

Base Shear-Deformation Analysis for Buildings with Isolation and Damping System Using Time-History Method

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Abstract

Seismic hazard refers to the potential for earthquakes to occur in a particular area and cause damage, based on factors such as the frequency, magnitude, and location of past earthquakes, as well as geological conditions. Areas with high seismic hazard may experience more frequent and/or more intense earthquakes, making it essential for residents and authorities to take appropriate measures to reduce the risk of damage and loss of life. Seismic disaster mitigation involves implementing measures to reduce the impact of earthquakes on human life, infrastructure, and the environment. These measures aim to minimize casualties, injuries, and property damage by enhancing preparedness, improving building codes and construction standards, implementing land use planning, and developing emergency response plans. Seismic disaster mitigation technique is being adopted which causes reduction in earthquake forces by different methods. The proposed paper investigates the ability of base isolation and energy absorption system using lead rubber bearings and fluid viscous dampers to protect the structure by controlling seismic response. Concrete building structures of regular type with various plan dimensions have been modelled in SAP 2000 for story heights of G+5 and G+15. Non-linear Time history method has been performed for both conventional and buildings with isolation and damping system. Seismic responses e.g. base shear, max drift / displacement etc. have been compared for the conventional and isolated / damped structures of different aspect ratio (plan / height) for each of the building models with same seismic considerations.

Keywords: Seismic analysis, Base isolation, Damping, Fluid viscous damper, Base shear, Lead Rubber bearings, Time history, Time period, Seismic disaster.

1. Introduction

Seismic mitigation is critically important for several reasons; protecting lives, reducing economic losses, preserving infrastructure, maintaining social stability. The application of seismic mitigation strategies to protect structures from earthquakes is more critical particularly in high seismic prone regions. There are different techniques used for mitigation which sometimes used alone or sometimes combined together. The major and popular method is engineering solutions which include design of structures to withstand seismic force and be more seismic resilient. Structures are required to be designed for life safety in Design basis earthquake and collapse prevention in Maximum credible earthquake. However, the important structures should not only survive for DBE but also to remain operational immediately after an earthquake. Conventional design is comparatively costlier to resist earthquake in active manner. Seismic isolation and

damping are two techniques used as mitigation systems to reduce the impact of earthquakes on structures. These work on the principle of the flexibility of structure is enhanced by lengthening time period by means of isolation and the excess energy introduced to a structure during an earthquake is safely dissipated, e.g. by means of damping. Seismic isolation involves placing a flexible or low-stiffness material between a structure and its foundation, allowing the structure to move independently of the ground motion during an earthquake. This isolation effectively decouples the building from the shaking ground, reducing the transfer of seismic forces to the structure. Damping systems are designed to dissipate the energy generated by seismic forces, reducing the amplitude of vibrations in a structure and minimizing structural damage. Damping devices can be passive or active and are typically integrated into the building's structure or added externally. Commonly used isolators are Lead rubber bearings (LRB) and dampers are Fluid viscous dampers (FVD). Lead rubber bearings consist of rubber which acts as elastic system and adds flexibility and lead core adds required damping. Fluid viscous dampers consist of viscous fluid which provides damping and acts on the constitutive law; force, velocity and damping.

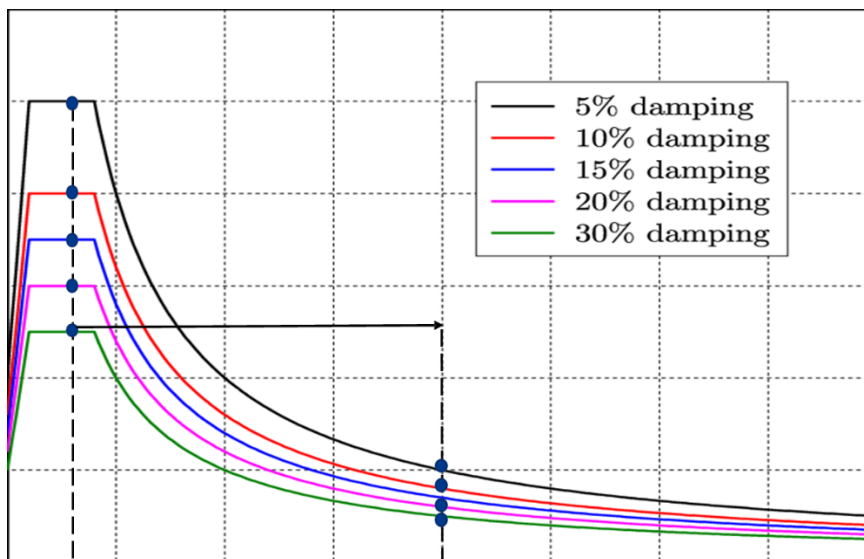


Fig. 1 Response spectrum graph with isolation and damping

Figure 1 shows the variation of spectral acceleration value with the change of time period which is enhanced by using isolation in the structure. The reduction of acceleration followed by seismic base shear follows non-linear equation which ensures the considerable reduction of force due to increase in time period up to 4 sec. It also defines the reduction of acceleration with increased damping for same time period. The basic response spectrum graph is considered for structure with 5% effective damping and it is seen that using additional damping of 30-35% can reduce base shear up to 50%.

