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ANALYSIS OF ENERGY DISSIPATION IN SERIES AND PARALLEL

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Abstract

The seismic response of a cinema structure located in a high seismic zone of Mexico structured based on steel frames and composite slabs is analyzed. The response of the structure was analyzed using viscous fluid dampers with a 18.9-meter span, and the response is obtained through nonlinear time-history analysis. The results show that there were problems with a single viscous fluid damper due to the long span of the diagonal, resulting in large dimensions and also its connection. The damper resulted in difficult capacities to manufacture and test in the laboratory. As an alternative, the frame was studied with viscous fluid and frictional dampers placed in series and parallel, analyzing their response for twenty fully reversed cycles at the maximum expected displacement, with a frequency ω equal to the fundamental of the structure-damping system, comparing the energy dissipation and its equivalent linear properties. The equivalent system of viscous fluid dampers connected in series is incorporated into the cinema project, resulting in smaller dimensions and capacities, as well as its steel connecting elements. The proposal of parallel energy dissipation was viable with fluid viscous dampers connecting them with steel elements generating the necessary stiffness so that they behave axially, reducing the cost of the dampers and achieving the energy dissipation necessary for the project.

Keywords: Energy dissipation; series and parallel system; long-span

1. Introduction

Due to the advances in technology referent to seismic protection devices, principally on fluid viscous dampers (FVD) [1], it was intended to implement these devices in a construction project where the seismic demand is considerably high due to its closeness to the Mexican pacific coast, a zone repeatedly struck by intense seismic events. The original project, which will be explained in the current article, use FVD in a diagonal position, resulting on large forces, deformations and velocities, although its elaboration was still feasible, verification trough laboratory test was hard to realize.

Hence of the described above, alternatives were sought in the position of FVD whether they should be installed in series or parallel. Similar to springs and electric circuit studies, the position of FVD devices for major cost/benefit ratio is pursued. Worth mentioning, there may be other alternatives to this project as well: double diagonals or chevron configuration, which have already been used in the past. In this paper only FVD are examined and its problem in the testing process.

Although the three-dimensional model of the structure with the FVD devices in diagonal, a two-dimensional frame was considered with equivalent characteristics in order to reduce the computational effort and compare alternatives of use in a faster way. Results obtained by this simplified model will be used to make adjustments on the three-dimensional model to obtain all responses and compare the alternatives with better precision.

2. Model description

The mathematical model was realized on SAP2000 computational software [2], which takes into account architectonic requirements for a cinema theater. The ground level height is 6.5 m, while the second level has two different heights of 4.5 m and 7.15 m. Fig. 2 shows an elevation where the differential heights can be clearly identified. The plan view of the structure is shown in Fig. 1. This structure has an approximate plan dimension of 65.6 x 60.4 m with a slightly irregular form.

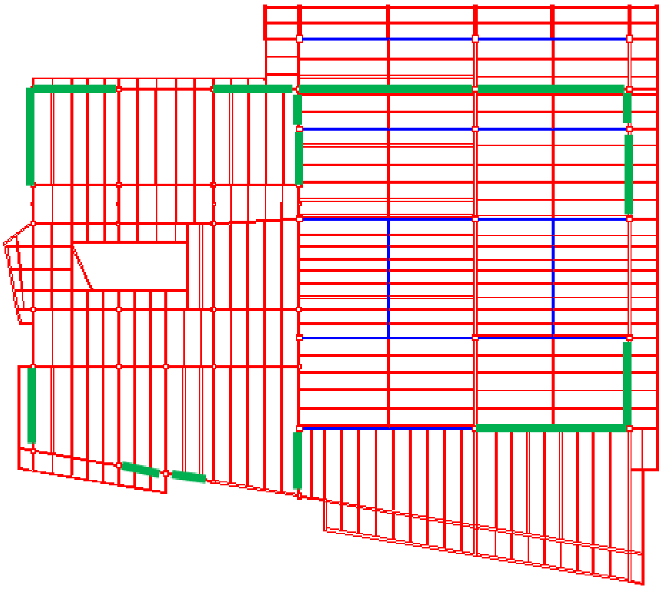


Fig. 1 – Plan view

Building´s structure is conformed by steel plates formed columns, I section beams, and steel deck. Due to the seismic zone where the cinema its located high stresses are induces to the structure, and therefore considerable displacements. Thus, FDV devices were implemented [3], the FVD were modeled like damper links, a predefined type of element in SAP2000 software [2]. Nineteen FVD were installed on the building, which are shown as green lines in Fig. 1, all FVD were positioned in a diagonal configuration as is can be observed in Fig. 2.

