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Seismic Response Control of High-Rise Mass Varied Structures Using Linear Fluid Viscous Damper

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Abstract: Seismic event induces undesirable motion in buildings, energy dissipation systems in civil engineering are indeed needed. There is a mix of structures with passive energy dissipation supplied by Fluid Viscous Dampers systems (FVD). This technology is increasingly being utilized to improve seismic protection for both existing and new structures. The findings of the FVD systems are investigated in order to compare the structural response with and without this device of energy dissipation compared for low and high rise structures, the damper installed at different storey and varying the coefficient of damping (Cd) has been focused in this paper which provides an insight when the variation of Cd and its locations,. The findings of the FVD's impressive ability to increase the structure's dissipative capabilities without increasing its stiffness. In the case of high rise FVD performance has been evaluated through the top storey displacements which will allow for a conclusion.
Keywords: Coefficient of Damping, Fluid Viscous Damper, High Rise Buildings, Seismic Response, Tall Structure

I. INTRODUCTION

Earthquake is a phenomena which no one can predict and control it, tectonic plates movement causes earthquake which will release energy in the form of Primary, Secondary and Love waves on the surface of the earth. Structures built on the earth will be affected by seismic energy due to inertial forces, inherent damping force and resisting force by stiffness, will induce for the oscillation. Structures under oscillation for low rise to some extent can be resisted by structure itself without undergoing large top storey displacement but when the structure is tall large top storey displacement can make the occupants at the top storey in a pathetic condition, to avoid large displacements at the top storey one can use dampers. Dampers can be classified into 4 categories like passive, semi-active, active and hybrid[1], in this study we focus on passive fluid viscous dampers [2]. Fluid viscous dampers are easy to install and for maintenance, in passive system of damping doesn't require any external power to dissipate seismic energy of structure, absorption of energy through an orifice connected to a piston moving from one part of the cylinder to other filled with silicon or mineral oil. 3[3] and 11[4] storey benchmark mass varied buildings considered for the study using matlab as a tool by state space [5], frequency of the lumped mass models matches exactly with benchmark problems and hence study focused on reducing the top storey displacement for Elcentro 1940 earthquake for 5 g and 0.3417 g [6] accelerograms for low rise and high rise building [7] respectively, using fluid viscous damper at different location or storey's [8] in the building or structure, finding minimum numbers and location of dampers were discussed in this paper.

II. PASSIVE FLUID VISCOUS DAMPERS

Fluid viscous dampers was invented by Houde Engineering at the time of world war 1[9], initially it was used in the automobile industry below engine to reduce vibrations, drastically in the 1960s it was used by NASA in the large scale developed by Taylor[10], [11]. Later it was designed for use in structural engineering in the late of 1980s and early of 1990s by Makris and Constantinou. FVD typically consist of a piston head with orifices contained in a cylinder filled with a highly viscous fluid like mineral or silicon oils or similar type of oil which can work under - 40 to + 60 degree Celsius [10] varying temperature. Energy is dissipated [12] in the damper by fluid orifice when the piston head moves through the fluid. The fluid in the cylinder is nearly incompressible [11], and when damper is subjected to a compressive force fluid volume inside the cylinder is decreased as a result of the piston rod moves which in-turn energy consumed to do work [13].

A decrease in volume results in a restoring force. The seismic force is prevented by using an accumulator. An accumulator works by collecting the volume of fluid that is displaced by the piston rod and storing it in the makeup area. As the rod retreats, a vacuum that has been created will draw the fluid out. A damper with an accumulator is illustrated in the figure 1.

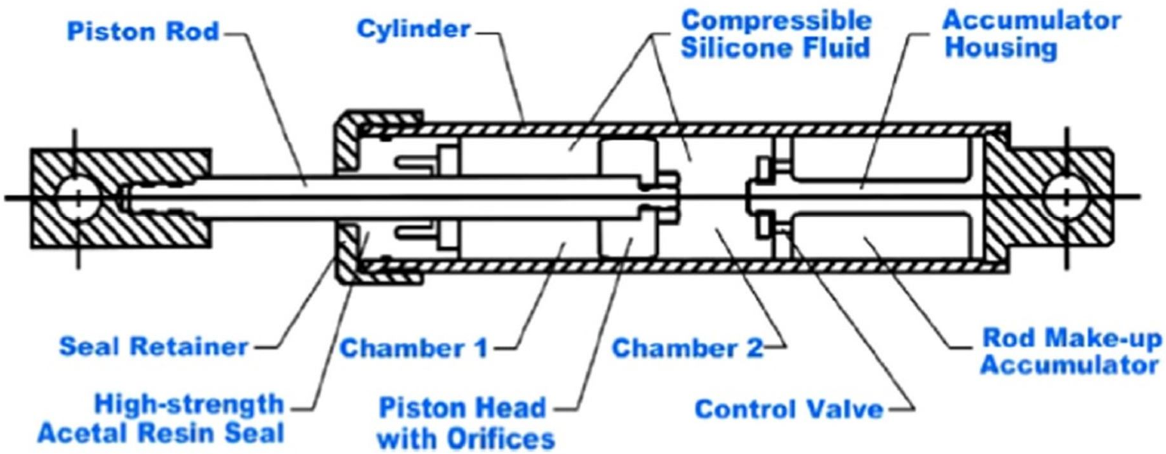

Fig. 1 Anatomy of Fluid Viscous Damper [14]