The objective of the proposed study is to check the variation of seismic forces for different building structures with same seismic inputs and also for different seismic zones and soil types using same isolators and dampers. The requirement is to find out the optimum zone, which can help to decide isolation / damper type for effective control of structural response. The base shear is aimed to be within the limit which can be comfortable and acceptable for the structure.

The scope includes the numerical parametric study based on dynamic analysis (Non-linear Time history) of concrete building structure with following variation:

Structure with conventional support system

Structure with lead rubber bearings between superstructure and foundation at each column support

Structure with fluid viscous dampers diagonally placed between support and columns at ground floor

Comparison study has been made for important building models for the following different parameters considered in seismic analysis Importance factor (1.5 for both conventional and isolated models)

- Seismic zone V, IV, III
- Response Reduction factor (1.0 for both conventional and isolated models)
- Soil type Medium

2. Numerical Analysis

Numerical Models have been developed for conventional, isolated support and damped system. Study has been made of different kind of structures for different seismic parameters with similar Lead rubber bearing and fluid viscous damping system.

Analysis has been done in SAP:2000 platform by Non-linear Time history Method. The FEM based software seems to be applicable for analysis of different type of structural system as state-of-the-art practice with non-linear and dynamic consideration.

Two types RCC building models have been developed for G+5 & G+15 storey. All of the building models are regular in plan with 4x4 to 8x8 grid. Each panel area is 4 mx 4 m. The height of each storey is 4m. The columns are of 300 mm width and 400 mm depth, beams are assigned with 250 mm width and 300 mm depth. Slabs are of 150mm depth and walls are 250 mm thick. The grade of concrete is M30 for all the models. Supports are defined as conventional for fixed and isolated for lead rubber bearings.

Lead rubber bearings are assigned as link supports. Link element has been defined with non-linear properties, initial stiffness, yield force and post yield stiffness ratio. Fluid viscous dampers are also modelled as links and non-linear properties are given as stiffness, damping constant, damping exponent based on constitutive law.

$$F = CV^n$$

F is the force, C is the damping constant and n is the damping exponent.

Different types of building models are designated as mentioned in Table 1 for the entire paper.

Table 1: Building models in SAP 2000

Support	Story	Plan				
		16x16	20x20	24x24	28x28	32x32
Fixed	G+5	CM5-16	CM5-20	CM5-24	CM5-38	CM5-32
	G+15	CM15-16	CM15-20	CM15-24	CM15-28	CM15-32
With LRB	G+5	IM5-16	IM5-20	IM5-24	IM5-38	IM5-32
	G+15	IM15-16	IM15-20	IM15-24	IM15-28	IM15-32
With damper	G+5	DM5-16	DM5-20	DM5-24	DM5-38	DM5-32
	G+15	DM15-16	DM15-20	DM15-24	DM15-28	DM15-32

The plan and elevation of each regular building are shown in Fig. 2. To Fig. 7.