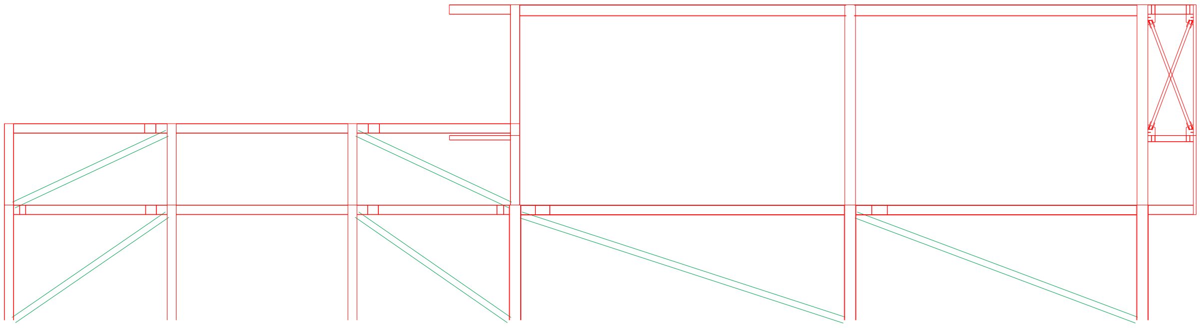


Fig. 2 – South elevation

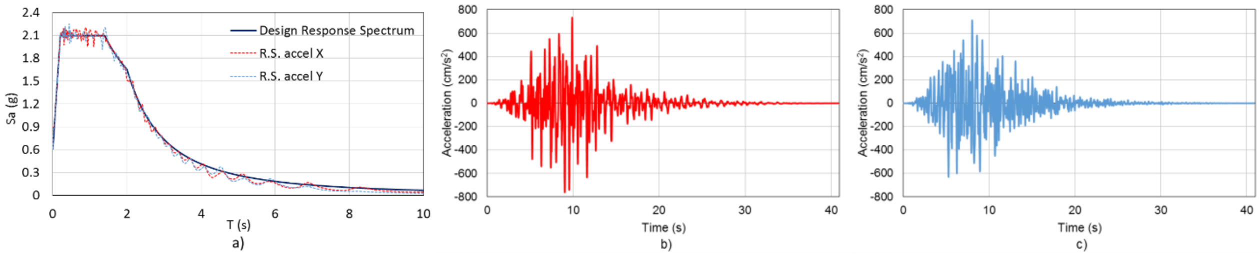
The following properties were asigned to the elements in the model:

- Structural shape beams: A992, Fy = 3515 kgf/cm^2, Fu = 4570 kgf/cm^2
- HSS sections: A572Gr50, Fy = 3515 kgf/cm^2, Fu = 4570 kgf/cm^2
- Plate sectins: A36, Fy = 2530 kgf/cm^2, Fu = 4080 kgf/cm^2
- Concrete, steel deck and foundation: f’c = 250 kgf/cm^2
- Reinforcment rebars: A615GR60, 4200 kgf/cm^2, Fu = 6325 kgf/cm^2

2.1. Design loads

The steel deck has a concrete layer 13 cm thick due to the use of the building and the many service equipment it needs, a dead load of 500 kgf/cm^2 on floors and 700 kgf/cm^2 on the roof was considered; regarding weight of steel columns and beams. A live load of 350 kgf/cm^2 and 100 kgf/cm^2 were considered in floors and roof respectively, in compliance with Mexican construction codes.

Seismic demand was obtained through PRODISIS software [4], using as inputs geographical location: latitude 19° 41.410’ and longitude -103° 28.958’, and soil type II, the software shows the following results: Seismic zone C (2nd highest according to CFE´s manual) and seismic coefficient of 2.1g. The design response spectrum of the specified location is shown in Fig. 3 [5]. Attempting to incorporate FVD in the structure design, nonlinear time-history analysis with pairs of accelerograms compatible with the design response spectrum were chosen [6], these accelerograms are shown in Fig. 3.



a) b) c)

Fig. 3 – a) Design response spectrum, b) accelerogram X, c) accelerogram Y

3. Description of studied models

The study of the structural responses of the models was divided into 4 parts:

1. Original model with FVD in a diagonal configuration.
2. A simplified model to analyze the viability of the proposal.
3. Model with FVD placed in series.
4. Model with FVD placed in parallel.

3.1. Model with FVD in a diagonal position

The first option for the configuration of FVD was a simple diagonal. One of the major disadvantages of this option were the large spans of up to 18.9 m, which means excessive large diagonals. In the following paragraphs, some of the results obtained through this configuration will be presented. The general behavior of the building was satisfactory, in Fig. 4 it is observed that frame hinges developed plastic behavior [7].

