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# INFLUENCE OF LAYOUT OF FLUID VISCOUS DAMPERS IN THEIR EFFECTIVENESS FOR SEISMIC PROTECTION OF BUILDINGS

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## *Abstract*

In the last decade, due to the importance of government buildings, the government of some countries in Latin America aims to safeguard these buildings against a severe earthquake, reinforcing them with energy dissipation systems, being the most used the fluid viscous dampers. This paper describes the proposed reinforcement of the building of the Legislative Assembly of El Salvador, where the layouts of fluid viscous dampers influence in their effectiveness for seismic protection of building. The effectiveness is measured by less interstory drifts, more supplemental viscous damping ratio, and less damper forces. The building was analyzed for each layout of fluid viscous dampers taking into account the studies realized by different researchers about the supplemental damping ratio. Three pairs of acceleration time histories were scaled in any manner which they are compatible with the design spectrum El Salvador. Two of the ground motions were the earthquakes that occurred on 10 October 1986 and 13 January 2001. After time history analyzes, it was determined that the best alternative of reinforcement of building is the layout Upper Toggle Brace. Although the interstory drifts are relatively smaller for building with layout Lower Toggle Brace than for building with layout Upper Toggle Brace, as well as the damper forces, the layout Toggle Upper Brace is chosen as a solution to reinforcement of building, due to higher additional damping is achieved, thus the reinforcement of columns and beams were not necessary and the initial request was satisfied, not interrupt the activities into the building.


*Keywords: Fluid viscous damper; Toggle Brace Damping System; Supplemental viscous damping ratio; Layout of fluid viscous dampers; nonlinear properties of the dampers*

## 1. Introduction

In the last years, some countries in Latin America have introduced the reinforcement of old buildings with energy dissipation systems. Among the energy dissipation systems widely used are the fluid viscous dampers, which have gained more popularity in recent years for reinforcement of existing buildings.

The layout of fluid viscous dampers (FVD) most commonly used, that provide greater comfort in their installation, are dampers in diagonal brace and chevron brace. These layouts require bigger dampers to ensure that the interstory drift is less than the allowable, which implies that the cost of reinforcing the building is higher. However, in recent years it has been used other layouts that allow better results such as the Upper Toggle Brace and Lower Toggle Brace, which make possible amplify the displacement and velocity in the damper [1], which increases the effective damping and decrease the interstory drift.

Examples of studies for reinforcement of old buildings with FVD are: the building of the Legislative Assembly of El Salvador, the building of the Ministry of Economy and Finance of Peru and one of the buildings of National Superintendency of Tax Administration of Peru (SUNAT).

This paper presents the reinforcement of the Legislative Assembly of El Salvador. The building was analyzed for different layouts of fluid viscous dampers and their effectiveness was measured by less interstory drifts, more supplemental viscous damping ratio, and less damper forces.

## 2. Layouts of fluid viscous dampers

The layouts of fluid viscous dampers used for measured their efficiency for seismic protection of the building studied are:

**Diagonal Brace**

In this layout, the damper is placed in a diagonal position, as shown in Figure 1. The amplification factor of the relative displacement between the two ends of the damper depends on the angle of the brace that will hold the damper. In this case, the axial displacement devices are less than or equal than the story drift, thus lowering their efficiency energy dissipation [2].

**Chevron Damper**

The dampers are placed horizontally parallel to the plane of the roof floor or the interstory floor (inverted Chevron) as shown in Figure 2. The damper in horizontal direction (direction of excitation) has an amplification factor of one, since the relative displacement in the dampers is equal to the displacement of floor. For this installation scheme, the diagonal braces are subjected to tensile stress or compressive stress. These elements are connected to the structure by bolts, anchor plates, which usually lead to a reinforcement of beams and columns of the frame.