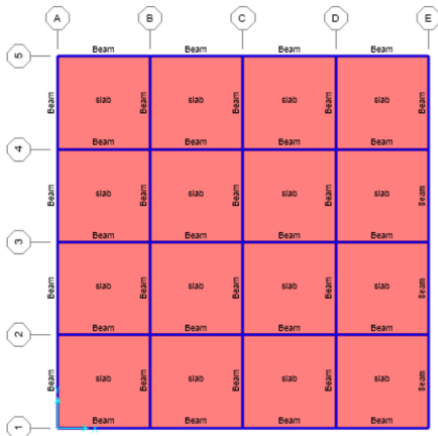


Fig. 2 Plan of CM5-16 / IM5-16 / DM5-16

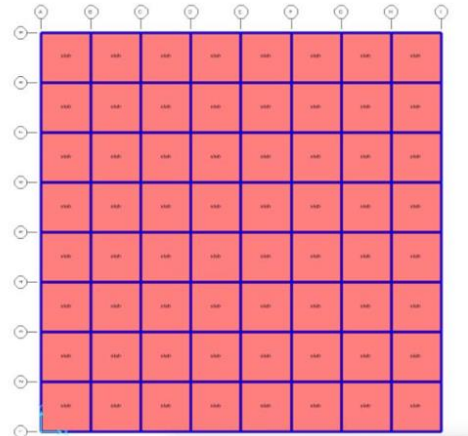


Fig. 3 Plan of CM5-32 / IM5-32 / DM5-32

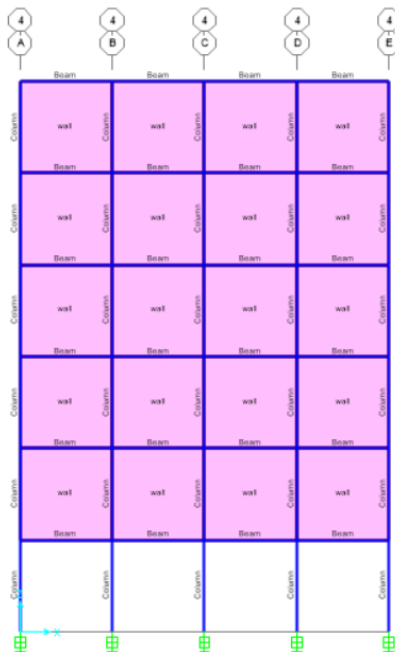


Fig. 4 Elevation of IM5-16

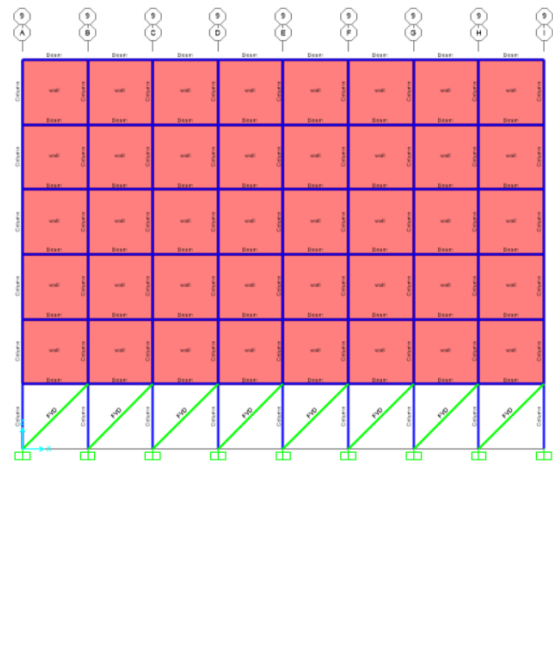


Fig. 5 Elevation of IM5-32

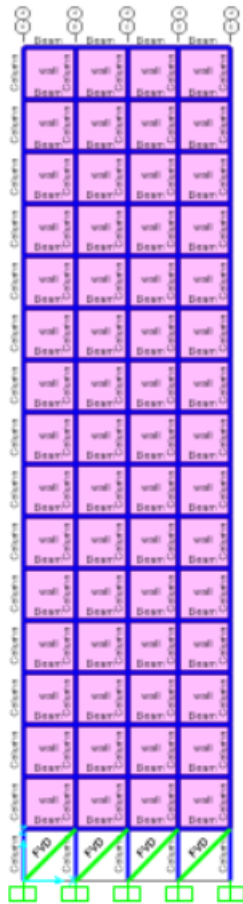


Fig. 6 Elevation of DM15-16 building

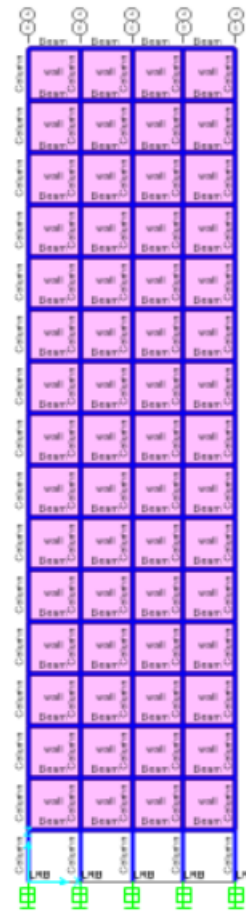


Fig. 7 Elevation of IM15-16 building

Different material properties, load cases for various zones and soil types, support restraints, non-linear properties of links have been incorporated in the models. The time history function has been derived by matching the accelerogram data from Elcentro with target response spectrum for various zones and soil types. Input function for non-linear dynamic analysis has been defined for load pattern as acceleration in X & Y direction with scale/conversion factor as 9.81. Scale conversion factor is the value of “g” to match the unit of both input and matched accelerogram. Total duration of Time history acceleration function is 30s (time step of 0.02s) for Elcentro earthquake.

The non-linear properties of Link/Support for Lead rubber bearings are considered as follows in Table 2.

Table 2: Non-linear properties of LRB

Initial stiffness (kN/m)	Yield force (kN)	Post yield stiffness ratio
7000	60	0.15

Initial stiffness is the combination of stiffness of lead core and rubber till the yield point of lead or it can be defined as elastic stiffness. Yield force is the force required to yield and go beyond the elastic limit. Post yield stiffness ratio is the ratio between post yield stiffness and initial/elastic stiffness. The lead rubber bearings work as isolator with additional damping property which helps to reduce the seismic force. The hysteresis graph in Fig. 8 shows the force-displacement nature of lead rubber bearings.

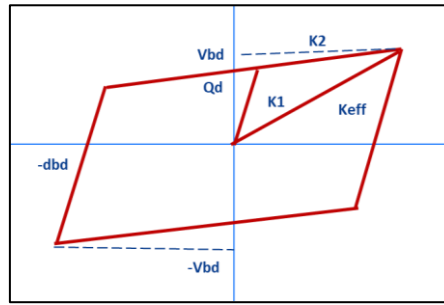


Fig. 8 Force-displacement behavior of LRB

K_1 is the initial stiffness and it is considered until yield point. Q_d is the characteristics load/yield point of the isolator. K_2 is the post yield stiffness ratio, stiffness after yield/ initial stiffness.

The non-linear properties of Link/Support for fluid viscous dampers are considered as follows in Table 3.

Table 3: Non-linear properties of dampers

Force (kN)	Initial stiffness (kN/m)	Damping constant (kN/(m/s) ⁿ)	Damping exponent
100	20000	126	0.1
200	40000	252	0.1
300	60000	378	0.1
400	80000	504	0.1
500	100000	630	0.1

3. Results and discussions

The G+5 and G+15 storeyed buildings are modelled with different widths in plan. The aspect ratio for different configurations of G+5 and G+15 buildings are shown in Table 4 and Table 5.

