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Assessment and Retrofitting of R.C. Structures with Fluid Viscous Dampers Using Pushover Analysis

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Abstract

Evaluating the seismic performance of existing structures and retrofit techniques is crucial for verifying a building's ability to resist seismic activities. This study focuses on assessing the efficiency in seismic response of structures retrofitted with Fluid Viscous Dampers (FVDs) post-earthquakes. Two key scenarios are assumed regarding the building model. One scenario examines the building model devoid of dampers (uncontrolled building model). The second scenario examines the building model retrofitted with dampers (controlled building model). A symmetrical 15-story RC frame building that has been equipped with FVDs is evaluated using a nonlinear static analysis. The analysis, design, and evaluation are conducted using the ETABS software, which employs response spectrum curves based on Peak Ground Accelerations (PGA) with different intensities in accordance with European code standards. The numerical results for the uncontrolled and controlled building models with FVDs dispersed at different locations and heights are compared and analyzed. The use of FVDs reduces earthquake-induced roof displacement. In comparison to the uncontrolled structure, this reduction can be as much as 53.2% lower in both longitudinal and transverse directions. The provided results clearly illustrate that when dampers are used, the structures' plastic hinges remain in the immediate occupancy domain; however, when dampers are not used, the plastic hinges reach life safety and then collapse the border. Moreover, the results show that the number and location of dampers significantly influence the structural response. On the other hand, many dampers do not always lead to the best benefit in terms of cost and energy dissipation.

Keywords: Nonlinear Static Analysis, Pushover Analysis, Fluid Viscous Dampers, Plastic hinge, performance level.

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1 Introduction

The philosophy of designing concrete structures under the effect of dynamic loads, such as earthquakes, varies based on the behavior of the structural elements. These elements are exposed to large changes in stresses during earthquakes, transitioning from tension to compression and vice versa in a short period of time. This rapid change leads to violent effects on the structure, as earthquakes are not a single force but rather a series of displacements that result in forces within the structures. These displacements themselves do not pose a problem if the entire building moves as a single unit. However, the main issue arises from the variations in displacements between the different storeys. This concept led to the development of the science of structural dynamics under the effect of seismic loads in the era of technology and computers. New approaches of seismic analysis including performance-based engineering concepts have been increasingly used in the past several years to pay more focus on damage mitigation.

Performance-Based Design (PBD) is becoming the preferred approach over strength-based design because it helps to limit displacements and can respond to seismic risks with a guaranteed reaction, especially for important structures projected to continue operating following an earthquake. The nonlinear response of the building is estimated by PBD standards. The structural model is initially developed, and its performance is subsequently simulated in response to the anticipated seismic excitation. During each simulation, the structural engineer is provided with the information that is necessary to evaluate and control the risk of damage in terms of the expenses associated with recovery. Many researchers have conducted studies in the field of PBD, such as: **Hassaballa et al. [1]** presented a research paper on the pushover analysis of a four-story residential reinforced concrete building that already exists in the city of Khartoum, Sudan. The pushover analysis was conducted on the building following the guidelines of Applied Technology Council (ATC-40) code using SAP2000 software to simulate the required earthquake intensity. The evaluation has shown that the residential building is not structurally safe in terms of the required seismic activity. **Rahman et al. [2]** conducted a study on a building located in the Kingdom of Saudi Arabia. The building consists of 8 floors and a dome at the top, and is situated in a moderate seismic zone. The researchers conducted an evaluation of the building using a pushover analysis method by the SAP program. The results indicated that the building was structurally unable to resist seismic loads due to its design, which only considered vertical loads. Through numerical simulations, **Abd-Elhamed and Mahmoud [3]** implemented a nonlinear static analysis to evaluate the functionality of a 12-story residential RC moment-resisting-frame structure situated in Cairo. The framed building model was implemented, and the pushover analysis was conducted using the well-known program ETABS. The study's findings indicated that buildings that are properly designed exhibit exceptional performance under seismic loads that are appropriate for the Cairo region. Specifically, the building exhibits a strong column-weak beam mechanism. **Hakim et al. [4]** conducted a study on four reinforced concrete buildings with different heights. These buildings were designed in accordance with the Saudi Building Code (SBC). The researchers used the pushover analysis method to evaluate these buildings under the effect of seismic forces using the ATC-40 code method, Federal Emergency Management Agency (FEMA-356), and FEMA-440. The results showed that buildings designed in accordance with the requirements of the SBC code are structurally acceptable based on the permissible level of performance. **Abass and Jarallah [5]** conducted a condition assessment of a hospital building located in the city of Baghdad, Iraq. The hospital was studied using pushover analysis, following the earthquake code (ISC-2017) for Iraq. The analysis was conducted using the Capacity Spectrum Method (CSM) in accordance with ATC-40, and the Displacement Coefficients Method (DCM) in accordance with FEMA440. A comparison was made between the two methods, and the results indicated that the pushover analysis method was more effective for evaluating the seismic performance. **Daniel and John [6]** analyzed a ten-story building that is asymmetrical in both directions. The study was carried out using pushover analysis under the effect of the required seismic force, which is supposed to be located in zone 3. The analysis was done using the SAP program.

Results showed that collapse occurs in beams before columns through plastic hinges. Additionally, 77.6% and 84.56% of plastic hinges were formed within the life safety level for X-axis and Y-axis loading, respectively. The researchers clarified that pushover analysis is one of the best methods to evaluate the behavior of a building through non-linear static analysis. **Shehab Eldin et al. [7]** conducted a seismic evaluation of four reinforced concrete buildings of varying heights. The buildings were designed based on the Egyptian code ECP (201). The evaluation was performed using the pushover analysis method according to ATC-40. The study utilized the Seismostruct program to evaluate these buildings under the effect of different seismic forces. The results were presented through inter-story drift ratio, capacity curves with performance points, and performance criteria checks for each model. The results showed that for the same building located in different seismic zones, the performance point of the building increases with increasing seismic zone hazards. Therefore, the inter-story drift ratio also increases. **Shaikh et al. [8]** conducted an evaluation of two reinforced concrete buildings. One building was a 4-storey structure without a floating column, while the other had a floating column. The study was conducted using pushover analysis under the influence of the required seismic force. The analysis was performed using the ETABS program. The researchers clarified that the roof displacement for the building containing a floating column is larger than the building without a floating column. The results also showed that the base shear is slightly greater in the building containing a floating column than in the building without it. **Shoaib and Swetha [9]** studied twelve (12) RC framed structures, each 15 storeys tall. Four (4) of the structures were square-shaped in plan, while eight (8) were rectangle-shaped. Despite their different shapes, all of the buildings had approximately the same plan area and FVD positions. The height from floor to floor is 3 meters, and Zone III is the location of the buildings. Pushover analysis for dynamic analysis is the analytical approach employed for this study, which is done with the help of ETABS software that helps in the analysis and design of the models. The objective of this study is to determine the ideal location for fluid viscous dampers in high-rise buildings that are subjected to seismic loads. Some results showed that the basal shear decreased by 85.98%. **Aydin et al. [10]** presented a study in this research on the rapidly growing field of Performance-Based Design Optimization (PBDO), providing researchers with a comprehensive review in this field. This study conducts a thorough literature review on PBDO for structures, such as bridges and buildings, under seismic and wind loads. The study focuses on summary of previous research focuses on various problem formulations.

Creating a vibration control system for multi-story frame systems is a crucial subject in structural engineering, as it can significantly enhance a building's stability and safety under severe loads. One effective approach to achieving this is through the use of passive energy-dissipation devices, which provide additional damping to the structure. By installing these devices, damage to the primary frame system can be mitigated by reducing the demand for inelastic energy dissipation, rather than increasing its strength. Furthermore, passive control techniques, such as tuned mass dampers **Abd-Elhamed and Mahmoud [11]** and tuned liquid dampers **Abd-Elhamed and Tolan [12],** have gained widespread acceptance in the engineering community for reducing seismic responses in RC buildings with varying heights and slab configurations, thereby highlighting their versatility and effectiveness in enhancing structural resilience.

