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A SIMPLIFIED SEISMIC DESIGN METHODOLOGY OF DAMPED PIN SUPPORTED WALLS FOR THE RETROFITTING OF FRAMES

R. Jeries(1), O. Lavan(2)

(1) B.Sc., Graduate student: Technion – Israel Institute of Technology, raed@rj-engineers.co.il
(2) Ph.D., Associate Professor: Technion – Israel Institute of Technology, lavan@technion.ac.il

Abstract

Frames are one of the common lateral load resisting systems of existing buildings. Many of these frame buildings were designed and built based on previous versions of seismic codes. In some countries, some of these buildings were even designed and built before seismic codes were published. Thus, their detailing is not appropriate and they were not capacity designed. Consequently, their strength and ductility capacities are insufficient. Furthermore, their probability of experiencing a soft story mechanism is much higher than that of their seismically designed counterparts.
Recently, Wada et al. (2012) [1] have proposed the pin supported wall system for the seismic retrofitting of frame buildings. They also applied it for the seismic retrofitting of the G3 building at the Suzukakedai campus of Tokyo Institute of Technology. These systems comprise a wall attached to the existing building and connected by a hinge to the foundation. Due to its relatively large bending stiffness, and the pin connection at the base, the wall imposes a first mode shape where the displacements linearly increase with height. Thus, soft/weak story mechanisms are efficiently prevented. Furthermore, the fundamental period of the building remains almost unchanged. In the G3 building, yielding devices were introduced to improve the energy dissipation and the seismic performance of the system.

In this paper we propose to use viscous dampers in strategic locations of the pin supported wall system (see Fig. 1). While the pinned walls enforce similar inter-story drifts in all stories, the use of viscous dampers may lead to reductions of displacements, forces and accelerations in the main structure. Furthermore, their allocation as depicted in Fig. 1 leads to very small axial forces in the pinned walls and their foundations. In addition to proposing the viscously damped pin supported wall system, this paper presents a simplified design methodology for such systems. An approximated pushover curve of the existing frame is first presented. Then, an equivalent nonlinear single degree of freedom is formulated. The required added damping is then evaluated, so as to obtain a desired target displacement.

An example of a nine-story moment resisting steel frame is used to assess the performance of the proposed approach. The design obtained using the proposed methodology is subjected to a suit of ground motions and analyzed using a linear time history analysis. The comparison shows that the peak displacements experienced by the system are very close to the target.

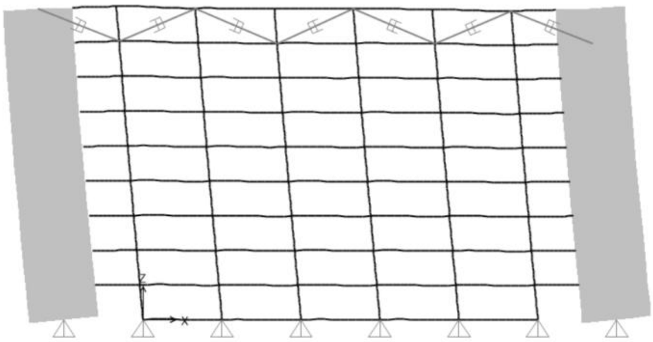

Fig.1 - Damped pin supported wall system

Keywords: pin-supported walls; viscous dampers; seismic retrofitting

Introduction

Earthquakes are one of the most destructive natural hazards throughout human history. Over the last century, earthquakes have claimed hundreds of thousands of lives[2]. The main cause of structural failures was the collapse of buildings and the lack of knowledge and inadequate codes and standards. For instance, 25,000 people were killed in the 1988 Armenian earthquake versus 63 people in California in the 1989 Loma Prieta earthquake of the same magnitude.

Over the last few decades, significant efforts have been made to retrofit existing buildings in general and frame structures in particular. However, many frame structures that were not designed to resist lateral forces still exist. These structures are characterized by insufficient global strength and stiffness and low ductility capacity. In many of these frames, a soft story mechanism is expected with a brittle shear failure[3].

The traditional methods for the seismic retrofitting of such systems rely on an increase of strength and stiffness, which attracts more seismic loadings that, in turn, result in increasing the elements section and footings dimension. Moreover, it increases the absolute accelerations which may increase the damage to nonstructural components, which in many cases can be more expensive than the building structure skeleton. In addition, nonstructural damage can also hinder the functionality of the building, as can be learned from the 1994 Northridge earthquake, In which 6 of 91 hospitals were evacuated because of nonstructural damage such as water damage and loss of electrical power [4].

In order to avoid a soft and weak story mechanism, a frame pin-supported wall system has been introduced for enhancing the story-by-story integrity of frames [5-8]. As shown in Fig. 2, the pin supported wall system is a combination of a frame and a pin-supported wall, which can rotate around a hinge at the base. These walls are usually placed on the perimeter of the building and are connected to the frame at each story

