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A DESIGN METHODOLOGY FOR SUPPLEMENTAL DAMPING FOR SEISMIC PERFORMANCE ENHANCEMENT OF FRAME STRUCTURES

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ABSTRACT

Supplemental damping using passive energy dissipation (PED) devices is often used for enhancing the seismic performance of a seismically deficient structure to reduce the seismic response under earthquake loading. Such PED devices are normally incorporated within the frame structure between adjacent floors through different bracing schemes like diagonal, chevron, scissors and toggle or through non-structural in-fill walls, so that they efficiently enhance the overall energy dissipation ability of the seismically deficient frame structure under earthquake loading. These PED devices function based on the large and stable energy dissipation obtained using energy dissipation mechanisms like visco-elastic and elasto-plastic. This paper presents a methodology based on the direct displacement based design (DBD) for designing PED devices for providing supplemental damping to enhance the energy dissipation ability of frame structures subjected to earthquake loading. The presented design methodology is validated through an experimental study consisting of shake table tests of sweep sine, steady state and seismic types, conducted on a single bay-three storey reinforced concrete (RC) frame structure incorporated with designed visco-elastic PED devices.

Keywords: Supplemental damping; displacement based design; seismic performance enhancement; passive energy dissipation; seismic response control; shake table testing

1. INTRODUCTION

One of the principal current challenges in structural engineering, concerns the development of innovative design concepts to better protect structures, along with their occupants and

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contents, from the damaging effects of destructive environmental forces due to earthquakes. The traditional approach to seismic design has been based on providing a combination of strength and ductility to resist the imposed earthquake loads. For major earthquakes, the structural design engineer relies upon the inherent ductility of structure to prevent catastrophic failure, while accepting a certain level of damage. In this traditional seismic design, acceptable performance of a structure during an earthquake is based on the lateral force resisting frame system being able to absorb and dissipate energy in a stable manner for a large number of cycles. Energy dissipation occurs in specially detailed ductile plastic hinge regions of beams and columns, which also form part of the gravity load carrying system. Plastic hinges are regions of concentrated damage to the gravity frame which often is irreparable. Nevertheless, this design approach is acceptable because of economic considerations provided, of course, that structural collapse is prevented and life safety is ensured. Some times, situations exist in which this traditional seismic design approach is not applicable. When a structure must remain functional after an earthquake, as the case of lifeline structures, the conventional seismic design approach is inappropriate. For such cases, the structure may be designed with sufficient strength so that inelastic action is either prevented or is minimal; an approach that is very costly. Moreover, in such structures, special precautions need to be taken in safeguarding against damage or failure of important secondary systems which are needed for continuing serviceability. But this draw back can be mitigated, and perhaps eliminated, if the earthquake-induced energy is dissipated in supplemental damping devices placed in parallel with the gravity load resisting system. The new approach for improving seismic performance and damage control is that of passive energy dissipation (PED) systems. This strategy is attractive for two primary reasons:

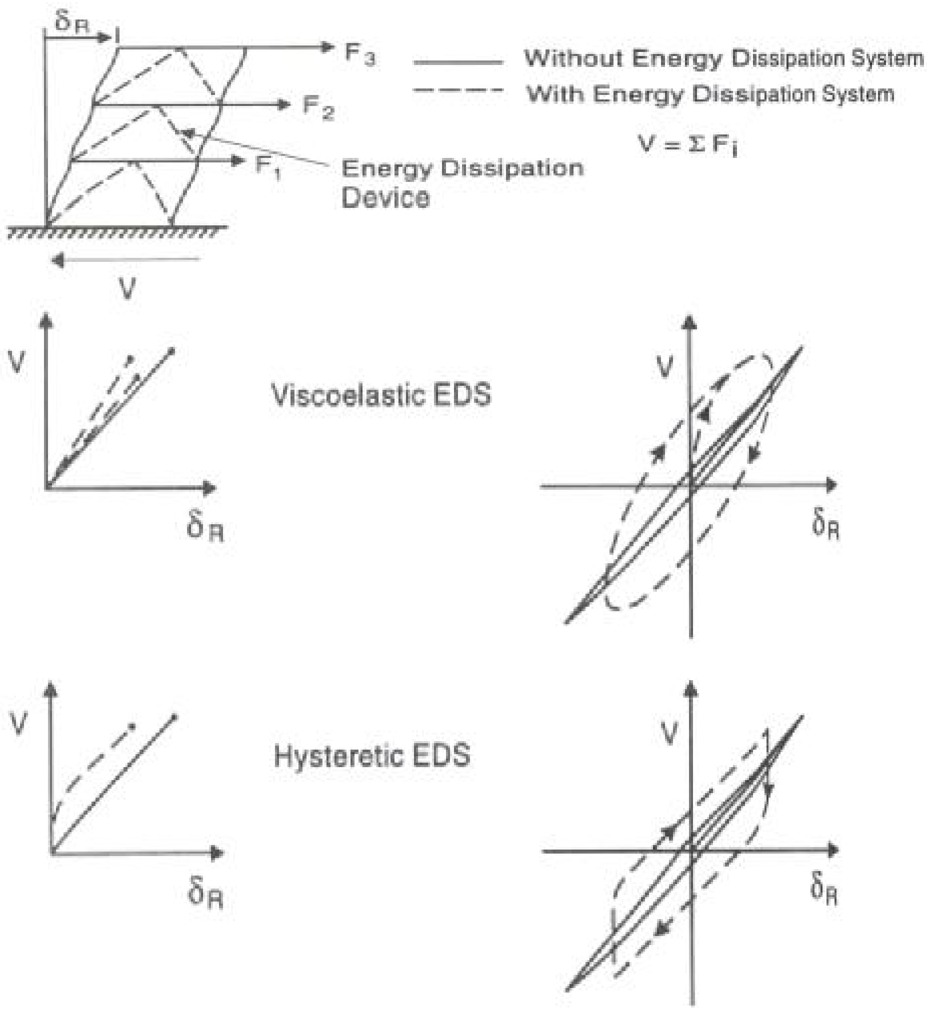
1. Damage due to the gravity load resisting system is substantially reduced, leading to major reduction in post earthquake repair costs.
2. Earthquake damaged PED devices can be easily replaced without the need to shore the gravity framing.

Alternative seismic performance enhancement strategies adopting passive energy dissipation systems have been developed which incorporate earthquake protective systems in the structure (Kelly et al. [1]; Soong and Dargush [2]; Constantinou et al. [3]). In these systems, mechanical devices are incorporated into the frame of the structure to dissipate energy throughout the height of the structure. The means by which energy is dissipated is either yielding of mild steel, sliding friction, motion of a piston or a plate within a viscous fluid, orifice action of fluid or visco-elastic action in polymeric materials. In addition to increasing the energy dissipation capacity per unit drift of a structure, some energy dissipation systems also increase the strength and stiffness (Muthumani et al. [4]; Sathish Kumar et al. [5]; Sathish Kumar et al. [6]). Such systems include the following types of energy dissipation mechanisms: yielding, extrusion, friction, viscous and visco-elastic action.

2. MECHANISM OF SUPPLEMENTAL DAMPING

Figure 1 shows the pushover curves of a linearly elastic frame and yielding frame which is essentially a plot of base shear vs. roof displacement. Similarly, the corresponding force displacement hysteretic loops depict linear behavior and limited ability to absorb energy.

Consider the case when energy-dissipating devices are added to the frame, it is assumed that the connection details of the devices are such that neither inelastic action nor damage occurs in the frame at the points of attachment during seismic excitation. It is also assumed that the design of the energy dissipation system is such that it functions properly and dissipates energy throughout the height of the frame. The ability of the frame to dissipate energy is substantially increased as demonstrated in the force-displacement hysteretic loops of the frame. Accordingly, the frame undergoes considerably reduced amplitude of vibration in comparison to the frame without the energy dissipation system under the same earthquake motion. While the energy dissipation system can achieve a considerable reduction in the displacement response, it can also achieve a reduction in the total force exerted on the structure. In general, reduction in force will not be as much as reduction in displacement which is due to the increased strength or increased stiffness provided by the energy dissipation system. Comparable reductions in displacement and force can be achieved with systems that do not increase the strength or stiffness of the structure to which they are attached.