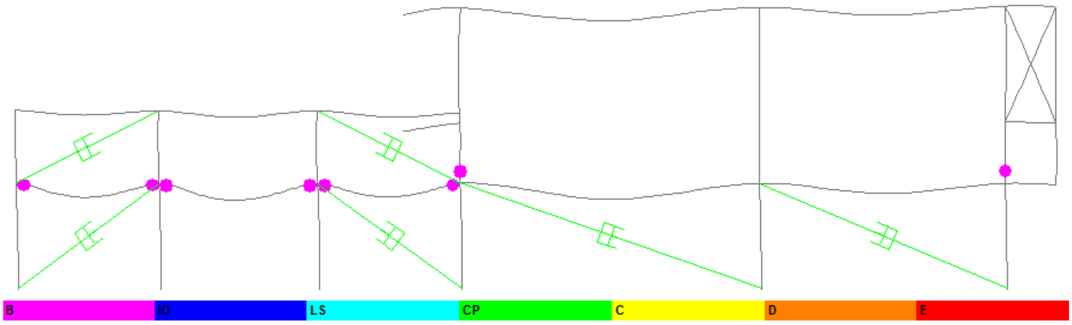


Fig. 4 – Plastic hinges development.

3.2. Simplified model

The main porpuse of this model was to compare different damper properties and thus achieve an equivalence between the simple configuration and the series and parallel proposals. A 2D three-story frame model was developed. The model was calibrated to have the same period, base shear and deformations of the three-dimensional model exposed previously. Different configurations for the FVD were implemented to the model: simple diagonal (Fig. 5a), devices in series (Fig. 5b), and devices in parallel (Fig. 5c).

The comparison of the three systems was performed, where minimal changes between them were observed as it was expeted by the seeking of equivalent properties. As can be seen in Fig. 6, story drifts are practically the same at each step. With the simplified model can be observed that the global response of the structure does not change. Which brings us to the next point, reduce the capability of the FVD for economic benefit and feasibility of testing.

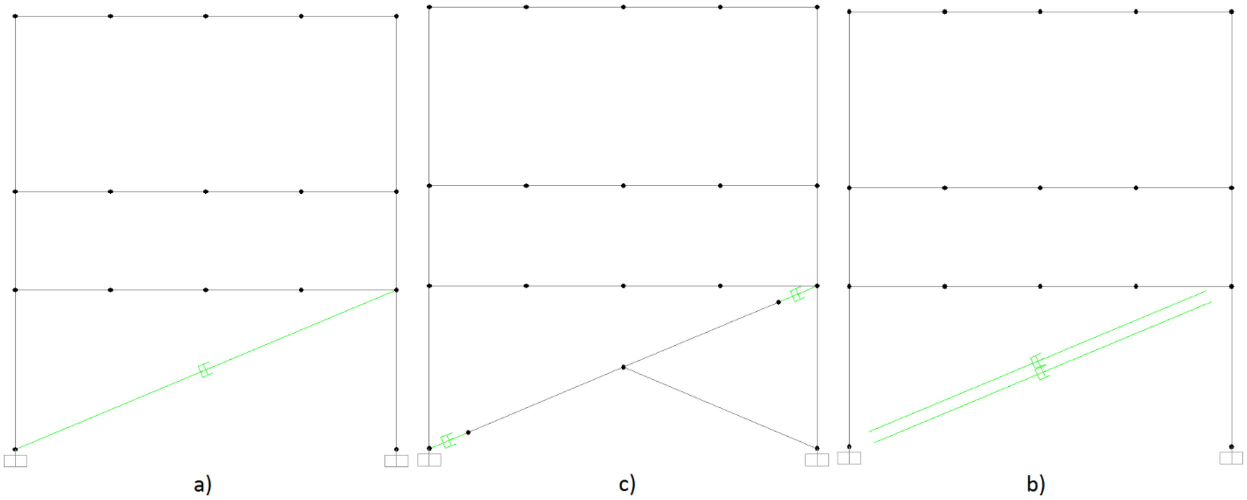


Fig. 5 – Simplified model with FVD a) simple diagonal, b) in series, c) in parallel