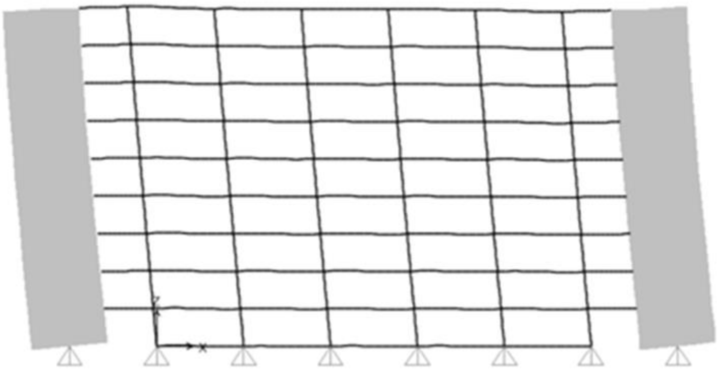

Fig. 2 - Pin Supported Wall System

The addition of a pin-supported wall to the frame guarantees a well-controlled mechanism, prevents a weak/soft story mechanism and often does not change the stiffness and strength of the structure. Thus, its main contribution is to the overall ductility capacity of the building. Pan et al. [9] have developed a distributed parameters model to investigate the strength demand of the wall in a frame pin supported wall structure. They found that this system can effectively reduce the drift concentration factor.

Since energy dissipation may also improve the response of the structure, and in order to reduce displacements and acceleration demands, integrating dampers was also proposed [10-12]. Wada et al.[1] have retrofitted the G3 building in Tokyo using the same system with post-tensioned concrete walls and steel dampers, as shown in Fig. 3.

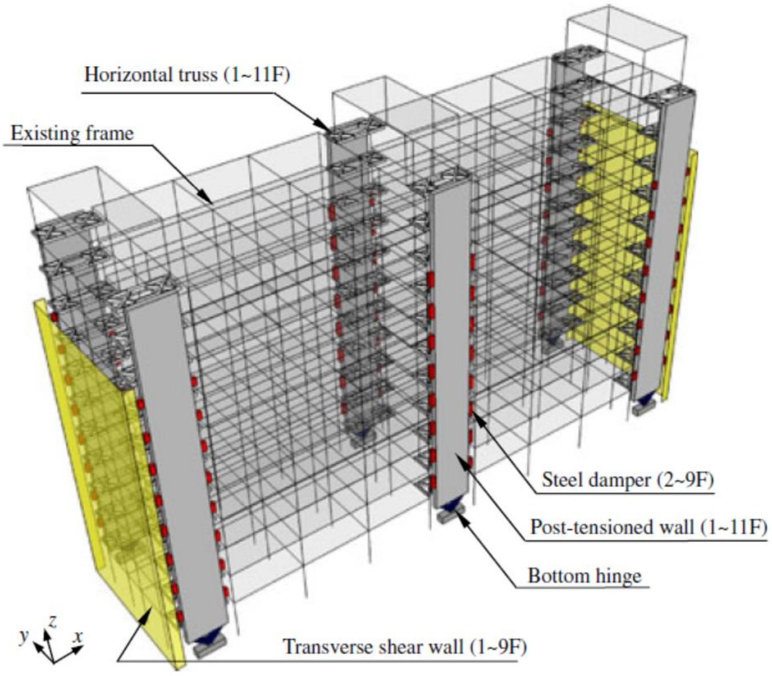

Fig. 3 - Retrofit plan of G3 building [1]

In this paper, it is proposed to combine fluid viscous dampers (FVDs) with the pin supported wall system. The FVDs are expected to reduce displacements, forces and acceleration in the structure. Furthermore, while the analysis of such systems is relatively straightforward, simple design tools are not available. Thus, the paper presents a new simplified methodology for the design of retrofitting frame structures using a damped pin supported walls system.

Retrofit Approach and Design Methodology

The proposed retrofitting approach is based on adding pin supported walls and FVDs to the existing frame structure. In some cases, the existing frame is not stiff/strong enough, from stability considerations. Hence, adding damping may not be sufficient. In this case stiffness/strength should be added to meet some minimum requirements. This can be done by adding diagonals between the added pin supported walls (Fig. 4). Then, the required added damping is computed. If the required added damping is too large, the best trade-off between adding stiffness and adding damping is chosen. This process is depicted in Fig. 5. Its main stages are as follows:

- An approximated push-over curve for the multi-degree-of-freedom (MDOF) Structure is calculated.
- The effective stiffness k_{eff} and the other characteristics of the equivalent inelastic single-degree-of-freedom (SDOF) structure are calculated.
- The stiffness k_0 (the minimum stiffness required from stability considerations) corresponds to a stability coefficient $\theta = 0.2$ is calculated.
- The effective damping ξ_{eff} corresponds to k_s (the maximum stiffness between k_0 and k_{eff}) is calculated.
- If $\xi_{eff} \leq 35\%$, the structure should be designed with k_s and ξ_{eff} .
- If $\xi_{eff} \geq 35\%$, additional stiffness is needed and the structure should be designed with a selected combination of $(k_{s-new}, \xi_{eff-new})$ in which $k_{s-new} > k_s$ and $\xi_{eff-new} \leq 35\%$.