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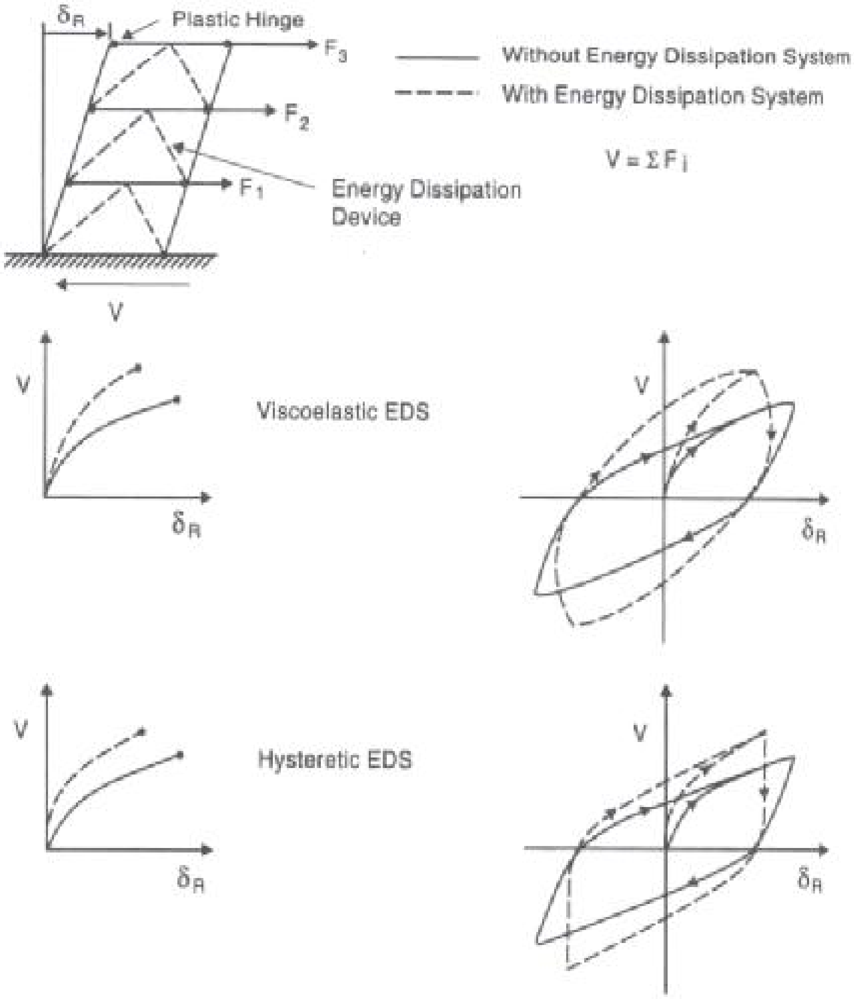


(b)

Figure 1. Pushover curves and force-displacement hysteretic loops of (a) an elastic structure and (b) yielding structure having proper plastic hinge formation, without and with passive energy dissipation devices (Soong and Dargush [2])

2.1 Modeling of PED devices

For analysis of structures with PED devices, various mathematical modeling techniques have been developed. Various models with increased complexity are reviewed in Reinhorn et al. [7] for PED devices of viscous (VD) type. Constantinou and Syman [8]) showed that the Maxwell model is adequate to capture the frequency dependence of the viscous PED device. They have showed that, below a cut off frequency of approximately 4 Hz, the model can be further simplified into a purely viscous dashpot model. It is stated in FEMA-274 (FEMA) [9] that the damping force of a viscous PED device can be modeled to be proportional to the velocity with a constant exponent ranging between 0.2 and 2.0. In preliminary analysis and design stages, the velocity exponent of 1.0 is recommended for simplicity. In this study, based on those references, the behavior of viscous PED device is modeled by a linear dashpot.

