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Telescopic columns as a new base isolation system for vibration control of high-rise buildings

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Abstract. In this paper, a new type of passive energy dissipating system similar to added damping and stiffness (ADAS) and triangular added damping and stiffness (TADAS) is proposed and implemented in the analytical model of a building with hybrid structural system in the structure's base which we call it; *Telescopic column*. The behavior and performance of a high rise R.C. structure equipped with this system is investigated and compared with conventional base isolation systems such as rubber isolator bearings and friction pendulum bearings. For this purpose a series of ground acceleration records of the San Fernando, Long Beach and Imperial Valley earthquakes are used as the disturbing ground motions in a series of numerical simulations. The nonlinear numerical modeling which includes both material and geometric nonlinearities were carried out by using SAP2000 program. Results show suitable behavior of structures equipped with telescopic columns in controlling the upper stories drifts and accelerations.

Keywords: telescopic columns; seismic behavior; nonlinear analysis; rubber isolator bearings; friction pendulum bearings

1. Introduction

In structural engineering, the mitigation of damage induced by large loads is of paramount interest. Especially in seismic regions, earthquakes pose a serious threat to human lives and the integrity of the infrastructure. Passive energy dissipating systems such as viscous dampers, tuned mass dampers and base isolation systems have been installed in new or existing buildings (Noroozinejad and Adnan 2012, Matta 2011, Konara and Ghosh 2010, Fujita *et al*. 2010a,b, Patel and Jangid 2011, Silvestri *et al*. 2011, Abbas and Kelly 1993, Ahlawat and Ramaswamy 2000, Aiken *et al*. 1990, Ashour and Hanson 1987, Bhaskararao and Jangid 2006, Chang *et al*. 1993, Cherry and Filiatrault 1993, Kasai *et al*. 1998, Pong *et al*. 1994, Shen and Soong 1995, Boller *et al*. 2009, Singh and Moreschi 2000, Soong and Dargush 1997, Zhang and Soong 1992). Base isolation is one of the most widely used and accepted seismic protection systems. While standard base isolation techniques, such as insertion of rubber bearings or friction pendulum bearings between the ground and a structure that is to be protected, have been applied for a number of years resulting in improved structural response to earthquakes (Sheikh *et al*. 2012, Naeim and Kelly 1999), the addition of supplemental damping devices is being considered for large structures in order to reduce

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the base drift. However, the addition of damping to minimize base drift may increase both internal deformation and absolute accelerations of the superstructure, thus defeating many of the gains for which base isolation is intended (Naeim and Kelly 1999).

In general, protection of the contents of a structure is achieved through minimization of structural accelerations. Active or semi-active strategies may be able to reduce base drifts without the significant increase in superstructure motion that occurs with the installation of passive devices. A number of studies have focused on the use of active control devices in parallel with a base isolation system for limiting base drift (Nanda and Nath 2012, Liu *et al*. 2011, Chen *et al*. 2011, Kelly *et al*. 1987, Reinhorn *et al*. 1987, Nagarajaiah *et al*. 1993, Schmitendorf *et al*. 1994, Yoshida *et al*. 1994, Yang *et al*. 1996). However, active control devices are not fully embraced by practicing engineers, in large part due to the challenges of large power requirements that may be interrupted during an earthquake, concerns about stability and robustness, and so forth.

In this study a new base isolation system called telescopic columns is proposed and implemented in a high-rise hybrid RC structure. The mechanism of the proposed system is very similar to ADAS and TADAS systems. Metallic dampers such as ADAS and TADAS are among energy dissipating devices that have been using in design of the new generations of earthquake-resisting buildings (Goel *et al*. 1989, Balendra *et al*. 2005, J´armai *et al*. 2006, Whittaker *et al*. 1989, ATC-17-1 1994, Sakamoto and Kobori 1996). The analytical model and configuration of the proposed system will be discussed in the next parts.

2. Structural model and material properties

2.1 Telescopic column configurations

Since earthquakes cannot be prevented, methods must be developed to reduce the damage they cause (Noroozinejad and Adnan 2012, Goel *et al*. 1989, Karabörk 2001). This can be achieved by

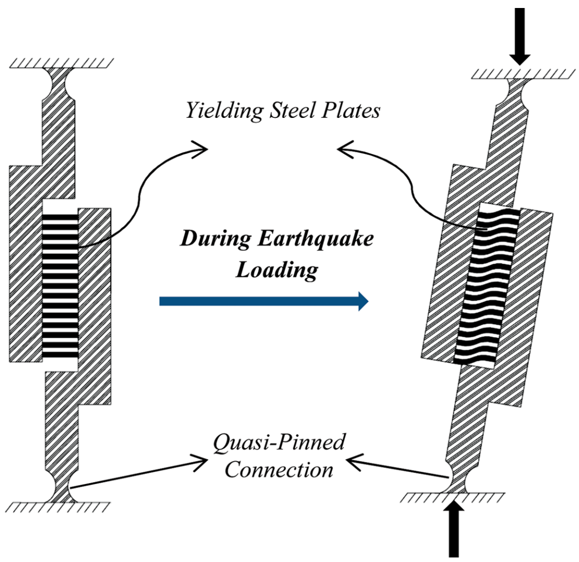

Fig. 1 Configuration and behavior of telescopic columns during earthquake

ensuring that vulnerable structures have increased damping or that the displacement caused by earthquakes is reduced.