Fluid viscous dampers (FVD) are passive devices that have gained increased use in mitigating the impacts of strong earthquakes and wind activity. FVDs, which are hydraulic devices used to discharge kinetic energy from seismic vibrations, are among the most widely utilized passive devices. They disperse a considerable portion of the seismic energy input through a viscous fluid. This damper is comprised of a cylinder that is filled with a very viscous fluid, much like a car's shock absorber. The fluid eventually emerges from the other side as the piston presses on it from one side. FVDs don't make the structure more rigid; instead, they add more damping to make the building more resistant to earthquakes, which means that the structure doesn't need to be more rigid. Many researchers have conducted studies in the field of FVD, such as: **Ekwueme et al. [13]** conducted a study explaining how to use FVD to improve the performance of high-rise buildings. The study was conducted on a 42-floor building located in Los Angeles, California, using the ETABS program to analyze the building's response to seismic forces. The study showed that FVDs are effective in improving the performance of high buildings, and can achieve a significant reduction in story drifts. **Koshti et al. [14]** studied an unsymmetrical reinforced concrete building consisting of 11 floors using the ETABS program. The building was analyzed both with and without FVD at the four external corners of the building. The results show that without the use of a fluid viscous damper, the top story can move a maximum of 89.23 mm and 112.48 mm in the X and Y directions, respectively. However, after the introduction of a damper in the building, there is a decrease in story displacement by 35.68 mm and 36.64 mm in the X and Y directions, respectively. Overall, base shear and displacement decrease when the FVD is applied, enhancing the building's earthquake resilience. **Mujeeb et al. [15]** conducted a study on an unsymmetrical reinforced concrete building consisting of a ground +10 storey structure. The building is supported approximately in the middle by a U-shaped core throughout its entire height. The ETABS program was used to analyze the buildings under the effect of seismic forces FVD were studied in the building and distributed using four different models in order to achieve optimal results. The study was then repeated without FVDs to compare the outcomes. The study showed that, in comparison to central damping and alternating damping, placing FVDs at the exterior corner on all four sides is effective. Additionally, storey displacement has been decreased by 89.90% and 89.91% in the X and Y directions, respectively, when dampers are installed at each corner of the building, compared to when there are no dampers. **Alataby et al. [16]** studied a ten-story steel building subjected to four different seismic forces. The study was conducted in two stages: one with a FVD and one without a FVD installed on the outer frames in 6 different models. The SAP software was used to compare results and determine the optimal location for the damper. Based on the results, the best option is to have the FVD on the cross two bay damper. In order to reduce costs, the dampers should be distributed across five floors, as determined by base shear analysis, drift ratio, and maximum displacement. **Gupta and Singh [17]** conducted a study on the impact of FVDs on the seismic performance of multi-story RC buildings, with a specific focus on the differences between regular and irregular floor plans. The objective of the study was to measure the extent to which these damping devices enhance seismic resilience and mitigate the adverse effects of seismic events. ETABS is used to analyze buildings with regular and irregular plans, both with and without FVD. A comparison has been made between the lateral reactions in terms of maximum displacement, story drift, and story shear. The study showed that buildings with FVDs displace less than those without. Therefore, when compared to buildings without dampers, FVDs successfully minimize the lateral displacement of buildings with dampers by 25% to 30%.

The aim of this study is to investigate the performance of a symmetrical building that is 15 stories high and designed in accordance with BS8110 as well as being subjected to solely vertical loads. This study has compared the seismic performance of building models designed based on European code standards using different intensities. Several retrofit scenarios are explored wherein modifications were made to the existing structure. These included placing FVDs at various locations and levels to determine the best placement with the fewest number of FVDs. A comparison was made between the results to determine the extent to which the building was affected by the presence of FVD. The ETABS software was used to do the numerical simulations of the buildings. The displacement coefficient approach was applied in the simulations, and the standards of FEMA 440 IE were adhered to throughout the process.

2 Non-linear Static Analysis or Pushover Analysis Method

Nonlinear static analysis, sometimes referred to as pushover analysis, has gained prominence with the emergence of performance-based design. Seismic engineers employ this approach because it accurately predicts the location and amount of plastic yielding in a structure. The pushover analysis method is a simple, straightforward and efficient technique used in seismic analysis and the design of structures. This method entails initially applying vertical gravity loads to the structure, followed by the progressive application of static equivalent earthquake loads until the desired displacement is achieved. As the

magnitude of loading increases, weak links within the structure become apparent. These weak positions can then be analyzed to evaluate whether the structure, as well as its deformation capacity under probable seismic events, meets the design requirements and functions properly. In pushover analysis methodologies, "target displacement" refers to the maximum displacement that a structure can experience during an earthquake. This typically relates to the displacement of the structure's top.
The pushover curve is linked to the inelastic response spectrum to assess a performance point, which represents the maximum displacement the building can withstand. There are various methods for pushover analysis, but this paper presents the DCM which was introduced in provisions FEMA 1997, 2000 and 2005 **[18]**.

2.1 Displacement Coefficients Method (DCM) applied in FEMA-440 EL

FEMA-440 EL Improved procedures for equivalent linearization:
An enhanced equivalent linearization procedure has been developed as a modification to CSM outlined in ATC-40. By utilizing an effective period, T_{eff} and effective damping, B_{eff} as shown in **Fig. 1** , the objective is to evaluate the maximum displacement response of the nonlinear system by comparing it to an equivalent linear system. This comparison is conducted within a nonlinear static procedure that models the nonlinear response of a building using a single-degree-of-freedom (SDOF) oscillator.

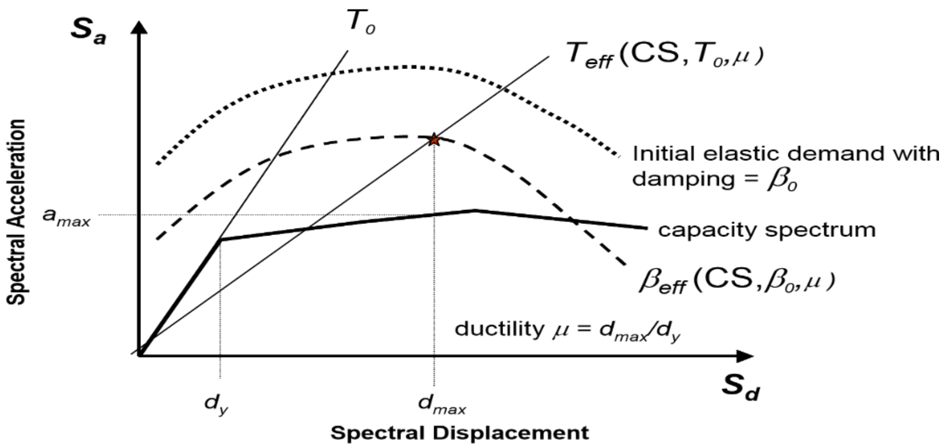


Fig. 1. Effective period and damping parameters of the equivalent linear system **[18]**

I. Estimation of Effective Period:

The capacity spectrum can be calculated using the following formulas, regardless of the post-elastic stiffness value or hysteretic model form. The following equations are used to determine the effective period, which is dependent on the ductility level.

For $\mu < 4.0$:

$$T_{eff} = \{0.20(\mu - 1)^2 - 0.038(\mu - 1)^3 + 1\}T_0 \quad (1)$$

For $4.0 \leq \mu \leq 6.5$:

$$T_{eff} = [0.28 + 0.13(\mu - 1) + 1]T_0 \quad (2)$$

For $\mu > 6.5$:

$$T_{eff} = \{0.89 \left[\sqrt{\frac{(\mu_{-1})}{1 + 0.05(\mu - 2)}} - 1 \right] + 1\} T_0 \tag{3}$$

Where T_0 Fundamental period in the direction under consideration, α is the post-elastic stiffness and μ the ductility, (α and μ) calculated as follows

$$\alpha = \frac{\left(\frac{\alpha_{P_i} - \alpha_y}{d_{P_i} - d_y}\right)}{\left(\frac{\alpha_y}{dy}\right)} \quad (4) \qquad \text{And} \qquad \mu = \frac{d_{P_i}}{dy} \quad (5)$$

Where α_{P_i} Trail spectral acceleration, d_{P_i} Trail spectral displacement, α_y bilinear curve yielding spectral acceleration and d_y bilinear curve yielding spectral displacement.