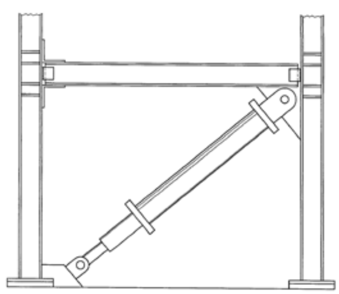

Fig. 1 – Installation of Diagonal Brace

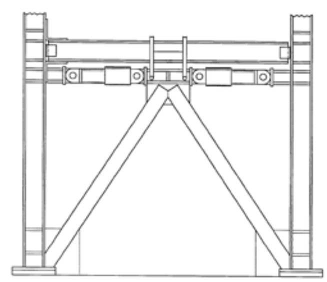

Fig. 2 – Installation of Chevron Damper

**Toggle Brace**

Taylor proposed two improved Toggle Brace system, as shown in Figure 3 and Figure 4, in which the damper and brace elements are connected directly to the beam-column joints. The Taylor Devices Toggle Brace Damping System enable to amplify the displacement and velocity in damper, while reducing the damper force required. Therefore, a much more cost-effective damper size can be used. Because of these characteristics, Toggle Brace system is intended for relatively stiff structures, including those structures with shear walls, or heavy bracing.

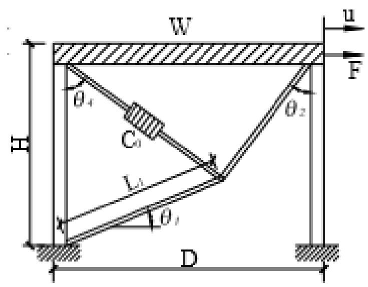


Fig. 3 – Installation of Upper Toggle Brace system [1]

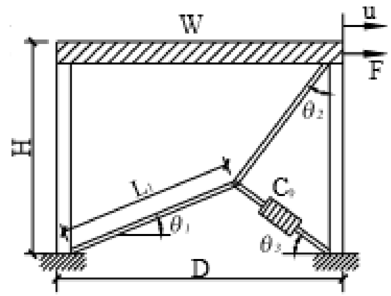


Fig. 4 – Installation of Lower Toggle Brace system [1]

## 3. Calculation of supplemental viscous damping ratio for different layouts of fluid viscous dampers

According to the study by Jenn-Shin Hwang and Yin Nan Huang [3], the damping ratio contributed by the nonlinear fluid viscous dampers takes into account the horizontal and vertical relative displacement between the two ends of viscous damper installed in a frame panel, and is equal to:

$$\xi_d = \frac{T^{2-\alpha} \sum_j C_j \lambda_j \left| (f_h)_j (\phi_h)_{rj} - (f_v)_j (\phi_v)_{rj} \right|^{1+\alpha}}{(2\pi)^{3-\alpha} A^{1-\alpha} \sum_i m_i (\phi_h)_i^2}$$

where:

T = fundamental period of the building

α = damping exponent

$(\phi_h)_{rj}$ = horizontal relative displacements between the ends of the *j*th damper for the first vibration mode

$(\phi_v)_{rj}$ = vertical relative displacements between the ends of the *j*th damper for the first vibration mode

$(f_h)_j$ = magnification factor in the horizontal direction of the *j*th nonlinear viscous dampers

$(f_v)_j$ = magnification factor in the vertical direction of the *j*th nonlinear viscous dampers

A = roof response amplitude corresponding to modal displacement

$C_j$ = damping coefficient of the nonlinear viscous damper

$m_i$ = mass at the *i*th floor level

λ = parameter which can be calculated by

$$\lambda = 2^{2+\alpha} \frac{\Gamma^2(1+\alpha/2)}{\Gamma(2+\alpha)}$$

The magnification factors according to layout of FVD are:

**Diagonal Brace** : $f_h = \cos\theta$ $\quad f_v = \sin\theta$

**Chevron** : $f_h = 1$ $\quad f_v = H/D$

**Upper Toggle Brace** : $f_h = \dfrac{\sin\theta_2 \cos(\theta_4 - \theta_1)}{\cos(\theta_1 + \theta_2)} + \sin\theta_4$ $\quad f_v = \dfrac{\cos\theta_2 \cos(\theta_4 - \theta_1)}{\cos(\theta_1 + \theta_2)}$

