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Seismic Response Control of Structures with Stiffness Irregularities through Optimally Placed Active Tendons using Multiobjective Genetic Algorithm

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Abstract

This paper studied the seismic response control of structural building with stiffness irregularities through active tendon system (ATS) using Linear Quadratic Regulator control algorithm. The various responses considered are the floor displacements, story drifts, and base shear. The optimal number and the optimal position of these active tendons are obtained through multiobjective optimization using Genetic Algorithm to reduce the responses and the cost of the control system simultaneously. The conflicting objectives minimized are the base shear of the irregular building and the number of active tendons to be used. The maximum story drift and maximum floor displacement are used as constraints. For numerical results, six combinations of stiffness irregularity in critical storys 1,2,and 10 of a ten story defecient shear building frame subjected to El Centro earthquake is considered. The results show that the optimized control system is capable of keeping the responses of the building frame to an earthquake within permissible limits and stiffness irregularity in the same defecient frame cost only the tendon in atmost one additional story.

Keywords: Stiffness irregularity, active control, multiobjective genetic algorithm, active tendon system, LQR.

1. Introduction

vertical irregularites in a structure arise due to irregular distribution of mass, stiffness and strength along the height of the structure. Such irregular distribution occurs owing to reasons viz., inconsistent construction and materials, certain functional requirement like discontinuity of some columns. Poor performance of structure with irregularities under seismic load is well known. Thus this aspect can not be ignored while designing a structure to resist lateral loads. Many studies on the behaviour of structure with irregularities are available in literature. Moehle [1] studied vertically irregular reinforced concrete structures. The irregularities were introduced by providing the tall 1st story and by changing the height of the structural wall. He tested four small scale RCC structures. The results revealed that both the location and extent of irregularity affects the seismic performance of a structure. Ali and Krawinkler [2] investigated the individual and combined effect of mass,stiffness, and strength irregularities on the seismic response of a structure. From the results, they concluded that the strength irregularity affected the roof displacement both individually and in combination with stiffness irregularity.
performance of structures with and without mass, stiffness and strength irregularities.
Magliulo et al [3] did research on the comparative seismic performance of structures with and without mass, stiffness and strength irregularities. They observed that the plastic demand is not affected by mass irregularity but by strength irregularity. The strength irregularity increased seismic demand in beams and has no impact on seismic demand in columns. Chintanpakdee and chopra [4] studied seismic performance of frames with strength and stiffness irregularities. These frames were modelled on the bases of weak-beam strong column theory. They found that the combined effect of strength and stiffness irregularities on the response was more compared to their individual effects. Also the irregularities in lower storys had more impact on the seismic response.

Some researchers have also investigated different methods to control the responses of irregular structures and have tried to extend various active, passive, and hybrid control systems developed for regular structures to irregular ones. Chi-chang et al [5] used passive tuned mass dampers (PTMD) for seismic response reduction of multistory torsionally coupled shear building. The results suggested that a single PTMD is sufficient to reduce both the translations and the rotations of the building. The need of second PTMD arises for a building with nearly same stiffness in both directions. Sophocleous [6] studied use of visco-elastic passive dampers in seismic response control of regular and irregular buildings. Mode shape values were used to determine optimal position of the damper. The results show great improvement in the resposne of both regular and irregular buildings by using viscoelastic dampers. Hongjin and Hojjart [7] investigated seismic control of irregular steel buildings. They used a hybrid control system comprising of a passive damping system and tuned liquid column damper. This hybrid system proved both effective and reliable in reducing the response of the

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irregular system in consideration. Lavan and Daniel [8] proposed a method to design a multi-tuned mass damper for use in 3D irregular structures using performance based control strategy. The results showed that the proposed method performed well in all types of irregularities.