One of most effective mechanisms for dissipating input energy to the structure during an earthquake is non-elastic deformation of metals. During earthquakes, the story drifts cause movement of the left side of telescopic columns relative to the right side. This causes yielding of metallic plates of the damper and as a result, the energy is dissipated. Fig. 1 shows the behavior of telescopic columns during an earthquake.

2.2 Telescopic column hysteretic behaviour

Empirical hysteresis models are commonly used in structural engineering and are constructed by specifying a set of rules for loading and unloading paths. These rules usually involve a set of parameters which are calibrated to an observed experimental response for a given load or displacement history. This approach uses from rather coarse models involving straight segments

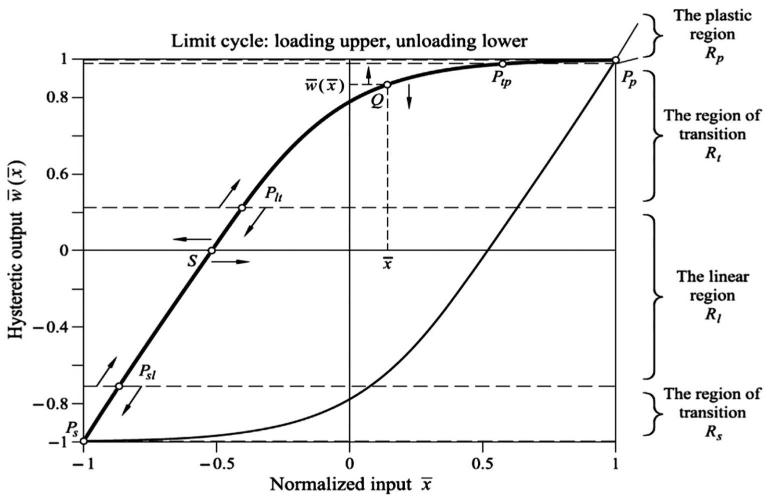

Fig. 2 Bouc-Wen curvilinear model

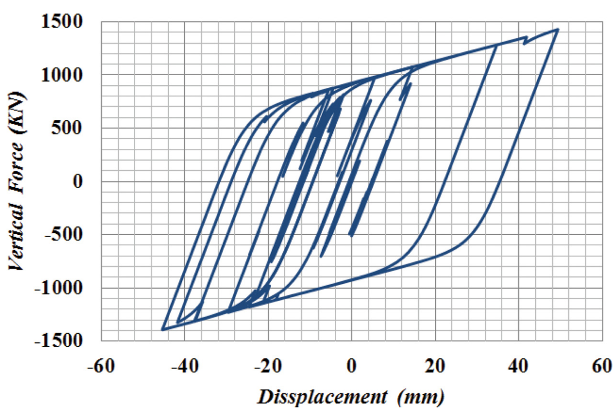

Fig. 3 The hysteretic behavior of the telescopic columns subjected to Imperial Valley EQ

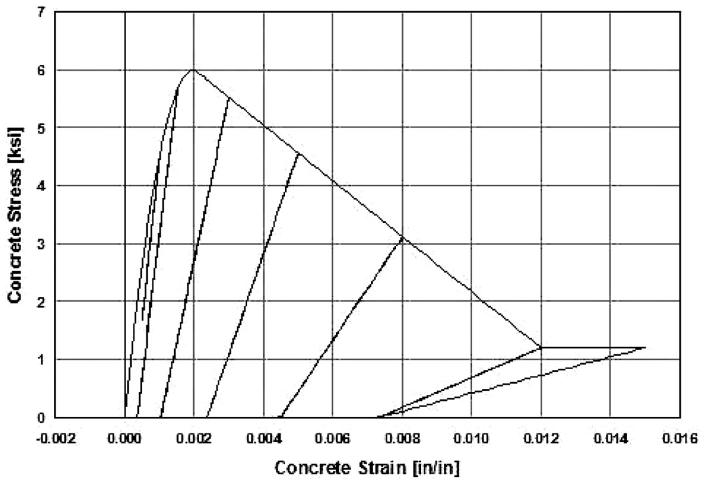

Fig. 4 Typical hysteretic stress-strain relation of concrete with zero tensile strength

between changes in displacement direction, to more sophisticated and versatile techniques. Among the available hysteresis models, Bouc-Wen hysteresis model (Fig. 2) is particularly noted. The load-deformation curve in axial loadings of the telescopic columns can be idealized by Bouc-Wen curve as a curvilinear one with 10% strain hardening (SAP 2000 User Manual 2010). The analytical hysteresis curve for the proposed base isolating system based on Bouc-Wen is extracted and illustrated in Fig. 3.