A. Characteristics of Passive Fluid Viscous Dampers

FVD are characterized by a resistance force F which it depends on the velocity of piston movement [15], fluid viscosity, orifices size of piston and storage stiffness of damper which it is not considered in the study if it is considered it will be called as viscoelastic damper. The value of damping force F is given by the relationship:

$$F_d(t) = C_d * V(t)^{\alpha} \qquad \text{----- (1)[16]}$$

Where,

F – Damping Force induced by Damper in Newton

Cd - is the damping constant in Newton-second/metre,

V - is velocity between the two end of damper in metre/second &

α - is the exponent which depends on viscosity properties of fluid and orifice dimensions of the piston. Values of $\alpha < 1$ behaves as nonlinear FVD, $\alpha = 1$ behaves as linear FVD & $\alpha > 1$ behaviour not so far seen in practical applications.

A typical force displacement relationship [14] shown in below figure 2 of FVD, Structure and structure installed with FVD.

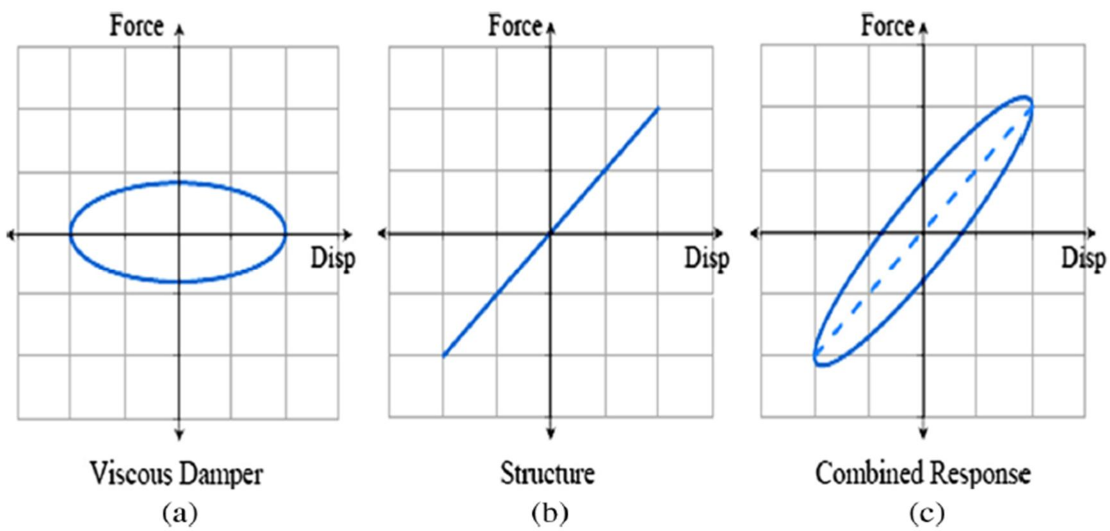

Figure 2 Hysteretic Curves of FVD, Structure and FVD Installed Structure [17]

B. *Linear Fluid Viscous Damper*

The current study focused on linear fluid viscous damping. It can be achieved by substituting α = 1 in the equation 1 modifies to:

$$F = F_d(t) = C_d * V(t) \qquad \text{----- (2) [18]}$$

C. *Governing Equations of Motion*

Mathematically a structure can be modelled as a lumped mass at each storey with multi degree of freedom can be written as:

$$M * x(\ddot{t}) + C * x(\dot{t}) + K * x(t) = -M * x(\ddot{t})_g \text{ [19]}$$

In the above equation if we add FVD it can be rewritten as:

$$M * x(\ddot{t}) + C * x(\dot{t}) + K * x(t) + F_d(t) = -M * \ddot{x}_g(t)$$

Where,

M – Mass matrix, diagonal matrix in kg
C – Damping matrix, tri-diagonal matrix in N-s/m
K – Stiffness matrix, tri-diagonal matrix in N/m
$x(\ddot{t})$ – Storey Acceleration vector due to excitation at that storey
$x(\dot{t})$ – Storey Velocity vector due to excitation at that storey
$x(t)$ – Storey Displacement vector due to excitation at that storey
$\ddot{x}_g(t)$ – Ground acceleration