There are also some investigations done on different optimization algorithms for use in determining the optimal location of actuators in active seismic control of both regular and irregular structures. Nazarimofrad et al [9] proposed a multiobjective genetic algorithm to get the optimum number and location of active tendons in 3D irregular buildings with plan irregularity. The proposed method was successful in reducing the number of tendons by 50%. Rao and sivasubramanian [10] proposed a method to find the optimal actuator location in active seismic control using multiple start guided neighbourhood search algorithm. Rao et al [11] studied optimal placement of actuators in tall buildings using genetic algorithm. For the same purpose Liu et al [12] used a discrete nonlinear optimization method and genetic algorithm. Askari et al [13] used multi-objective genetic algorithm in active control and magneto rheological dampers in semi-active control simultaneously.

From the above discussion, it is found that most of the research done on irregular structures is based on their performance in a seismic event and the seismic structural control of irregular structures is yet to be fully investigated. In this research, firstly the relative performance of a regular and an irregular shear building frame with stiffness irregularities in different storys is investigated, compared and then their response is controlled using active tendon system through LQR control algorithm. The optimal number and position of the tendons are obtained using multiobjective genetic algorithm with the aim to reduce the cost of the control system. The ratio of the controlled and uncontrolled base shear and the number of tendons are taken as two objective functions in Pareto optimization.

2. Problem formulation

a) Reference regular 2D shear building frame

As shown in fig 1, consider a defecient shear building frame model equipped with active tendons in each story.The story height and width is 3m and 4m respectively. The stiffness of each story and mass of each floor is $2.68\text{x}10^7$ N/m and 17100 kg respectively. The tendons used in this study have stiffness equal to $2.30\text{x}10^6$ N/m and are inclined at 36.87^0 with the floors. The damping ratio is taken as 5% and size of both beams and columns is same and equal to 300x300 mm^2.

The equation of motion of the frame shown in fig 1 from its free body diagram can be written in matrix form as :

$$M\ddot{X} + C\dot{X} + KX = \delta\ddot{X}_g + \gamma U \tag{1}$$

$$M = \begin{bmatrix} m_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & m_{10} \end{bmatrix}, C = \begin{bmatrix} c_1 + c_2 & -c_2 & \cdots & 0 \\ -c_2 & \ddots & \cdots & \vdots \\ \vdots & \vdots & \ddots & -c_{10} \\ 0 & \cdots & -c_{10} & c_{10} \end{bmatrix}$$

$$K = \begin{bmatrix} k_1 + k_2 & -k_2 & \cdots & 0 \\ -k_2 & \ddots & \cdots & \vdots \\ \vdots & \vdots & \ddots & -k_{10} \\ 0 & \cdots & -k_{10} & k_{10} \end{bmatrix}$$

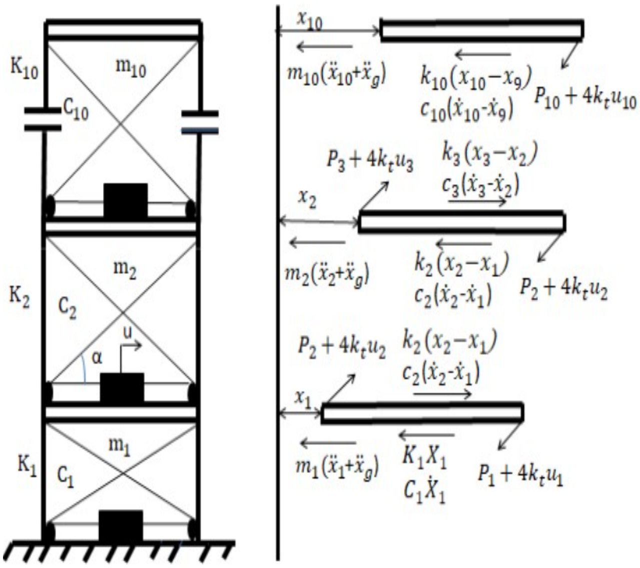

Fig. 1. Model and free body diagram of the ten story shear building frame model

are its mass, damping and stiffness matrices respectively. X (t) and u (t) are the vectors showing floor displacements and control forces respectively. [γ] denotes the tendon location and {δ} is the coefficient vector for ground acceleration. k_c, α and P are the stiffness, inclination and prestressing force of tendons respectively.

