Analytical study on seismic response of RC and steel structures with fluid viscous dampers

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Abstract. This paper presents a comparative study of the performance of Fluid Viscous Damper (FVD) in mitigating the seismic response of both Reinforced Concrete (RC) and Steel structures. The aim of the study is to understand the behavior of the seismic resistant structures and to study the advantages of FVD over other dampers. The study is done to determine the optimum positioning of FVD in order to reduce the storey displacements and storey drifts. G+3, G+5, G+7 RC and steel structures were modeled in SAP2000 software and were subjected to non linear time history analysis under three different earthquake ground motions such as Imperial Valley – 02 (1940), Loma Prieta (1989) and Northridge-01 (1994). The dampers were placed in four different configurations such as alternate (AT), corner (CR), diagonal (DL) and middle (ML). The seismic response parameters such as the storey displacements and the storey drifts were determined for the structures. It is found that the presence of FVD reduces the storey displacement and storey drift values to about 40-70% from the uncontrolled structure. It is also understood that the optimum positioning of the dampers is greatly influenced by the aspect ratio of the building.

1. Introduction
Earthquake is one of the natural phenomenon that challenge most of the engineers of the construction industry. Thus designing the structures to resist seismic forces is of vital importance. Protection of tall and large structures against seismic disturbances is a major topic of research for many years. Generally, buildings possess low inherent damping capacity and thus they are easily susceptible to earthquake forces. There are many seismic design strategies and devices for the structures such as moment resisting frames, construction of diaphragms, shear wall, braced frames etc. Dampers provide passive energy dissipation and they reduce the seismic energy by friction or by deformation. The damping devices take up the seismic energy to perform its function rather than transmitting it to the structure. Isolating the base is also a best method of passive energy dissipation. But providing dampers is more advantageous compared to base isolation because base isolation cannot be used for tall buildings since the building might overturn. When existing buildings are retrofitted, the process becomes easier with dampers than with the base isolators. This is more advantageous only when the application is external and the residents are not disturbed.
Murat Dicelilia, et al., [4] studied the behaviour of the fluid viscous dampers by comparing the performance of steel frames with bracings provided in chevron configuration. Authors studied the effect of the damping ratio and the velocity exponent on the seismic performance of the structure. When FVDs were installed, it improved the performance by maintaining the elastic behaviour. The dampers with larger damping ratios and smaller velocity exponents were more effective in seismic mitigation. Moreover the FVDs with damping ratios more than 50% did not significantly improve the seismic performance of the CBFs.

Mehdi Banazadeh, et al., [1] investigated the seismic performance of steel moment resisting frames installed with both linear and non linear FVDs with the same damping ratio. Incremental dynamic analysis was carried out to determine the collapse probability, under far field records. It was noted that the use of the damper improves the performance and reduces the collapse probability when compared to that of the conventional steel frames. It was also understood that the frames with linear FVDs performed better than the steel frames with non linear FVDs with an equal damping ratio and thus the collapse probability was lower.

Ras A., et al., [10] conducted a 3D numerical investigation on a twelve storey steel moment resisting frame by performing non linear time history analysis. The frame was provided with fluid viscous dampers in diagonal configuration because it possesses linear relationship between force and velocity. From the results, it was observed that the maximum displacements of the damped frame structure decreased to about 32% when compared to the braced frame and also the maximum acceleration was also reduced to about 37%, which in turn resulted in reduction of the base shear force values.

The main objective of this study is to develop knowledge on seismic resistant structures by modelling and analysing RC and steel structures against seismic loads using the software SAP2000 and interpret the results, to find the optimum positioning of the energy dissipating dampers in the structures to reduce the storey displacements and inter storey drifts by carrying out various trials and to understand the behavior of FVD and the advantages of the damper over other types of dampers. In this study, G+3, G+5, G+7 RC and steel structures were compared and the efficiency of FVD in reducing the storey displacements and storey drifts was also determined. The buildings were analysed for three different earthquake ground motions and the optimum positioning of the damper was found using SAP2000 software.

