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Seismic response of active or semi active control for irregular buildings based on eigenvalues modification

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Abstract. A reduction of the response of irregular structures subjected to earthquake excitation by control devices equipped by suitable control algorithm is proposed in this paper. The control algorithm, which is used, is the pole placement one. A requirement of successful application of pole placement algorithm is a definition-selection of suitable poles (eigen-values) of controlled irregular structures. Based on these poles, the required action is calculated and applied to the irregular structure by means of control devices. The selection of poles of controlled irregular structure, is a critical issue for the success of the algorithm. The calculation of suitable poles of controlled irregular structure is proposed herein by the following procedure: a fictitious symmetrical structure is considered from the irregular structure, adding vertical elements, such as columns or shear walls, at any location where is necessary. Then, the eigen-values of symmetrical structure are calculated, and are forced to be the poles of irregular controlled structure. Based on these poles and additional damping, the new poles of the controlled irregular structure are calculated. By pole placement algorithm, the feedback matrix is obtained. Using this feedback matrix, control forces are calculated at any time during the earthquake, and are applied to the irregular structure by the control devices. This procedure results in making the controlled irregular structure to behave like a symmetrical one. This control strategy can be applied to one storey or to multi-storey irregular buildings. Furthermore, the numerical results were shown that with small amount of control force, a sufficient reduction of the response of irregular buildings is achieved.

Keywords: structural control, pole placement, irregular structures, earthquake engineering

1. Introduction

The last thirty years remarkable progress has been made in the field of control of civil engineering structures subjected to environmental loadings which among others are winds and earthquakes, (Soong 1990, Kobori *et al*. 1991, 2003, Housner *et al*. 1997). Research and implementation in practice have shown that seismic control of structures has a lot of potential but also many limitations. Most of studies assumed that the controlled structure is a planar structure.

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However, it is generally recognized that a real building is actually asymmetric in plan. Because of this asymmetry, it will undergo concurrently lateral as well as torsion vibrations. Both steel andconcrete irregular structures should be analyzedby accountingthe substantial differences in ductility demands between the two sides of building (Stathopoulos and Anagnostopoulos 2004, Kyrkos and Anagnostopoulos 2011).

To compensate the torsional effect, one approach is to retrofit and strengthen the building. Creating a new vertical structural elements, shear walls, in a suitable position in order to cancel the irregularities that exists and satisfy also the design criteria of the current codes. This is a traditional approach and is followed when no architectural or functional limitations are exists on the building.

A second approach to faced irregularities is to use passive control devices. Such devices can be base isolators as it is shown in the works of (Colunga and Soberon 2002-2007, Gavin and Alhan 2002).

Passive control devices such as dampers can also be used in suitable locations on the building in order to cancel again the irregularities. The works of (Lavan and Levy 2006, 2009, 2010;Goel, 1998,2000; Lin and Chopra 2001) are representative. Other important work on the optimal placement control for asymmetric structures using passive energy dampers have been done by (Aguirre *et al*. 2013, Almaz´an and Llera 2009, Kim and Bang 2002, Singh and Moreschi 2002, Wu *et al*. 1997). Experimental results using frictional dampers for reduction in torsion of asymmetric structure has been presented by Vial *et al*. (2006). An algorithm for optimal damper placement using steepest direction search was proposed by Takewaki (1999).

Tuned mass dampers can also be used to reduce the response of irregular structures. In the work of Desu *et al*. (2006), an arrangement of tuned mass dampers, termed coupled tuned mass dampers (CTMDs) where a mass is connected by translational springs and viscous dampers in an eccentric manner have been utilized to control coupled lateral and torsional vibrations of asymmetric buildings. Li and Qu (2006), estimated optimum properties of multiple tuned mass dampers for reduction of translational and torsional response of structures subjected to ground acceleration. A multiple tuned mass dampers (MTMD) can also be applied on the vibration control of irregular buildings considering soil-structure interaction, Li *et al*. (2010). A recent work where multiple tuned mass dampers are used for seismic design of irregular structure is presented by Lavan and Daniel (2013).In the work of Fu (2011), a torsional tuned liquid column gas damper (TTLCGD) was investigated in order to reduce the coupled flexural torsional response of plan-asymmetric buildings under wind or seismic loads. Li *et al*. (2010) proposed an optimum design methodology for asymmetric structures equipped by active tuned mass damper. Soil–structure interaction effects of active controlled irregular buildings are investigated in the work of Lin *et al*. (2010).

Other structural control techniques for the rehabilitation of historical structures due to their peculiar character following a probabilistic approach and using of fragility curves is demonstrated in the work of (Syrmakesis 2006, Wong and Harris 2013).

Seismic response of torsionally coupled structures with active control device is investigated in the work of (Kobori *et al*. 1991, Date and Jangid 2001). A semi active control system, using magnetorheological dampers (MR dampers), can also be applied in order to reduce the coupled lateral and torsional motions in asymmetric buildings subjected to horizontal seismic excitations, Yoshida *et al*. (2003). Hybrid control system consisting of a passive supplementary damping system and a semi-active tuned liquid column damper (TLCD) system used to control irregular building under various seismic excitations have been proposed by Kim and Adeli (2005).

When a semi active or hybrid control system is applied to a structure, then a control algorithm that used to direct the semi active devices is needed. In research studies and practical applications, various control algorithms have been investigated in designing controllers, such as pole placement control, linear quadratic or Gausian regulator LQR, LQG, H_∞ or H_2 control, sliding mode control, control strategies based on neural network are employed for the nominal controller design. The most suitable algorithms for structural application and the practical considerations that should be taken into account are described by Soong (1990). More innovative algorithm using fuzzy logic approach is used in the work of Battaini *et al*. (1998). An evolutionary control of damaged systems using a rehabilitative, modified LQR algorithm has been proposed by Attard and Dansby (2008). A model based predictive control strategy is presented in the work of Blachowski (2007).

One of the most suitable algorithms for controlling the structure is the pole placement algorithm. Pole placement algorithm has been studied extensively in the general control literature,(Sage and White 1997, Kwakernaak and Sivan 1972 Brogan 974, Ogata 1997, Kautsky and Nichols 1985). The application of the algorithm in structural control can be found in the work of (Martin and Soong 1976, Rohman and Leipholz 1978, Wang *et al*. 1983, Meirovotch 1990, Soong 1990, Utku 1998, and Preumont 2002). Pole placement algorithm where used as control algorithm for mitigating the response of structures subjected to earthquake actions, (Pnevmatikos and Gantes 2010). They calculated the poles of controlled structure, on-line based on the essential frequencies of seismic excitation.

In case of the performance limit state is life safe or collapse prevention where the structural elements will exhibits inelastic behavior, non linear approach is required. Relative work can be found in the research of (Roberts *et al*. 2002, Barroso and Smith 1999).