II. Estimation of Effective Damping:

The following formulas are applicable to any capacity curve, regardless of the type of hysteretic model or post-elastic stiffness value (α) that is used. Depending on the ductility level (μ) of the structure, the effective damping is calculated using the following equations.

For $\mu < 4.0$:

$$B_{eff} = 4.9(\mu - 1)^2 - 1.1(\mu - 1)^3 + B_0 \tag{6}$$

For $4.0 \leq \mu \leq 6.5$:

$$B_{eff} = 14.0 + 0.32(\mu - 1) + B_0 \tag{7}$$

For $\mu > 6.5$:

$$B_{eff} = 19 \left[\frac{0.64(\mu - 1) - 1}{[0.64(\mu - 1)]^2}\right] \left(\frac{T_{eff}}{T_0}\right)^2 + B_0 \tag{8}$$

Where B_0 Initial viscous damping (5% - concrete buildings).

III. Estimation of spectral reduction factor:

The spectral reduction factor is determined by the effective damping, which is referred to as the damping coefficient, B (βeff). It is calculated using Equation (9)

$$B(\beta_{eff}) = \frac{4}{5.6 - \ln \beta_{cff}(\text{in }\%)} \tag{9}$$

IV. Estimation of adjusted spectral acceleration ordinates:

According to Equation (10) , it is used to adjust spectral acceleration ordinates.

$$(S_a)_B = \frac{(Sa)_{5\%}}{\beta(\beta_{eff})} \tag{10}$$

2.2 Define the performance of the structure

The force-deflection behavior of the plastic hinge is defined by five positions, designated as A, B, C, D, and E as shown in **Fig. 2** .These points are explained as follows: A to B for elastic state, B to IO for below immediate occupancy, IO to LS for between immediate occupancy and life safety, LS to CP for between life safety and collapse prevention, CP to C for between collapse prevention and ultimate capacity, C to D for between C and residual strength, and D to E for between D and collapse >E. **[19]**.

The salient points in the idealized Force-Displacement curve can be defined as follows **[20]**:

Point A:

Is the structure's original state (OL).

Point B:

Is an example of yielding. Up until point B, the hinge does not deform.

Point C:

Is the maximum capacity or limit of the pushover analysis.

Point D:

This is the structure's residual strength limit. The structure will begin to collapse once this limit is reached.

Point E:

Denotes the structure's complete collapse. After this, the hinges break down.

Pushover analysis is used to characterize building performance using different performance levels, as explained in FEMA 356 Code **[21]**. as shown below.

- **Immediate Occupancy Level:**

Overall Damage: Light

General: No drift that lasts. The structure largely maintains its initial stiffness and strength. Facades, partitions, ceilings, and structural components all have minor cracks. It is possible to restart elevators and operate fire defense systems.

- **Life Safety Level:**

Overall Damage: Moderate

General: Every story of the building still maintains its rigidity and strength, with gravity-bearing elements intact. There is no parapet tipping or wall failure out of plane, some drift is permanent. Partition damage. The building might be beyond cost-effective repair.

- **Collapse Prevention Level:**

Overall Damage: Severe

General: The load-bearing walls and columns work, but there is little remaining stiffness or strength. large, long-term drifts. A few exits are blocked. Unbraced parapets and infills failed or were about to fail. The building is on the verge of collapsing.

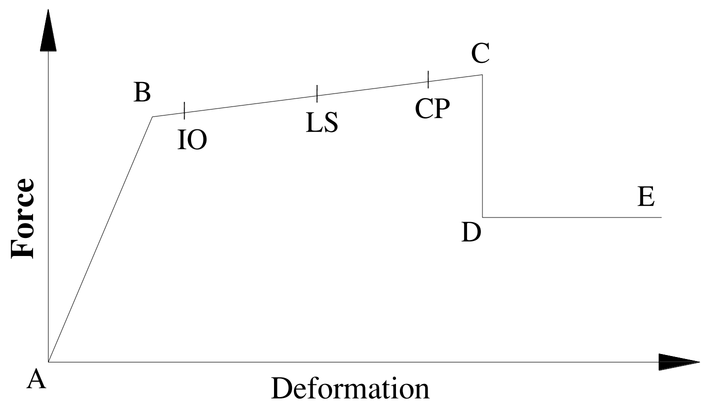


Fig. 2: Force-Deformation for pushover analysis **[22]**

3 Use of Fluid Viscous Dampers (FVD) in structural control

The use of a new high-tech structural element that disperses energy using a fluid viscous damper increased dramatically in the 1990s. This damper is produced in a factory under strict quality control guidelines, leading to this type of damping being known as synthetic viscous damping or manufactured damping.

Viscous fluids work on the basis of liquid flow through nozzles. The silicone oil-filled chambers are traversed by the stainless-steel piston. Silicone oil is characterized by long-term stability, non-flammability, and non-toxicity. The silicone oil passes through a hole in the piston head due to the pressure differential between the two chambers, converting the seismic energy into heat that is released into the atmosphere.

Fig. 3 clarifies the specific details of the FVD according to Taylor Company, one of the companies that produce this type of FVD **[23]**. **Table 1** displays a comparison of FVD properties with various capacities (Taylor Devices) **[24]**&**[25]** and **Table 2** displays the specifications of the FVDs used in ETABS for FVD500 as **Table 1.** The FVD500 values for the structure are defined in the Link properties, and a Damper-Exponential is added in the Link Property Data in the software. Weight and mass values are compensated for by weight and force, respectively as **Table 1.[14],[15],[17]** and **[24]**

Table 1 FVD with Different Capacities Force (kN) **[23],[24]** and **[25]**

FORCE (kN)	TAYLOR DEVICES MODEL NUMBER	SPHERICAL BEARING BORE DIAMETER (mm)	MID-STROKE LENGTH (mm)	STROKE (mm)	CLEVIS THICKNESS (mm)	MAXIMUM CLEVIS WIDTH (mm)	CLEVIS DEPTH (mm)	BEARING THICKNESS (mm)	MAXIMUM CYLINDER DIAMETER (mm)	WEIGHT (kg)
250	17120	38.10	787	±75	43	100	83	33	114	44
500	17130	50.80	997	±100	55	127	102	44	150	98
750	17140	57.15	1016	±100	59	155	129	50	184	168
1000	17150	69.85	1048	±100	71	185	150	61	210	254
1500	17160	76.20	1105	±100	77	205	162	67	241	306
2000	17170	88.90	1346	±125	91	230	191	78	286	500
3000	17180	101.60	1441	±125	117	290	203	89	350	800
4000	17190	127.00	1645	±125	142	325	273	111	425	1088
6500	17200	152.40	1752	±125	154	350	305	121	515	1930
8000	17210	177.80	1867	±125	178	415	317	135	565	2625