2. Fluid viscous damper
2.1. Selection of the damper
Seismic dampers are used in buildings and other structures to mitigate the vibrations induced by earthquakes. It is a mechanical device that dissipates the energy of the seismic waves affecting the structure. The dampers are classified into various types. They are friction dampers, yielding dampers, viscous dampers, tuned mass dampers and magnetic dampers. Viscous damper was selected for the study because it is passive device that does not have any sensors or actuators and does not consume any power, instead, it relies on the damping properties of materials used in its design.

2.2. Principle of working
The basic principle with which FVD works is the dissipation of energy because of the fluid flowing through the orifices. The detailed view of FVD is depicted in Figure 1. In FVD, the fluid flows from one chamber to the other chamber through orifice when the piston moves from left to right or from right to left. There will be dissipation in energy due to the loss in head that occurs when the fluid circulates from a larger area i.e. cylinder to a smaller area i.e. the orifice and then again from the smaller area to a larger area. The damping force of FVD is proportional to the pressure difference across the piston head.
Figure 1. Fluid viscous damper [10].

F is directly proportional to $V^\alpha$, where $\alpha$ is a constant parameter called as the velocity exponent and this constant is influenced by the shape of the orifice that changes the characteristics of the fluid along with the speed of the fluid. Generally the value of $\alpha$ is taken from 0.3 to 1.0, for seismic protection. When the value of $\alpha$ is taken as one, the device becomes a linear FVD as force varies linearly with velocity. When the value of $\alpha$ is taken less than one, the force has non-linear relationship with velocity and hence called as non-linear FVD. Non-linear damper with the value of $\alpha$ greater than one is generally not used for practical applications.

3. Methodology

3.1. Selection of ground motion data

ATC-63 guidelines categorised the strong ground motion parameters and as per the guidelines, three of the most commonly used earthquake records in vibration control are selected for the study to understand the performance of fluid viscous dampers. The details of the ground motion are tabulated in Table 1.

| RSN Number | Earthquake name          | Station name      | Magnitude | PSA (g) |
|------------|--------------------------|-------------------|-----------|---------|
| 6          | Imperial valley – 02 (1940) | El Centro Array #9 | 6.95      | 0.68    |
| 752        | Loma prieta (1989)         | Capitola          | 6.93      | 1.14    |
| 953        | Northridge-07 (1994)       | Beverly Hills – 14145 Mulhol | 6.69 | 1.82 |

Source: http://ngawest2.berkeley.edu/

3.2. Damper configuration

Out of the many configurations like chevron, upper toggle, lower toggle bracing systems, the diagonal bracing system was chosen since it minimizes the usage of materials and it reduces the cost of the structure.

3.3. Method of analysis

Non-linear time history analysis is a step by step procedure to determine the dynamic response of the structure that varies with time for the applied seismic loading of the respective earthquake. Direct integration method is used under which the value of $\gamma$ is taken as 0.5 and $\beta$ is taken as 0.25.
4. Design procedure of FVD

Generally, the existing design formulae and procedure for FVD are provided by FEMA 273 and many other research papers. New design formulae were derived by Hwang et al., [6] considering the relative vertical deformations as they are comparable with the horizontal relative deformations of the end locations of the damper. The stiffness of the supporting bar were determined from the paper by Lu et al., [8]