$$\{\delta\} = -M * I = [-m_1, -m_2 \dots\dots\dots m_{10}]^T \tag{2}$$

I represent the influence coefficient vector.

$$U(t) = [u_1, u_2, \dots\dots u_r]^T, X(t) = [x_1, x_2, \dots\dots, x_{10}]^T \; \gamma = \bar{\gamma}\theta \tag{3}$$

$$\bar{\gamma} = 4k_c \cos\alpha \begin{bmatrix} -1 & 1 & \cdots & 0 \\ 0 & \ddots & \cdots & \vdots \\ \vdots & \cdots & -1 & 1 \\ 0 & \cdots & 0 & -1 \end{bmatrix}, \theta = \begin{bmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{bmatrix}$$

Eq 1 is written in state space as:

$$\dot{Z} = AZ + B_r\ddot{X}_g + B_uU \tag{4}$$

$$\text{Where } Z = \begin{Bmatrix} X \\ \dot{X} \end{Bmatrix}, A = \begin{bmatrix} [0]_{10x10} & [I]_{10x10} \\ \left[\frac{-K}{M}\right] & \left[\frac{-C}{M}\right] \end{bmatrix}_{20x20}, B_r = \begin{Bmatrix} \{0\} \\ \left\{\frac{\delta}{M}\right\} \end{Bmatrix}, B_u = \begin{Bmatrix} \{0\} \\ \left\{\frac{\gamma}{M}\right\} \end{Bmatrix}_{20xr} \tag{5}$$

b) Defecient frame with stiffness irregularity:

A total number of seven cases have been considered. Case 1 is reference regular defecient frame. Case 2 to case 7 are the frames with introduced stiffness irregularity as shown in figure 2 with 0.5 stiffness modification factor MF.

3. Linear Quadratic Regulator (LQR)

In LQR, control force is obtained by minimising a quadratic performance index given in equation 6.

$$J = \int_0^{t_f} \left(Z^T(t)QZ(t) + U^T(t)RU(t) \right) dt \tag{6}$$

The duration of an earthquake is denoted by t_f . Z is given by equation 5. Q is a 2nx2n positive semi-definite matrix, and R is an n x r positive definite matrix, n represents the degrees of freedom and r is the number of control devices used. In this minimization problem, equation 7 is used as a constraint

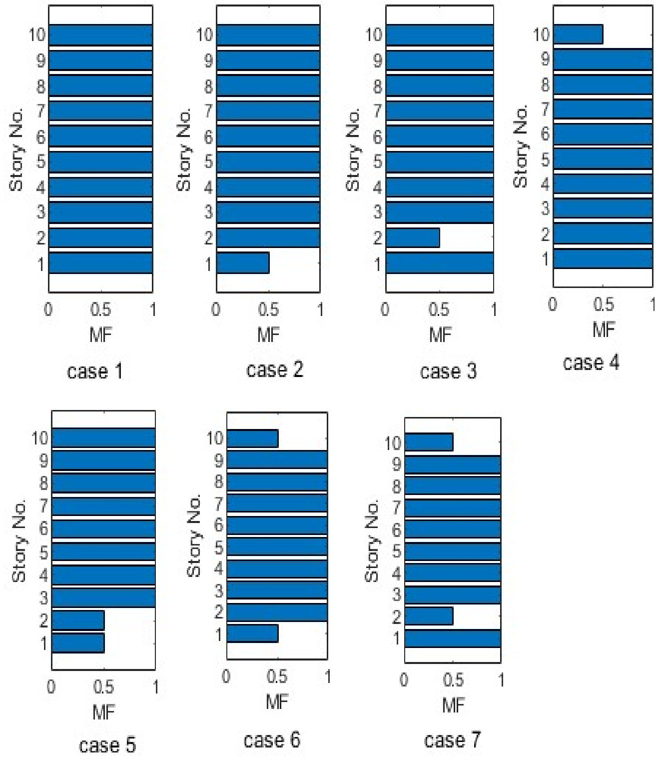

Fig. 2. Modification factors (MF) in different cases

$$\dot{Z} = AZ + B_r\ddot{X}_g + B_uU \tag{7}$$

After minimizing equation 6, the optimal control force obtained is given below:

$$U(t) = \left(\frac{-1}{2}\right) R^{-1}B^{T}PZ(t) = -GZ(t) \tag{8}$$

P in equation 8 is the solution of matrix Riccati equation as shown below:

$$\left[PA - \left[\frac{1}{2}\right] PBR^{-1}B^{T}P + A^{T}P + 2Q\right] = 0 \tag{9}$$