A typical visco-elastic PED device consists of thin layers of visco-elastic material bonded between steel plates. In practice, the dynamic behavior of visco-elastic PED device is generally represented by a spring and a dashpot connected in parallel (Soong and Dargush [2]). For the linear spring-dashpot representation of the visco-elastic PED device, the stiffness K_d and the damping coefficient C_d are obtained as follows:

$$K_d = \frac{G'(w)A}{t}$$
$$C_d = \frac{G''(w)A}{wt} \tag{1}$$

Where, *G'(w)* & *G"(w)* are the storage shear modulus and loss shear modulus respectively; *A* & *t* are the total shear area and the thickness of the visco-elastic material respectively; and *w* is forcing frequency for which the fundamental natural frequency of the structure is generally utilized in time domain analysis. With this spring-damper idealization, the dynamic system matrices of the structure with added visco-elastic PED devices can be constructed by superposing the damper properties to the stiffness and damping matrices of the structure. Figure 2 represents the mathematical models of viscous and visco-elastic PED devices employed in this study.

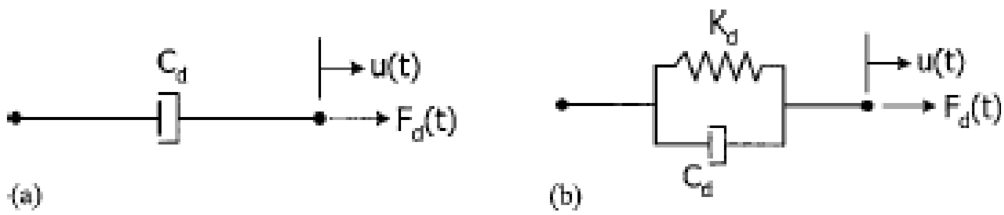


Figure 2. Mathematical models representing viscous and visco-elastic PED devices

3. PERFORMANCE EVALUATION USING DISPLACEMENT SPECTRUM AND CAPACITY CURVE

The direct displacement based design (DBD), which focuses on displacement as the key design parameter, is considered to be an effective method for implementing performance based seismic design utilizing deformation capacity and ductile detailing standards. In the present study, the general procedure of the DBD documented in the SEAOC Blue Book [10] is applied in reverse order for evaluation of seismic performance of an existing structure. In principle, the proposed analysis procedures are similar to the capacity spectrum method (ATC-40 [11]: FEMA [12]; Freeman [13]) in that performance point is determined as a location where the displacement demand of the earthquake becomes equal to the plastic deformation capacity of the structure. The difference is on the use of displacement spectrum instead of the so called acceleration displacement response spectrum (ADRS). Therefore, the extra work required for transforming the capacity and demand curves to ADRS format can be avoided. Although this may not be a significant improvement, it has the advantage of maintaining consistence with the proposed design procedure for supplemental damping using PED devices. Two nonlinear static analysis procedures, the step by step and the graphical procedure, which correspond to the nonlinear static procedures A and B of ATC-40 [11] respectively, are proposed for seismic performance evaluation of structures (without PED devices). The two procedures are summarized as in the following sub-sections:

3.1 Step by step procedure

1. Obtain base shear versus roof storey displacement capacity curve for the frame structure from pushover analysis.
2. Approximate the capacity curve by bilinear lines based on equal energy concept (area A_1 = area A_2), and determine the quantities such as effective elastic stiffness K_e, elastic natural period T_e, base shear at yield V_y, yield displacement Δ_y and post-yield stiffness ratio α (Figure 3).
3. Transform the roof storey displacement coordinate into pseudo-displacement coordinate S_d using the following relation:

$$S_d = \frac{\Delta_R}{\Gamma f_R} \tag{2}$$

Where, Δ_R is the roof displacement and Γ and f_R is the modal participation factor and the roof storey component of the fundamental mode respectively. This process corresponds to the transformation of the structure into an equivalent single degree of freedom (SDOF) structure.