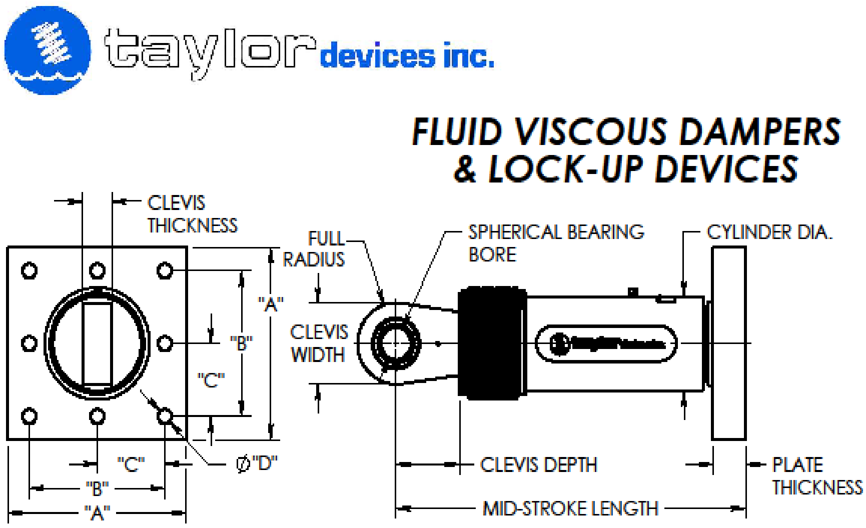


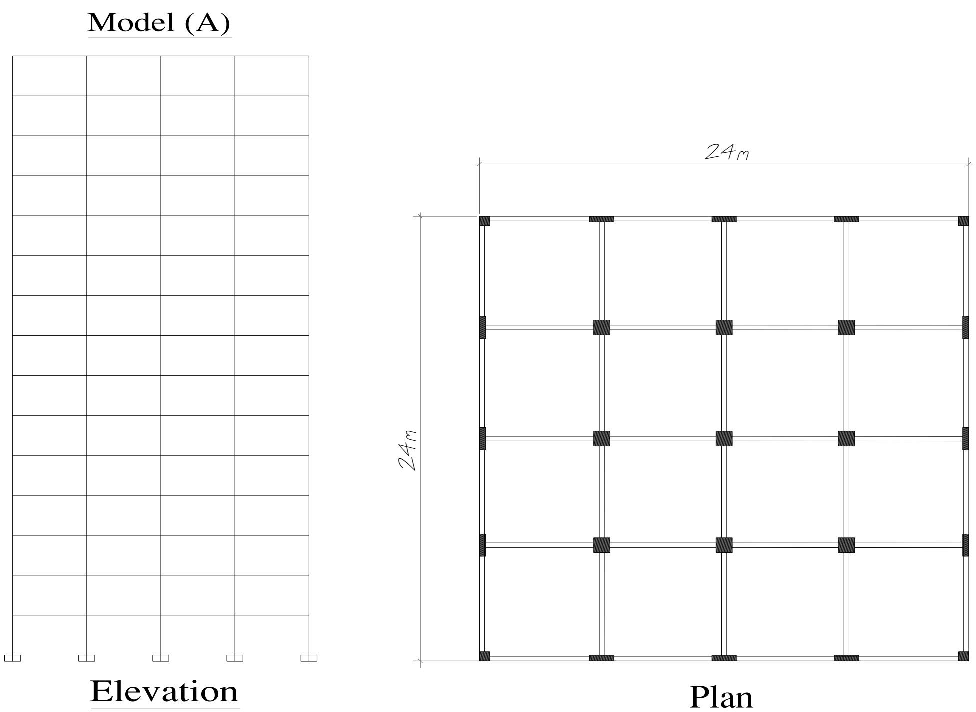
Fig. 3. Specification of FVD **[23]**

Table 2 Link Property of FVD define in ETABS **[23]**,**[24]** and **[25]**

Mass	98 kg
Weight	500 kN

4 Building description

The case examined in this study is a typical 15-story model of a residential building constructed with a reinforced concrete structural frame. The total dimensions of the plan are 24m x 24m, and the building is 45 meters high. The floor is composed of a 160 mm thick flat slab system, and the cross sections of the beams and columns are 25cm x 60cm for the beams and 60cm x 60cm, 35cm x 140cm, and 90cm x 90cm for the columns. The detailed structural plan and elevation are shown in **Fig. 4**.



(a) (b)

Fig. 4. (a) The elevation and (b) plan for the studied symmetrical multi-story building.

4.1 Material properties

High-grade steel with a yield strength of $f_y = 360$ N / mm^2 and concrete with a characteristic strength of $f_{cu} = 25\ N\ /\ mm^2$ after 28 days are used for analysis and design. The modulus of elasticity E_c , is calculated using the formula $E_c = 4400\sqrt{fcu}\ N\ /\ mm^2$ (ECP-203, 2017) **[26],** and the specific weight of reinforced concrete is assumed to be $\gamma_c = 25KN\ /\ m^3$. The elastic modulus of steel is calculated to be $210\ KN\ /\ mm^2$. Concrete and steel are assumed to have Poisson's ratios υ of 0.2 and 0.3, respectively.

4.2 Gravity loads

Dead and live loads are included in the category of gravity loads that operate on the RC building. The dead load values allocated to the flooring cover weight and the portioning parts weight are $0.15\ t\ /\ m^2$ and $1.05\ t\ /\ m'$, respectively. The structural software application being utilized automatically calculates the weight of the structural parts as part of the dead loads. The live load value for residential reinforced concrete buildings has been set at 0.2 t/cm^2 in accordance with Egyptian design code **[27].**

4.3 Reinforced Concrete Design

The building was designed for vertical loads only in accordance with the BS 8110-97 code **[28]** using the ETABS program. The cross sections of the inner and corner columns are considered to be square, while the remaining columns of the edge frames are designed to be rectangular in shape. This is illustrated in **Fig. 5** , **Fig. 6** and **Table 3** provides the columns dimensions and reinforcement at ground level. It is assumed that each column is securely anchored at the foundation level. Additionally, the reinforced concrete building includes floor slabs that are 0.16 meters thick and are considered rigid floor diaphragms.

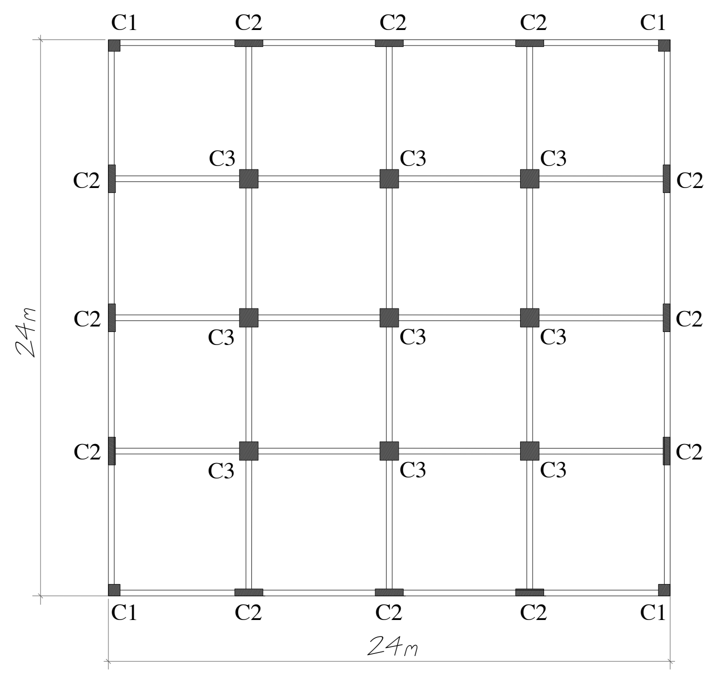


Fig. 5. Views of structural floor plans

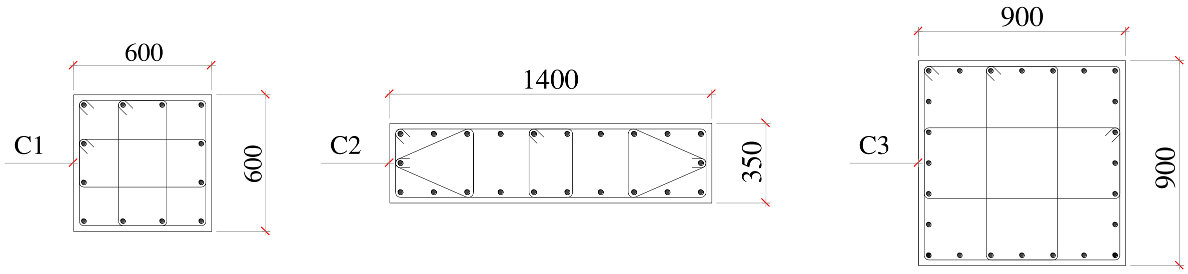


Fig. 6. Dimensioning and reinforcement of columns

Table 3. Reinforcing steel details for columns

Section	C1=600X600mm		C2=1400X350mm		C3=900X900mm	
	Reinforcement	Stirrups	Reinforcement	Stirrups	Reinforcement	Stirrups
	12Y22	3Y10@200	22Y25	4Y10@200	24Y25	3Y10@200