2.3 Material properties

For concrete material in the frame members and shear-walls a trilinear model (Fig. 4) that assumes no resistance to tension and features a residual strength plateau is implemented.

2.4 Case study

For comparing different systems, a ten-story building is selected. The studied building is a concrete frame with symmetrical plan, 5 m span, and 3 m story height with a core shear wall in all stories. The plans of all stories are the same and loadings of all frames are similar (Fig. 5). In dynamic analysis of the structures by SAP2000, the analysis is carried out on a single frame representative of the whole structural system (Fig. 6). For designing systems equipped with telescopic columns, at the first stage a hybrid (moment frame + core shear-wall) structural system is designed for the minimal base shear force based on ACI-05 considerations (Table 1).

Under the static equilibrium condition, gravity loadings will be distributed in all the supports (telescopic columns + central column). For the investigated building with 225 m^2 floor area, 40 telescopic columns are considered in the perimeter of the structure's base. These columns will remain in their elastic range for a load factor of 1.15×(*DL*+*LL*) and after that the steel plates in the telescopic columns will start to yield and the proposed seismic isolating system will damp the earthquake loading by its nonlinear behavior. It's worth mentioning that after the earthquake event, the telescopic columns can be easily replaced with a new one for the future earthquakes.

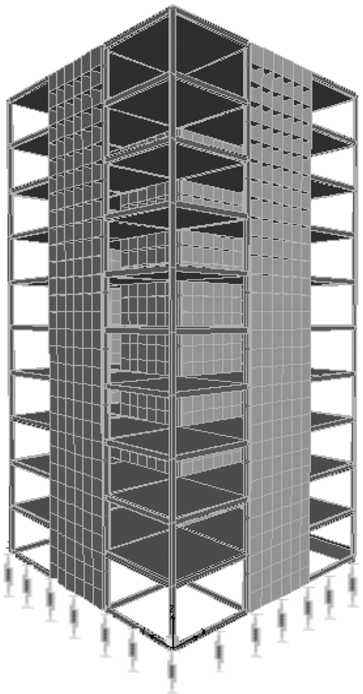

Fig. 5 Schematic view of telescopic columns placement in the structure's base

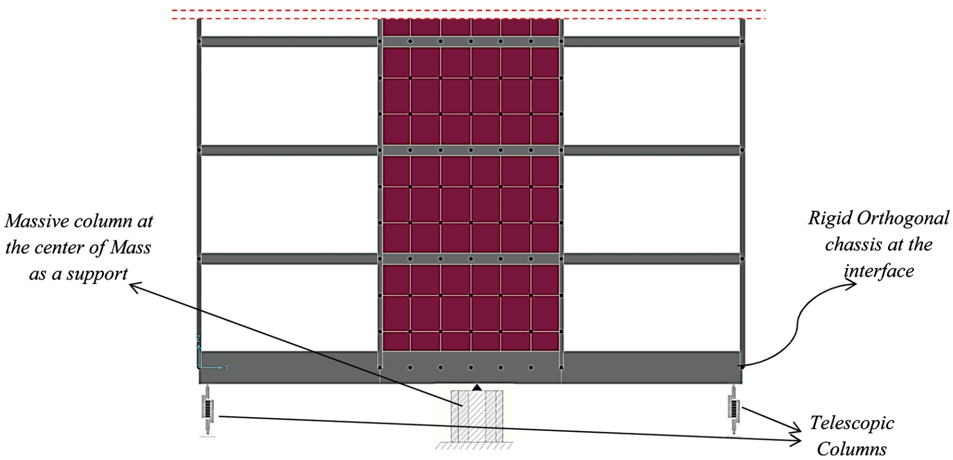

Fig. 6 Details of telescopic columns used in the structural model

Table 1 Specifications of the 10 storeys building (Designed based on ACI-05)

Storey No.	Column sections (cm^2)	Shear walls thickness (cm)	Beams sections (cm^2)	Floor slabs thickness (cm)
1, 2	60×60 (20Φ24)	50	40×40	15
3, 4, 5	50×50 (16Φ20)	40	40×40	15
6, 7, 8	40×40 (12Φ18)	30	40×40	15
9, 10	30×30 (8Φ18)	20	40×40	15

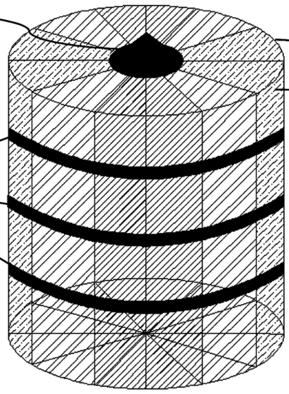

Fig. 7 Central massive column configuration

2.5 Central column

The giant central column plays an important role in our proposed system; it will tolerate most of the gravity loading in the static stability condition and will let the structure to go in the rocking mode under the seismic loadings. The proposed configuration by the authors for this column is illustrated in Fig. 7. The main reason for manufacturing the column with such configuration is to simplify the column replacement in case of severe ground motions where the central column would yield as well as the telescopic columns and should be replaced. By the proposed configuration each slice of the column can be easily replaced with a new one while the overall structure's stability will be retained.