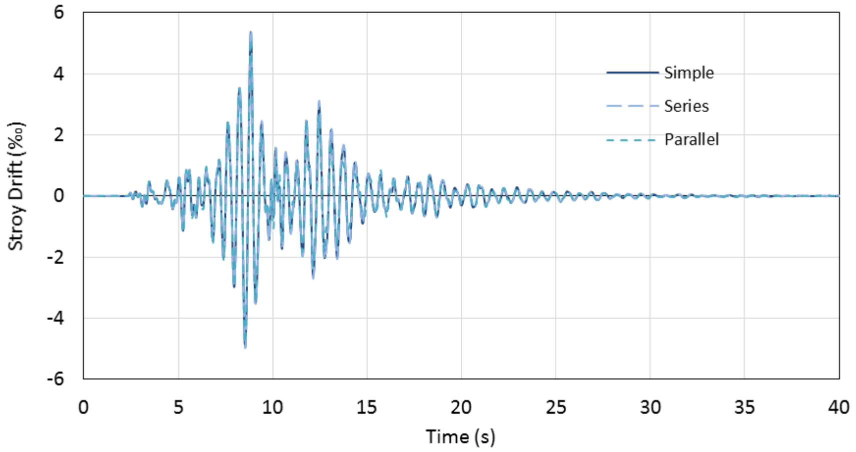


Fig. 6 – Story drift

3.3. Model with FVD in series

With the results observed in the simplified model the changes in the three-dimensional model were made. The proposed configuration was made on the largest spans. One of the main drawbacks on this proposal was that only one FVD activated, leaving the other damper inactivated. To counteract this problem, an element to amplify the deformation was placed [8] in order to activate both dampers. Fig. 7 presents the mathematical model with the proposed solution. An important point about this model is that the extra element connecting the diagonal to the opposite column has a better contribution to the series configuration if this element is connected as fully rigid. This explains the reason why FVD placed in series does not convey load to both dampers.

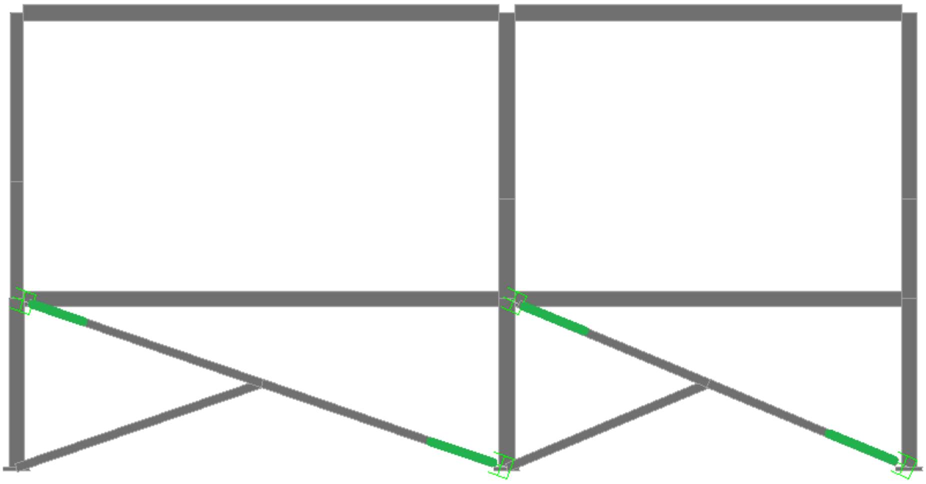


Fig. 7 – Mathematical model of FVD in series

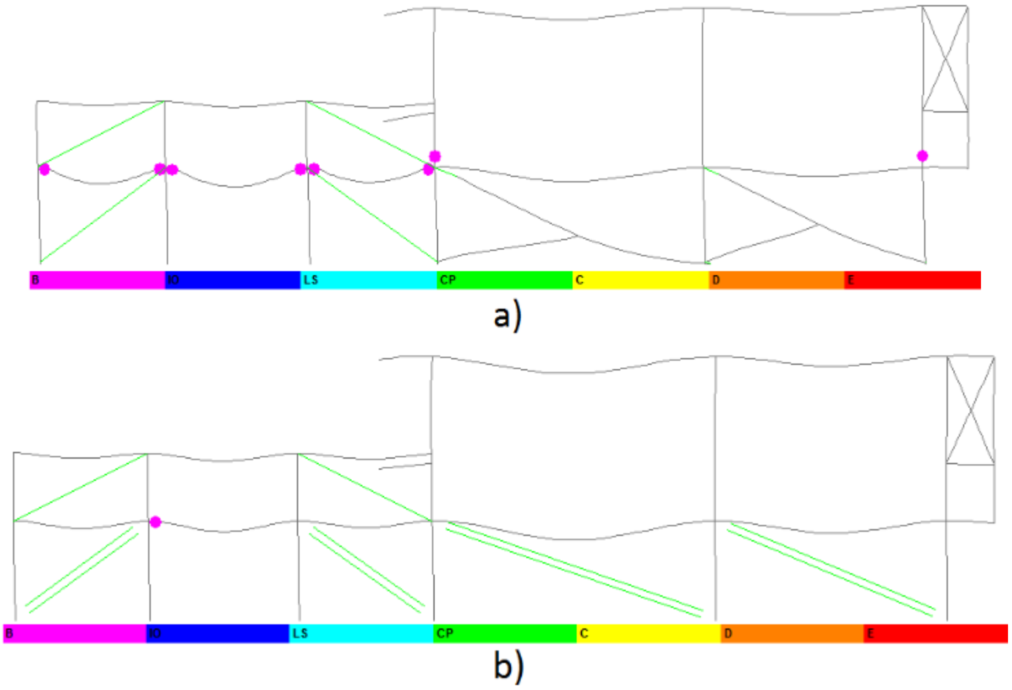
3.4. Model with FVD in parallel

In this model the diagonal configuration of the FVD was held. Fig. 8 shows the mathematical model used in this configuration. Analogous to the theory of spring stiffness in parallel, the force distributed to each damper is half of that one in the original model with a single damper.