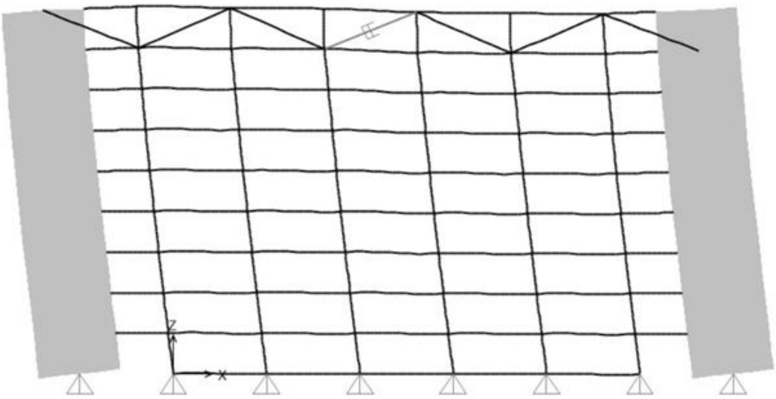

Fig. 4 – Damped pin supported walls

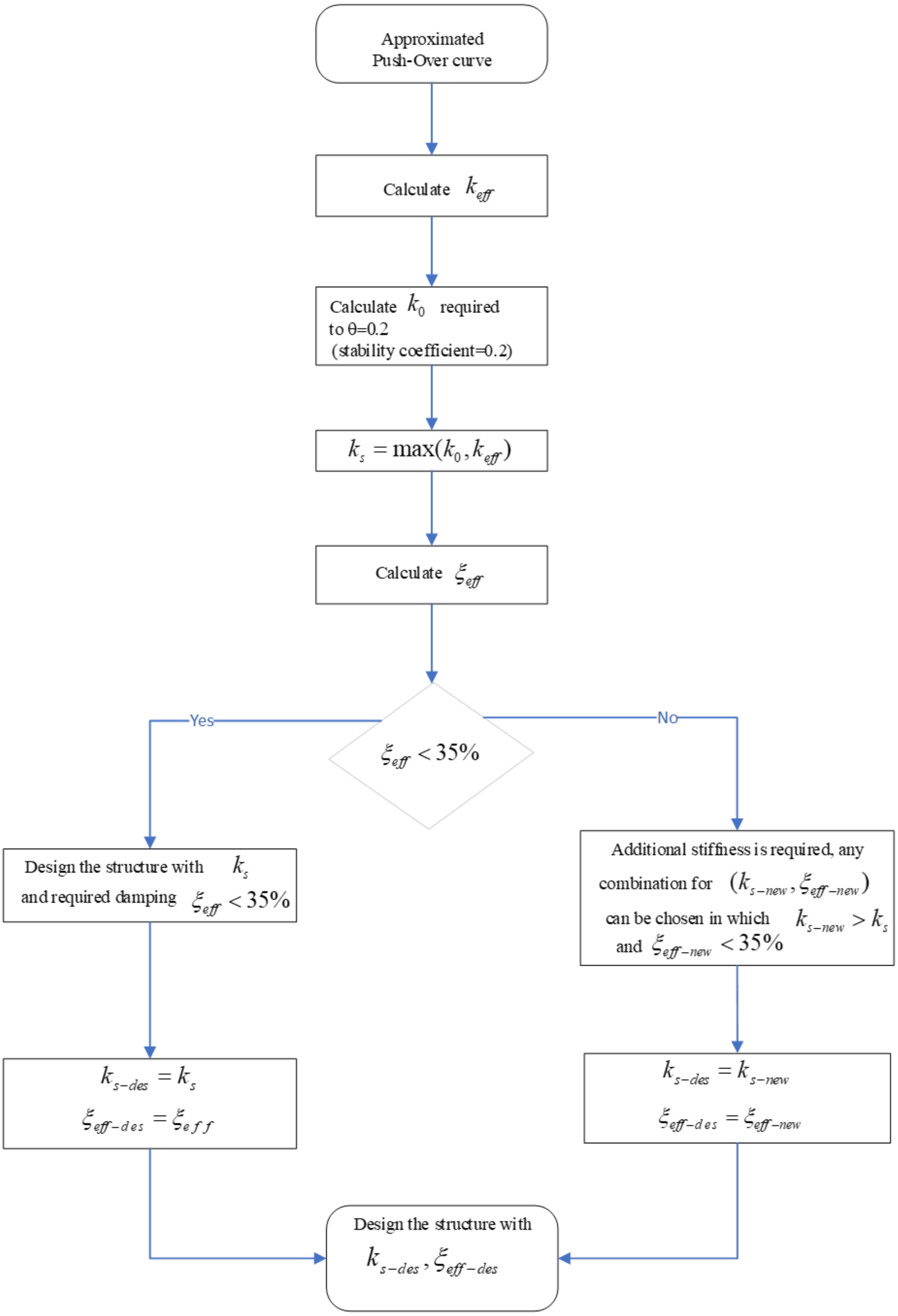

Fig. 5 - Methodology for the seismic retrofitting of frame structures using damped pin supported walls

Example

The following example illustrates the retrofitting of a nine-story steel frame which is 45.75 m in plan, and 35.64 m in elevation. The bays are 9.15 m on center, and the height of each floor is 3.96 m. The columns are 345 MPa steel wide flange and the beams are 248 MPa steel wide flange. The beam sections are W36X135, The column sections are W14X500 , and the seismic mass of each story is 513 ton. The distributed loads on beams corresponding to the critical gravity load combination is 110 kN/m. The properties of the frame sections are shown in table 1.

The steel frame wasn't designed to withstand lateral forces, so a seismic retrofitting is presented using the damped pin supported walls system. A pin supported wall is first added to the steel frame as shown in Fig. 6. The first mode of the pin supported wall system is shown in Fig. 7. The horizontal response spectrum and the displacement spectrum are shown in Fig. 8 and Fig. 9 respectively. The push-over curve is calculated according to a hand-calculation approach that is not elaborated on in this paper. The obtained pushover curve is compared in Fig. 10 with that obtained using sap2000 with relatively good agreement.