4. Assume the first trial value for the maximum displacement Sdm of the equivalent structure, and determine the ductility factor μ = Sdm/Sdy. The equivalent damping ratio ξeq can be obtained as

$$x_{eq} = \frac{2(m-1)(1-a)}{pm(1+am-a)} \tag{3}$$

Then, the effective damping for the structure can be obtained as the sum of the equivalent damping and the inherent damping of the structure.

$$x_{eff} = x_{eq} + x_i \tag{4}$$

Where, x_i is the inherent damping for which 5% of critical damping is generally utilized. Also, the effective period T_{eff} corresponding to the maximum displacement can be obtained as

$$T_{eff} = T_e \sqrt{\frac{m}{1+am-a}} \tag{5}$$

Where, T_e is the fundamental period of the structure.

5. Construct the displacement response spectrum for design earthquake using the effective damping obtained in the previous step, and read from the spectrum the next trial value

for the maximum displacement S_{dm} corresponding to the effective period T_{eff}.

6. Repeat the process from step 4 using the maximum displacement computed in the above step. Once the maximum displacement S_{dm} converges, then convert it into the maximum roof displacement using Eq. (2).
7. Carry out pushover analysis until the roof displacement reaches the maximum value computed above to estimate the maximum inter-storey drifts.

3.2 Graphical procedure

1. Steps 1 & 2: The same as those of the step by step procedure.
2. Step 3: Draw displacement response spectra with various damping ratios.
3. Step 4: For a series of ductility ratios, obtain maximum displacements ($S_{dm} = \mu \cdot S_{dy}$), effective periods $T_{eff}(\mu)$ [Eq. (5)] and effective damping ratios (x_{eff}) [Eqs. (3) & (4)].
4. Step 5: Find out the point at which the effective damping ratio corresponding to a ductility ratio, obtain in step 4, is equal to the equivalent damping ratio of a displacement spectrum crossing the point [$T_{eff}(\mu)$, $S_{dm}(\mu)$].
5. Step 6: Convert the maximum displacement computed in the above step into the maximum roof displacement, and carry out pushover analysis until the roof displacement reaches the maximum value computed above to estimate the maximum inter-storey drifts.