2.6 Other base isolating systems

For a better comparison and to show the efficiency of the proposed system, 2 conventional base isolation methods are simulated in SAP2000 as well and a *NL* Dynamic analysis have been performed on them. In this study rubber isolator bearing and friction pendulum bearing are chosen for the comparison.

2.6.1 Rubber isolator bearings

The seismic isolators in the system are defined as *NL*-link components 0.4 m in length placed between the fixed base and the columns. The parameters selected to define the utilized isolators in the SAP2000 program are as follows:

Nonlinear Link Type: Rubber, U1 Linear Effective Stiffness: 2500 kN/mm, U2 and U3 Linear Effective Stiffness: 1.5 kN/mm, U2 and U3 Nonlinear Stiffness: 4.5 kN/mm, U2 and U3 Yield Strength: 80 kN, U2 and U3 Post Yield Stiffness Ratio: 0.1.

All the values remaining outside the above indicated parameters are entered as zero. The reason for the effective damping value being entered as zero is its non-functionality in the nonlinear time history analysis. Damping in here occurs with the conversion of hysteresis curve under the influence of seismic loading. The modal damping values for the first 3 mode are assumed to be zero while carrying out the analysis for this damping value not to coincide with the modal damping value. In this way, the structure shall behave as if without damping, and all damping requirements shall be met by the isolators (Torunbalci and Ozpalanlar 2008).

2.6.2 Friction pendulum bearings

Friction pendulum isolators are defined as *NL*-link components 0.4 m in length placed between the fixed based and the columns just like in the case of rubber isolators. The parameters selected to define the utilized isolators in the program are as follows:

Nonlinear Link Type: Friction Isolator, U1 Nonlinear Effective Stiffness: 15000 kN/mm, U2 and U3 Linear Effective Stiffness: 1 kN/mm, U2 and U3 Nonlinear Stiffness: 20 kN/mm, U2 and U3 Friction Coefficient, Slow: 0.03, U2 and U3 Friction Coefficient, Fast: 0.05, U2 and U3 Rate Parameter: 40, U2 and U3 Radius of Sliding Surface: 2.5.

3. Input earthquake records

In general, earthquakes have different properties such as peak acceleration, duration of strong motion and ranges of dominant frequencies and therefore have different influences on the structure (Takewaki and Tsujimoto 2011, Takewaki 2006). In order to ensure that the chosen mitigation procedure is effective under different types of excitations, three, well-known earthquakes records