Table 4: Aspect ratio for G+5 (CM5/IM5/DM5) building

Building	Height	Width	Aspect ratio
G+5	24	32	1.33
	24	28	1.17
	24	24	1.00
	24	20	0.83
	24	16	0.67

Table 5: Aspect ratio of G+15 (CM15/IM15/DM15) building

Building	Height	Width	Aspect ratio
G+15	64	32	0.50
	64	28	0.44
	64	24	0.38
	64	20	0.31
	64	16	0.25

The buildings are isolated using LRBs and the results for buildings with different aspect ratio are analysed. It is seen that the isolated base shear decreases with increase in aspect ratio. Isolation ratio which is the ratio between isolated and fixed base shear, varies within the range of 17-20% for IM5 buildings (Fig. 9). It seems that the buildings with higher aspect ratio have less base shear for isolated support. The isolation works more efficiently for wider buildings. The wider buildings are already stiffer than others and hence use of isolation at supports help in much reduction of base shear.

Now the base shear values are checked for G+15 storeyed or IM15 buildings for same seismic zone and soil type (Fig. 10). Isolation ratio is checked for different aspect ratio. The analysis has been performed for seismic zone V.

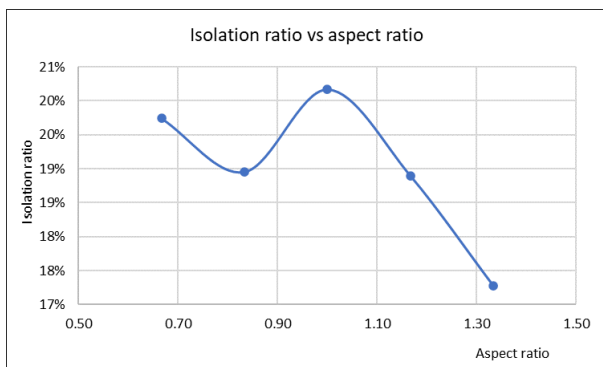


Fig. 9 Change in isolation ratio-IM5 buildings

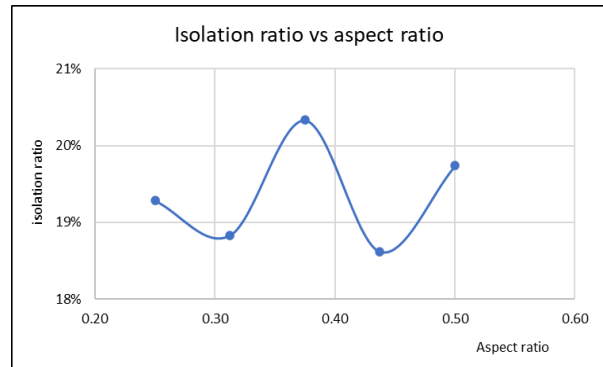


Fig. 10 Change in isolation ratio-IM15 buildings

For IM15 buildings it is observed that the isolation ratio is in the range of 18-20%. Due to the height, building is already very flexible and having fixed support base shear only 24% of seismic weight. Additional isolation at supports makes the base shear further reduced to 5%. In standard design structures are designed for different load cases including dead, live, wind etc. other than seismic condition. Reduction of base shear up to 5% may not be the critical base shear for which structure to be designed. However, since there is further reduction in base shear using isolation, it can be said that isolation works for CM15/IM15 buildings as well.

Fluid viscous dampers (FVD) are modelled as link system connected diagonally between support and the column. Support condition is considered as fixed and restraints in all directions. Both G+5 and G+15 buildings are analysed with this combination of FVD and fixed / conventional supports. Base shear for buildings with and without FVDs are compared and result is shown in Fig. 11.

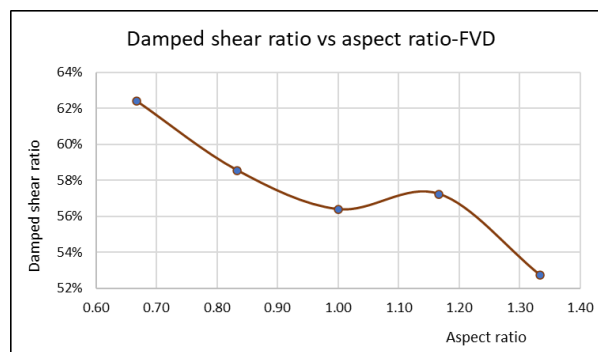


Fig. 11 Change in damped shear ratio-DM5 buildings

Damped shear ratio which is the ratio between damped and fixed support base shear decreases with increase in aspect ratio. It means that if the buildings are stiffer then isolated base shear is lesser in comparison with shorter width buildings. The damped shear ratio varies between 53 to 62%, it defines that damped base shear reduction is from 38 to 47% from the fixed support base shear. The base shear has been compared using FVD of axial force 300 kN. The reduction in base shear is considerably higher using isolated support than the buildings with dampers. The analysis and resulted base shear depend on the non-linear properties selected for LRBs and FVDs. For different stiffness and yield properties, base shear values and the reduction pattern may be different. The comparison has been drawn for G+15 buildings also and shown in Fig. 12.