Fig. 8 – Mathematical model of FVD in parallel

4. Results comparison

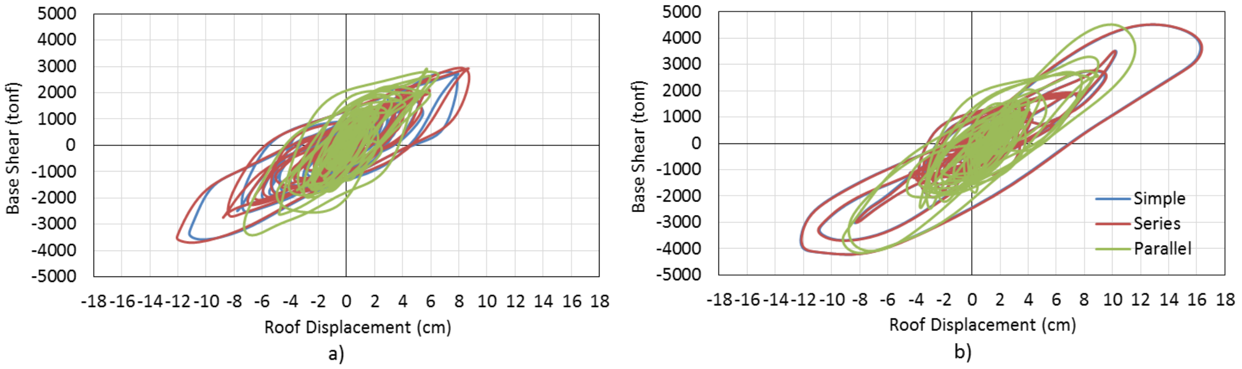
In this section, some of the most relevant structural responses will be presented, the comparison of results between the original model and the three-dimensional models with FDV in series and parallel are showed. In Fig. 9 it is observed that in the proposal with FVD in series the plastic hinges formed are the same as the original model. However, placing the FVD in parallel reduced the number of plastic hinges [7]. Fig. 10 shows base shear and the roof displacement relationship on both directions, where it is noted that in the original and the model with FVD in series there is no significant difference, while in the model with FDV in parallel the displacements are reduced in 15%.



a)

b)

Fig. 9 – Plastic hinge formation a) FVD in series, b) FVD in parallel.



a)

b)

Fig. 10 – Base shear vs roof displacement a) X direction, b) Y direction

As evidenced above, some plastic hinges are forming in beams and columns. Fig. 11 shows the variation of moment demand along the time where it is evident that the model with FVD configuration in parallel has lower demand than the original and the model with FVD in series, but still both reach plastic deformation. Fig. 12, once again presents that elastic capacity was overpassed in all configurations, it is also evident that FVD in parallel has lower demands in columns.