D. *Numerical Study*

The storey shear building frame model with and without viscous damper at different storey's were modelled as linear lumped mass [20], governing equations of motion are stated above. The benchmark problem of 3 storey building configured with MR damper of passive off case [21] is considered with FVD installed at ground storey. Using state space matrix it can be solved to determine the displacement and velocity of the storey at the time t for the ground motion of NS component of El-centro 1940 data reproduced at 5 times the original record. The exact modelling of the problem using equations modelled in Matlab. System matrices are as mentioned below:

$$Mass\ matrix = M = \begin{bmatrix} 98.3 & 0 & 0 \\ 0 & 98.3 & 0 \\ 0 & 0 & 98.3 \end{bmatrix} \quad in\ kg$$

$$Damping\ matrix = C = \begin{bmatrix} 50 & -50 & 0 \\ -50 & 100 & -50 \\ 0 & -50 & 175 \end{bmatrix} \quad in\ N-s/m$$

$$Stiffness\ matrix = K = (10^5) * \begin{bmatrix} 6.84 & -6.84 & 0 \\ -6.84 & 13.7 & -6.84 \\ 0 & -6.84 & 12 \end{bmatrix} \quad in\ N/m$$

State Space matrices:

$$A = \begin{bmatrix} -M_i^{-1} * C_i & -M_i^{-1} * K_i \\ 0 & I \end{bmatrix} \qquad B = \begin{bmatrix} M_i^{-1} * \Gamma \\ 0 \end{bmatrix} \qquad E = -\begin{bmatrix} \Lambda \\ 0 \end{bmatrix}$$

State space output matrices:

$$C = \begin{bmatrix} 0 \quad 0 \quad 0 & 0 \quad 0 \quad 1 \\ -M_i^{-1} * C_i & -M_i^{-1} * K_i \end{bmatrix} \qquad D = \begin{bmatrix} 0 \\ M_i^{-1} * \Gamma \end{bmatrix}$$

Where,

$$Damper\ Location\ matrices = \Gamma = \begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix} \qquad State\ matrices = \Lambda = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$$

i =storey level

$$\dot{z} = A * z + B * F_d + E * \ddot{x}_g \qquad y = C * z + D * F_d$$

Validation or Comparison of results with the benchmark problem (BMP) considered as low rise structure [22]:

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Table1. Comparison of study results with Benchmark Problem for low rise case.

Parameter	Storey	Uncontrolled of BMP	Uncontrolled of study	% of difference	Passive off case of BMP	FVD installed model of study	% of difference
Storey Displacement in mm	Top - 1	9.62	9.647	0.28 %	4.55	4.553	0.07 %
	First - 2	8.20	8.246	0.56 %	3.57	3.654	2.35 %
	Ground - 3	5.38	5.407	0.50 %	2.11	2.262	7.20 %
	Base	0.0	0.0	0.0	0.0	0.0	0.0
Mean Difference				0.45 %			3.20 %
Force developed by FVD installed at ground storey in N		-			258	280.64	8.8 %

Further the study continuous to locating FVD at different storey's and the top storey displacement reduces from 9.647 to 4.55 mm for that coefficient damping C_d and damper force 'f' results are listed as below:

Table2. Comparison of FVD force for Cd variation for different models of low rise case.

Sl. No.	Model	Description	Coefficient of Damping Cd in N-s/m	Damper force fi in N
1.	M-1	FVD installed at ground storey only	1330	f3 = 281
2.	M-2	FVD installed at first storey only	1380	f2 = 183
3.	M-3	FVD installed at top storey only	930	f1 = 158.8
4.	M-4	FVD installed at all storey	470	f1 = 81
				f2 = 61
				f3 = 45
5.	M-5	FVD installed at ground & top storey only	730	f1= 124
				f3 = 67

The force (N) displacement (cm) curves are as follows for the different models as mentioned in the above table:

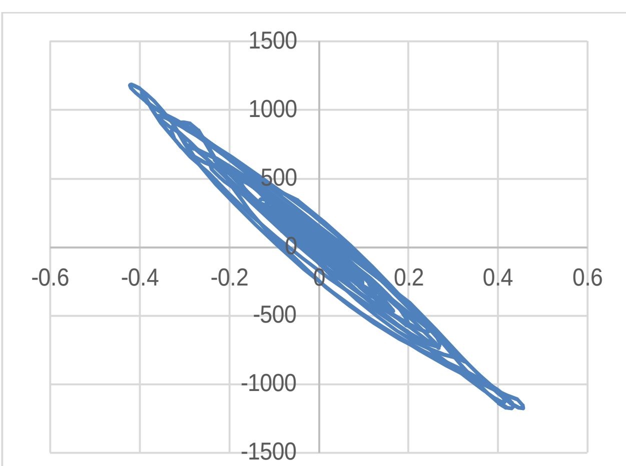

Fig. 3 M1 model

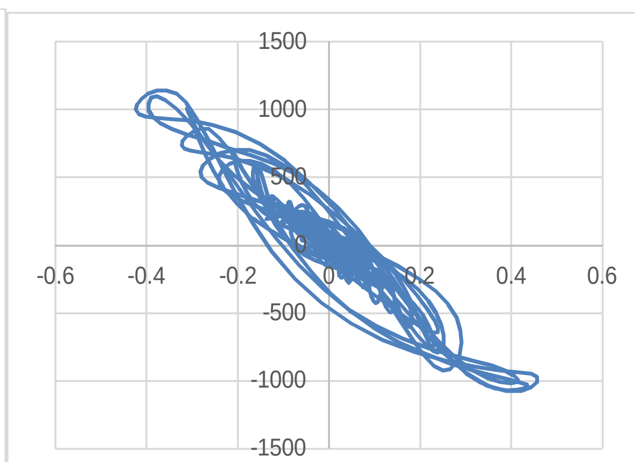

Fig. 4 M2 model

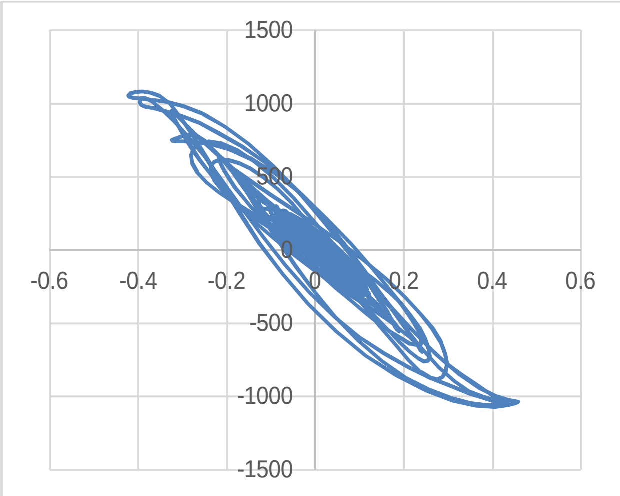

Fig. 5 M3 model

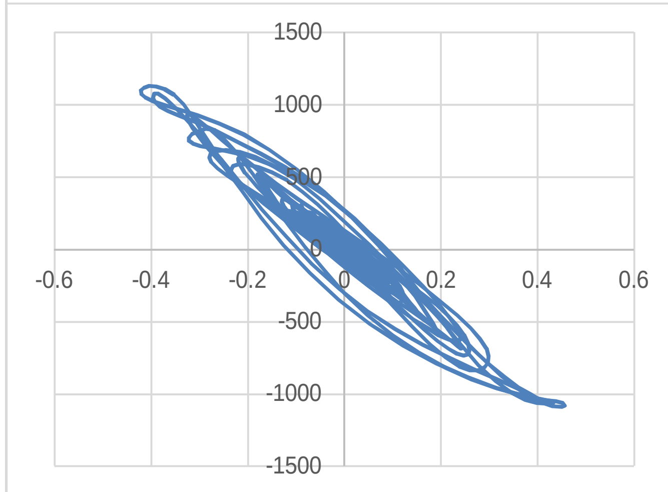

Fig. 6 M4 model

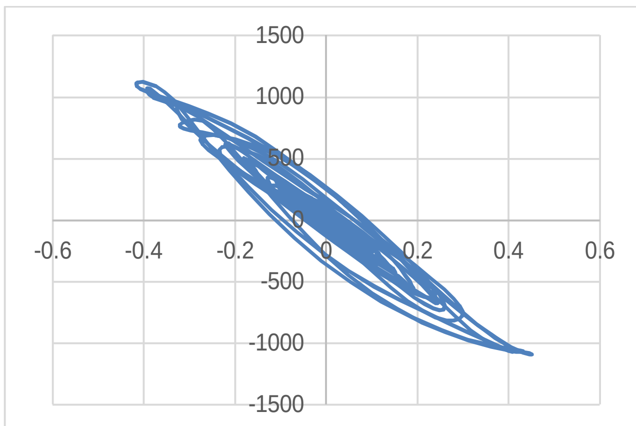

Fig. 7 M5 model

Top storey displacement curve for NS component of Elcentro 1940 earthquake force for FVD installed models:

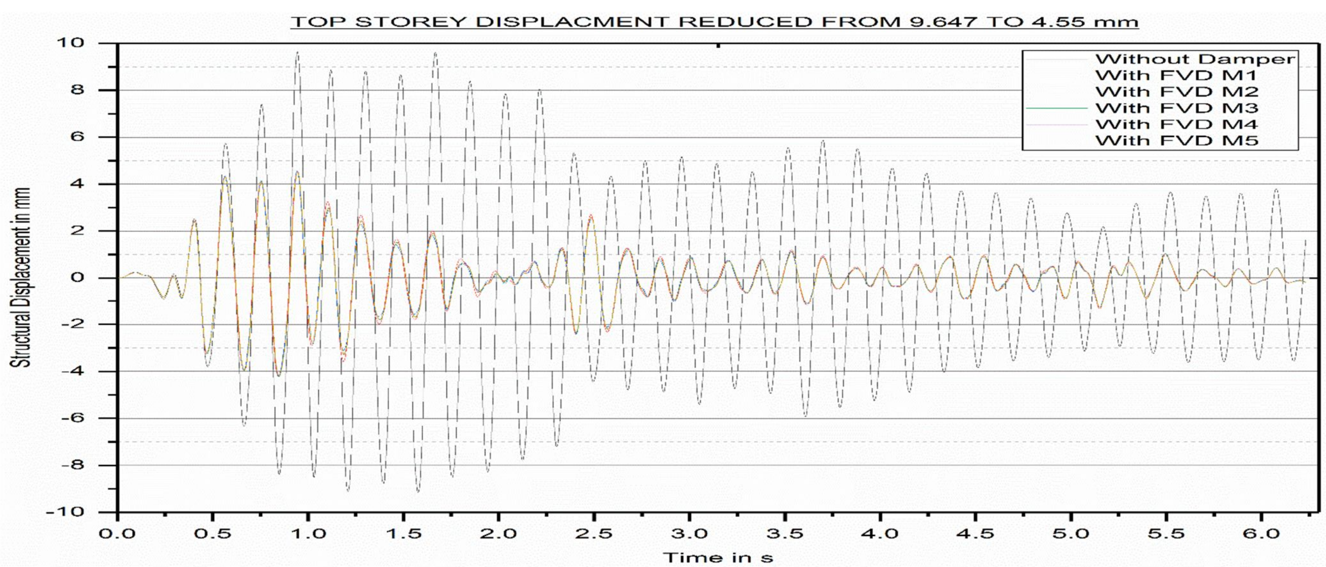

Fig. 8 Top Storey displacement v/s time graph for dampers with varying Cd.

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Further the study continuous to locating FVD at different storey's and the top storey displacement reduces for constant coefficient damping Cd and damper force f results are listed as below:

Table3. Comparison of FVD force for constant Cd for different models of low rise case.

Sl. No.	Model	Description	Coefficient of Damping Cd in N-s/m	Damper force fi in N
1.	M-1	FVD installed at ground storey only	1330	f3 = 281
2.	M-2	FVD installed at first storey only	1330	f2 = 360
3.	M-3	FVD installed at top storey only	1330	f1 = 392
4.	M-4	FVD installed at all storey	1330	f1 = 272
				f2 = 229
				f3 = 149
5.	M-5	FVD installed at ground & top storey only	1330	f1= 351
				f3 = 192