Damped shear ratio = (Base shear for buildings with dampers)/(Buildings with fixed support)

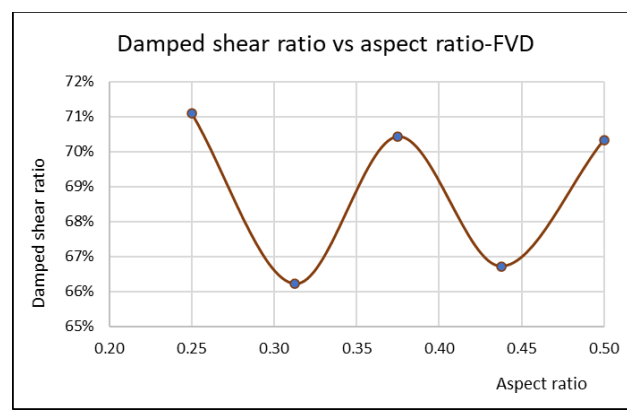


Fig. 12 Change in damped shear ratio-DM15 buildings

The damped shear ratio varies between 66 to 71% with change in aspect ratio from 0.25 to 0.50 for DM 15 buildings. Base shear reduction is in the range of 30% than the fixed support base shear. Since DM15 building is flexible and fixed support base shear is already very less, 23% of the seismic weight, further reduction of base shear at around 30% using FVDs helps to have an economic and safe design during seismic event. Final reduced base shear using FVDs is 14% and using LRBs is only 5%. It can be said that use of FVDs is more realistic and suitable for G+15 buildings. As design of buildings only for 5% seismic base shear may not ideally be the design load depending on other load cases, the reduced base shear of 14% using FVDs can be a more optimum solution. On the other side, use of LRBs for G+15 buildings can be a suitable and economic proposal as 17-20% base shear for isolated support during seismic event is a realistic approach.

The seismic base shear has been checked for different capacity of FVDs. The non-linear properties of FVD are shown in previous section. Non-linear time history method was performed considering different FVDs. The base shear has been checked for different FVDs for DM5 buildings with 32x32m width. From the below chart (Fig. 13), it is observed that reduced base shear varies from 53 to 66%. It is interesting that use of 300 kN capacity FVD, isolation ratio is less and use of 100 kN as well as 500 kN FVDs, provides higher isolated base shear. It denotes that the FVD with 300 kN capacity helps in maximum reduction in base shear.

The comparison between base shear values using same FVD properties are done for G+15 buildings as well (Fig. 14).

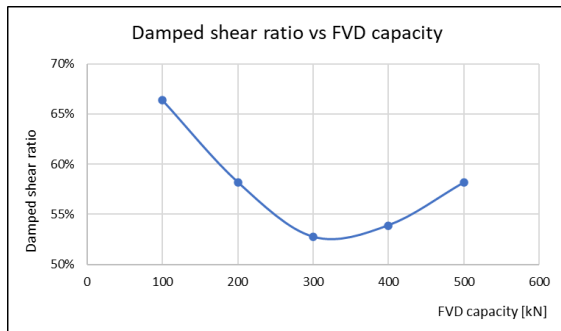


Fig. 13 Damped shear ratio -DM5-32 buildings

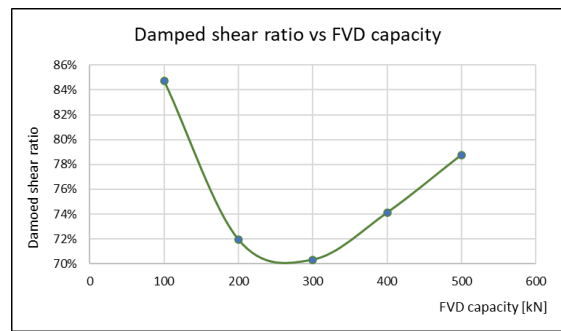


Fig. 14 Damped shear ratio -DM15-32 buildings

The reduced base shear using FVDs from 100 to 500 kN FVD capacity, varies between 70-85%. FVD of 300 kN capacity produces the maximum reduction in base shear whereas FVD of 100 kN provides minimum reduction. The damped base shear ranges from 14-20% for FVD of 100 kN to 500 kN capacity. Using FVD of 300 kN is the most suitable solution as it produces the minimum base shear. It defines that increase in force capacity of FVDs can help in increase of damping but it can stiffen the building. Hence, increase in damping and selection of FVD need to be optimum to finally reduce the base shear at the desired level.

The building models have been analysed (Fig. 15, Fig. 16) for seismic zone IV and III to check the performance of FVDs and the reduction in base shear. The damped shear ratio values have been recorded for different capacity FVDs (from 100 kN to 500 kN).

The damped shear ratio varies from 61 to 77% and the least value has been derived using FVD capacity of 200 and 300 kN. Use of higher capacity FVDs, i.e., 400 and 500 kN increases the damped shear ratio which means the isolated base shear is higher in comparison to the value using lesser capacity FVDs. The similar analysis has been done for seismic zone III also and the result is shown in following graph.