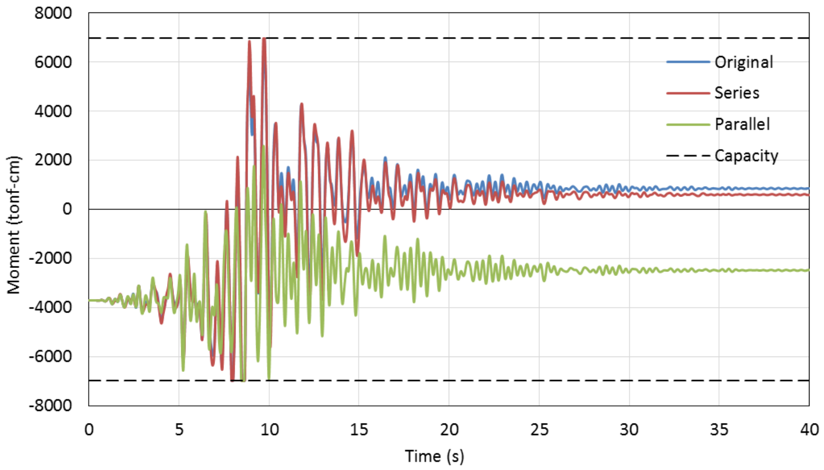


Fig. 11 – Plot moment demand in beam

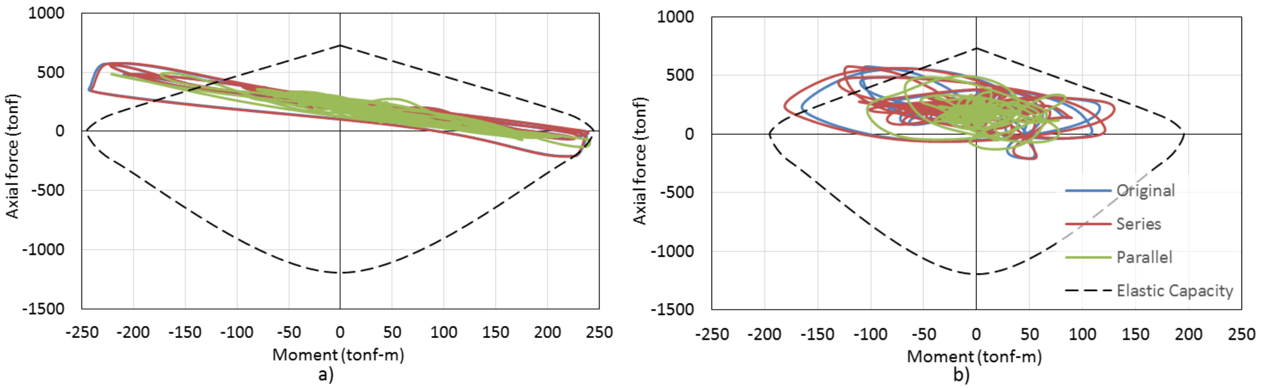


Fig. 12 – P-M interaction a) Mx, b) My

Fig. 13 shows both, hysteresis loop and force-velocity of the FVD in the different models, as it can be observed the FVD of the original model have larger deformations close to 9 cm, compared to the other configurations where maximum deformation is 6 cm. A very important part of projects that incorporate FVD is the prototype test [5], since FVD are velocity-dependent it is intended to reduce maximum velocity and facilitate the damper tests. As shown in Fig. 13b and Fig. 13d the velocity in the original and the model with FVD in series, there are no significant changes, however, the model with FVD in parallel did manage to lower the maximum velocity by 30%.