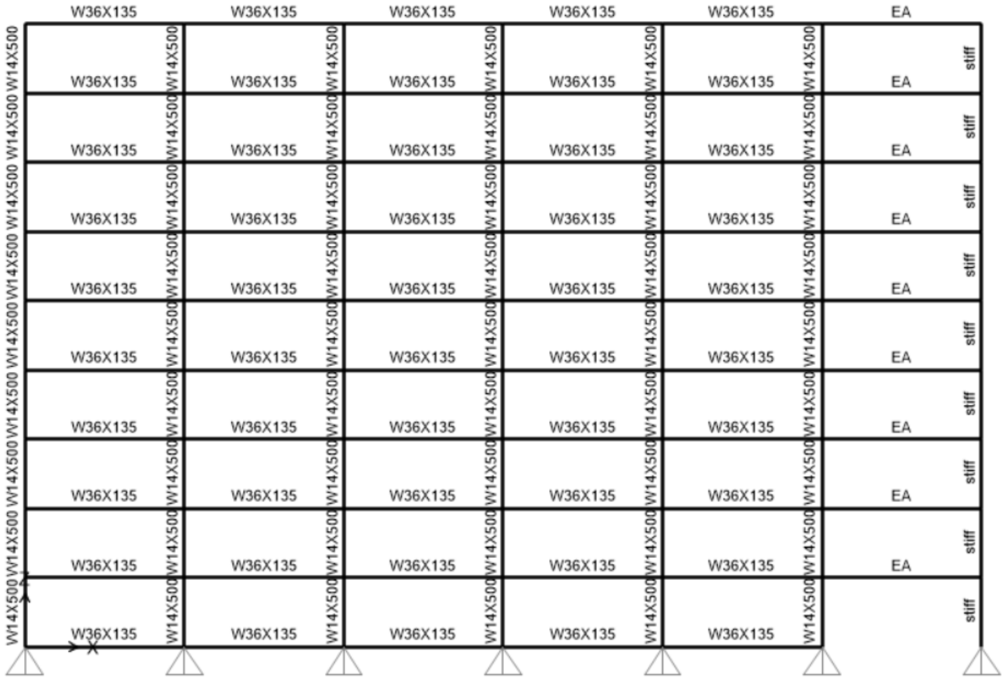

Fig. 6 - Nine-story moment steel frame connected to a pin supported wall

Table 1. The properties of the frame sections

Section Properties							
section	E(kn/m^2)	G(kn/m^2)	Area (m^2	I (m^4)	Wpl(m^3)	fy (Mpa)	My(knm)
W14*500	2E+08	76903069	0.0948	0.00341	0.0172	345	5936.24
W36*135	2E+08	76903069	0.0257	0.0032	0.0083	248	2068.58