In this study, the pole placement or pole assignment control algorithm is used in order to control irregular buildings. The way that the eigenvalues (poles) of controlled irregular structures are calculated is as follows: Firstly, a fictitious symmetrical building which satisfies all the requirements for regular building mentioned in Eurocode 8, is created. This building can be obtained from the irregular building cancelling all irregularities. The eigenvalues (poles) of this fictitious symmetrical building are then figured. The eigenvalues (poles) of the controlled irregular building are forced to be equal with the eigenvalues (poles) of the symmetrical building. Next, the feedback matrix is calculated by pole placement algorithm and the equivalent control force is obtained. This control force is applied to irregular building during the excitation by means of control devices like semi-active devices (MR damper) which are installed to the structure. Consequently, this procedure indicated that the total controlled structure (irregular building with the devices) behaves like the fictitious symmetrical building.

The proposed control algorithm can be applied either for linear or for nonlinear behavior of structural elements. Given that expensive control devices are installed to structure, the target of the limit design state should be making the structure perform in linear range. Otherwise, the cost of repairs makes all the control strategy inefficient from financial point of view if somebody is to pay for both the installation of the control devices and for structural damage repairs. Taking this statement into consideration a linear behavior for structural elements was adopted.

2. Theoretıcal background

The equation of motion of multi story, irregular, controlled structure based on orthogonal system with center of axis located at the center of mass of diaphragm is the following

$$\mathbf{M}\ddot{\mathbf{U}}(\mathrm{t})+\mathbf{C}\dot{\mathbf{U}}(\mathrm{t})+\mathbf{K}\mathbf{U}(\mathrm{t})=-\mathbf{M}\mathbf{E}a_g(\mathrm{t})+\mathbf{E}_\mathrm{f}\,sat\mathbf{F}(\mathrm{t}\text{-}\mathrm{t_d}) \tag{1}$$

where, **M**, **C**, **K** denote respectively the mass, damping and stiffness matrices of the structure. In irregular structure, the mass, stiffness matrix and saturation delayed function, sat**F**(t-t_d),is given below

$$[\mathbf{M}]=\begin{bmatrix} m_1 & 0 & 0 & . & . & . & 0 & 0 & 0 \\ 0 & m_1 & 0 & . & . & . & 0 & 0 & 0 \\ 0 & 0 & I_{CM,1} & . & . & . & 0 & 0 & 0 \\ . & . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . & . \\ 0 & 0 & 0 & . & . & . & m_n & 0 & 0 \\ 0 & 0 & 0 & . & . & . & 0 & m_n & 0 \\ 0 & 0 & 0 & . & . & . & 0 & 0 & I_{CM,n} \end{bmatrix},\ [\mathbf{K}]=\begin{bmatrix} k_{1,1} & k_{1,2} & & . & . & . & k_{1,3n-1} & k_{1,3n} \\ k_{2,1} & k_{2,2} & & . & . & . & k_{2,3n-1} & k_{2,3n} \\ & & & . & . & . & & \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ & & & . & . & . & & \\ k_{3n-1,1} & k_{3n-1,2} & & . & . & . & k_{3n-1,3n-1} & k_{3n-1,3n} \\ k_{3n,1} & k_{3n,2} & & . & . & . & k_{3n,3n-1} & k_{3n,3n} \end{bmatrix},\quad I_{CM,n}=m_n\cdot\left(\frac{L_{X,n}{}^2+L_{Y,n}{}^2}{12}\right)$$

m_n, is the story diaphragm mass and $I_{CM,n}$ is the moment of inertia around the vertical axis that passes from center of mass, CM. Lx , Ly are the external dimensions of the floor slab, **K** is the stiffness matrix of the building with respect to the axis, x_m-y_m, and passes from the center of mass. The stiffness matrix of structure is assembled from story-matrix of each floor. The story-matrix is obtained from the diagonal matrix around the principal axis I-II with two additional transformations: One rotation from the axis I-II to the axis x_r-y_r, which passes from the center of rigidity and are parallel to global coordinated system and a second transformation from the axis x_r-y_r to the axis x_m-y_m related to the center of mass. The second transformation accounts from the eccentricity of center of rigidity, CR, to the center of mass, CM, of each story where the equations of motions are defined.

The damping matrix is assumed as Rayleigh damping one:

$$[\mathbf{C}]=a_o[\mathbf{M}]+a_1[\mathbf{K}],\qquad a_o=\zeta\frac{2\omega_i\omega_j}{\omega_i+\omega_j},\qquad a_1=\zeta\frac{2}{\omega_i+\omega_j}\tag{2}$$

It should be noted that in an irregular building, torsional modes are often significant and in this case, the use of Caughey damping matrix might be more preferable than Rayleigh damping.

In Eq. (3), **E** and $\mathbf{E}_f$ are respectively both the location matrices for the earthquake and the control forces on the structure. **F,** is the matrix of equivalent control forces, which should be applied to the structure directly, if active control devices are used, or indirectly if semi-active control devices are used to control the structure.

$$\mathbf{E}=\begin{bmatrix}1\\1\\0\\.\\1\\1\\0\end{bmatrix},\ \mathbf{E}_f=\begin{bmatrix}1 & 0 & . & 0 & 0\\ 0 & 1 & . & 0 & 0\\ \mathrm{e_{fy,1}} & \mathrm{e_{fx,1}} & . & 0 & 0\\ . & . & . & . & .\\ 0 & 0 & . & 1 & 0\\ 0 & 0 & . & 0 & 1\\ 0 & 0 & . & \mathrm{e_{fx,n}} & \mathrm{e_{fx,n}}\end{bmatrix},\qquad \mathbf{F}=\begin{bmatrix}\mathrm{F_{cx,1}}\\ \mathrm{F_{cy,1}}\\ .\\ \mathrm{F_{cx,n}}\\ \mathrm{F_{cy,n}}\end{bmatrix}\tag{3}$$

Since the control devices have limited capacity and applied to the structure with time delay, saturation delayed function, sat $\mathbf{F}(\mathrm{t\text{-}t_d})$, should be used, which is given by

$$sat\mathbf{F}(\mathrm{t\text{-}t_d})=\begin{cases}\mathbf{F}(\mathrm{t\text{-}t_d}), & \mathbf{F}(\mathrm{t\text{-}t_d})<\mathbf{F}_{\mathrm{allowable}}\\ \mathbf{F}_{\mathrm{allowable}}, & \mathbf{F}(\mathrm{t\text{-}t_d})\ge\mathbf{F}_{\mathrm{allowable}}\end{cases}\tag{4}$$

where t_d is the time delay and $\mathbf{F}_{allowable}$ is the maximum capacity of the control device.
Finally, **U** is the displacement vector with respect to the mass center:

$$\mathbf{U} = \left\{u_{x,1}\ u_{y,1}\ \theta_1 ... u_{x,n}\ u_{y,n}\ \theta_n\right\}^T \tag{5}$$