4. Genetic Algorithm

Genetic algorithm is a search technique based on the concept of genetics and natural selection, used to solve different optimization problems. The advantages of using this algorithm are that it can handle large number of variables, suitable for both continous and discrete variables, it can be used for non-differentiable objective functions also and it gives a set of optimum variables. The three main operations in genetic algorithm are selection of chromosomes, crossover and mutation. In multiobjective optimization more than one objective function is optimized simultaneously to obtain a set of optimal solutions known as pareto front. In this paper, multiobjective optimization is done through genetic algorithm to obtain optimal nmber and placement of tendons in different storys of the irregular shear frame. The aim is to reduce the three responses viz. maximum floor displacement, maximum story drift and base shear as well as the number of tendons. Since these are in conflict to each other, use of multiobjective optimization becomes obvious. The two objective functions minimized are J_1(ratio of controlled base shear to uncontrolled base shear) and J_2 (number of tendons). The maximum controlled floor displacement (CFD) and maximum story drift (SD) are kept as constraints. The variables in this optimization are position of the tendons (X). The whole optimization process is summarized as:

Minimize: $J_1(X), J_2(X)$ (10)

Subjected to constraints :

$$CSD(X) \leq SD_p \tag{11}$$

$$CFD(X) \leq FD_p \tag{12}$$

Where, X is a design vector of the position of the tendons. SD_p and FD_p are the permissible limits of maximum story drift and maximum floor displacement.

5. Results and discussions

The simulation of the ten story 2D defecient shear building frame is done in Matlab and the uncontroled results obtained are presented in figures 3 (a-l) and 4. The response of the defecient frame with considered stiffness irregularities in critical storys of the case no 2 to 7 with respect to the response of the defecient regular frame in case 1 are as under:

The figure 3(a) shows that the displacement of all floors in case 2 decrease except 1st floor displacement, which has shown a small increase. The story drift results given in figure 3(b) shows significant increase in 1st story drift which is nearly 40%. Fig 3(c) shows that all floor displacements have decreased in case 3 except 2nd floor displacement which remains unchanged.The story drift in 2nd story of case 3 has increased by nearly 40%. There is no change in any floor displacement in case 4 (stiffness irregularity in 10th story). Though the increase in top story drift is nearly 70% but it has not exceeded the maximum story drift in case 1. Figures 3(g,h) indicate that both 1st, 2nd floor displacements and 1st, 2nd story drifts have increased and the other floor displacements and story drifts have decreased. The increase in floor displacements is negligible but the increase in story drifts is 33%. Figures 3(i,j) show an increase in 1st and 10th story drifts in case 6 (stiffness irregularity in 1st and 10th storys) but the floor displacements are same as in case 1. The increase in 1st story drift is 40% and increase in 10th story drift is negligible. The 2nd floor displacement increases slighltly and 2nd story drift increases by 40% as given by figures 3(k,l). The increase in 10th story drift is negligible. The above discussion clearly indicates that the stiffness irregularity in any story increases its drift and the effect is a matter of concern in lower storys since here it exceeds the maximum drift of the reference frame. Whereas, the increase in floor displacements in all cases is so small that it can be neglected. The base shears as shown in fig 4 in all cases except case 4 (where no change has occurred) has decreased as compared to regular frame.

Since in all cases the maximum story drift and maximum floor displacement exceed their permissible limits of 12mm and 60 mm respectively, these responses are controlled using active tendons through LQR as discussed in sections 3 and 4.