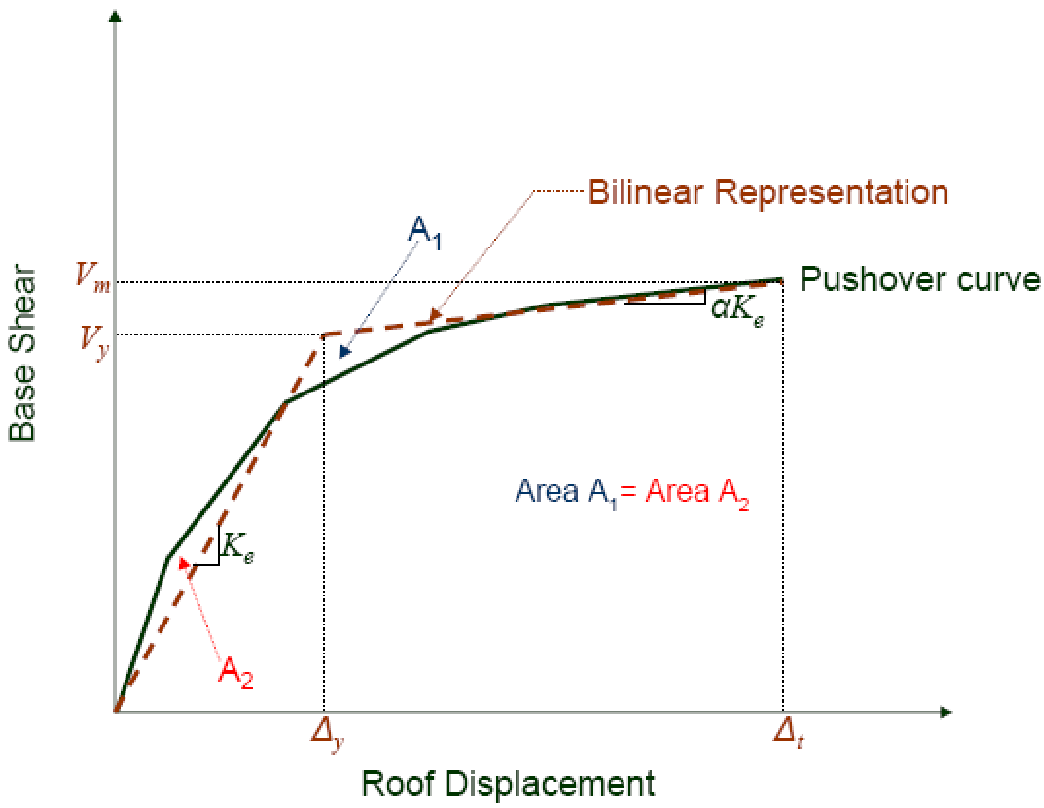


Figure 3. Bi-linear representation of a push-over curve

4. DESIGN METHODOLOGY FOR PASSIVE ENERGY DISSIPATION DEVICES

If the maximum storey drift of a structure subjected to a code-specified earthquake load exceeds the desired performance level, the structure needs to be retrofitted. Among the various methods for seismic retrofit, the present study focuses on increasing damping to decrease earthquake induced structural responses. To this end, a procedure for estimating the amount of supplemental damping required to satisfy the given performance objective is proposed. The basic idea is to compute the required damping from the difference between the total effective damping needed to meet the target displacement and the equivalent damping provided by the structure at the target displacement.

4.1 Required damping to meet target displacement

The damping ratio of the displacement response spectrum that intersects the point of the target displacement S_{dt} on the displacement ordinate (vertical axis) and the effective period T_{eff} on the period ordinate (horizontal axis) corresponds to the total effective damping x_{eff} for the structure to retain to meet the performance objective. For structure with supplemental dampers, the total effective damping is composed of the three components: inherent viscous damping $x_{i,}$, equivalent damping of the structure contributed from inelastic deformation of the structural members x_{eq} and the damping required to be added by the PED devices x_d. The equivalent damping of the structure is obtained from the following equations (FEMA [12]):

$$x_{eq} = \frac{1}{4p}\frac{E_{DS}}{E_S} = \frac{V_y S_{dt} - S_{dy} V_t}{p V_t S_{dt}} \quad \text{for Viscous PED devices} \qquad (6a)$$

$$= \frac{V_{yd} S_{dt} - S_{dy} V_{td}}{p V_{td} S_{dt}} \quad \text{for Visco-elastic PED devices} \qquad (6b)$$

Where, $V_{yd} = V_y + K_d S_{dy}$, $V_{td} = V_t + K_d S_{dt}$ and E_s and E_{DS} are the stored potential energy in the structure and the energy dissipated by hysteretic behavior of the structural members in the retrofitted structure respectively. Tsopelas et al. [14] provides the contribution of the added damping to the total effective damping as $(x_d \,.\, T_{eff})/T_e$, where x_d is the supplemental damping ratio. Then the required supplemental damping can be computed from the following equation:

$$x_d = (x_{eff} - x_{eq} - x_i)\frac{T_e}{T_{eff}} \qquad (7)$$

Where, the total effective damping and the equivalent damping can be obtained from the displacement response spectrum and from Equation 6 respectively.