The geometric properties, eccentricities, the center of mass and rigidity, and also the location of control devices of each story, are shown in Fig. 1.
In the state space approach the above Eq. (1) can be written as follows

$$\begin{aligned}\dot{\mathbf{X}}(\mathrm{t}) &= \mathbf{AX}(\mathrm{t}) + \mathbf{B}_g a_g(\mathrm{t}) + \mathbf{B}_f sat\mathbf{F}(\mathrm{t}\text{-}\mathrm{t_d}) \\ \mathbf{Y}(\mathrm{t}) &= \mathbf{CX}(\mathrm{t}) + \mathbf{D}_\mathrm{f} sat\mathbf{F}(\mathrm{t}\text{-}\mathrm{t_d}) + \mathbf{D}_\mathrm{g} a_\mathrm{g}(\mathrm{t}) + \mathbf{v}\end{aligned} \tag{6}$$

The matrices **X**, **A**, $\mathbf{B}_g$, $\mathbf{B}_\mathrm{f}$ are given by:

$$\mathbf{X} = \begin{bmatrix}\mathbf{U} \\ \dot{\mathbf{U}}\end{bmatrix}_{2nx1},\ \mathbf{A} = \begin{bmatrix}\mathbf{0} & \mathbf{I} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C}\end{bmatrix}_{2nx2n},\ \mathbf{B}_g = \begin{bmatrix}\mathbf{0} \\ -\mathbf{E}\end{bmatrix}_{2nx1},\ \mathbf{B}_f = \begin{bmatrix}\mathbf{0} \\ \mathbf{M}^{-1}\mathbf{E}_f\end{bmatrix}_{2nx1} \tag{7}$$

Furthermore, the matrices **Y, C,** $\mathbf{D}_f$, $\mathbf{D}_g$, and **v** are respectively the output states, the output matrix, the feed forward control force matrix, the excitation matrix and the noise matrix. In the event that the output variables are the same as the states of the system and there is no application

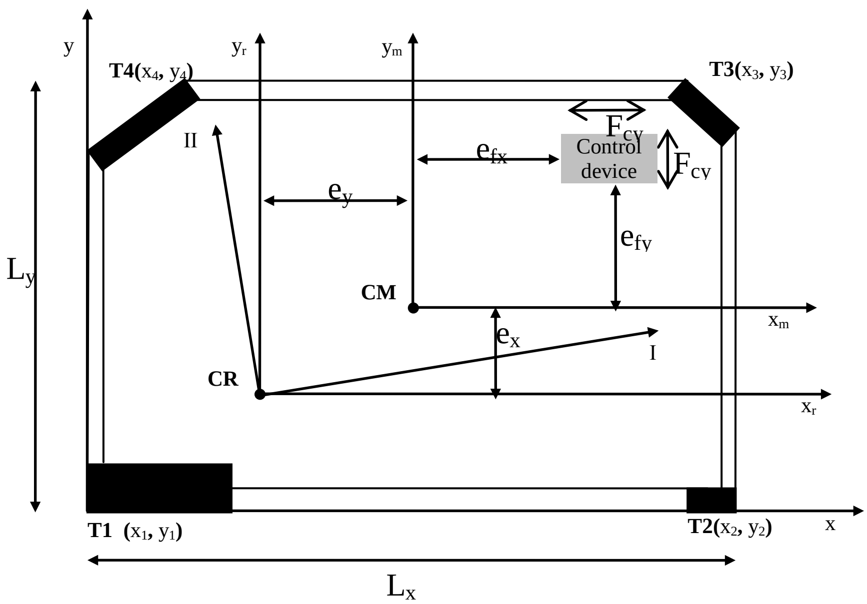


Fig. 1 Geometrical properties, eccentricities e_x, e_y, centre of mass, CM, centre of rigidity, CR, and location of control devices, e_{fx}, e_{fy}.

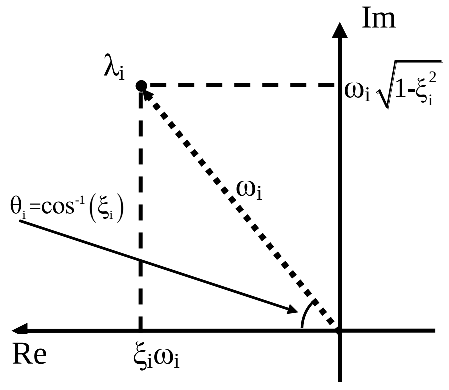


Fig. 2 Representation of the poles in the complex plane

of the control forces to the output variables, so the matrixes **C, D** are respectively the identity and zero matrix and this case is considered in the following. The noise matrix depends on the sensor that is used to measure the response of the system. The above equation can be solved numerically in MATLAB software by using the SIMULINK toolbox.

The modes are not normal any more but this is not affect the analysis since the equations of motion is transformed to state space equations and then they are solved numerically by direct integration. In this work, the time stepping, a Bogacki-Shampine's method (1989) for ordinary differential equation is adopted.

3. Control algorithm for irregular structure

The control force **F** is determined by linear state feedback:

$$\mathbf{F} = -\mathbf{G}_1\mathbf{U} - \mathbf{G}_2\dot{\mathbf{U}} = -\begin{bmatrix}\mathbf{G}_1 & \mathbf{G}_2\end{bmatrix}\begin{bmatrix}\mathbf{U} \\ \dot{\mathbf{U}}\end{bmatrix} = -\mathbf{GX} \tag{8}$$

where **G** is the gain matrix, which is calculated using pole placement algorithm. This algorithm requires desired poles location of the controlled system.

The eigenvalues or poles of a structural system are given by

$$\lambda_i = -\xi_i\,\omega_i \pm j\omega_i\sqrt{1-\xi_i^2} \tag{9}$$

where ω_i and ξ_i are the cyclic eigenfrequencies and the damping ratio, respectively. If a state space formulation is adopted, these poles are obtained directly from the eigenvalues of matrix A

$$\det\left[\lambda\mathbf{I} - \mathbf{A}\right] = 0 \rightarrow \lambda_i = \alpha_i \pm j\beta_i \tag{10}$$

The representation of the poles in the complex plane is shown in Fig. 2

Replacing the force **F** from Eq. (8) into Eq. (1), the controlled system can be described by:

$$\mathbf{M}\ddot{\mathbf{U}}(\mathrm{t}) + \left(\mathbf{E}_f\mathbf{G}_2 + \mathbf{C}\right)\dot{\mathbf{U}}(\mathrm{t}) + \left(\mathbf{E}_f\mathbf{G}_1 + \mathbf{K}\right)\mathbf{U}(\mathrm{t}) = -\mathbf{M}\mathbf{E}a_g(\mathrm{t}) \tag{11}$$

From the above equation it is clear that control of structures modifies their stiffness and/or damping and consequently their dynamic characteristics.