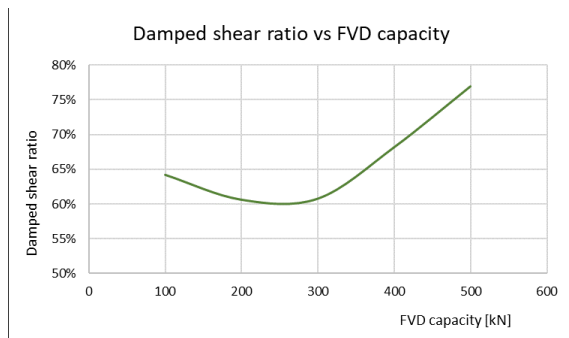


Fig. 15 DM5-32 buildings- zone IV

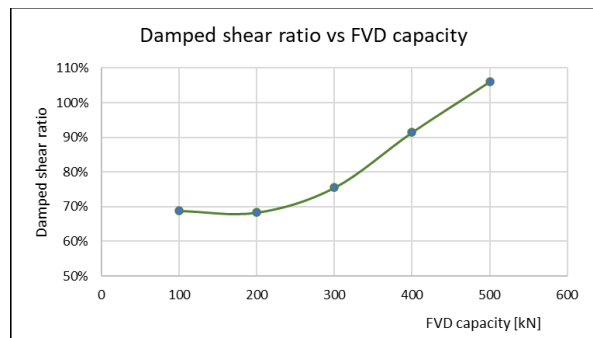


Fig. 16 DM5-32 buildings- zone III

For zone III, damped shear ratio varies between 68 to 106% and it has been observed that use of 400 and 500 kN capacity FVDs produce higher base shear than the fixed or conventional support. FVD with capacity 200 kN are the most suitable damper for zone III. It defines that 500 kN FVD capacity makes the structure stiffer, and the time period becomes lesser than the conventional models. Considering the damped shear ratio using different capacity FVDs for different seismic zones, it is seen that FVD of capacity 300 kN is the most suitable for this DM5 building models as it produces the minimum base shear

and damped shear ratio. Also, the use of FVD is most effective for high seismic zone, i.e., zone V as the reduction in base shear is maximum among all other zones.

The base shear value has been checked and analysed for CM15 buildings. Fig. 17 shows the change in damped shear ratio with respect to the different capacity of FVDs. In zone IV, the damped shear ratio varies from 71 to 93%. FVD of 200 kN capacity reduces the base shear up to 29% whereas 500 kN FVD reduces only up to 7%. In general dampers are used to reduce the base shear at least 20% to achieve the economic and safe design. Hence the use of FVD of 500 kN capacity may not be a suitable and desired solution. Fig. 18 shows the change in damped shear ratio for zone III using same parameters.

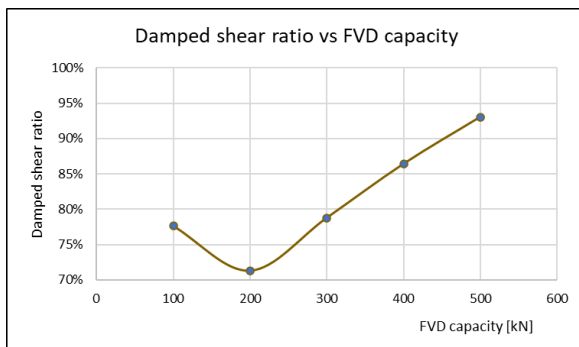


Fig. 17 DM15-32 buildings- zone IV

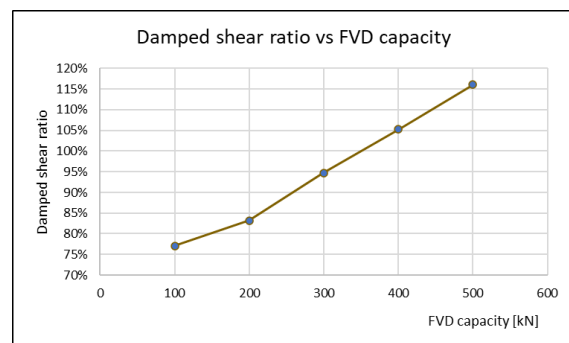


Fig. 18 DM5-32 buildings- zone III

For zone III, FVD of 100 kN produces the most optimum result as the damped shear ratio is the lowest and reduction in base shear is the highest. FVD of 500 kN cannot be considered a solution as the damped base shear is higher than the conventional support. Only FVD of 100 and 200 kN are the suitable solution. FVD of 200 and 300 kN are the suitable solutions for DM5-32 buildings for all seismic zones whereas FVD of 300 kN does not reduce the base shear in considerable amount for DM15-32 buildings. Since the DM15 buildings are already very flexible even with fixed supports because of the large height. Addition of FVDS of higher capacity makes the structure stiffer and hence results in less reduction in base shear and higher damped shear ratio.

The building models of plan 16 x 16 m, CM5-16 and CM15-16 have been analysed with different FVD capacity and the damped shear ratio has been studied for zone V (Fig. 19 and Fig. 20).