4.4 The study procedure

The study procedure aims at determining the optimal damper selection by considering the primary factors that affect structural behavior. These factors include the type of earthquake, support condition, distribution of viscous dampers in both vertical and horizontal directions as **Fig. 7**, analysis method, and damper coefficient parameters. Pushover analysis of the building is performed using the ETABS software. This is done by first applying vertical loading, and then progressively increasing displacement-controlled lateral load in both the +x and +y directions. A plastic P-M-M hinge and a one-component plastic moment hinge are considered to provide the nonlinear characteristics for columns and beams, respectively. Using a combination of dead and live loads (D+0.25L), the axial force for columns and the shear force for beams are calculated.

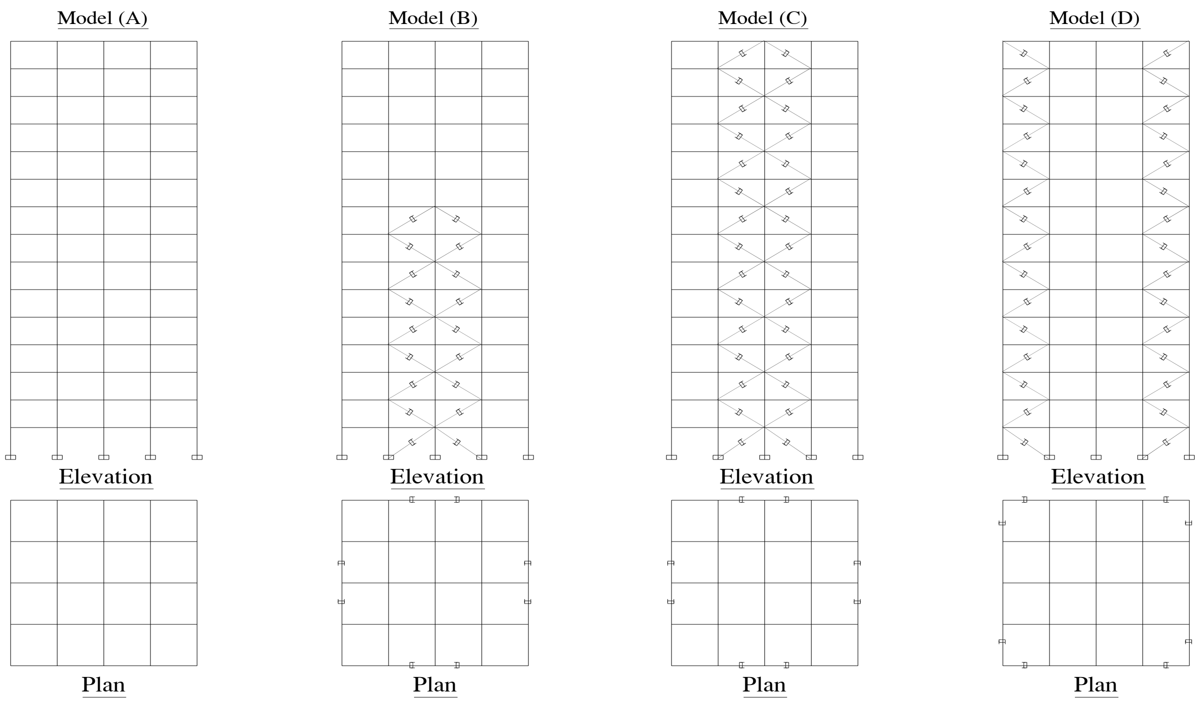


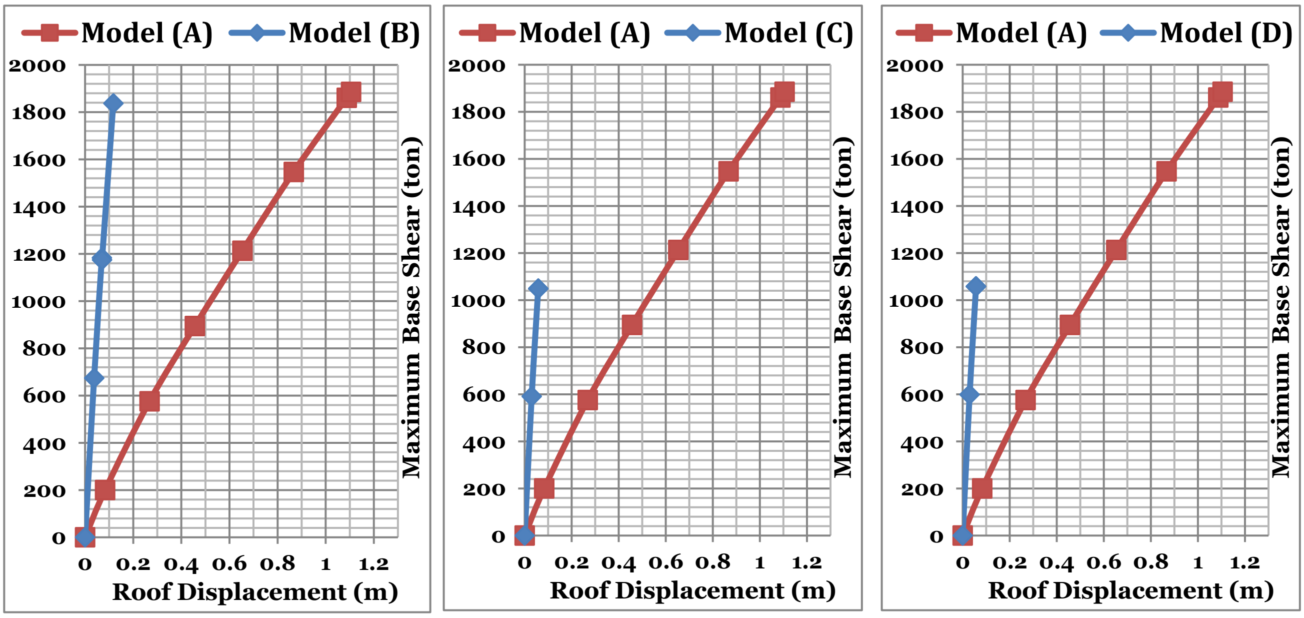
Fig. 7. Multi-story buildings are symmetrical without and with FVD

5 RESULT AND DISCUSSION

A brief discussion of the analytical results, which include pushover curves and the hinge creation sequence, is provided below.

5.1 Pushover Curve

The capacity curve, also known as the pushover curve, is a plot of base shear against the roof displacement of a structure. The pushover curve can be used to determine the structure's maximum displacement at the roof and the base response during displacement-controlled analysis. After the elastic stage, the capacity curve is a useful predictor of the structure's inelastic behavior. **Fig. 8** illustrates the pushover curves for the building when evaluated using displacement-controlled pushover analysis in both the +X and +Y directions. There is no doubt that viscous dampers, in a variety of configurations and locations, have significantly enhanced the safety factor of the building by significantly reducing the maximal displacement values, as illustrated in **Fig. 8**. It is obvious that the maximum displacement obtained when dampers are installed on all floors (Models C and D) is **94.5%** of the displacement in the original state (Model A), as demonstrated in the final step of **Table 4 to Table 7**. Nevertheless, the maximum displacement decreases to **89.1%** when dampers are implemented exclusively on the building's lowest nine levels. The incorporation of dampers throughout the building's floors reduced the base shear value to **43.88%,** resulting in a base shear of **1049.39** tons in Model C, in contrast to the peak value of **1885.62** tons in Model A, which lacked damping. Moreover, the installation of dampers over nine levels of the structure further reduced the base shear to **2.58%**, resulting in a base shear of **1836.93** tons in Model B.