Proportional damping, **C**, was considered for the irregular initial structure but in the analysis of controlled structure the damping matrix, ($\mathbf{E}_f\mathbf{G}_2$+**C**), is not proportional anymore.

In this study the control force or the feedback matrix **G** is estimated in a way that the irregular controlled structure has similar dynamic characteristics to a fictitious symmetrical structure. The procedure of calculating the feedback matrix is as follows: firstly, a symmetric structure is obtained from the irregular one, by adding at specific locations new structural elements (shear walls or columns) cancelling, thus, all the irregularities. In this stage, no limitations for the location of the elements exist because this symmetric structure is a fictitious one which is not going to be constructed. The poles of uncontrolled irregular structure, λ_i, and those from the symmetric structure $\lambda_{i,\,sym}$ are calculated. Then, the poles of controlled irregular structure, $\lambda_{i,c}$, are forced to be equal to the poles of the fictitious symmetric structure $\lambda_{i,\,sym}$. Later, supplementary equivalent damping is added and the final location of the poles of the controlled irregular structure, $\lambda_{i,c}$, is obtained. Based on these poles, the feedback matrix, **G**, is calculated with the pole placement algorithm. The three structures and the relative poles locations in complex plane are shown in Fig. 3. A flowchart of the proposed algorithm is shown in Fig. 4. Additionally, the graphical representation of poles from irregular, symmetrical and controlled structures are shown in Fig. 5.

Based on the feedback matrix, **G**, a control analysis takes place according to the scheme shown in Fig. 6. The response of controlled, uncontrolled irregular structure and the symmetric structure subjected to earthquake excitation is calculated.

As a consequence, this controlled procedure shows that the irregular controlled building behaves like the symmetrical one. This process can be followed when there is a difficulty in retrofitting or adding new structural elements, such as shear walls, due to architectural or functional limitations. Instead of adding new structural element to eliminate the irregularity, active or semi-active devices can be installed at specific locations with eccentricity e_{fx}, e_{fy} from the centre of mass. As a result, the irregular structure with the devices (controlled irregular structure) behaves like the symmetrical one.

Theoretically, the poles of controlled asymmetric structure can be placed anywhere. However, this counts on the controllers and the energy that will be needed. In the present work, the location of poles of controlled asymmetric structure depends on the choice of the fictitious symmetrical structure. Based on the symmetrical structure, its poles are calculated and they are forced to be the poles of the controlled asymmetric structure. So, the location of poles of controlled asymmetric structure is the same with the location of symmetric structure.

Symmetric structure has only translational modes while their rotational ones do not contribute to the response of the structure. In case of the earthquake excitation, a symmetric structure, which has the same translational stiffness with an asymmetric one, has better response since no rotation is observed (centre of mass identical to center of stiffness). Assigning the poles of the controlled asymmetric structure to be equal to the eigenvalues of a fictitious symmetric structure, asymmetric structure is forced to behave like the symmetrical one. As a result, the controlled asymmetric structure will experience reduced rotation, compared to the uncontrolled asymmetric structure. The

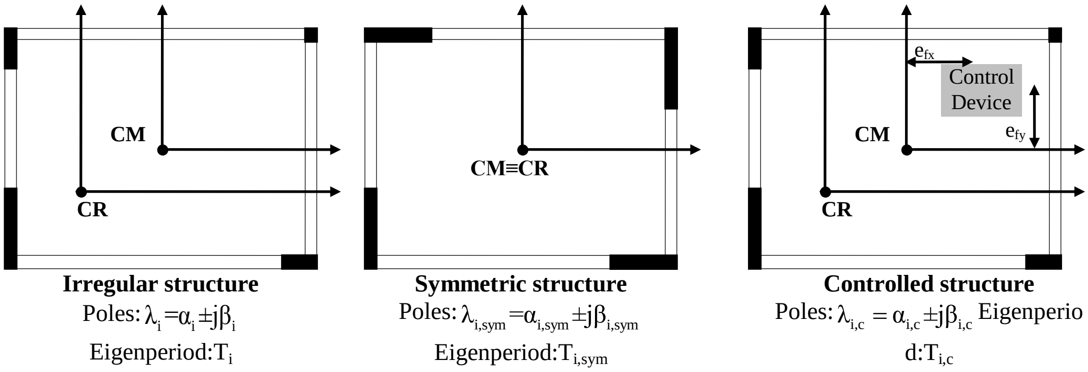


Fig. 3 Poles of irregular, symmetrical and controlled structure

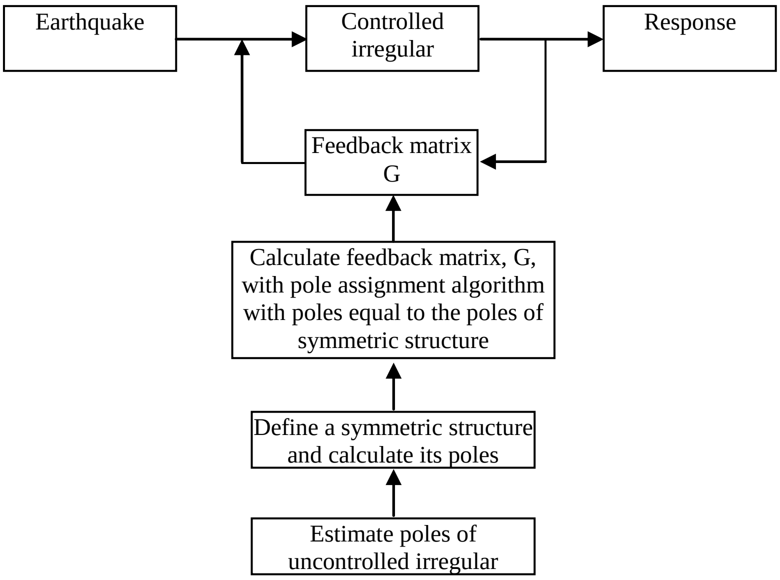


Fig. 4 Flowchart of the proposed algorithm

rotation will not been totally compensated since the eigen-modes of controlled asymmetric structure is not exactly the same with the modes of the symmetric structure.

It should be noted that the control algorithm which is adopted here is for active or semi active type of control. The algorithm cannot be applied to the passive devices located at a predetermined location in the structure.