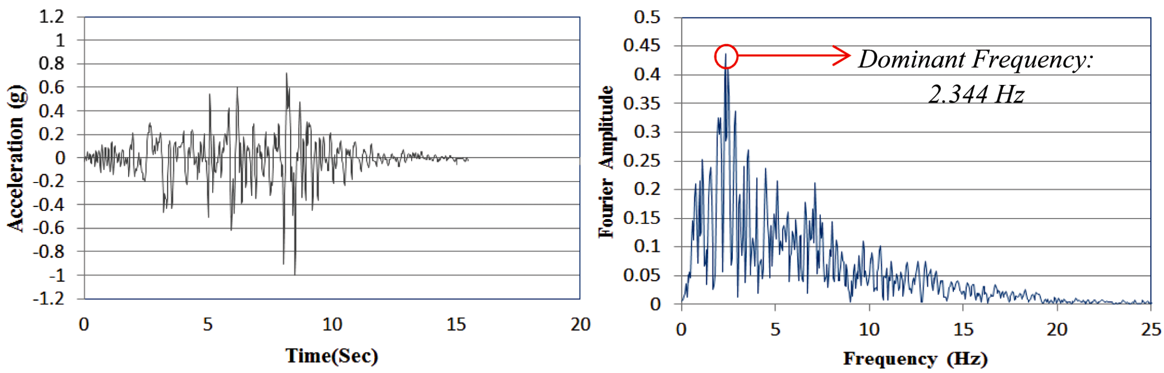

Fig. 8 San Fernando earthquake record and its dominant frequency

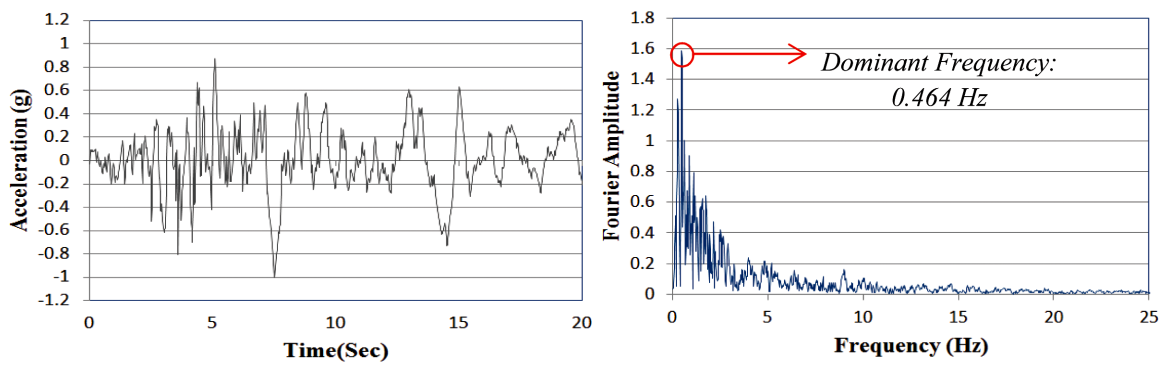

Fig. 9 Long Beach earthquake record and its dominant frequency

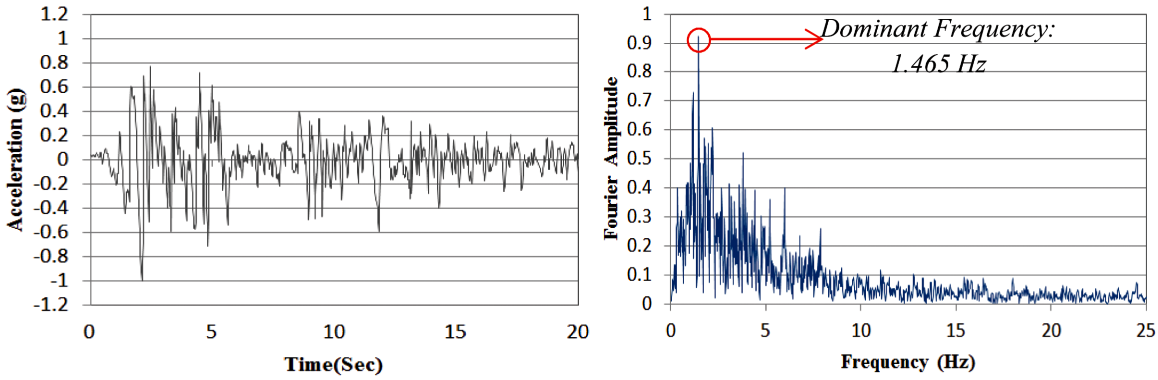

Fig. 10 Imperial Valley earthquake record and its dominant frequency

were used in this study. These were all applied for the first 20 s of their duration, during which the strong motion took place.

For more consistent comparison and considering severe seismic excitations, all earthquake records were scaled to peak ground acceleration (PGA) of 1.0 g. Durations of the strong motions were kept unchanged and Power spectrum graphs produced based on Fast Fourier Transform Techniques, using *SeismoSignal* Version 4.3.0. The earthquake records, which were selected to investigate the dynamic response of the models are shown in Figs 8-10.

4. Non-linear dynamic analysis

The time history analysis determines the response of a structure due to forces, displacements, velocities or accelerations that vary with time. There are two types of this method, first is direct integration and the second, modal superposition (Karabörk 2001, Zienkiewicz and Taylor 2005). Modal superposition is only suitable for linear analysis, whereas direct integration can be used also for nonlinear analysis. The most popular integration scheme is the Newmark-β method, which is implicit and unconditionally stable. The following approximations are made in this method

$$\{\dot{U}\}_{t+dt} = \{\dot{U}\}_t + (\{\ddot{U}\}_t + \{\ddot{U}\}_{t+dt})\frac{dt}{2} \tag{1}$$

$$\{U\}_{t+dt} = \{U\}_t + \{\dot{U}\}dt + \left(\left(\frac{1}{2}-\beta\right)\{\ddot{U}\}_t + \beta\{\ddot{U}\}_{t+dt}\right)(dt)^2 \tag{2}$$

where dt is the time step of the analysis, and β is the structural damping depend on an amplitude decay factor, but usually a value of 0.25 is used (Zienkiewicz and Taylor 2005).