(a) (b) (c)

Fig. 8. Comparison between results of original building **Model A** without FVD, and after being retrofitted by FVD: (a) **Model B** compared to **Model A**, (b) **Model C** compared to **Model A**, and (c) **Model D** compared to **Model A**

5.2 Hinge Formation

The results of the pushover analysis show the process of plastic hinge formation and the condition of the hinges at different building performance levels. This provides information on the structure's weakest point. Therefore, it is possible to identify the members that need to be strengthened if the building requires retrofitting.

The analysis for Model A was conducted in 7 steps, as detailed in **Table 4**, while Models B, C, and D were analyzed in 4, 3, and 4 steps, respectively, as presented in **Table 5** to **Table 7** . All plastic hinges for models supported by FVD are in the Immediate Occupancy stage, while the unsupported building consists of 10 plastic hinges in the Collapse Prevention stage. The plastic hinges indicate that the anticipated performance goal has been met through the application of FVD. This suggests that using fluid viscous dampers would significantly improve the building's overall performance.

Table 4. Pushover result and limits of plastic hinges in longitudinal direction For **Model (A)**

Step	Roof Displacement (m)	Base Shear (ton)	A-IO	IO-LS	LS-CP	>CP	Total
0	0	0	3900	0	0	0	3900
1	0.0831	200.039	3900	0	0	0	3900
2	0.2677	575.6405	3900	0	0	0	3900
3	0.4563	894.8523	3900	0	0	0	3900
4	0.6534	1213.0842	3900	0	0	0	3900
5	0.8667	1547.1441	3872	24	0	4	3900
6	1.0870	1860.9624	3790	106	0	4	3900
7	1.1049	1885.6155	3784	106	0	10	3900

Table 5. Pushover result and limits of plastic hinges in longitudinal direction For **Model (B)**

Step	Roof Displacement (m)	Base Shear (ton)	A-IO	IO-LS	LS-CP	>CP	Total
0	0	0	3900	0	0	0	3900
1	0.037535	674.1636	3900	0	0	0	3900
2	0.069731	1183.2447	3900	0	0	0	3900
3	0.070302	1174.4602	3900	0	0	0	3900
4	0.117229	1836.9258	3888	12	0	0	3900

Table 6. Pushover result and limits of plastic hinges in longitudinal direction For **Model (C)**

Step	Roof Displacement (m)	Base Shear (ton)	A-IO	IO-LS	LS-CP	>CP	Total
0	0	0	3900	0	0	0	3900
1	0.029771	591.1088	3900	0	0	0	3900
2	0.057639	1048.8281	3900	0	0	0	3900
3	0.057702	1049.3857	3900	0	0	0	3900

Table 7. Pushover result and limits of plastic hinges in longitudinal direction For **Model (D)**

Step	Roof Displacement (m)	Base Shear (ton)	A-IO	IO-LS	LS-CP	>CP	Total
0	0	0	3900	0	0	0	3900
1	0.029563	598.6254	3900	0	0	0	3900
2	0.056895	1058.3437	3900	0	0	0	3900
3	0.056926	1058.435	3900	0	0	0	3900
4	0.056929	1058.1326	3900	0	0	0	3900

5.3 Lateral static loads equivalent to seismic loads

This paragraph's goal is to determine the response spectrum for seismic activity in accordance with Eurocode 8 requirements. This spectrum will be used as a reference to check ground motion records using four different PGA as clarified in **Table 8**. This process was carried out using pushover analysis, which will be discussed in this study.

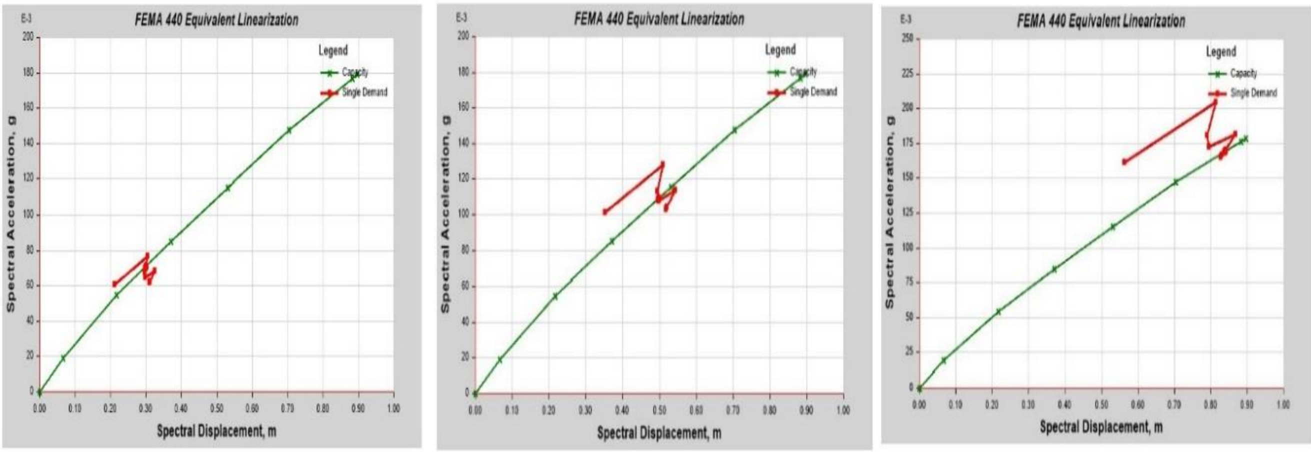
Table 8. Seismic Load Data as Euro Code 8

Parameters	Seismic Data			
Design Ground Acceleration (Ag)	0.1	0.15	0.25	0.4
Subsoil Class	A	C		
Damping Correction Factor (n)	1	1		
Function Damping Ratio	0.05	0.05		

5.4 Performance point

The pushover analysis was conducted on a 15-story 3D model using ETABS software. The program displays pushover and capacity spectrum curves, with their intersection determining the performance point.

Fig. 9 shows the pushover curve with the performance point for Model (A) in different seismic zones according to FEMA-440EL calculations. As shown in these figures, for the same building, the performance point of the building increases with increasing seismic activity, while the capacity curve remains the same. The performance points resulting from the intersection between the nonlinear capacity spectrum and the reduced effective earthquake spectrum are illustrated in **Table 9**.