Time delay and saturation capacity acting either separately or simultaneously have negative influence to the response of controlled structure. In the work of Pnevmatikos and Gantes (2011), it can be shown the need of performing numerical simulations, which account for the coupling of time delay and saturation capacity, before installing the control system in the building. Such numerical simulations will provide limits of time delay and saturation capacity that should not be exceeded, so that the response of the controlled system will be lower than that of the uncontrolled one. They define A “safe region” of values of time delay and saturation capacity can be defined that should be used as design specification for the control devices that are going to be installed in the building.

4. Examples and numerical experiments

4.1 Single story building

A single-storey irregular structure, where its geometrical characteristics are shown in Fig. 7(a), is investigated. The mass of the structure is 25 tones. Based to the irregular structure a fictitious symmetrical structure where the center of rigidity, CR, is coinciding with the center of mass, CM is shown in Fig. 7(b). The irregular structure with the control device is shown in Fig. 8. The poles of each structure are illustrated in Figs. 7(a)-(b) and Fig. 8 The control analysis procedure is performed according to the Fig. 6 and the response is estimated. The time delay was taken t_d = 1msec, and saturation control force capacity F_{sat} = 500kN. The inherent viscous damping ratio is assumed to be 5%. The Athens earthquake (1999) was used as the excitation signal. The location of the control device was 2m far from the center of mass as shown in Fig. 8.

The stiffness and mass matrixes from symmetrical and asymmetrical structure are shown below.

$$[\mathbf{M}] = \begin{bmatrix} 25 & 0 & 0 \\ 0 & 25 & 0 \\ 0 & 0 & 150 \end{bmatrix} \quad \left[\mathbf{K}_{sym}\right] = \begin{bmatrix} 230546 & 0 & 0 \\ 0 & 230546 & 0 \\ 0 & 0 & 4224002 \end{bmatrix}, \left[\mathbf{K}_{irreg.}\right] = \begin{bmatrix} 86140 & 0 & 16913 \\ 0 & 185150 & -241565 \\ 16913 & -241565 & 2500540 \end{bmatrix}$$

The displacement in both directions, rotation and acceleration response of the symmetrical, irregular uncontrolled and controlled structure are shown in Fig. 9. The equivalent control forces in both directions are shown in Fig. 10. Generally, the response, displacement, rotation, and

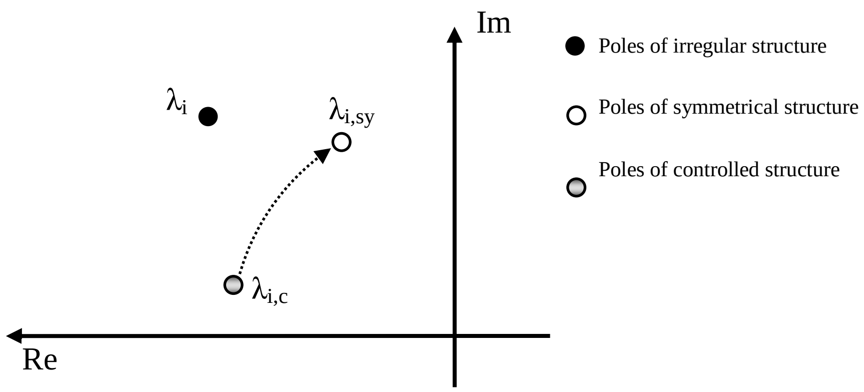


Fig. 5 Location of poles in complex plane of irregular, symmetrical and controlled structure

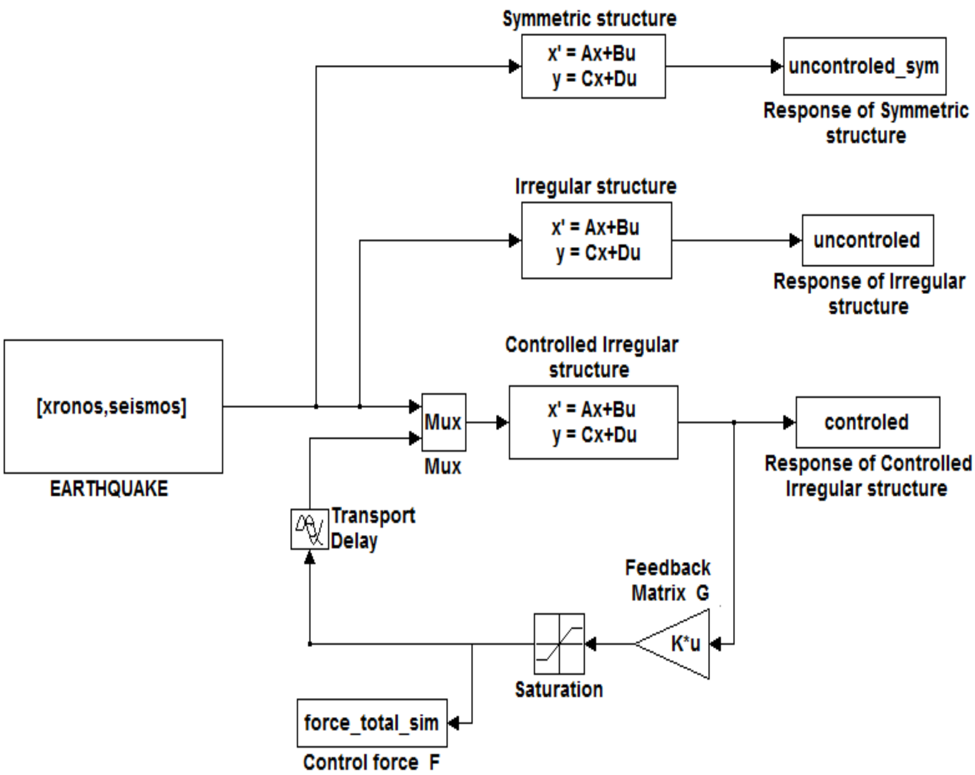
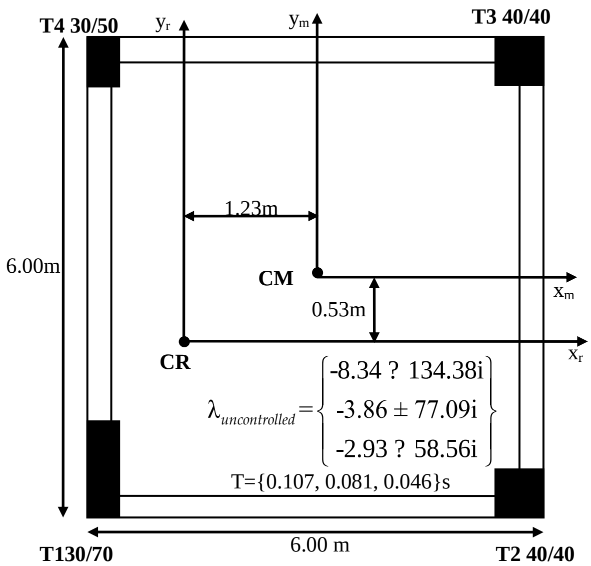
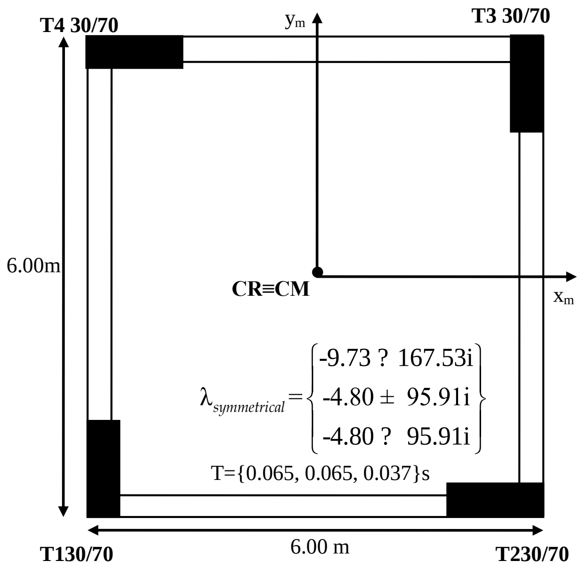