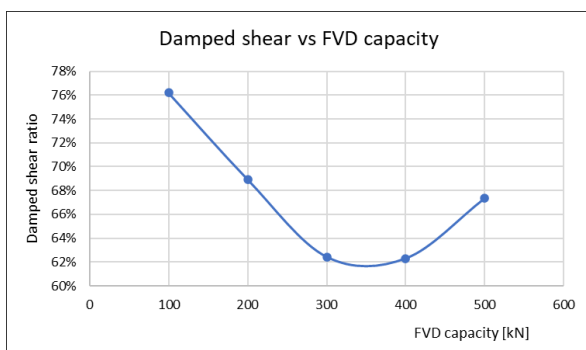


Fig. 19 DM5-16 building-zone V

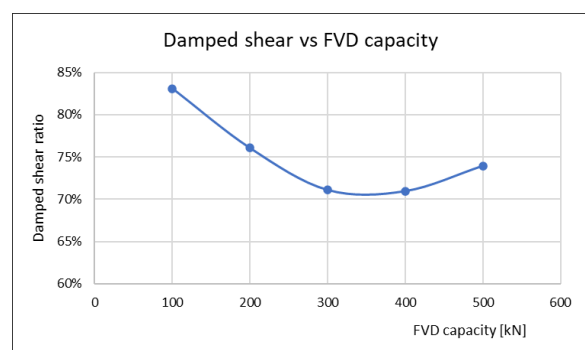


Fig. 20 DM15-16 building-zone V

The damped shear ratio varies from 62 to 76% for DM5 building and 71 to 83% for DM15 building. The higher capacity of FVD results in larger reduction in base shear and lesser damped shear ratio for both the

buildings. FVD of capacity 300 and 400 kN help in more reduction in base shear than 100 kN, 200 kN and 500 kN FVDs. From the study of damped base shear for DM5 building with different seismic zones and aspect ratio, it has been observed that the damped shear ratio varies between 62 to 77%. For DM15 building the ratio is in the range of 70 to 85% using FVD of 100 kN to 400 kN.

For G+5 buildings, the base shear has been analysed considering different support conditions, fixed / isolated / damped and the values are compared in Figure 21. Values have been considered for seismic zone V and FVD of 300 kN capacity. The base shear for different conditions, isolation, damping and fixed supports are shown in Fig. 22.

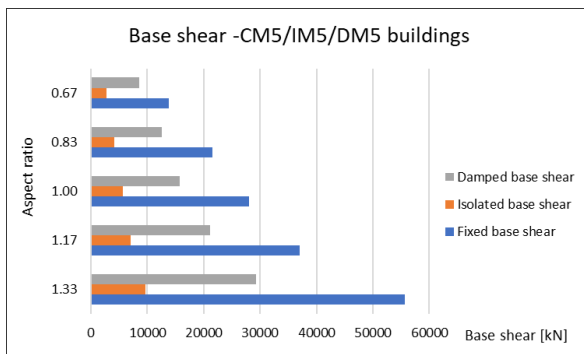


Fig. 21 Base shear for-zone V

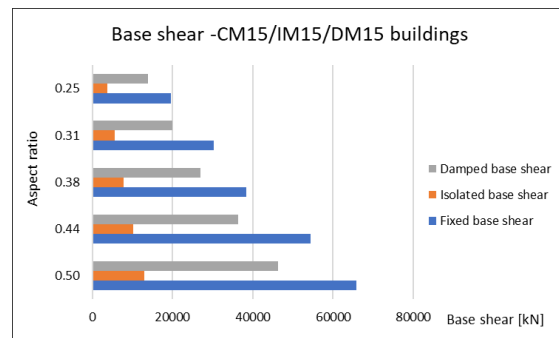


Fig. 22 Base shear for-zone V

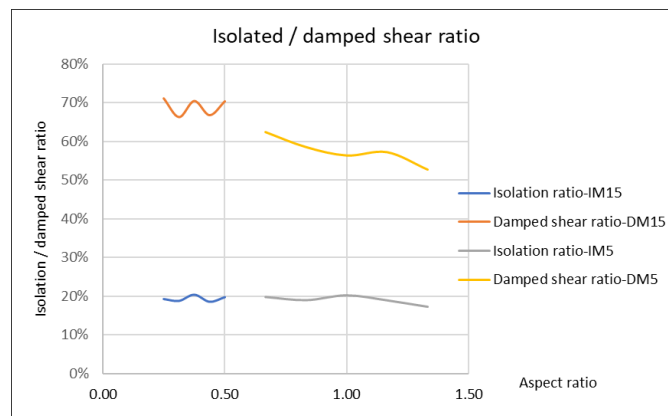


Fig. 23 Base shear ratio-zone V

From the above figures, it has been noted that for zone V, medium soil and using Elcentro earthquake data, both CM5 and CM15 buildings' responses range from 50 to 70% which is the commonly used design criteria for safe and economical design. The similar boundary conditions have been taken into account for the analysis of CM15 buildings with different aspect ratio. Hence use of FVDs and LRBs can be an effective solution for a structure in high seismic zone.

Deformation values are also checked for both CM and DM buildings for FVDs of capacity 50 to 1000 kN. Deformation decreases with increase in damper's axial load capacity. Comparison has been done and the interaction between damped shear ratio and deformation ratio is studied in Fig. 22 and Fig. 23. The analysis has been carried out for seismic zone V.