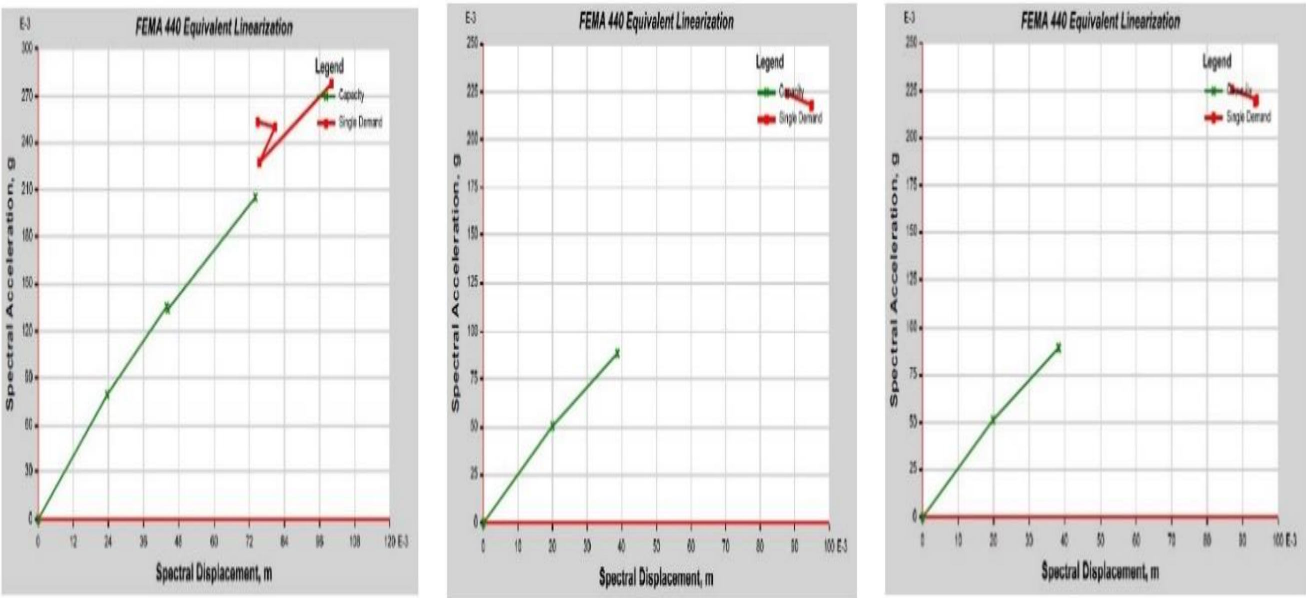
(a) PGA=0.15 **(b) PGA=0.25** **(c) PGA=0.40**

Fig. 9. Pushover curve with performance point for: (a), (b) and (c) AS **Model (A)**

Table 9 Performance point data for **Model (A)** with different seismic zones

Models	Symmetrical	Model (A)		
	System	Without FVD		
Response Spectrum by Euro Code 8	Design Ground Acceleration (Ag)	0.15	0.25	0.40
Performance Point According to FEMA 440 EL	Programs	ETABS		
	Direction	Push (X) and Push (Y)		
	Base Share (tonf)	746.419	1143.836	1783.339
	Roof Displacement (m)	0.36861	0.610538	1.032541

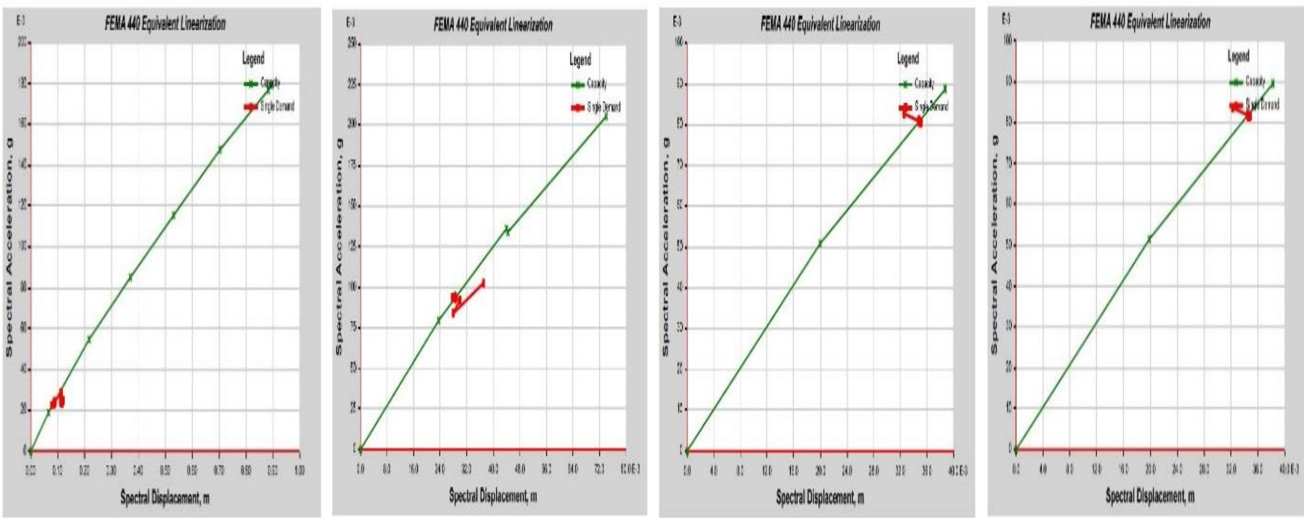
Fig. 10 clarifies the performance point for PGA = 0.15 for models B, C, and D. It is noted from the figures that the intensity of the earthquakes acting on the building is significant, leading to the separation of the nonlinear capacity spectrum from the reduced effective earthquake spectrum. As a result, no results appeared.



(a) Model (B) **(b) Model (C)** **(c) Model (D)**

Fig. 10. : Pushover curve with performance point for: (a) **Model (B)**; (b) **Model (C)**; (c) **Model (D)**; with FVD AS PGA=0.15

Fig. 11 shows the effect of reducing the PGA to 0.1. In this case, the nonlinear power spectrum intersects with the reduced effective earthquake spectrum. Consequently, performance points for the four models appear, and their results are displayed in **Table 10**



(a) Model (A) **(b) Model (B)** **(c) Model (C)** **(d) Model (D)**

Fig. 11. Performance point for **Model (B, C, and D)** as PGA=0.10

Table 10. Performance point data for **Method (A, B, C and D)** as PGA=0.10

<table>
<tr><td rowspan="2">Models</td><td>Symmetrical</td><td>Model (A)</td><td>Model (B)</td><td>Model (C)</td><td>Model (D)</td></tr>
<tr><td>System</td><td>Without FVD</td><td colspan="3">With FVD</td></tr>
<tr><td>Response Spectrum by Euro Code 8</td><td>Design Ground Acceleration (Ag)</td><td colspan="4">0.10</td></tr>
<tr><td rowspan="4">Performance Point According to FEMA 440 EL</td><td>Programs</td><td colspan="4">ETABS</td></tr>
<tr><td>Direction</td><td colspan="4">Push (X) and Push (Y)</td></tr>
<tr><td>Base Share (tonf)</td><td>252.6</td><td>798.0</td><td>954.1</td><td>965.1</td></tr>
<tr><td>Roof Displacement (m)</td><td>0.109</td><td>0.045</td><td>0.051</td><td>0.051</td></tr>
</table>

6 Summary and Conclusions

In this research, the performance of a symmetrical residential 15-storey reinforced concrete framed building has been investigated. The building was designed in accordance with BS8110-97 code and analyzed using ETABS software in both x and y-directions. The building was evaluated in three stages using pushover analysis through the displacement coefficient method according to the FEMM-440 code by ETABS. The stages were as follows:

6.1 The First Stage:

The building was evaluated without the use of any retrofit under the effects of three different seismic intensities: PGA of 0.15, 0.25, and 0.4. The results of the study were as follows:

- When the building was exposed to PGA of 0.15 and 0.25, the demand curve intersects with the capacity curve near the elastic region. In this region, no deformation occurs in the plastic hinge and the building's performance shows satisfactory behavior.
- When the building was subjected to PGA=0.4, the demand curve intersected with the capacity curve near the critical region. This region caused deformation of some of the plastic hinges as they were at the level of CP Consequently, significant damage appeared in some structural elements that are difficult to repair, leading to the collapse of the structure and posing a danger to human lives.

6.2 The Second Stage:

The building was evaluated after it was retrofitted using FVD on three different models (B, C, D). Each model differs from the others in the distribution and number of FVDs on the building. The results of this stage were as follows:

- When the three building models (B, C, and D) were exposed to PGA values of 0.15, 0.25, and 0.4, the demand curve did not intersect with the capacity curve. Consequently, the performance point results did not appear.
- When the four building models - Model A without FVD and Models B, C, and D with FVD were subjected to PGA = 0.1, which is less intense than previous levels, it was observed that the intersection of the capacity curve with the demand curve occurred near the elastic region for all models. This region is considered exceptionally safe.