Fig. 6 Control procedures for estimating the response of the controlled and the uncontrolled subjected to earthquake excitation



(a)

Fig. **7 (**a)Irregular and (b) fictitious symmetricalstructure



(b)

Fig. 7 Continued

acceleration are reduced in the case of controlled structure. More specifically, the displacement is reduced one order of magnitude; the rotation of the controlled structure is the half of the rotation of the uncontrolled structure, while the acceleration is reduced in 70%. On the other hand, in order to achieve the above reductions, control force should be applied to the structure. The maximum control force is 60kN and 40kN in x and y direction, respectively. This force is about one fifth of the structural weight.

It should be noted that the eigenvectors (modes) of the system changes with the addition of control and the new modes are not known in anticipation. In this way the rotation of the controlled asymmetric structure is not the same with symmetrical one (actually zero). Thus, a parametric studies for different control device location and different types of earthquake should be done in order to see that this difference is keeping in acceptable level before finalize the control design.

4.2 Two story building

A two-storey building with irregular plan section similar to the previous one is considered, Fig. 11. The two-storey symmetrical building has identical plan topology as in the single-storey building of Example 4.1 and the locations of the control forces are in both stories at the same

$$[\mathbf{M}]=\begin{bmatrix} 25 & 0 & 0 & 0 & 0 & 0 \\ 0 & 25 & 0 & 0 & 0 & 0 \\ 0 & 0 & 150 & 0 & 0 & 0 \\ 0 & 0 & 0 & 25 & 0 & 0 \\ 0 & 0 & 0 & 0 & 25 & 0 \\ 0 & 0 & 0 & 0 & 0 & 150 \end{bmatrix} \quad \left[\mathbf{K}_{sym.}\right]=\begin{bmatrix} 461092 & 0 & 0 & -230546 & 0 & 0 \\ 0 & 461092 & 0 & 0 & -230546 & 0 \\ 0 & 0 & 8448005 & 0 & 0 & 0 \\ -230546 & 0 & 0 & 230546 & 0 & 0 \\ 0 & -230546 & 0 & 0 & 230546 & 0 \\ 0 & 0 & 0 & 0 & 0 & 4224002.5 \end{bmatrix}$$