**Lower Toggle Brace** : $f_h = \dfrac{\sin\theta_2 \sin(\theta_1 + \theta_3)}{\cos(\theta_1 + \theta_2)} + \sin\theta_4$ $\quad f_v = \dfrac{\cos\theta_2 \sin(\theta_1 + \theta_3)}{\cos(\theta_1 + \theta_2)} - \sin\theta_3$

## 3. Description of Building Legislative Assembly of El Salvador

The Legislative Assembly is the legislative branch of the government of El Salvador. The building was designed and built in 1968. As with most buildings of its era, the building's moment frame was not detailed in a manner that would provide the ductility required to survive a major earthquake. Currently, the building is used by the deputies, who are worried about the lack of structural safety offered by the building. After the first structural assessment realized by *AA Diseño, Supervisor y Patalogía de Obras Civiles*, it has been determined that the building requires reinforced.

The structure is 9-story, 42.00m by 15.50m in plan and 32.00m in elevation. The lateral load-resisting system is comprised of reinforced concrete moment frame. A typical floor plan of the building is shown in Figure 5 and a panoramic view of the building is shown in Figure 6.

The compressive strength of concrete is 280 kg/cm$^2$ (27.45 MPa) and the steel rebar is Grade 50 ($f_y$ = 3520 kg/cm$^2$ - 345 MPa). The interstory slabs are composed of 11cm concrete and reinforced in two directions.

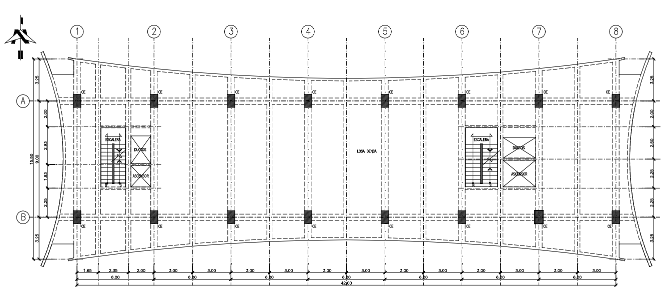

Fig. 5 – Typical building floor plan

Fig. 6 – Panoramic view of the building

Three ground motions were employed to analyze the structure with dampers, ground motions shall consist of pairs of appropriate horizontal ground motion acceleration components; two of the ground motions corresponded to earthquakes of 10 October 1986 (magnitude 5.4 and depth of about 8 km) and 13 January 2001 (magnitude 7.6), the other corresponded to artificial record. The first earthquake has been the most destructive in the capital city San Salvador, and the second earthquake, corresponds to subduction earthquake (Cocos Plate and the Caribbean Plate), however did not cause major damage in the capital.

The three pairs of acceleration time histories were scaled in any manner which they are compatible with the design spectrum El Salvador. Figure 7 shows the design spectrum El Salvador and the Figure 8 shows the earthquake response spectra generated by ground motion of 10 October 1986 compatible with design spectrum.