During strong and mediocre earthquakes, structures go into plastic range. Therefore, we have to use a nonlinear analysis. For this purpose, numerical simulations were carried out by SAP2000 software. Beams and columns were modeled as frame element. Shear walls are considered as Shell elements. For modeling telescopic columns, we used an equivalent spring by means of Link element with non-linear behaviour explained earlier and for the massive central column a nonlinear

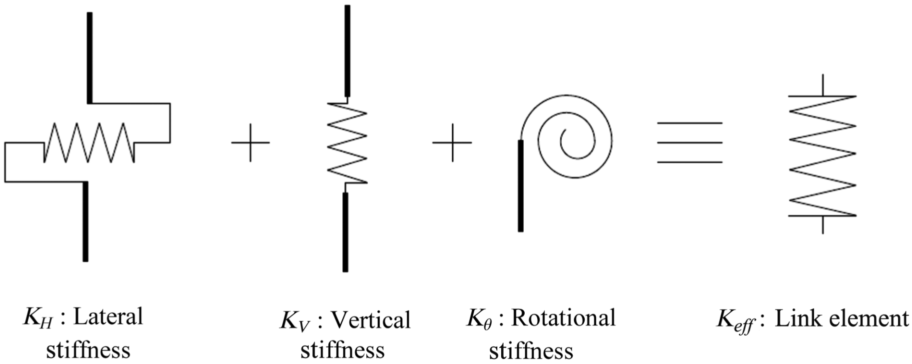

Fig. 11 Effective stiffness of a link element to consider nonlinear behavior

Table 2 The first three modes' periods of different systems

Structural system	1st Mode period (second)	2nd Mode period (second)	3rd Mode period (second)
Hybrid system equipped with rubber isolator bearings	2.29	0.40	0.10
Hybrid system equipped with friction pendulum bearings	2.73	0.37	0.10
Hybrid system equipped with telescopic columns	0.88	0.15	0.10

rotational spring by means of link element is considered. The general characteristics of a link element are shown in Fig. 11. It's worth mentioning that the *P*-Delta effect is also included in this study for considering the large deformations caused by rocking motions of the proposed seismic isolating system which would significantly affect the results. For numerical simulations, accelerograms related to horizontal component of the San Fernando, Long Beach and Imperial Valley are used (Figs. 8-10).

Assessment of structure period is another important factor in analyzing its flexibility and ductility. In addition, designers always try to avoid structural periods close to dominant period of the exiting force. To this end, the first three modes' periods of different systems are shown in Table 2. Considering this table, it could be found that periods of the system equipped with telescopic columns are lower than other systems and Hybrid (*MF*+*SW*) system equipped with friction pendulum bearings has the largest period among all. By comparing the results it can be observed that the proposed system will not be excited by resonance phenomenon under the considered *TH* loadings.

5. Results and discussions

A direct integration dynamic analysis was selected to obtain the response of the structure under seismic loadings. This analysis assembles the mass, stiffness and damping matrices and solves the equations of dynamic equilibrium at each point in time. The response of the structure is obtained for selected time steps of the input earthquake accelerograms. To study the effectiveness of the damping system in mitigating the seismic response of the buildings in this study, the maximum inter-storey drifts for all the storeys and acceleration at the top of the structure are obtained from the results of the analysis and compared with other base isolation systems.

In Fig. 12 maximum relative storey displacements (drifts) of different systems for San Fernando, Long Beach and Imperial Valley accelerograms along the buildings height are illustrated. It can be easily observed from the results that the structural system equipped with telescopic columns has a very good seismic isolating behaviour compared to other 2 systems and definitely after some modifications in the future studies for its configuration and material properties, it is expected that the new system would have relatively higher performance in comparison to other base isolating systems. This fact will minimize non-structural damages during earthquake.

For a better illustration and comparison of the results obtained from SAP2000 in terms of inter-storey drifts, the averaged drift for each storey from all earthquake loadings in each isolating system is calculated and shown in Fig. 13. As can be seen the new system has a more uniform trend