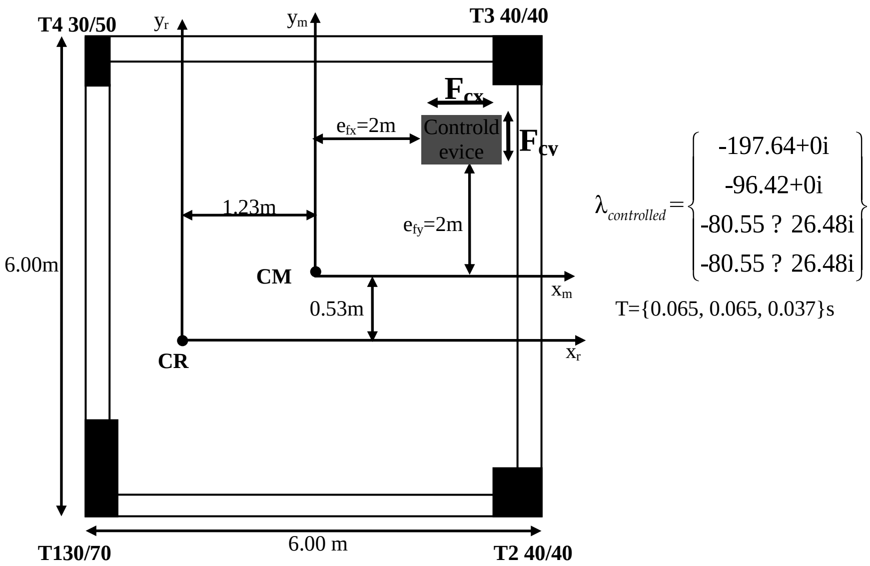


Fig. 8 Irregular structure with the control device

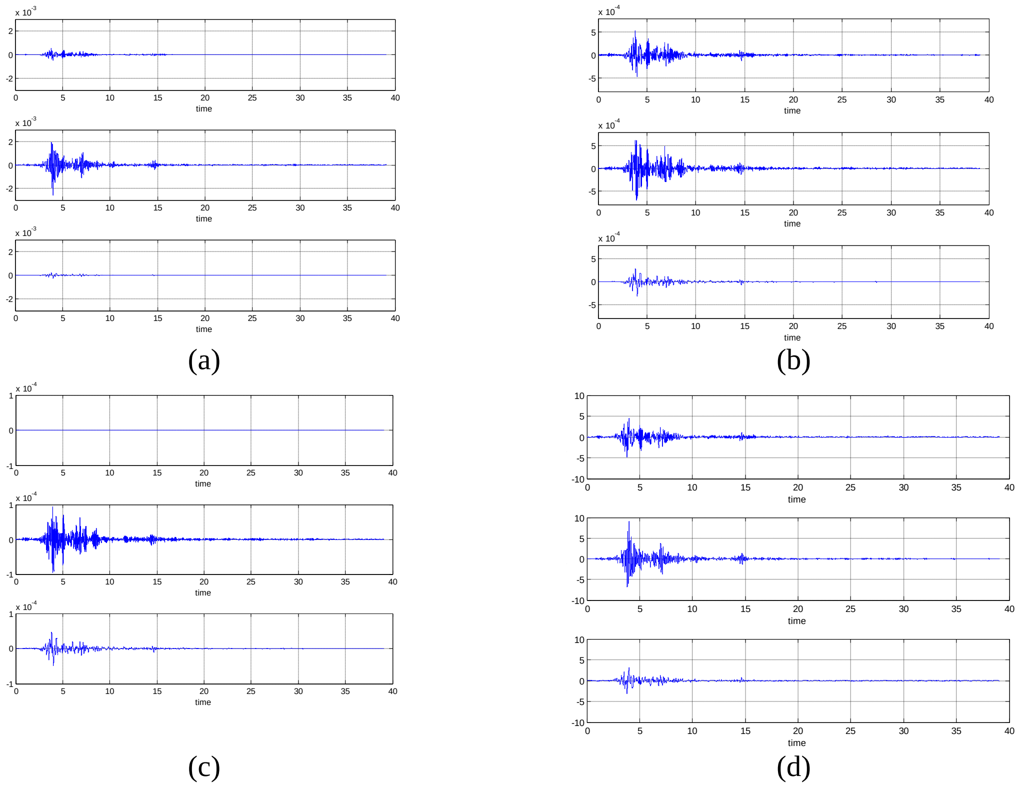


Fig. 9 a,b) Displacement along *x* and *y* direction, c) rotation and d) acceleration in *x* direction, of the symmetrical uncontrolled and the controlledstructure

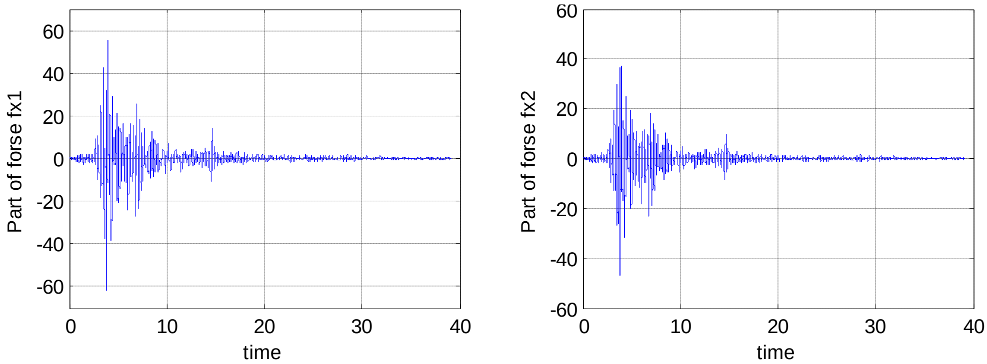
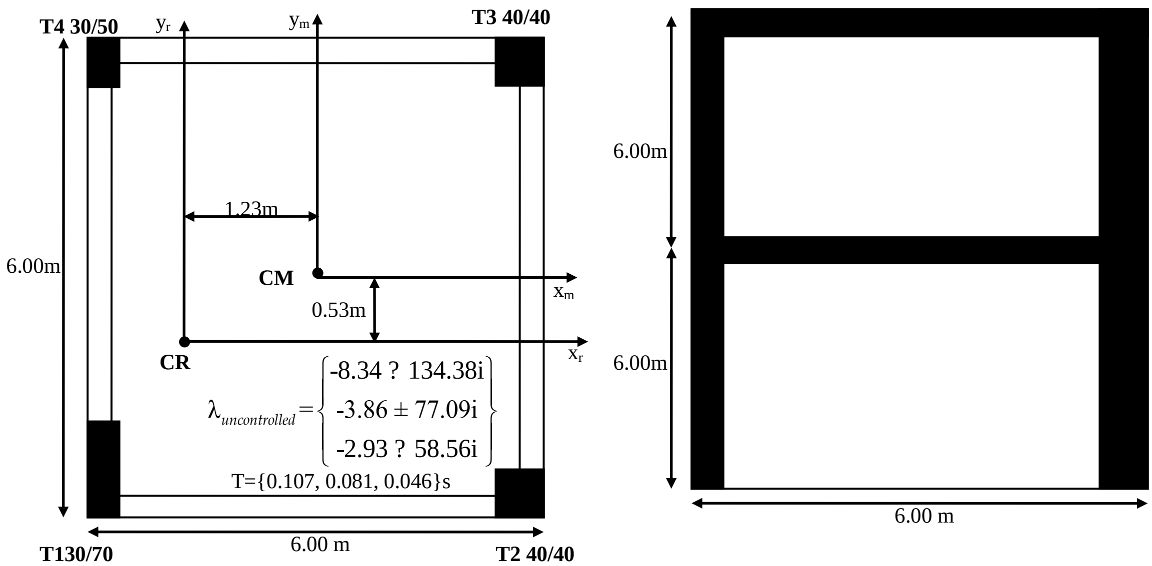


Fig. 10 The equivalent control force in both directions



(a) (b)

Fig. 11Two story irregular structure, plan, (a) and elevation, (b)

location as it was in a single-storey building, too.

The mass matrix for both irregular and symmetrical two story building is the same and isshown below. The stiffness matrixes for both symmetrical and irregular building are also observed below:

$$\left[\mathbf{K}_{irreg.}\right]=\begin{bmatrix} 172280 & 0 & 33826 & -86140 & 0 & -16913 \\ 0 & 370300 & -483129 & 0 & -185150 & 241564.5 \\ 33826 & -483129 & 5001081 & -16913 & 241564.5 & 2500540.5 \\ -86140 & 0 & -16913 & 86140 & 0 & 16913 \\ 0 & -185150 & 241564.5 & 0 & 185150 & -241564.5 \\ -16913 & 241564.5 & 2500540.5 & 16913 & -241564.5 & 2500540.5 \end{bmatrix}$$

The two-storey building is subjected to Athens (1999) earthquake excitation.Displacement, rotation and acceleration at the top story are calculated for the symmetrical building and both for uncontrolled and controlled irregular building and these results are shown in Fig. 12. It is observed