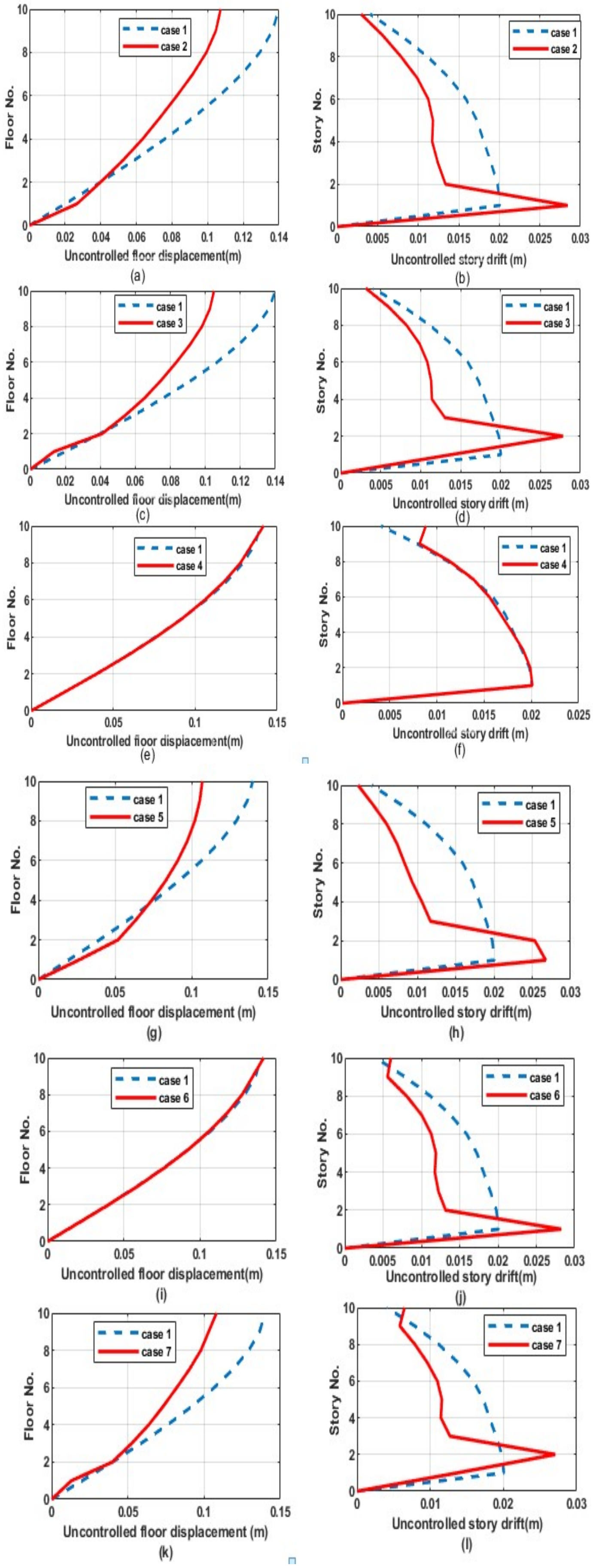

Fig. 3. Comparison of Uncontrolled floor displacements and story drifts of all cases with that of regular frame.