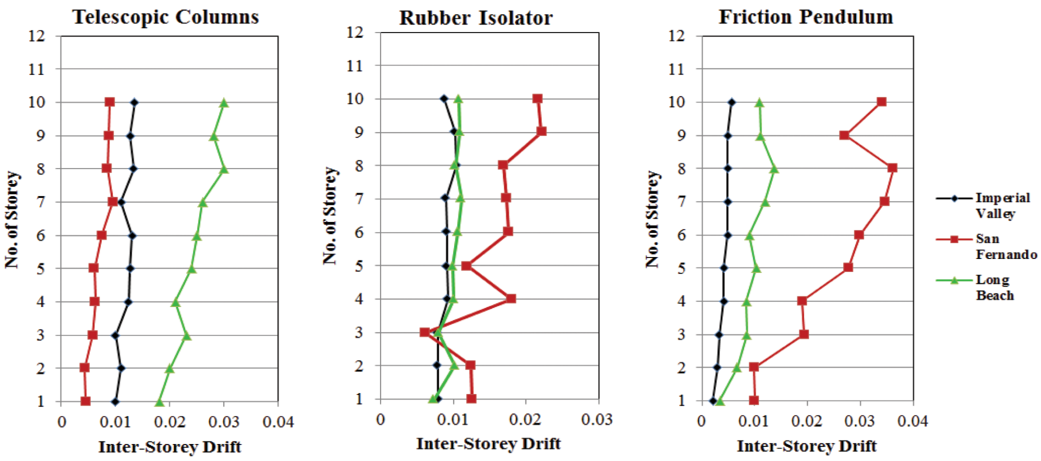

Fig. 12 Inter-storey drifts ratios vs. building height for different systems

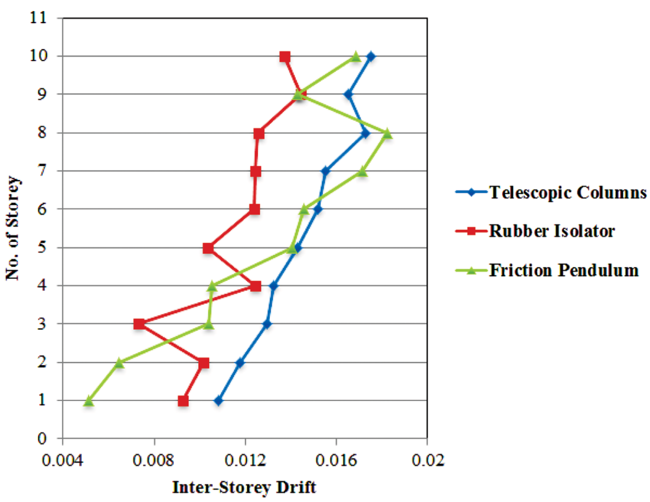

Fig. 13 Averaged inter-storey drifts of 3 earthquakes records in different systems

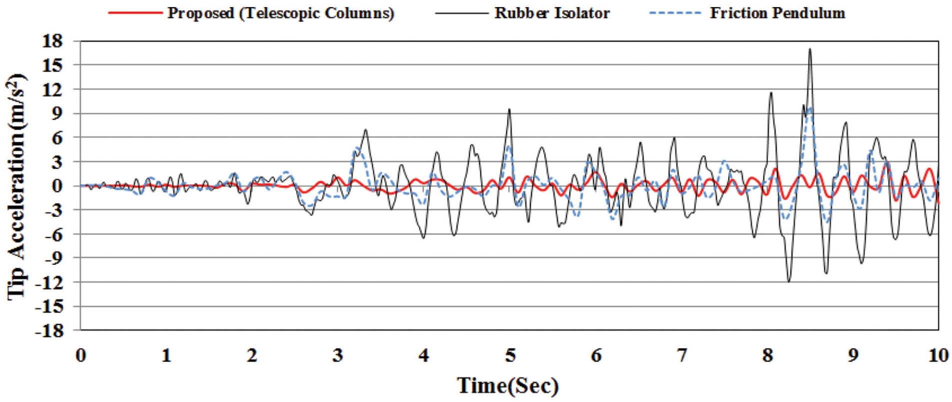

Fig. 14 Roof acceleration time history of the structures under San Fernando Eq.

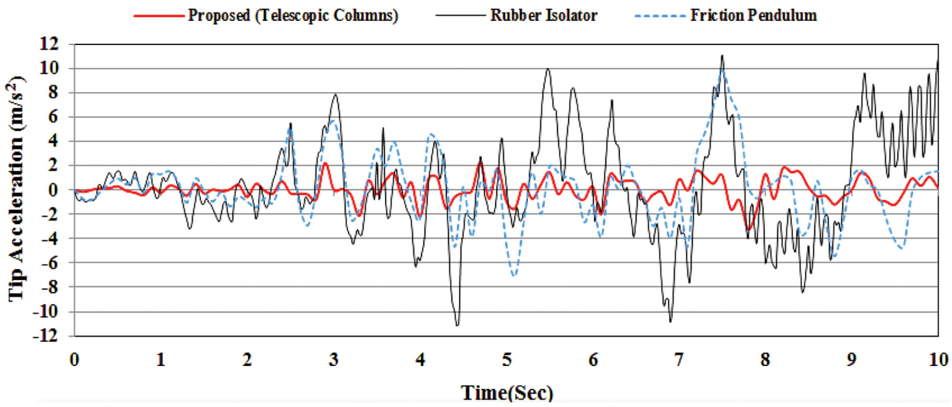

Fig. 15 Roof acceleration time history of the structures under Long Beach Eq.