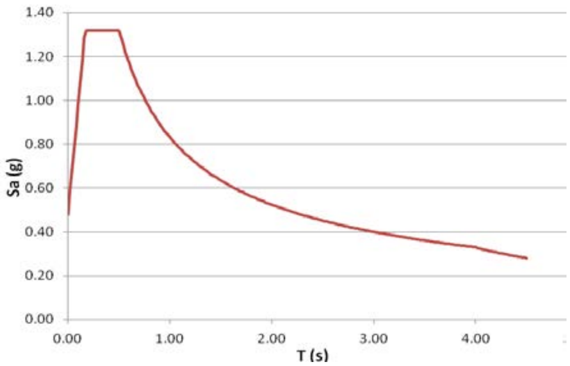


Fig. 7 – Design spectrum El Salvador

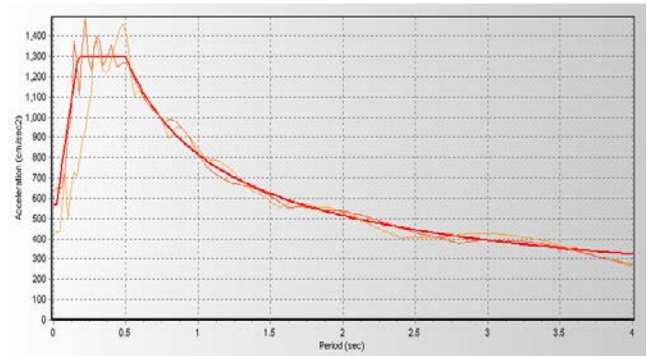


Fig. 8 – Earthquake response spectra generated by ground motions compatible with design spectrum

After modal analysis, the modal periods and the modal participation factors of the existing building are shown in Table 1. The inherent damping ratio of the structure is assumed to be 5%.

Table 1 – Results of modal analysis

| Modo | T (s) | Masa Part. UX | Masa Part. UY |
|---|---|---|---|
| 1 | 1.474 | 0.000 | 0.703 |
| 2 | 1.430 | 0.001 | 0.001 |
| 3 | 1.340 | 0.739 | 0.000 |
| 4 | 0.532 | 0.000 | 0.145 |

The building was analyzed for each layout of FVD described in the previous section. The nonlinear properties of the dampers were optimized to until to get the best seismic response of the building or to reach the allowable drift.  The velocity exponent for all layouts of FVD is 0.4, and the damping coefficients for each layout of FVD are detailed in the Table 2 and Table 3.

Table 2 – Damping coefficients – Longitudinal Direction

| Story | Damping coefficient, C (t-(seg/m)$^{0.4}$) | | | |
|---|---|---|---|---|
| | Diagonal | Chevron | UTB | LTB |
| 1° - 7° | 280 | 200 | 120 | 120 |
| 8° - 9° | 160 | 160 | 50 | 50 |

Table 3 – Damping coefficients – Transverse Direction

| Story | Damping coefficient, C (t-(seg/m)$^{0.4}$) | | | |
|---|---|---|---|---|
| | Diagonal | Chevron | UTB | LTB |
| 1° - 7° | 380 | 280 | 160 | 180 |
| 8° - 9° | 300 | 240 | 130 | 150 |

The Figure 9 and Figure 10 show the upper toggle brace layout in longitudinal direction and the transverse direction of building, respectively.

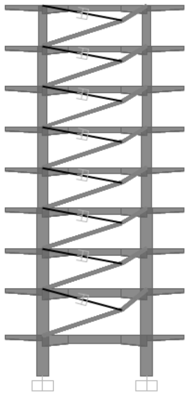

Fig. 9 – Upper Toggle Brace – Longitudinal Direction

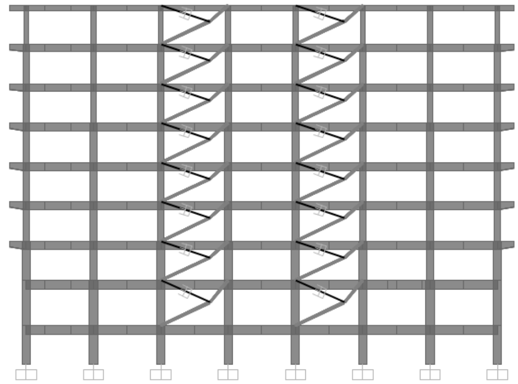

Fig. 10 – Upper Toggle Brace Transverse Direction

The results of time history analysis show that the interstory drifts of original building are greater than the allowable drift, 0.015, according to the El Salvador Seismic Code and are greatly reduced with fluid viscous dampers. However, the reduction factor is different for each layout of FVD in the same floor. For the maximum interstory drift in the longitudinal direction, the maximum reduction factor is 50% when the layout is Lower Toggle Brace, and the minimum reduction factor is 30% when the layout is Diagonal Brace; likewise, in the transverse direction, the maximum reduction factor is 41% when the layout is Lower Toggle Brace, and the minimum reduction factor is 9% when the layout is Diagonal Brace. The Figures 11 and 12 show the comparison of interstory drifts for each layout of FVD and for each direction.