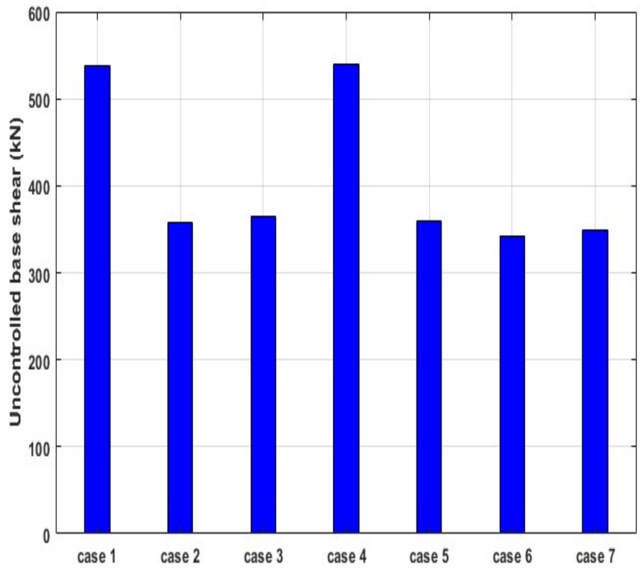

Fig. 4. Comparison of base shear of all cases

Since the base shear has no permissible limit, this parameter is minimized along with number of tendons. The maximum story drift and maximum floor displacement are constrained. After optimization the Pareto curves as shown in fig 5 are obtained for all cases. These curves are the plots of the two objectives in this optimization. The x-axis shows the number of tendons and the y-axis denotes the ratio of controlled base shear (CBS) to uncontrolled base shear (UCBS).

The results in fig 5 shows that four numbers of tendons can reduce base shear by 80.5% whereas tendons placed in each story reduce it by 83%. This indicates that addition of more six tendons to previous state leads to only 2.5% extra reduction in base shear and makes it less cost effective. Thus four numbers of tendons are optimal for this case. Due to the same reason, the optimal number of tendons in cases 2-7 can be taken as 5, 4,4,5,5 and 4 respectively as shown in figure 5. These findings reveal that the optimal number of tendons in all frames with irregularity in only 1st story or any other story in addition to 1st story is 5 whereas it is 4 for all other cases. The optimal positions of these optimal numbers of tendons in each case are shown in table 1. In this table 'X' denotes no tendon placed and ' ' shows tendon is placed. This table shows that it is necessary to place tendons in 1st and 6th story and in addition to these two Storys the tendons can be placed in 2nd, 4th or 5th Storys. Also the placement of tendons in upper three Storys is not required in any case.

The comparison of the controlled and the uncontrolled responses in all cases with tendons optimally placed as table 1 are shown in figure 6 (a-o). Here C denotes controlled, UC denotes uncontrolled and P denotes permissible values. All these figures show that the controlled floor displacements and story drifts are within their permissible limits. Figure 6(o) shows that the reduction in base shear in all cases is more than 67%.

The percentage reductions in all the three responses viz. maximum floor displacement, maximum story drifts, and base shear in all cases are tabulated in table 2.