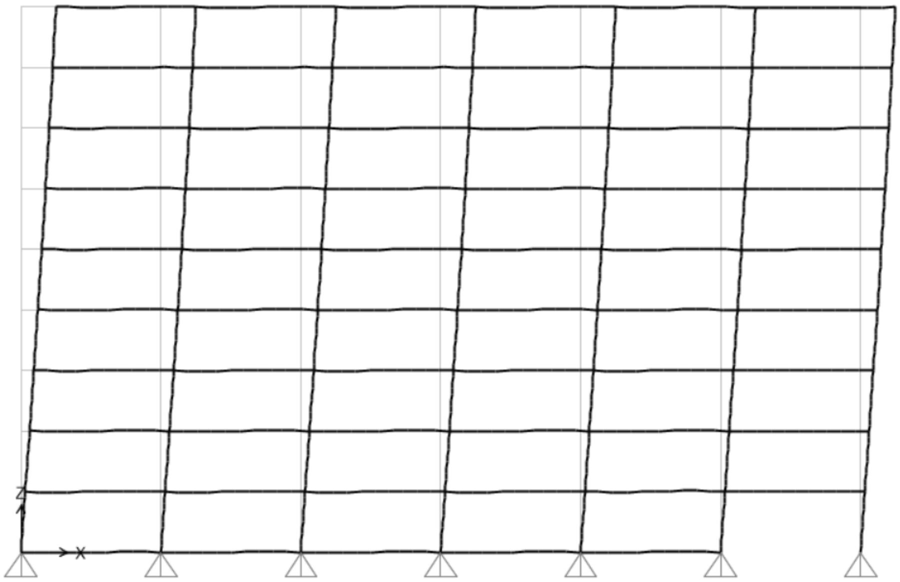

Fig. 7 – Mode 1 T-1.92 sec

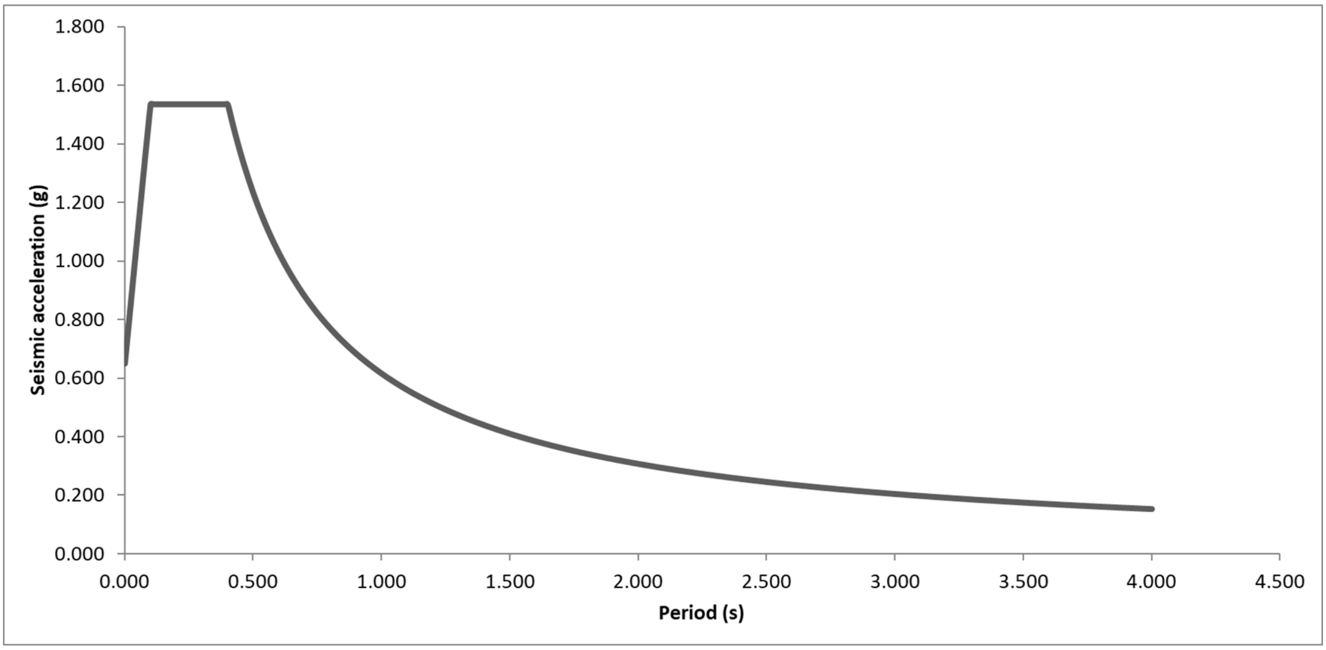

Fig. 8 - Response Spectrum

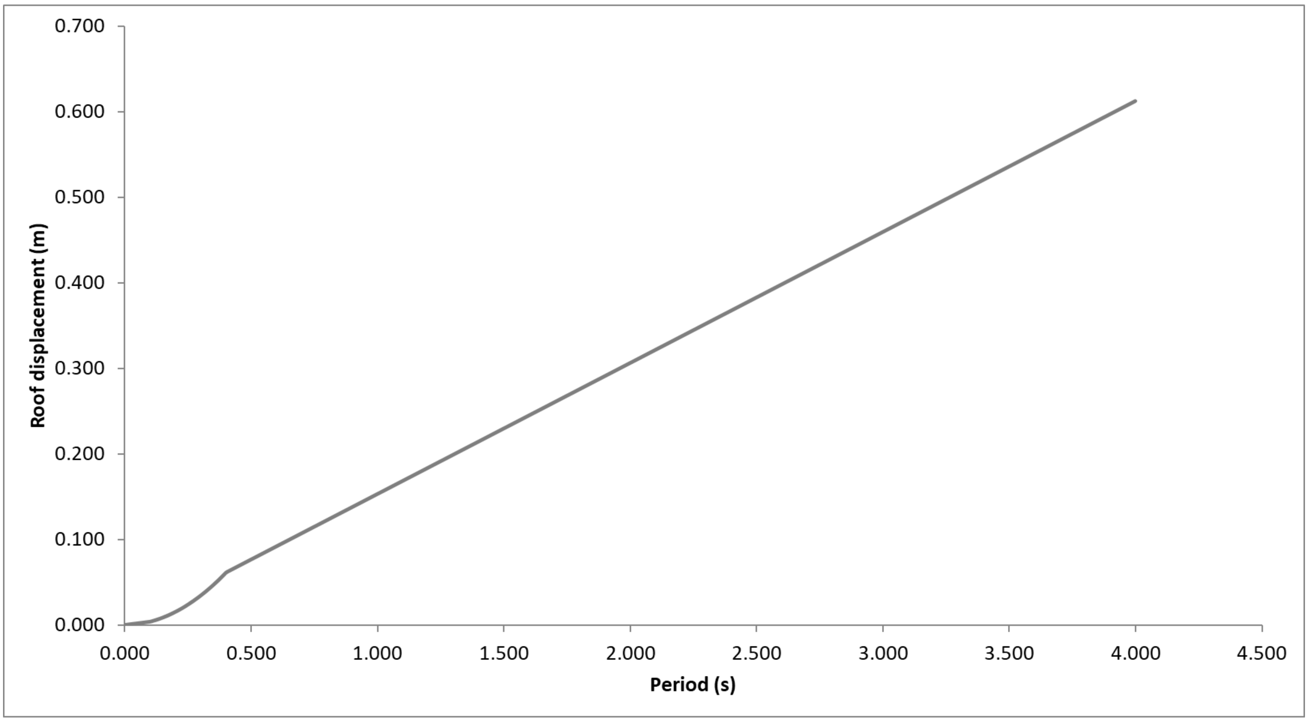

Fig. 9 - Displacement Spectra

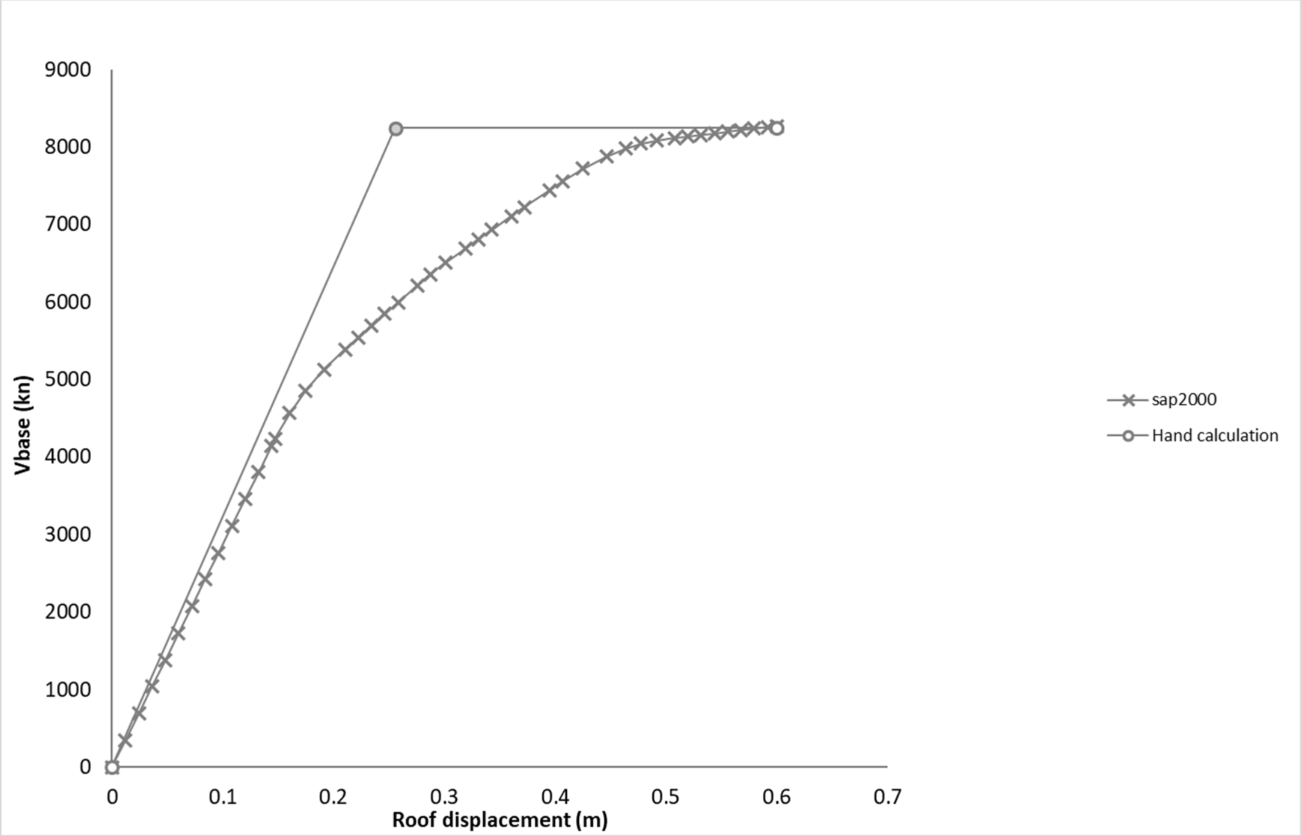

Fig. 10 - Hand calculated versus sap2000 push-over curve

The demand roof displacement of the un-retrofitted frame structure is 40.7 cm. Its yield roof displacement is 25.61 cm (see Fig. 10). Thus, the target roof displacement of the retrofitted structure is set to 25.6 cm so as to bring it to behave linearly. The effective stiffness is calculated as k_{eff}=31,723kN/m. The stiffness k_0, that is required from stability considerations is k_0=7,134kN/m. Thus, $k_s=\max(k_0,k_{eff})=k_{eff}$, and additional stiffness is not required to be added to the system. The effective period of the system with the pin supported wall is T_e=2.13sec and the required damping coefficient is ξ_{eff}=20.22%. Thus, the system should be designed with k_{eff} and ξ_{eff}. This indicates that, from both stability considerations and damping magnitude considerations, additional stiffness is not required. The damping coefficient required to lead to the desired damping ratio, with the configuration presented in Fig. 13, is C=247,178 kN·sec/m.

In order to compare the results with sap2000 program, a linear dynamic analysis was conducted, with seven scaled artificial time histories as shown in Fig. 11 with the corresponding response spectra shown in Fig. 12. A linear viscous damper has been added to the frame pin supported wall system as shown in Fig. 13:

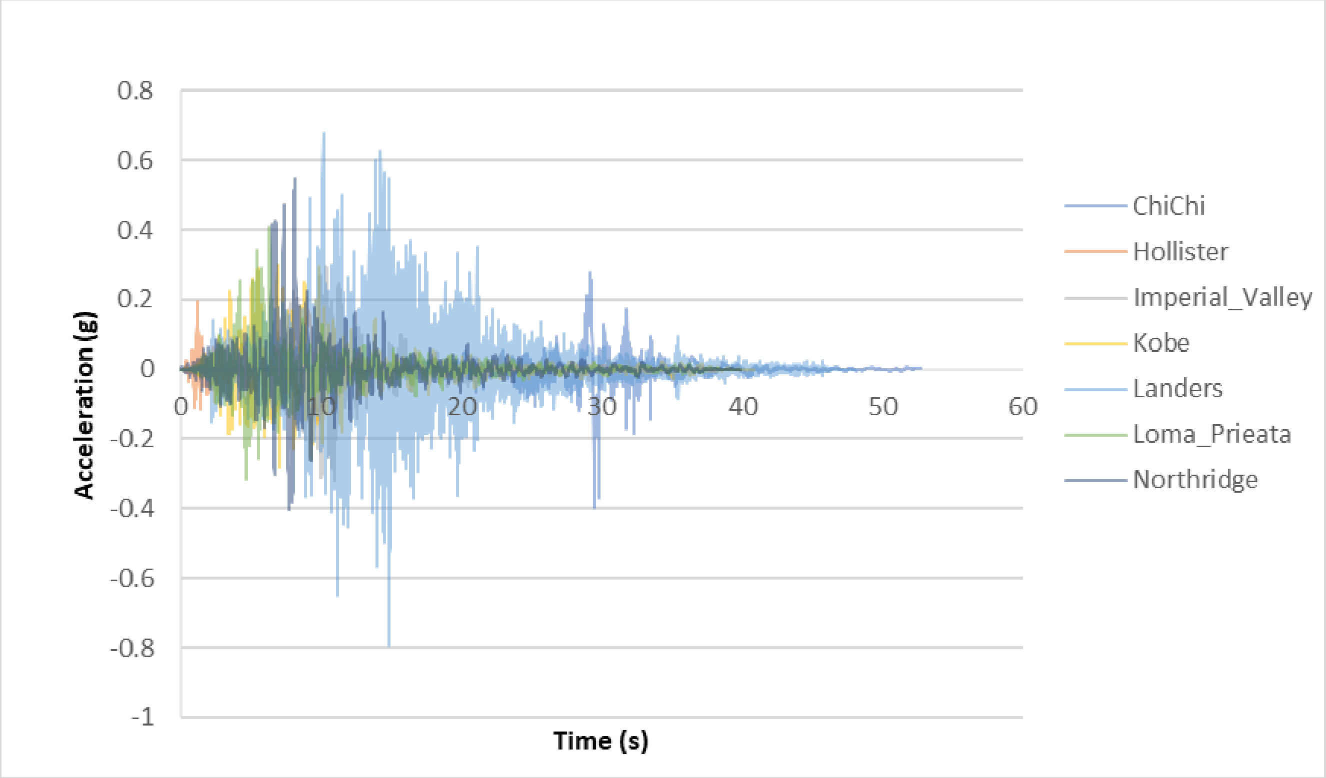

Fig. 11 - Seven scaled time histories

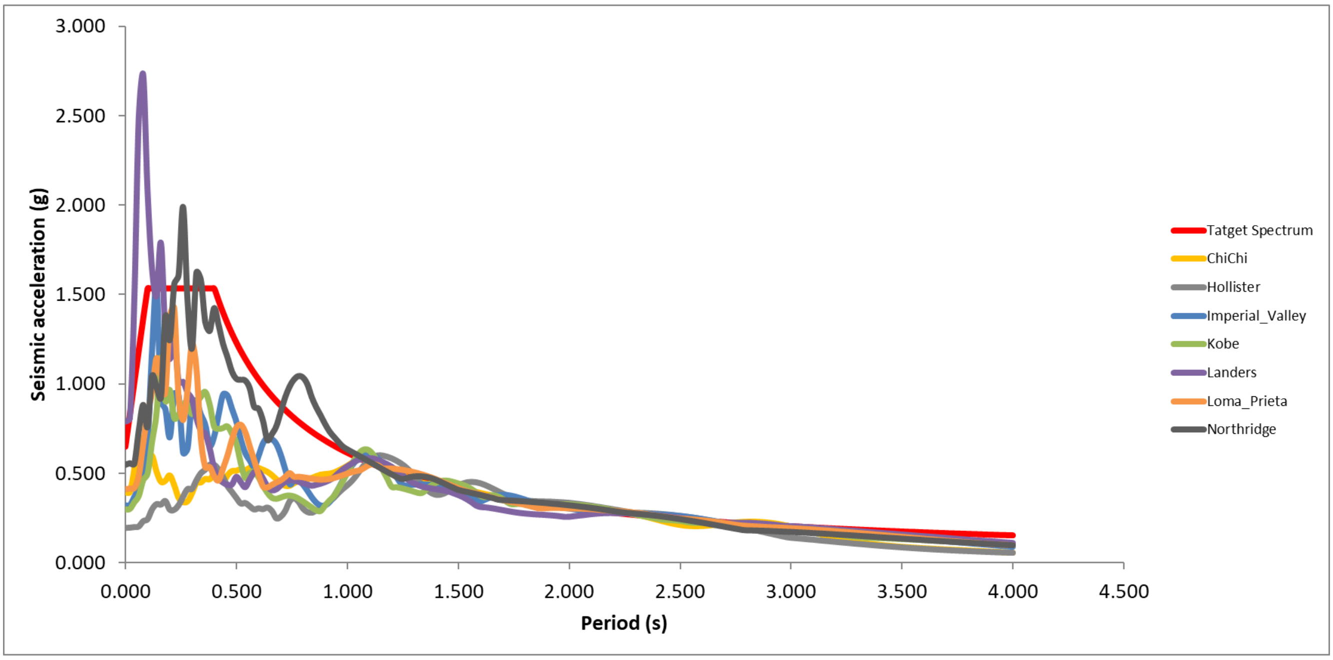

Fig. 12 - Seven scaled response spectrum

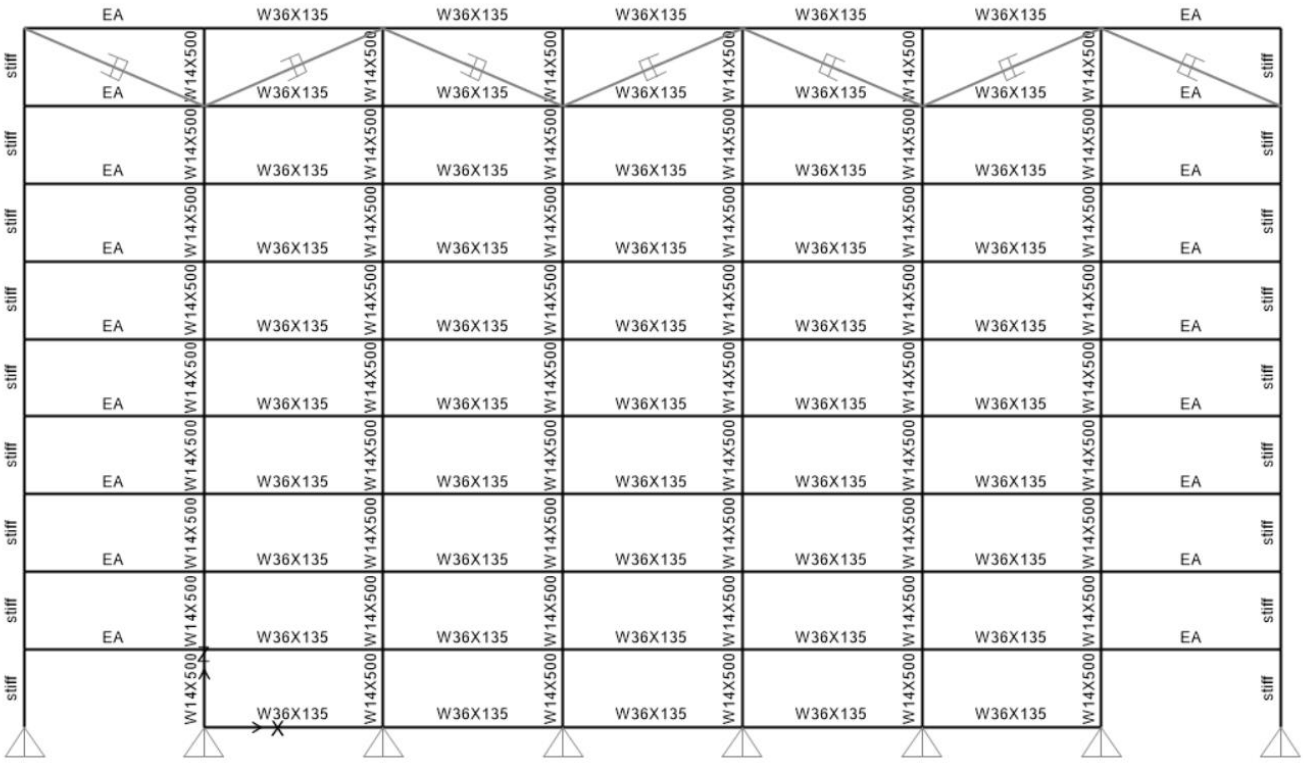

Fig. 13 - Damped frame pin supported wall system

The peak roof displacement of the frame was recorded for each scaled time-history as shown in table 2.

Table 2 - Displacement at the top of the frame at each scaled time history

	Time History-nonlinear analysis with linear dampers							
	TH1	TH2	TH3	TH4	TH5	TH6	TH7	**average**
Displacement(cm)	28.23	25.5	23.84	22.79	23.27	24.52	30.22	25.48

The average displacement as shown in table 2 is very close to the initial deformation design, which means that the initial design approach leads to good designs that closely satisfy the deformation design targets.

Conclusions

In this paper, a simplified design methodology for the retrofitting of frame structures using damped pin supported walls system is presented. A pushover curve is first evaluated, Then an equivalent nonlinear single degree of freedom is formulated. the required added damping is then evaluated, so as to obtain a desired target displacement.

The design obtained using the proposed methodology is subjected to scaled ground motions and analyzed using a nonlinear time history analysis. The main conclusions are summarised below:

- The frame pin supported walls system can prevent a weak/soft story mechanism, guarantee a well-controlled deformation of the whole structure and almost does not increase the stiffness compared to the frame alone.
- The large lever arm between the pinned walls can efficiently reduce the axial forces (compression and tension) in the pinned walls as well as in the foundations.
- Adding damping to the system reduces the acceleration and the displacements, so the damped frame pin supported walls system is a very efficient solution for seismic retrofitting of frame structures.
- The hand calculated Push-Over curve is very close to the one calcuated using sap2000.
- The approximate calculation of the additional amount of damping required leads to very good designs that closely satisfy the deformation design targets.
- The comparison shows that the peak displacement experienced by the system are very close to the target.

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