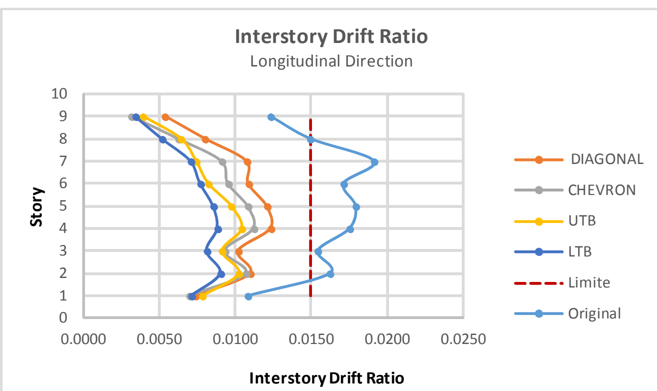


Fig. 11 – Interstory Drift Ratio – Longitudinal Direction

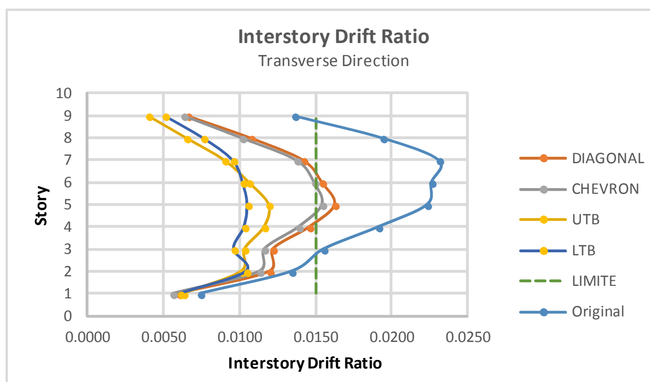


Fig. 12 – Interstory Drift Ratio - Transverse Direction

About the supplemental viscous damping ratio, the higher damping ratio is reached with the Upper Toggle Brace scheme for both directions. This supplemental viscous damping is 2.50 times greater than the damping reached with the diagonal brace scheme in transverse direction, and 1.85 times, in longitudinal direction. The results also show that the layouts Toggle Brace reach greater damping in the transverse direction than in the longitudinal direction. The comparison of supplemental viscous damping ratio for all layouts is shown in Figure 13 and Figure 14 for each direction, respectively.