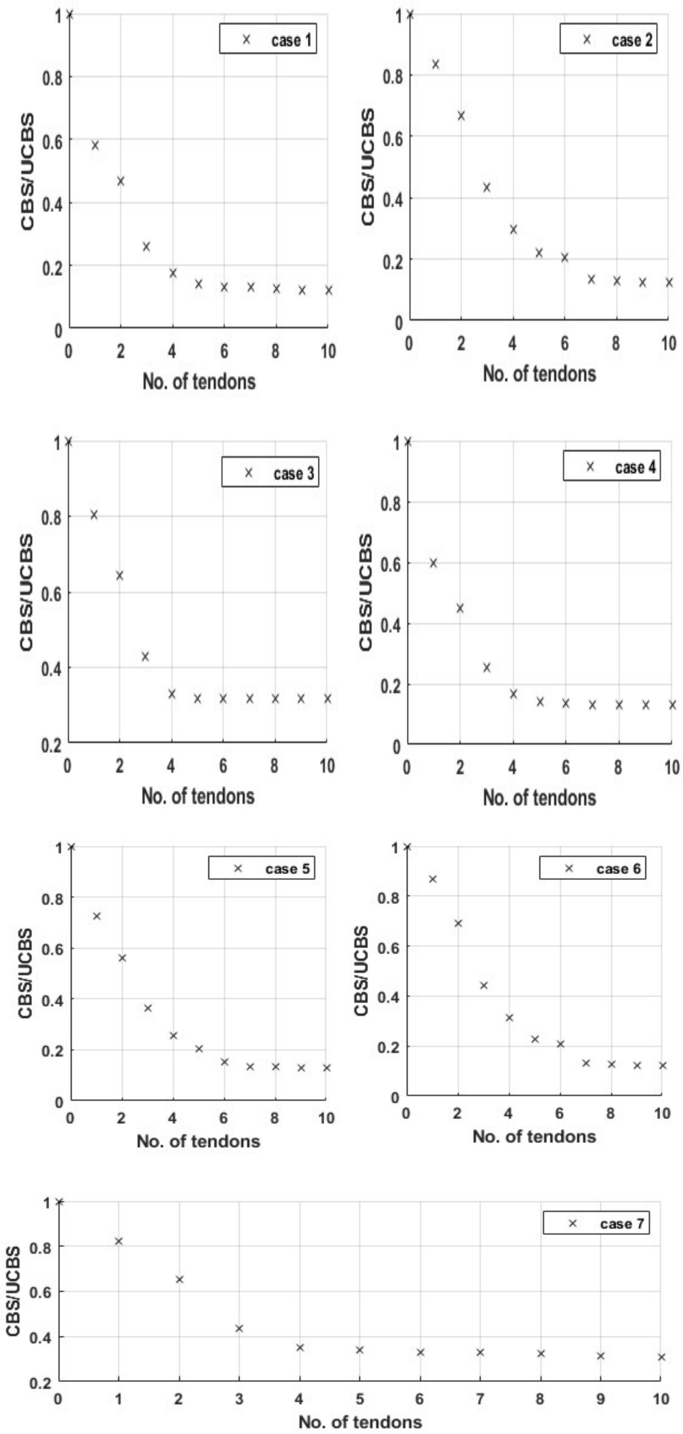

Fig. 4. Pareto curves

Table-1.Optimal placement of tendons in different Storys

Case No.	1st story	2nd story	3rd story	4th story	5th story	6th story	7th story	8th story	9th story	10th story
1	✓	x	✓	x	✓	✓	x	x	x	x
2	✓	✓	x	✓	✓	✓	x	x	x	x
3	✓	✓	x	x	x	✓	✓	x	x	x
4	✓	x	✓	x	✓	✓	x	x	x	x
5	✓	✓	x	✓	✓	✓	x	x	x	x
6	✓	✓	x	✓	✓	✓	x	x	x	x
7	✓	✓	x	x	x	✓	✓	x	x	x