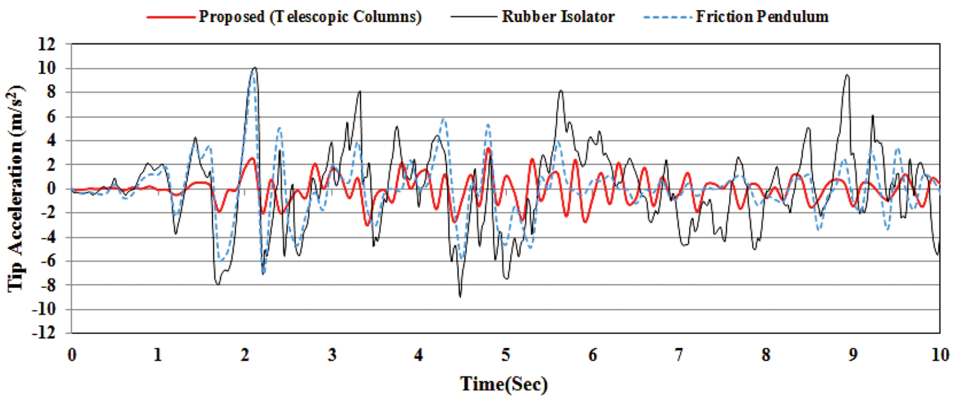

Fig. 16 Roof acceleration time history of the structures under Imperial Valley Eq.

compared to other 2 systems and in higher levels it has relatively better performance in comparison to friction pendulum bearing system.

Acceleration of stories is an index of the comfort of inhabitants especially from psychic point of view. To this point, the acceleration of roof for different systems in the accelerograms of San

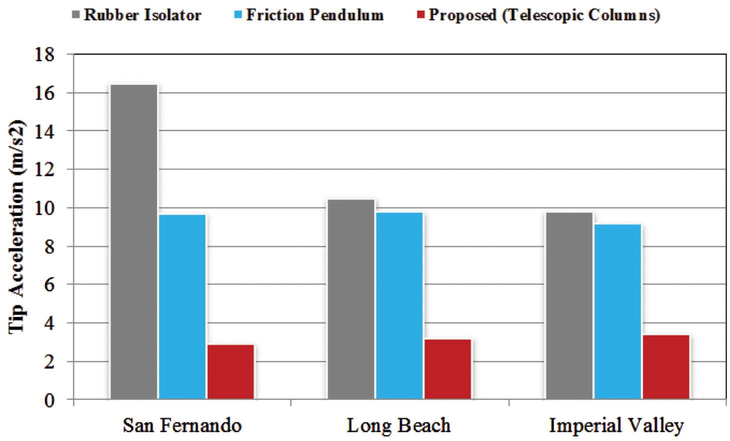

Fig. 17 Maximum tip acceleration for different systems under 3 earthquakes loadings

Fernando, Long Beach and Imperial Valley are analyzed. Figs. 14-16 show the *TH* responses of investigated systems in terms of tip acceleration under 3 earthquake records. For a better comparison and illustrating the effectiveness of the proposed system the maximum amount of acceleration for different systems is also shown in Fig. 17. As it can be seen, the maximum acceleration of the roof for the structure equipped with the proposed system (Telescopic columns) in all earthquakes is surprisingly lower than other systems (Around 77.6%, 68.3% and 64% differences can be observed for San Fernando, Long Beach and Imperial Valley earthquakes).

The results have shown that the new system can properly compete with the rubber isolator and friction pendulum bearings. The conventional base isolation system might reduce the inter-storey drifts in a better way but the buildings large deformations and high acceleration in top storeys are their main drawbacks which our proposed system based on the above presented results overcomes these shortages and has the best overall performance among all the studied isolating systems.

6. Conclusions

The main contribution of this research was to establish that seismic mitigation of building structures can be achieved by using telescopic columns as a new seismic base isolating system. This is a novel method of seismic control and the feasibility of this approach has been considered and simply demonstrated in this study. A strategy for protecting buildings from earthquakes is to limit the higher storeys drifts and accelerations, which provides an overall assessment of the seismic response of the structure. Different building structures require different damping systems for the best results. To this end, findings of the present study revealed that:

• Telescopic columns can effectively reduce the drifts and accelerations in the upper storeys which show high comfort level of this system in comparison to other similar systems (Overall performance is much better).

• By the configuration proposed in section 2 of this research, manufacturing the proposed seismic isolating system seems to be feasible.

• For the first three modes as the results illustrated earlier, the proposed system has higher periods compared to conventional system which is caused by the rocking motion of the overall system but

relatively lower periods compared to other base isolating systems.
• Based on dominant frequency of the used *TH* loadings the proposed system is safe and secure against resonance phenomenon.

The followings are the authors' suggestions for further research in this area:
• A more detailed Finite Element Modeling should be investigated to get more accurate results.
• A real model of the proposed base isolating system should be manufactured and tested in the Lab. for the verifications of numerical analysis results.
• More study should be done on the configuration and dimensions of the proposed system especially the central column and its connection to the structures base to obtain the best results.
• The material used in the proposed system for the yielding plates might give better results if changed (In this study steel material used because of its availability in the construction industry)
• Performance of the proposed system under synthetic excitations with a wide range of frequencies and peak ground accelerations should be investigated.

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