- Initially modal analysis was done without the installation of the dampers and the fundamental time period (T) and the horizontal deformation ($\phi_{hi}$) for the first mode were noted down.
- The expected damping ratio ($\rho$) for the structure and the damping exponent ($\alpha$) for the damper were assumed as 20% and 0.5 respectively.
- For the expected damping ratio, the displacement at the roof level (A) was determined by conducting non linear time history analysis for all the considered earthquake ground motions.
- Generally the value of A is taken as the maximum value among the considered ground motions.
- Then for the first vibration mode, the horizontal ($\phi_{hj}$) and vertical displacements ($\phi_{vj}$) between the end positions of the damper to be fixed, were determined.
- The mass at the roof level was determined and noted as $m_i$.
- Then the damping coefficient ‘C’ of the damper can be determined from the formula:

$$\rho = \frac{T[(2-\omega)\eta_j C_j (\phi_{hj} - f_h \phi_{vj})]^{1+\alpha}}{2\pi(2-\omega)A(1-\omega)\sum m_i (\phi_{hi})^2}$$

where
- $\eta_j$ – number of identical dampers with the same damping coefficient in each storey.
- $C_j$ – damping coefficient for the damper j.
- $\alpha$ - damping exponent taken as 0.5.
- $\rho$ - expected damping ratio for the structure taken as 20%.
- $\phi_{hj}$ - horizontal displacement between the ends of the jth damper
- $\phi_{vj}$ - relative vertical displacement between the ends of the jth damper
- $f_h$ - horizontal magnification factor for diagonal damper – $\cos \theta$
- $f_v$ - vertical magnification factor for diagonal damper – $\sin \theta$

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

where
- $\lambda_j$ – magnification factors
- $f_h$ – horizontal magnification factor for diagonal damper
- $f_v$ – vertical magnification factor for diagonal damper

Lu et al., [8] derived the following formula to determine the stiffness of the supporting bar with 95% energy efficiency as the index,

$$\frac{K^2}{K^2 + (C_e \omega)^2} \geq 95\%$$

where $C_e$ is the equivalent linear damping coefficient that is calculated using the formula,

$$C_e = 2 C_e \omega^{\alpha - 1} \frac{\omega^{\alpha - 1}}{\alpha + 1}$$

K is the design stiffness of the supporting bar
$\omega$ is the vibration frequency.

5. Modelling and analysis of RC and steel structures

G+3, G+5, G+7 storied RC and steel structures were modelled for the same plan. The plan of the structure considered is shown in Figure 2.
The structures are considered to be located at Imphal (Manipur) which is in seismic zone 5 with medium stiff soil condition. The details of both RC and Steel Structures are tabulated in Table 2. The support conditions were considered as fixed at the base. The live load on the slab was taken as 3 kN/m². All the load combinations were defined as per IS 1893-2016 [11]. The bay length in X direction is taken as 7.35 m and the bay length in Y direction is taken as 6.6 m.

![Figure 2. Structural plan of RC and steel structures.](image)

**Table 2.** Details of RC and steel structures.

|                        | RC Structure          | Steel Structure        |
|------------------------|-----------------------|------------------------|
| Columns                | 0.4 m x 0.4 m         | ISMB 250               |
| Beams                  | 0.3 m x 0.4 m         | ISMB 300               |
| Thickness of slab      | 150 mm                | 150 mm RC slab         |
| Storey height          | 3 m                   | 3 m                    |
| Grade                  | M30                   | Fe 345                 |
| Importance factor (I)  | 1                     | 1                      |
| Soil type              | II (medium or stiff soils) | II (medium or stiff soils) |
| Response Reduction factor (R) | 5(RC building with SMRF) | 5(Steel building with SMRF) |
| Zone factor            | 0.36 (Zone V)         | 0.36 (Zone V)          |

The dampers are positioned in four different configurations to determine the optimum positioning of the dampers. They are depicted in Figure 3.
The buildings without the dampers were analysed for all the ground motions and the uncontrolled response was determined. The dampers were designed for all the buildings separately and the dampers were positioned and analysed. The responses such as storey displacements and storey drifts were determined for all the cases.

6. Results and discussion

6.1. Storey displacements
From the test results, it was found that the presence of FVD reduces the storey displacements. The results of the RC and steel buildings are depicted in Figure 4. These results were obtained by taking the average of the results of all the three earthquake ground motions.
Figure 4. Percentage reduction of storey displacements in: (a) RC structures and (b) Steel structures.