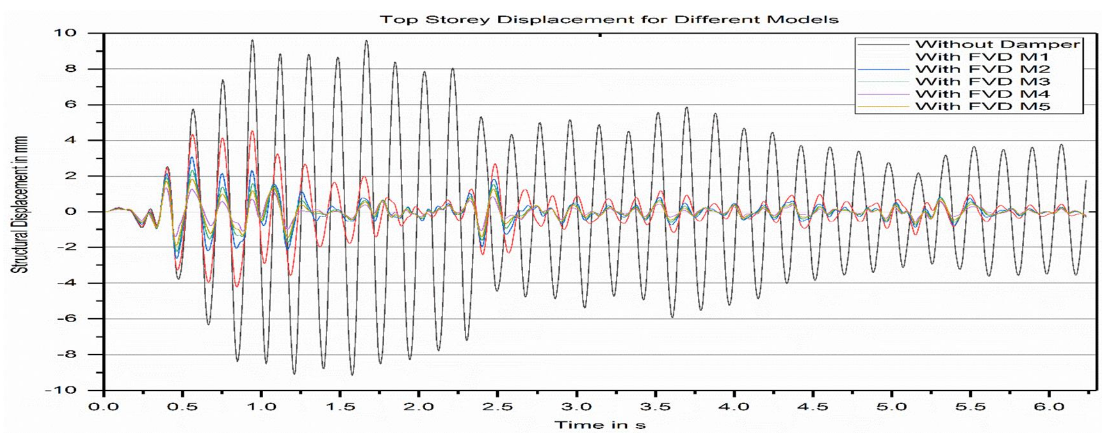

Fig. 9 Top Storey displacement v/s time graph for with and without dampers

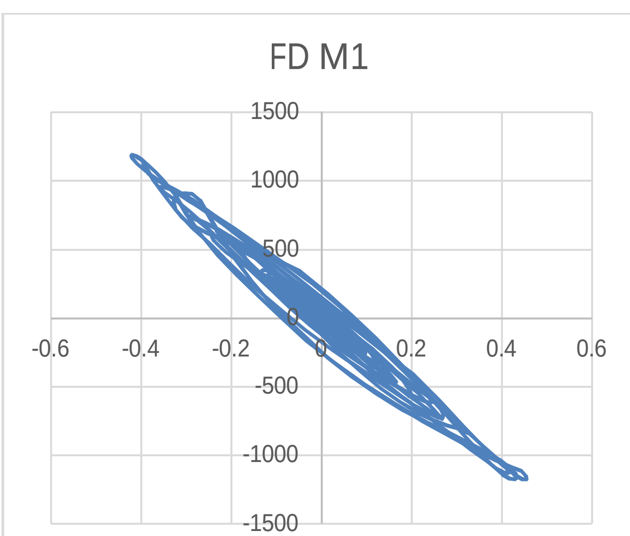

Fig. 10 M1 model

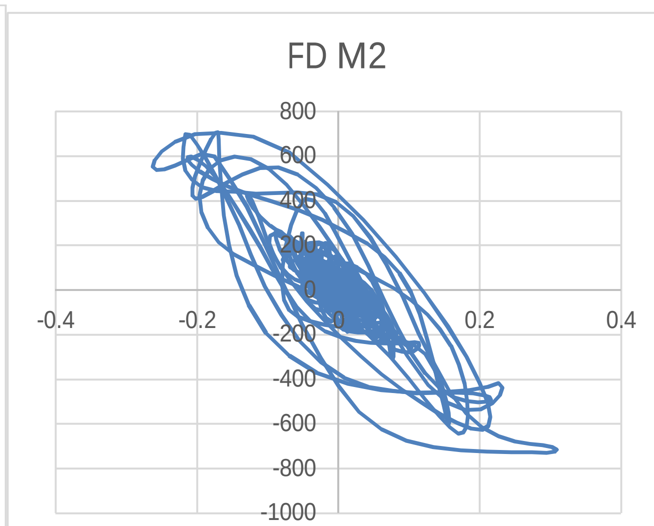

Fig. 11 M2 model

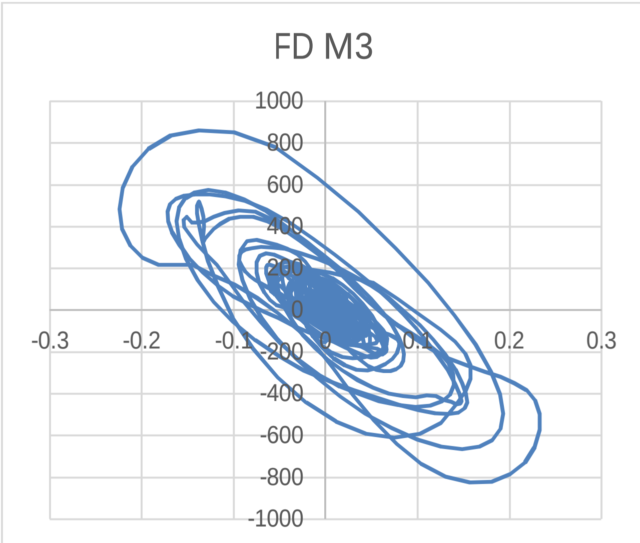

Fig. 12 M3 model

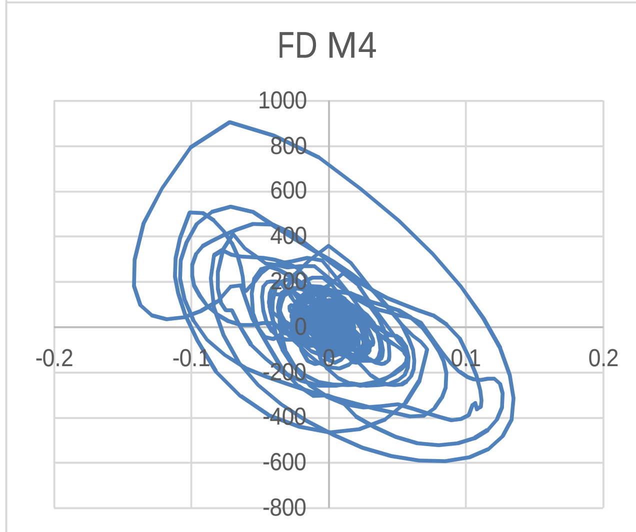

Fig. 13 M4 model

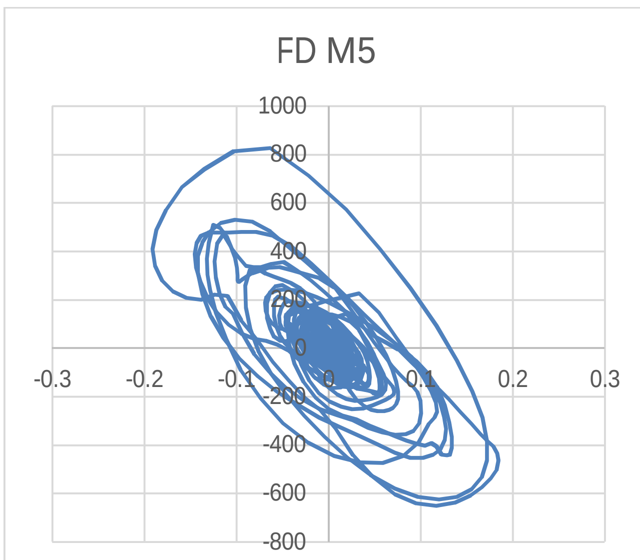

Fig. 14 M5 model

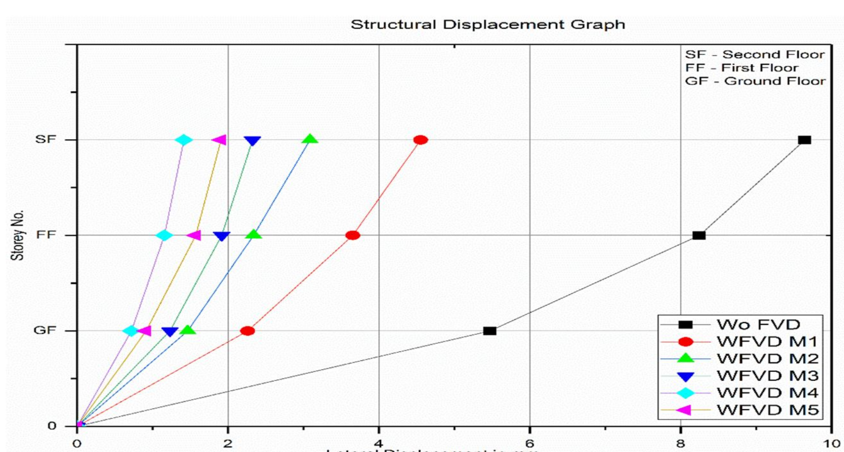

Fig. 15 Lateral displacement for FVD installed models

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E. High Rise Building

Further the study evaluates for the tall structure (high rise building 11 storey) [4], [22] are as follows:

$$Mass\ matrix = M = \begin{bmatrix} 1.76 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 2.03 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2.03 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2.03 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2.01 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2.01 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 2.01 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2.00 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2.01 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2.01 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2.15 \end{bmatrix} (1 * 10^5) in\ kg$$

$$Stiffness\ matrix = K = (1 * 10^8) \begin{bmatrix} 3.12 & -3.12 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -3.12 & 7.49 & -4.37 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -4.37 & 8.74 & -4.37 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -4.37 & 8.74 & -4.37 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -4.37 & 8.87 & -4.50 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -4.50 & 9.00 & -4.50 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -4.50 & 9.00 & -4.50 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -4.50 & 9.00 & -4.50 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -4.50 & 9.18 & -4.68 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -4.68 & 9.44 & -4.76 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -4.76 & 9.44 \end{bmatrix} in\ N/m$$

$$Damping\ Matrix = C = (1 * 10^6) \begin{bmatrix} 1.30 & -1.70 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1.70 & 3.02 & -1.70 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1.70 & 3.50 & -1.70 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1.70 & 3.50 & -1.76 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1.76 & 3.56 & -1.76 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1.76 & 3.61 & -1.76 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1.76 & 3.61 & -1.76 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1.76 & 3.61 & -1.82 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1.82 & 3.68 & -1.86 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1.86 & 3.78 & -1.82 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1.82 & 3.79 \end{bmatrix} in\ N - s/m$$

Validation or Comparison of results with the benchmark problem (BMP) considered as high rise structure:

Table 4. Comparison of storey wise displacement for high rise case.

Parameter	Storey	Uncontrolled of BMP	Uncontrolled of study	% of Difference
Storey Displacement in mm	11	147.0	148.26	0.86
	10	140.0	144.62	3.30
	9	140.0	139.10	0.64
	8	130.0	130.80	0.62
	7	120.0	119.88	0.10
	6	100.0	106.95	6.95
	5	90.0	91.97	2.18
	4	74.0	75.23	1.66
	3	57.0	57.06	0.10
	2	39.0	38.53	1.20
	1	19.0	19.62	3.26
	0	0.00	0.00	0.00
Mean Difference				1.90 %

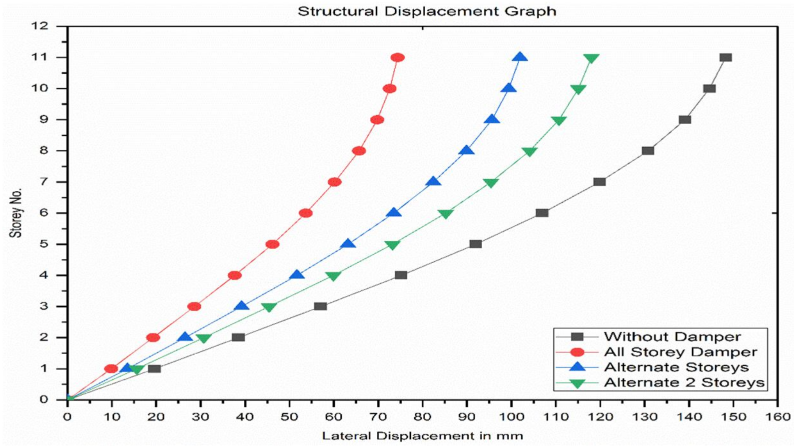

Fig. 16 Lateral displacement for FVD installed models

Fluid Viscous Damper parameters: Cd = 25000 N-s/m α = 1

1) Model 1: Dampers Installed at all storey's

Table 5. Comparison of storey wise displacement for FVD installed at all storey for high rise case.

Storey No.	Storey Displacement for without Damper in mm	Storey Displacement for with Damper in mm	% reduction	Force Developed in Damper in N
11	148.2	74.4	49.80	12788.52
10	144.6	72.6	49.79	12174.38
9	139.1	69.8	49.82	11717.22
8	130.8	65.7	49.77	11025.41
7	119.8	60.2	49.75	10111.23
6	106.9	53.7	49.77	9025.41
5	91.9	46.2	49.73	8712.03
4	75.2	37.7	49.87	7794.21
3	57.0	28.6	49.82	6225.05
2	38.5	19.3	49.87	4308.65
1	19.6	9.90	49.49	2305.36
0	0.00	0.00	0.00	-

2) Model 2: Dampers Installed at alternate storey's

Table 6. Comparison of storey wise displacement for FVD installed at alternate storey for high rise case.