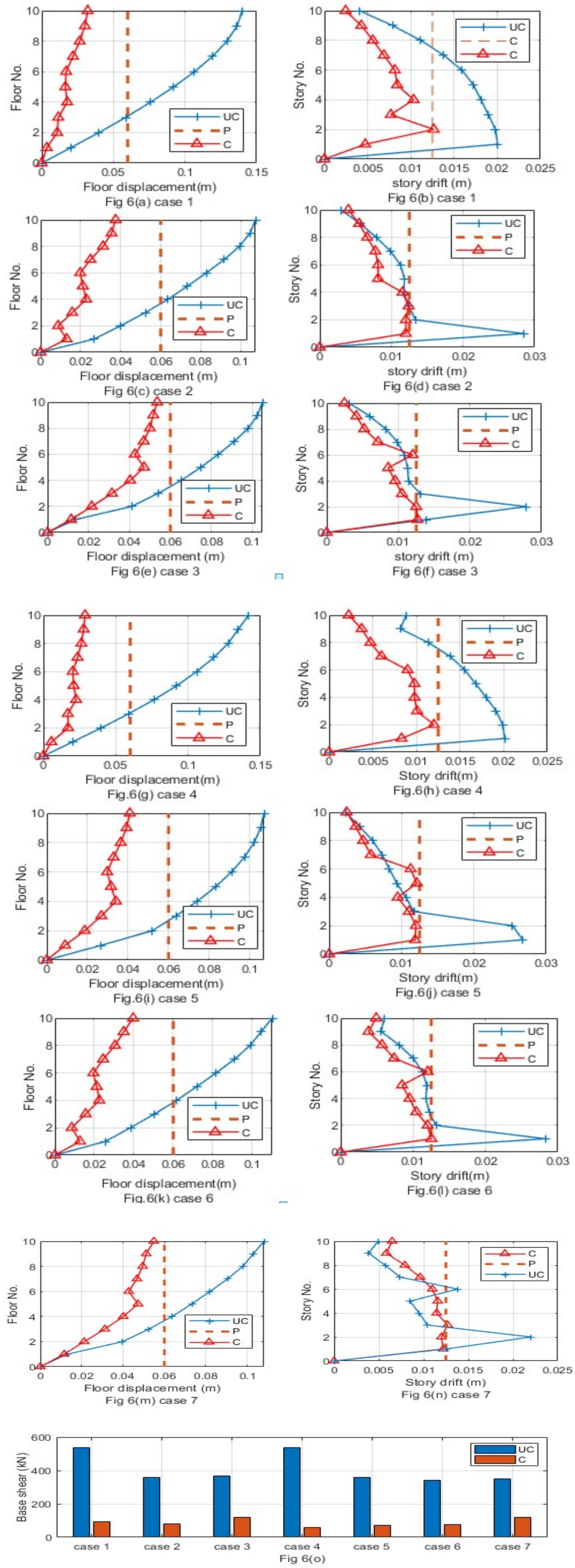

Fig 6(a-o): Comparison of uncontrolled and controlled responses in all cases

Table-2. Percentage reduction in different responses

Case No.	Uncontrolled			Controlled			Percentage reduction		
	Max. FD (m) (floor)	Max. SD (m)(story)	BS (kN)	Max. FD (m)	Max. SD (m)	BS (kN)	Max. FD	Max. SD	BS
1	0.1399(10th)	0.0201(1st)	537.4	0.0321	0.012	93.943	77.06	40.30	82.52
2	0.1073(10th)	0.0284(1st)	357.8	0.0375	0.012	78.77	65.05	57.75	77.98
3	0.1049(10th)	0.0278(2nd)	365.3	0.0536	0.012	120.3	48.9	56.83	67.07
4	0.1417(10th)	0.0201(1st)	538.8	0.0288	0.012	59.48	79.68	40.30	88.96
5	0.107(10th)	0.0268(1st)	358.6	0.0409	0.012	72.69	61.78	55.22	79.73
6	0.1101(10th)	0.0283(1st)	342.5	0.0397	0.012	77.07	63.94	57.60	77.50
7	0.1081(10th)	0.022(2nd)	348.5	0.0549	0.012	121.45	49.21	45.45	65.15

The table shows that the highest reduction in maximum floor displacement has taken place in case 4 (stiffness irregular in 10th story). The reason being that the uncontrolled maximum floor displacement is maximum in this case and needs more reduction to bring it in permissible range. Due to same reason, the highest reductions in story drift and base shear has occurred in case 2 and case 1 respectively.

6. Conclusions

This research investigated the use of active tendon system with LQR control algorithm to control the response of structural building frames having stiffness irregularities and subjected to earthquake excitation. A ten story deficient shear building frame subjected to El Centro time history was considered as a reference regular frame. The stiffness irregularity was introduced in this frame using a modification factor 0.5 in critical Storys i.e. 1st, 2nd, and 10th having six different combinations. The optimal number and position of the active tendons were obtained through multiobjective optimization using genetic algorithm of MATLAB toolbox. The number of tendons and the ratio of controlled to uncontrolled base shear in each combination were minimized simultaneously keeping maximum floor displacement and maximum story drift as constraints. The results obtained are summarized below:

1. The effect of stiffness irregularity is more on drift in lower Storys as compared to upper ones and negligible on floor displacements and base shear with reference to the regular deficient frame (case 1).
2. The optimization results obtained from the work indicate that to control the response of the deficient reference frame with stiffness irregularity in critical Storys, the active tendons are not needed in top three storys.
3. There is no tendon requirement in additional story when stiffness irregularity in deficient frame is introduced in 2nd story, 10th story and in both 2nd and 10th Storys.
4. The present optimal number and position of active tendons obtained through multiobjective optimization using genetic algorithm is able to reduce the maximum floor displacement and maximum story drift in case 4 and case 2 respectively by 79.68% and 57.75% . Also for the combination of stiffness irregularity in case 6 of the deficient frame has reduced the maximum floor displacement and maximum story story drift by 63.94% and 57.60% respectively.

Disclosures

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