6.3 The Third Stage:

The performance points for all models were compared to each other, and the following result was obtained:

- When comparing the results of building model (A) without FVD to building models (B, C, and D) with FVD500, it was found that the maximum roof displacement decreased by 58.7%, 53.2%, and 53.2%, and the base shear increased by 68.3%, 73.5%, and 73.8%, respectively. These results are in agreement with the research findings as follows:

✓ **[25],** which showed that using FVD500 significantly reduced the maximum displacements and decreased the base shear of the structures. Additionally, the stiffness values of the structure increased when FVD500 was used for exterior corners.

✓ **[29],** when using FVD500, it reduces the base shear of structures by 60% in time history evaluation, while also minimizing the displacements of the top story by 20%.

- The results showed that Model B is the most effective in economic reinforcement, as it produces good results with the fewest number of FVDs. Consequently, the optimal solution is to implement dampers on nine floors only for the building. These results are in agreement with the research findings as follow:

✓ **[16],** which showed that in order to reduce costs, dampers should be distributed across five floors in a ten-story building.

- When distributing FVD along the internal panel of the building, as shown in model (C), and along the external panel, as shown in model (D), the results were very similar. These results are in agreement with the research findings as follow:

✓ **[15]** When using FVD250, it reduces the maximum displacements of the top story in the x-direction at the external corner by 89.90% and 88.47% at central damping, while also minimizing in the Y-direction at the external corner by 89.91% and 88.34% at central damping.

REFERENCES

1. A.E.Hassaballa, M. A.Ismaeil, A.N. Alzead, and F. M. Adam. 2014. "Pushover Analysis of Existing 4 Storey RC Flat Slab Building." International Journal of Sciences: Basic and Applied Research (IJSBAR). Volume 16, Issue 2, pp. 242-257
2. M.K.Rahman, M. Ajmal, and M. H. Baluch. 2012. "Nonlinear Static Pushover Analysis of an Eight Story RC Frame-Shear Wall Building in Saudi Arabia." 15th World Conference on Earthquake Engineering. Lisbon Port., Issue. 9, pp. 1–7
3. A. Abd-Elhamed and S. Mahmoud. 2016. "Nonlinear static analysis of reinforced concrete framed buildings - A case study on Cairo earthquake" Volume 4, Issue 12, pp. 16–38
4. R.A.Hakim, M. S. Alama, and S. A. Ashour. 2014. "Seismic Assessment of RC Building According to ATC 40, FEMA 356 and FEMA 440." Arabian Journal for Science and Engineering 39(11):PP.7691–7699
5. H. A. Abass, and H. K. Jarallah. 2021. "Comparative Study of the Seismic Assessment According to ATC-40, FEMA-356 and FEMA-440 for Existing Hospital Building Located at Baghdad City." International Journal of Civil Engineering (June). Volume 1, Issue 1, pp. 1–17
6. D.M. Daniel and S. T. John 2016 "Pushover Analysis of Retrofitted RC Building." International Journal of Scientific & Engineering Research, Volume 7, Issue 10, pp. 88–92
7. H. K. S. Eldin, H. Hassan, H. A. Mohamed and Z. E. Ragab. 2021. "Seismic Evaluation Of RC Buildings" The Egyptian International Journal of Engineering Sciences and Technology Volume 34, pp.45–57.

8. A. A. Shaikh, A.P. Wadekar and D.N Kakade. 2021. "Pushover Analysis of RC Building with and without Floating Column." International Research Journal of Engineering and Technology (IRJET), Volume 08, Issue 04, pp. 4112–4115
9. M. Shoaib and A. Swetha. 2023. "Non-Linear Pushover Analysis Of RCC Framed Structure By Providing Fluid Viscous Dampers At Different Locations," Journal of Scientific Research And Technology (JSRT).Volume 1, Issue 9, pp. 21–47
10. A. Hassanzadeh, S. Moradi, and H. V. Burton, 2024 "Performance-Based Design Optimization of Structures: State-of-the-Art Review," J. Struct. Eng., Volume 150, Issue 8, pp. 1–22
11. A. Abd-Elhamed and S. Mahmoud. 2019. "Simulation analysis of TMD controlled building subjected to far-and near-fault records considering soil-structure interaction" J. Build. Eng. Volume 26, Issue 11,pp 1-26
12. A. Abd-Elhamed and M. Tolan. 2022 "Tuned liquid damper for vibration mitigation of seismic-excited structures on soft soil". Alex. Eng. J. Volume 61, Issue 12, pp. 9583 – 9599
13. C. G. Ekwueme, G. C. Hart, K. C. Ozegbe, C. Simsir, and G. E. Brandow. 2010. "The Benefits of Using Viscous Dampers in a 42-Story Building." Earthquake (May).
14. A. Koshti, S. Shinde, K. Yamagar and S. Shegunshi. 2019. "Seismic Response of Structure with Fluid Viscous Damper (FVD)." International Journal for Research in Applied Science and Engineering Technology (IJRASET). Volume 7, Issue 2, pp. 560–567
15. M. D. Mujeeb, J. S. R. Prasad, and V. Malagavelli. 2019. "Performance of Fluid Viscous Dampers on Seismic Response of RCC Structures." International Journal of Innovative Technology and Exploring Engineering. Volume 8, Issue 12, pp. 3685–3691
16. E. K. Alataby, J. A. Kadhim, and M. A. Ahmed, 2021 "Study on the Effect of Distribution of Viscous Damper for Steel Frame Structure," Journal of Physics: Conference Series, Volume 1973, Issue 1,pp.1-13
17. H. Gupta and R. Singh, 2024 "Seismic Analysis of Multi-Storied Reinforced Concrete Building with Fluid Viscous Dampers," Volume 12, Issue XI, pp. 1315–1322
18. FEMA 440. (2005). Improvement of Nonlinear Static Seismic Analysis Procedures. Federal Emergency Management Agency, June, 392.
19. Y. Dinar, M. I. Hossain, R. Kumar Biswas, and M. Masud Rana, 2014 "Descriptive Study of Pushover Analysis in RCC Structures of Rigid Joint," IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) Volume. 11, Issue. 1, pp. 60–68.
20. S. Tak and D. Garg, 2023 "Nonlinear Static Analysis of Building with Different Aspect Ratio," Tuijin Jishu/Journal Propuls. Technol., Volume. 44, Issue 4, pp. 5283–5305.
21. Federal Emergency Management Agency, FEMA-356 (2000) "Prestandard and Commentary for the Seismic Rehabilitation of Buildings," Rehabil. Requir., no. 1, pp. 1–518,
22. Applied Technology Council, ATC-40: (1996). "Seismic Evaluation and Retrofit of Concrete Buildings", Vols. 1 and 2, California.
23. Taylor devices inc. http:// www.taylordevices.com
24. M. K. Reddy, 2016 "Seismic Response Study of Multi-Storied Reinforced Concrete Building With Fluid Viscous Dampers," Int. Res. J. Eng. Technol.
25. W. Al Agha and N. Umamaheswari, 2020 "Comparative Study on Seismic Performance of Reinforced Concrete Building with and without Fluid Viscous Dampers," International Journal of Engineering Research And Management (IJERM) , Issue 11, pp. 80–90
26. Egyptian Code of Practice for Design and Construction of Reinforced Concrete Structures ECP-203, Housing and Building Research Center, Ministry of Building and Construction, Giza, Egypt, 2017
27. The Egyptian Code for Calculation of Loads and Forces in Structural and Building Work, ECL 201, Cairo, Egypt, 2012.
28. BS 8110-1:1997 Structural Use of Concrete – Part 1: Code of Practice for Design and Construction
29. CSI (Computers and Structures, Inc.), ETABS Version 20.3.0, Extended 3D Analysis of Building Systems, Computers and Structures, Inc, Berkeley, California.
30. Eurocode 8 (2004) Design of structures for earthquake resistance, Part 1: General rules, seismic actions and rules for buildings, European standard EN 1998-1. European Committee for Standardization (CEN),Brussels