Storey No.	Storey Displacement for without Damper in mm	Storey Displacement for with Damper in mm	% reduction	Force Developed in Damper in N
11	148.2	101.92	31.23	17196.18
10	144.6	99.4	31.26	-
9	139.1	95.6	31.27	16148.11
8	130.8	89.9	31.27	-
7	119.8	82.4	31.22	13934.39
6	106.9	73.5	31.24	-
5	91.9	63.2	31.23	10698.90
4	75.2	51.7	31.25	-
3	57.0	39.2	31.23	6633.39
2	38.5	26.5	31.17	-
1	19.6	13.5	31.12	2389.88
0	0.00	0.00	0.00	-

3) *Model 3:* Dampers Installed at alternate two storey's

Table 7. Comparison of storey wise displacement for FVD installed at alternate two storey for high rise case.

Storey No.	Storey Displacement for without Damper in cm	Storey Displacement for with Damper in cm	% reduction	Force Developed in Damper in N
11	148.2	118.0	20.38	-
10	144.6	115.1	20.40	19492.6
9	139.1	110.7	20.42	-
8	130.8	104.1	20.41	-
7	119.8	95.4	20.37	16185.44
6	106.9	85.2	20.30	-
5	91.9	73.2	20.35	-
4	75.2	59.9	20.35	10165.43
3	57.0	45.4	20.35	-
2	38.5	30.7	20.26	-
1	19.6	15.6	20.41	2647.78
0	0.00	0.00	0.00	-

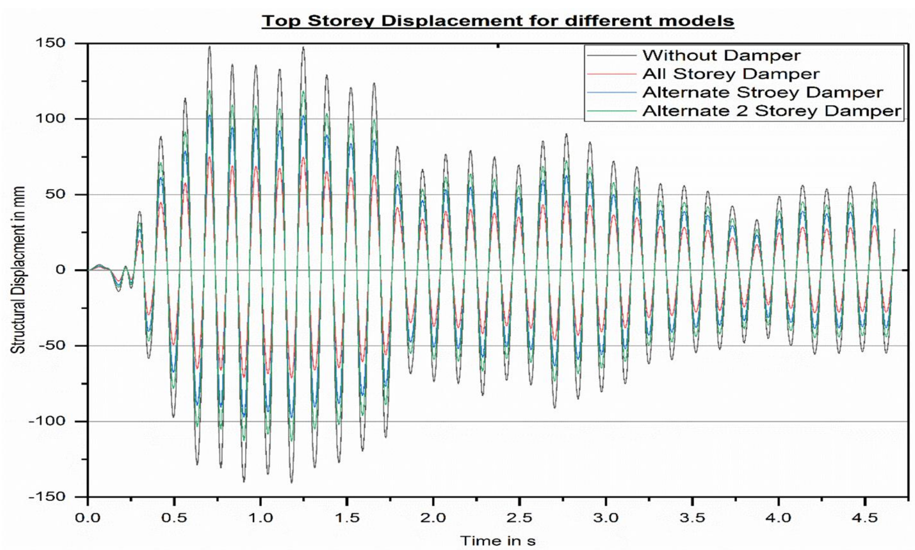

Fig. 17 Top Storey displacement v/s time graph for with and without dampers

III. RESULTS & DISCUSSIONS

A. *Low Rise Case*

1) Validating low rise benchmark problem to 0.45 % difference in results led to the conclusion that low value of Cd can be used with increased number of dampers to achieve better results with cost effective.
2) When the Cd is constant the force developed may be high, if top storey displacement can be set to a target value Cd can be varied and number of damper usage may be increased.
3) When the FVD numbers varied in buildings force developed by damper also varied.
4) The lowest top storey displacement achieved for M-4 but it is uneconomical, hence the M-5 model fetched the next better results when compared with M-4 & M-5 models as per table 3.
5) In without damper model clearly obeying a linear pattern as per the fig.2, for M-2 to M-5 models follows hysteretic curve.
6) Top storey displacement reduced 85 % when compared with WOD (without damper model) & M4 models, 80 % when compared with WOD & M5 models & 53 % when compared with WOD & M1.

B. *High Rise Case*

1) Mass and stiffness has been varied throughout the height of the 11 storey tall structure.
2) The Cd value has kept constant here based on the demand of damping.
3) The lateral displacement curve is parabolic as per the fig.16.
4) The mean storey wise displacement difference for the tall structure is 1.90 %.
5) In tall structures when FVD placed at different locations as discussed in table 5, 6 & 7 it clear that number of dampers as high the storey displacements are also low and damper force developed is also high .
6) From table 5, 6 & 7 the best models for tall structure is damper installed at alternate 2 storey-number of dampers less but up to 20 % of displacements reduced when compared with WOD.

IV. CONCLUSIONS

1) Mass kept same in all storey's with varying stiffness installed with FVD to reduce the top storey displacements up to 85 %.
2) Mass and stiffness are varied with FVD to reduce top storey displacements upto 50 %.
3) FVD at two alternate storey in low and high rise cases shows good results when compared to FVD installed at all storey's.

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