tuned to mitigate the most significant modal responses, is not always able to warrantee the 3D response control.

To show the effectiveness of the control system, an irregular L-shaped structure equipped with a properly designed hybrid control system is chosen as a case study. Several mass eccentricities with different magnitude and direction are considered for the analyses.

The main results of the parametric analyses carried out varying the direction of the earthquake and the type of seismic excitation are the following:
1) for irregular structures the hybrid control is much more effective in reducing the structural response than the purely passive control;
2) the effectiveness of the control system in reducing the structural rotations is significant;
3) the response reduction obtained by the purely passive system strongly depend on the magnitude and direction of the mass eccentricity while the response reduction obtained by the hybrid system is almost similar for all the analyzed structures;
4) for the structure with small mass eccentricity the influence of the earthquake direction on the response reduction of both the passively controlled and hybridly controlled system is limited;
5) for the structures with high mass eccentricity the influence of the earthquake direction on the response reduction of the passively controlled system is significant while its influence on the response reduction of the hybridly controlled system is negligible;
6) the different response reductions obtained with the different earthquakes can be ascribed to the mistuning of the passive control system due to the different spectral content of the seismic excitation and to the shape of the accelerograms; moreover the different response reductions obtained with the different seismic excitations by the hybridly controlled system can be ascribed mainly to the different choice of the parameters of the LQR algorithm corresponding to the imposition of the limits on the strokes and the control forces.
Therefore, from the results it can be deduced that a properly designed control system made of ATMDs is suitable for the retrofitting of irregular buildings under earthquake excitation.

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