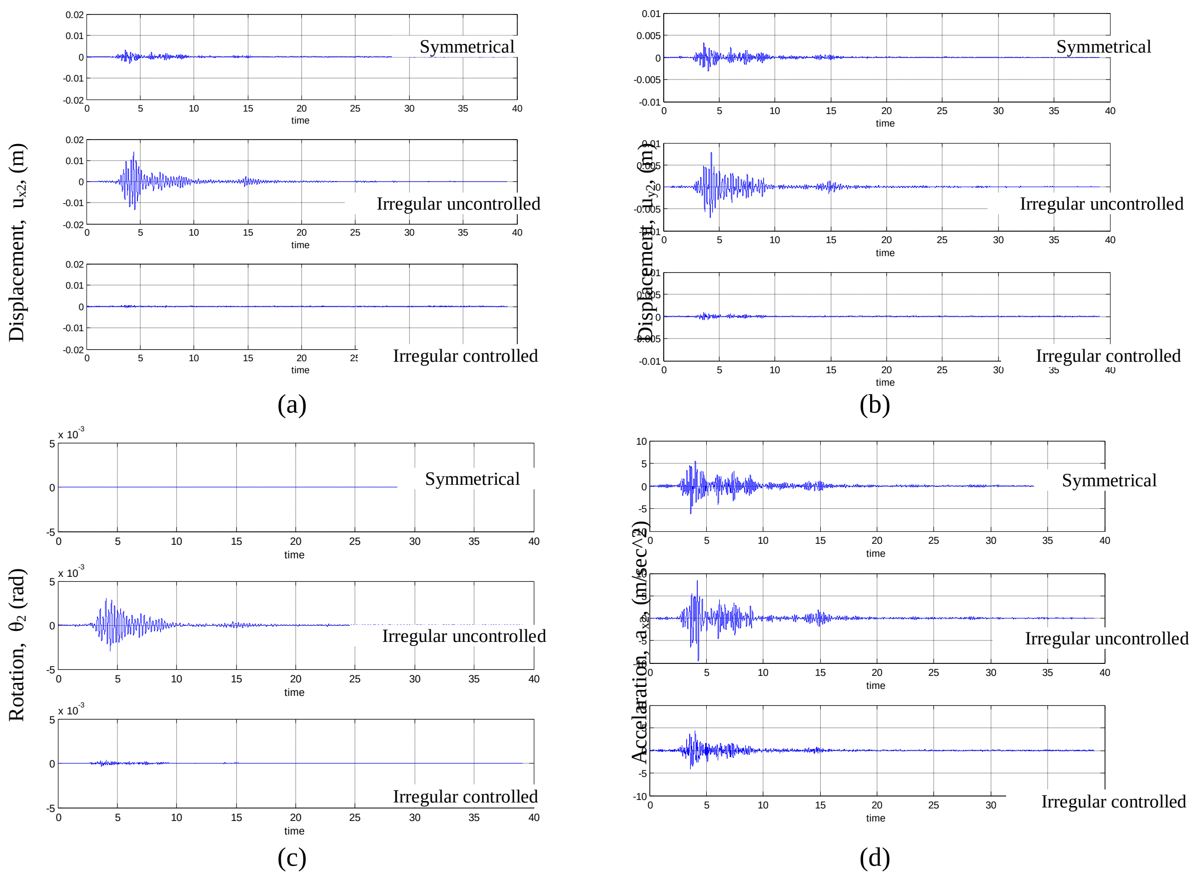


Fig. 12 a, b) Displacement along x, and y direction, c) rotation and d) acceleration in x direction, at the second floor of the symmetrical uncontrolled and the controlled structure

that the displacements for the controlled irregular building are reduced one order of magnitude in both directions compared to the uncontrolled irregular building. The rotation also reduced about one order of magnitude. The acceleration is half for the controlled irregular building compared to the uncontrolled one. The displacement and acceleration of symmetrical building is between the uncontrolled and controlled irregular building. The response of symmetrical building is not similar to the controlled building given that poles of controlled building has additional damping compared to poles of the symmetric building (see Fig. 5).

From the analysis results, which are presented in Figs. 9(a)-(b) and 12(a)-(b), the feasibility of the control algorithm to keep the structure in elastic range is evident since the drift limit ratio is quite small (less than 0.001or 0.1%).

In order to achieve the above reduction in the response, equivalent control force is needed to apply in structure through the control devices. The amounts of control force in each floor and in both directions are shown in Fig. 13. It is observed that the maximum demand for this force is about 250 kN which is the half of the total building’s weight.

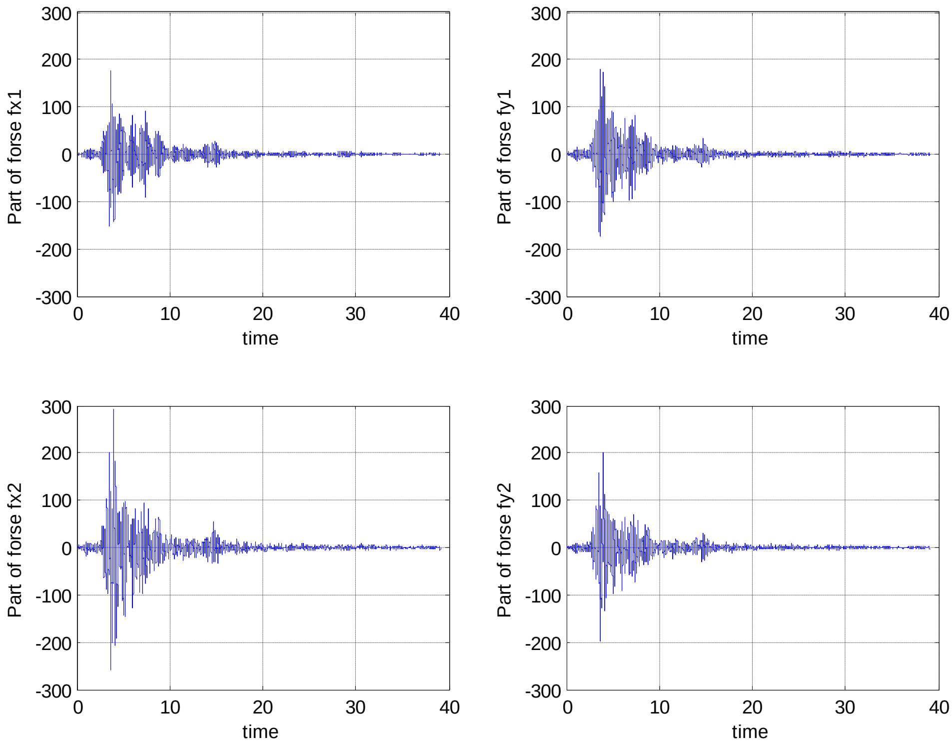


Fig. 13 The equivalent control force for each floor and in both directions

5. Conclusions

A control algorithm for irregular structures subjected to earthquake excitation is proposed. According to this algorithm the poles of the controlled irregular structure are forced to be equal with the poles of a fictitious symmetrical structure. Then, the feedback matrix is calculated with pole placement algorithm and the control forces which should be applied to the structure are obtained. The proposed control procedure makes the irregular structure together with control devices behave like a symmetrical one and much better. The proposed procedure is applied in two irregular reinforced concrete buildings with one and two storey. From these characteristic numerical results it is found that the above control procedure is efficient in reducing the response of irregular buildings and keeps it in elastic range, with small amount of required control action.

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