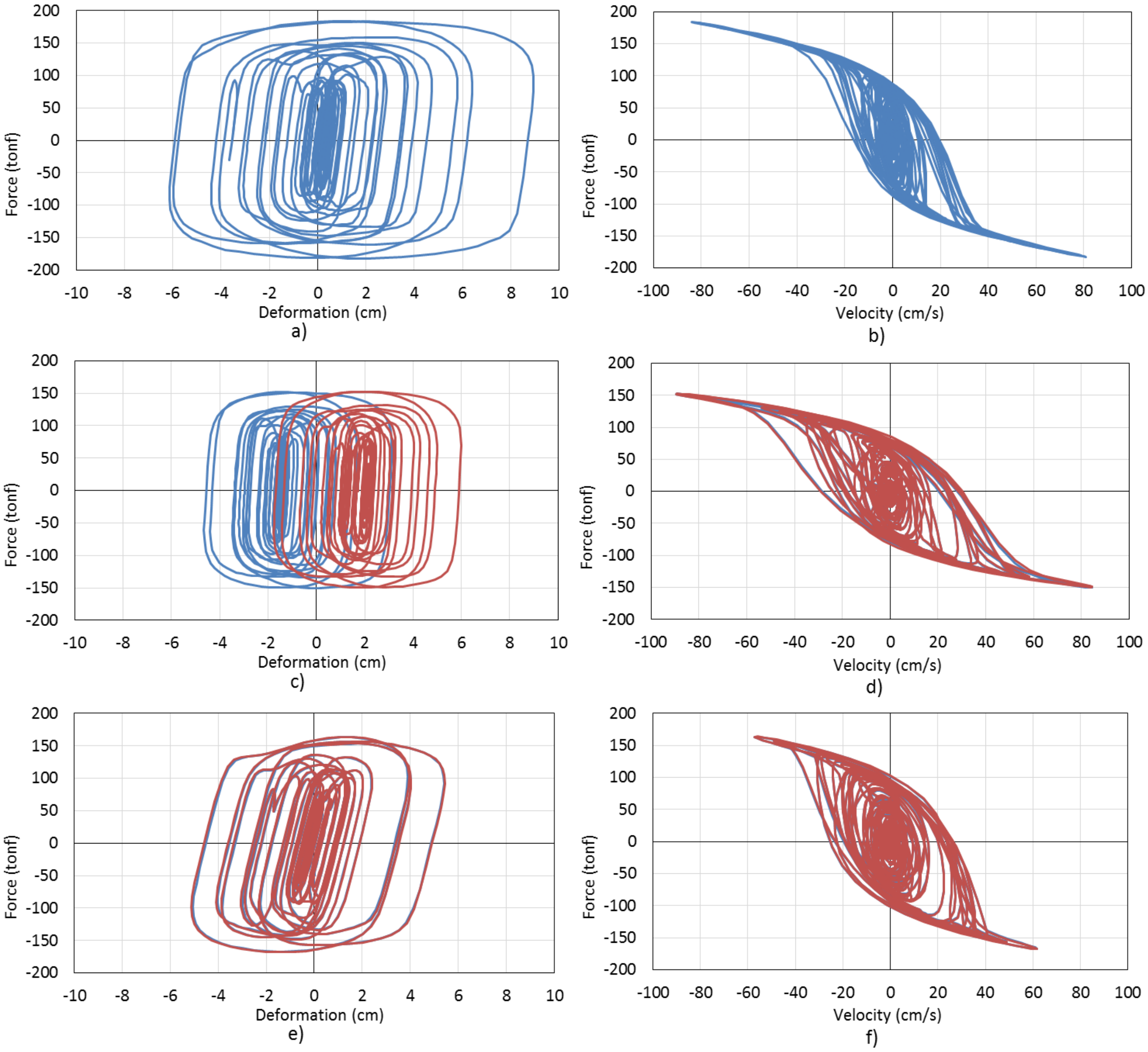


Fig. 13 – Hysteresis loop (left) and force-velocity (right) of a) and b) original model: c) and d) FVD in series; e) and f) FVD in parallel

The reactions of the most demanded columns are shown in Fig. 15. It can be observed in all case the original and the in-series configuration have the same reaction, oppositely the model with FVD in parallel have a lower reaction in vertical and in the Y direction, while the reaction in the X direction is a 30% larger. The foundation system used in the project is based on piles. Table 1 shows the maximum axial forces for each of the different configurations studied. It can be noted again that the original and the model with FVD in series have very similar reactions, while in the model with FVD in parallel both, compression and tension loads decreased. Therefore, savings in the foundation may be significant. The geotechnical report of the project suggests 1m-diameter and 12m-depth piles, of 435 tonf vertical capacity. In the parallel configuration, there would be required a group of 3 piles, while in case of using the original or the series configuration an extra pile would be required.

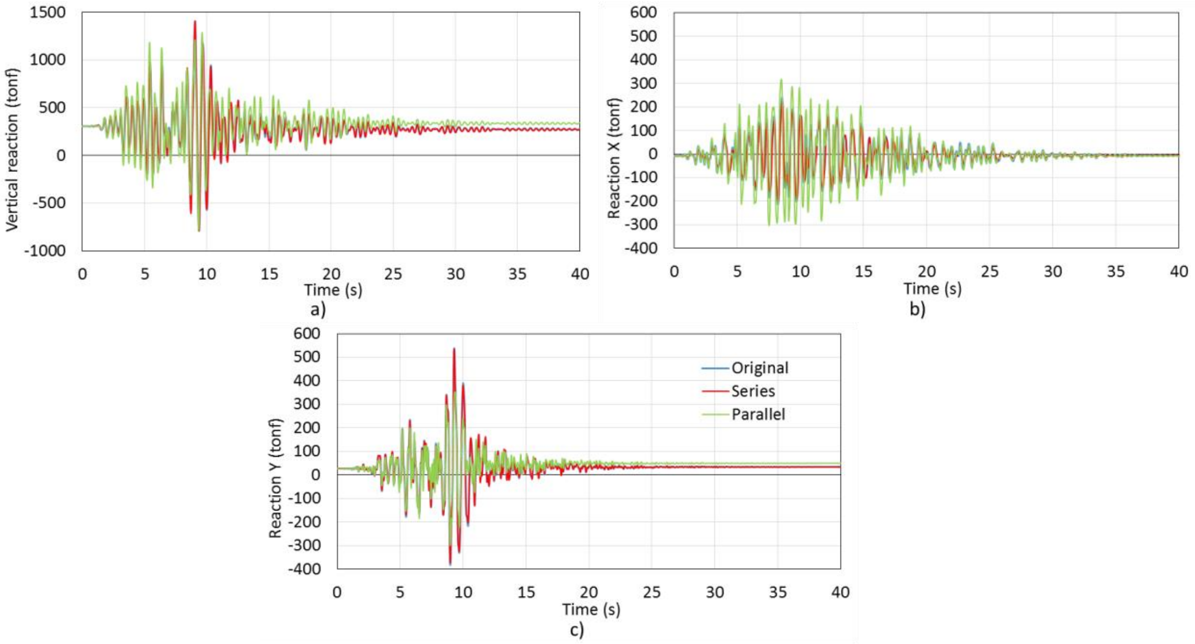


Fig. 14 – Reactions a) vertical, b) X direction, c) Y direction

Table 1 – Vertical reactions

Model	**Compression (tonf)**	**Tension (tonf)**
Original	1405	789
Series	1404	788
Parallel	1288	780