Deformation ratio=(Deformation of building with dampers)/(Defromation at fixed support)

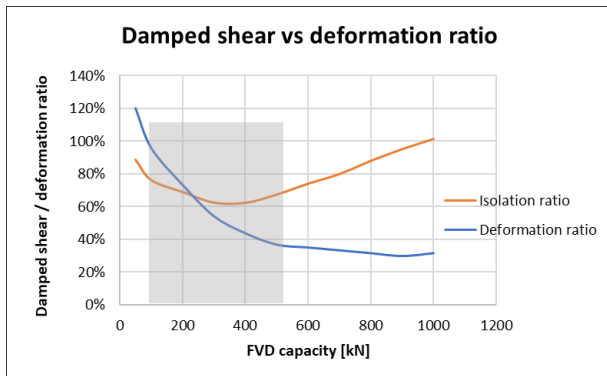


Fig. 24 DM5-16 building-zone V

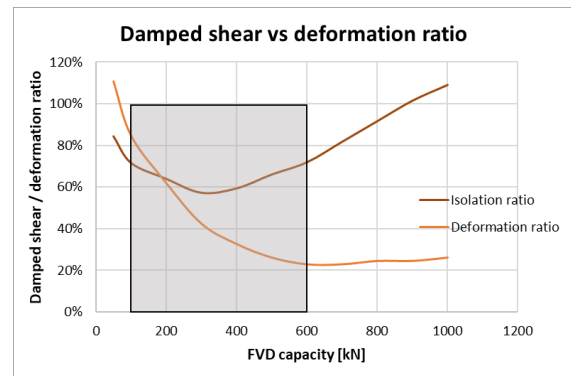


Fig. 25 DM5-28 building-zone V

It is observed that damped shear ratio using some capacity of FVDs decreases and for higher capacity beyond 500 kN, again it increases. It implies that increase of capacity of FVDs for a particular building helps in reduction of base shear but at certain extent, base shear again increases as higher capacity FVD make structure stiffer as well. Similarly, comparing the deformation values between damped and fixed support buildings, the deformation ratio does not change after use of certain load capacity of FVDs. It means that there is an optimum zone which actually balances between damping and deformation ratio for each building and the same has been identified using a grey shaded block in the above figures.

The similar comparison has been studied for DM15 buildings as well. Isolation and deformation ratio for DM15 building with 16x16 and 32x32 grid are shown in Fig. 26 and Fig. 27. Designer can select an optimum zone in between the acceptable isolation and deformation ratio for a particular building and accordingly range of capacity of FVDs can be decided. Similar analysis can be performed for buildings with different aspect ratio and optimum zone for design consideration of dampers can be chosen.

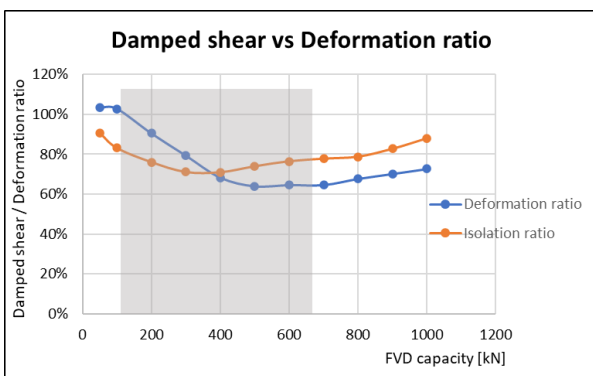


Fig. 26 DM15-16 building- zone V

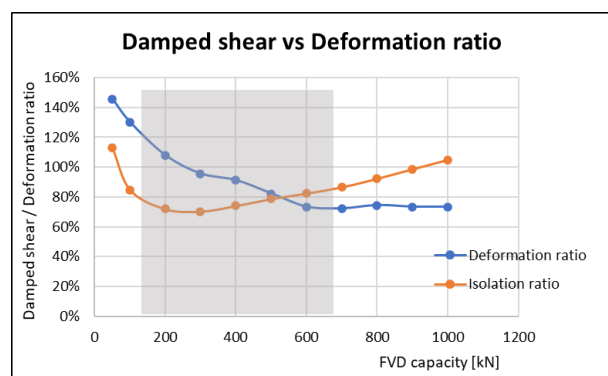


Fig. 27 DM15-32 building-zone V

4. Conclusion

- Selection of isolators and dampers is important in purpose of achieving the desired isolated / damped base shear.
- The performance of FVDs depends on geometry and mass of any structure and can vary depending on the plan / elevation ratio. The analysis presented in this paper shows the damped shear ratio and accordingly capacity of FVD can be selected.
- The purpose to check the buildings with isolated support using LRBs is to analyse the reduced or isolated base shear. Displacement for LRBs can also be critical for some structures as isolation reduces

base shear but increases displacement. The threshold displacement which is within the serviceability zone for a structure can dictate the selection of dampers and dampers reduces base shear without increasing displacement much.

- When aspect ratio is less, specially for high rise multi-storeyed buildings, due to the flexibility of the structure and less natural time period use of LRBs can further enhance the displacement at supports. It can be unsuitable for the application and appropriate use of FVDs can help to reach the target.
- Use of LRBs for some structures (with large number of storeys) generates very less seismic force. Also, use of FVDs help to reduce the base shear for those structures even beyond the level for isolated supports. In those cases, FVD capacity needs to be decided not to reduce the base shear beyond the isolated supports as much reduction may not finally produce economic design when cost of both modified structure and FVDs / LRBs are considered.
- The reduced base shear in seismic needs to be targeted at a level where the design force including all load cases for a structure is same or lesser than the reduced seismic force. In any case, if isolated / damped shear is lesser than the force derived from other load cases, the structure has to be designed for the larger force.
- Optimum selection of FVDs / LRBs with respect to the aspect ratio of a particular building structure in terms of isolated / damped base shear and isolated / damped displacement is ideal to make the structure safe and economic in seismic event.

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