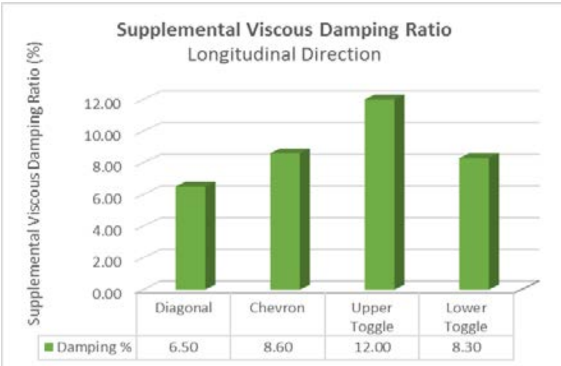


Fig. 15 – Damping Ratio – Longitudinal Direction

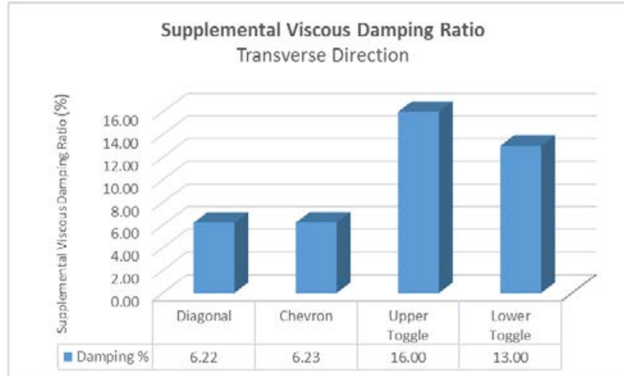


Fig. 16 – Damping Ratio - Transverse Direction

For maximum damper force demand, there is considerable difference among four layouts of fluid viscous dampers. The lower damper force is reached by Lower Toggle Brace scheme, while the greatest damper force is reached by Diagonal Brace scheme in both directions, the ratio between both damper forces is 0.47 in the longitudinal direction, and 0.52 in the transverse direction. For the layout of FVD that reached the higher damping (Upper Toggle Brace), the damper force is little higher than Lower Toggle Brace. Considering that the damper force determines the size of damper and therefore its cost, it is important choose the layout that reach lower damper force. The comparison of maximum damper force is shown in Figure 15 and Figure 16 for each direction, respectively.

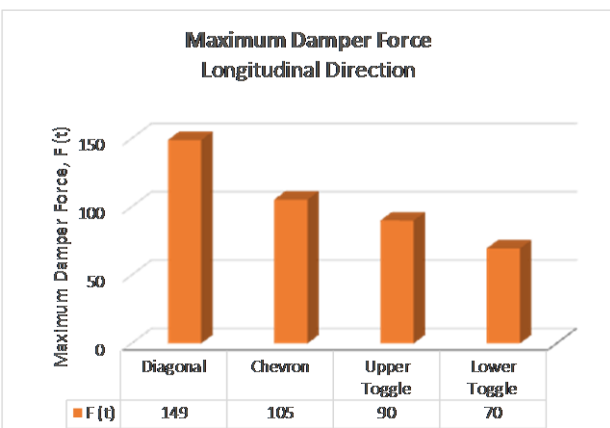


Fig. 17 – Maximum Damper Force of Longitudinal Direction

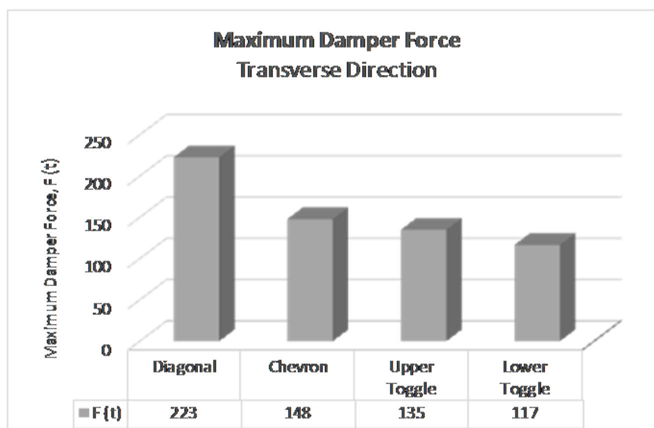


Fig. 18– Maximum Damper Force of Transverse Direction

## 4. Conclusions

Reinforce old buildings with fluid viscous dampers is a very good alternative reinforcement: the structural damage is reduced significantly, the reinforcement works are done in less time, and the activities into the building are not interrupted.

With the damping reached by the layout Upper Toggle Brace, the reinforcement of columns and beams were not necessary, thus the initial request was satisfied, not interrupt the activities into the building.

The reinforcement of building with layouts Diagonal Brace and Chevron are not sufficient to reach the allowable drift many times, these layouts reduce the drift but not as the layouts Toggle Brace. Therefore, the layouts Toggle Brace are the best alternative for the reinforcement of mid-rise buildings.

Although the interstory drifts with the layout Lower Toggle Brace are relatively smaller than with the layout Upper Toggle Brace, as well as the damper forces. It is chosen as a solution to reinforcement the layout Toggle Upper Brace, due to higher additional damping is achieved.

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