5. Constructive considerations

So far, the structural responses of the mathematical model have been described for each proposed configuration. Fig. 15 shows a schematic drawing of how the connections of the three proposed configurations would be. The configuration of a simple diagonal consists of gusset plate connections on both ends of the diagonal. The configuration of FDV in series is similar to the diagonal configuration, but an element to connect the diagonal to with the column is incorporated, with mentioning that major effectivity is accomplished if this element is a fully rigid connection, this configuration is similar to a toggle brace configuration. The configuration of FVD in parallel, to make it the closest to the mathematical model, uses two diagonals connected to a gusset plate, which has to be rigid enough to ensure that the diagonal has axial behavior.

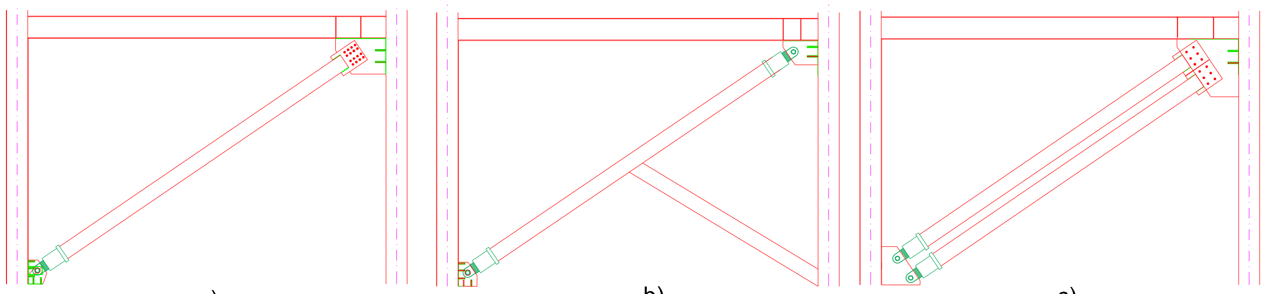


Fig. 15 – Schematic layout of connections for FDV a) simple diagonal, b) in series, c) in parallel

As mentioned above, FVD in series configuration was proposed in this way to try to match as much as possible the behavior with mathematical model. But this brings up a new topic, if there can be a manner of connecting both FVD to a single diagonal which besides lowering demands over the damper will also have a connection less robust than the resulting one with FVD placed in a simple diagonal. This will lead to a new investigation related to connections in systems with FVD in parallel.

6. Conclusions

One of the main motivations of this research was to reduce de demand on the FVD and make the prototype test more feasible to perform. Therefore, it was proposed to study the viability of placing FVD in series or in parallel, this as an alternative to the different existing configurations. The main conclusions are:

i. In general, the structural responses of the original and the model with FVD in series were very similar.

ii. The model with FVD in parallel resulted in lower displacements and lower structural demand, and also had lower reactions.

iii. There can be savings in the superstructure if the FVD are placed in parallel.

iv. As for the FVD, there is a substantial decrease in the demands over the dampers using the configuration of FVDin parallel. As previously shown the force acting on the FVD was reduced by 25%, and the deformation decreased by 30%.

v. A result of using configurations with FVD in parallel more economically dampers can be achieved than placing the dampers in simple diagonal, as long as two lower-capacity devices are cheaper than one large-capacity.

vi. The configuration with FVD in series in addition of using twice the amount of dampers, requires an additional element which means more material and more connections.

vii. Finally, the configuration of FVD in parallel resulted in the best structural response. However, besides requiring more devices of smaller capacity, more diagonals and gusset plates are required.

To determine which configuration is better, in addition to the technical issue it must be assessed whether the reduction in the demand of the FVD represents a significant saving in relation to the structure, its connections and the workforce. As seen in this research, configuration of FVD in parallel improves the structure behavior and could reduce the cost of the dampers. The FVD represent an important investment in a project and its benefits have already been quantified, however, it will be important to review the cost-benefits ratio of each case to choose the best proposal to use. Finally, due to high demands acting over the dampers and therefore the difficulty in carrying out the prototype test, the project was solved using buckling restrained braces. This choice was done mainly because the lack of time during the project to correctly analyze other alternatives, which it a common issue in real projects. However,with this research was shown that the project could have been satisfactorily resolved using FVD in parallel.

7. Acknowledgments

I thank the Organization of American States OEA and the Pontificia Universidad Católica de Chile for giving me the opportunity to study the magister and for allowing me to offer the knowledge acquired for the benefit of Mexican society through the constitution of VIRMEX Innovación Estructural, in which I have offered jobs and transmitted knowledge to new generations, as well as to the clients to whom we have been able to offer solutions in their construction projects.

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