It is found that the middle arrangement reduces the storey displacement to about 63.28% compared to the other arrangements for the G+3 RC structure. For G+5 and G+7 structures, the corner arrangement reduces the storey displacement to about 41.19% and 51.53% compared to the other arrangements respectively. It can be clearly understood that the optimum arrangement of the dampers varies with the storey height.

For the G+3 steel structure, it is found that the middle arrangement reduces the storey displacement to about 62.98% compared to the other arrangements. For G+5 and G+7 structures, the diagonal arrangement reduces the storey displacement to about 68.94% and 55.56% compared to the other arrangements respectively. FVD reduces the storey displacements of the structures to about 40-70% as per the results obtained. It is found that the aspect ratio of the building affects the optimum positioning of the dampers.

6.2. Storey drift
Storey drift is usually called as the inter-storey drift and it is defined as the lateral displacement of one level relative to the other. From the test results, it is also found that FVD reduces the storey drift to a greater extent. The percentage reduction of the storey drift values for the RC and steel structures are depicted in Figure 5. These results were obtained by taking the average of the results of all the three earthquake ground motions.
Figure 5. Percentage reduction of storey drifts in: (a) RC structures and (b) Steel structures.

It is found that the middle arrangement reduces the storey drift values to about 61.64% compared to the other arrangements for the G+3 RC structure. For G+5 and G+7 structures, the corner arrangement reduces the storey drift values to about 45.29% and 46.26% compared to the other arrangements respectively. From the determined results, it can be understood that the optimum arrangement to reduce storey drift values for a building is the one that reduces the storey displacements for the same building. Both are dependent to each other.

For the G+3 steel structure, it is found that the middle arrangement reduces the storey drift values to about 54.54% compared to the other arrangements. For G+5 and G+7 structures, the diagonal arrangement reduces the storey drift values to about 63.99% and 53.60% compared to the other arrangements respectively. FVD reduces the storey drift values of the structures to about 40-65% as per the results obtained.

7. Conclusion
From the analysis conducted, the following conclusions can be made.

- FVD is a passive device that does not have any sensors or actuators and does not consume any power. Instead, it relies on the damping properties of materials used in its design and hence it is more advantageous.
- The presence of FVD reduces the storey displacement and storey drift values for both RC and steel structures to about 40-70%.
- It was understood that the optimum positioning of the dampers depends on the aspect ratio of the building. Since the plan is kept the same, it directly depends on the height of the building.
- For the G+3 RC structure whose aspect ratio was 0.54, the optimum damper placement was found to be the middle placement with a reduction percentage of 63.28% for storey displacement and 61.64% for storey drift respectively.
- For the G+3 steel structure whose aspect ratio was 0.54, the optimum damper placement was found to be the middle placement with a reduction percentage of 62.98% for storey displacement and 54.54% for storey drift respectively.
- For the G+5 RC structure whose aspect ratio was 0.82, the optimum damper placement was found to be the corner placement with a reduction percentage of 41.19% for storey displacement and 45.29% for storey drift respectively.
- For the G+5 steel structure whose aspect ratio was 0.82, the optimum damper placement was found to be the diagonal placement with a reduction percentage of 68.94% for storey displacement and 63.99% for storey drift respectively.
For the G+7 RC structure whose aspect ratio was 1.09, the optimum damper placement was found to be the corner placement with a reduction percentage of 51.53% for storey displacement and 46.26% for storey drift respectively.

For the G+7 steel structure whose aspect ratio was 1.09, the optimum damper placement was found to be the diagonal placement with a reduction percentage of 55.56% for storey displacement and 53.6% for storey drift respectively.

Acknowledgement
The authors wish to record their sincere and heartfelt thanks to the Management, Principal in Charge, Head of the Department, Former Head of the Department, Department of Civil Engineering, PSG College of Technology, Coimbatore.

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