4.2 Storey-wise distribution of PED devices

In multi-storey frame structures, the supplemental damping computed in the equivalent SDOF system using Eq. (7) should be distributed throughout the stories of the original structure in such a way that the damping ratio for the fundamental mode becomes the required supplemental damping x_d. For this purpose, the expression for equivalent damping (Eq. (6)) is used again except that the energy dissipated by the PED device E_{DV} is used in the numerator instead of E_{DS}

$$x_{eq} = \frac{1}{4p}\frac{E_{DV}}{E_S} \tag{8}$$

If the PED devices are placed as diagonal members with the inclination q , then, the energy dissipated by the PED devices can be expressed as follows (FEMA [12]):

$$E_{DV} = \frac{2p^2}{T_{eff.d}}\sum_{i=1}^{N} C_{di}\cos^2 q_i(\Delta_i - \Delta_{i-1})^2 \tag{9}$$

Where, $T_{eff.d}$ is the secant period of the retrofitted structure; C_{di} and Δ_i are the damping coefficient and the maximum lateral displacement of the i^{th} storey respectively, and N is the number of storey. The potential energy stored in the multi-storey structure can be expressed as follows:

$$E_S = \frac{2p^2}{T_{eff.d}}\sum_{i=1}^{N} m_i\Delta_i^2 \tag{10}$$

$$T_{eff.d} = 2p\sqrt{\frac{M^*S_{dt}}{V_y(1+am-a)}} \quad \text{for Viscous PED devices} \tag{11a}$$

$$T_{eff.d} = 2p\sqrt{\frac{M^*S_{dt}}{V_y(1+am-a)+K_dS_{dt}}} \quad \text{for Visco-elastic PED devices} \tag{11b}$$

Where, M^* is the effective modal mass and m_i is the mass of the i^{th} storey. By substituting Eqs. (9) & (10) into Eq. (8), the damping ratio contributed from the PED devices can be expressed as:

$$x_d = \frac{1}{4p}\frac{T_{eff.d}\sum_{i=1}^{N} C_{di}\cos^2 q_i(\Delta_i - \Delta_{i-1})^2}{\sum_{i-1}^{N} m_i\Delta_i^2} \tag{12}$$

In Eq. (12), the left hand side of the equation x_d is obtained from Eq. (7) in the equivalent SDOF system. For viscous PED device, the damping coefficient of the damper in the i^{th} storey C_{di} can be determined in Eq. (12), whereas for visco-elastic PED device, both C_{di} and K_{di} are the variables that should be determined. This can be done by using the relation $K_d = (G'/G'')w.C_d$ obtained from Eq. (1). The simplest case is to assume that the PED devices in all storeys have the same capacity, and the damping coefficient in this case can be obtained from Eq. (12) as:

$$C_d = \frac{1}{4p}\frac{4px_d\sum_{i=1}^{N} m_i \Delta^2{}_i}{T_{eff,d}\sum_{i=1}^{N}\cos^2 q_i (\Delta_i - \Delta_{i-1})^2} \tag{13}$$

In this stage, however, the maximum storey displacements, except for the top-storey displacement given as performance limit state, are known. Therefore, the configuration for lateral storey drifts Δ_i needs to be assumed in Eqs. (12 & 13). A simple case is to assume that the maximum storey drifts are proportional to the fundamental mode shape or to the pushover curve. The storey-wise distribution pattern for the PED devices also needs to be assumed. For viscous PED devices, the design process ends here. However, for visco-elastic PED devices with stiffness, iteration is required, because the added PED devices increase system stiffness. In that case, the capacity curve of the system needs to be redrawn considering added PED devices, and the process is to be repeated until convergence.

4.3 Design procedure for PED device scheme

The proposed procedure to design supplemental dampers for performance based seismic retrofit of existing structures can be summarized in the following steps:

1. Carry out eigenvalue analysis of the structure to obtain natural periods and mode shapes. Using the mode shape, perform pushover analysis to obtain top storey versus base shear curve, and transform the pushover curve into a capacity curve using Equation 2. Idealize the curve into a bilinear shape, and read the yield displacement S_{dy}.
2. Decide a desired target roof displacement based on the desired performance objective, and transform it into the target value in the equivalent SDOF system S_{dt}. Obtain ductility ratio $\mu S_{dt}/S_{dy}$, the effective period T_{eff} (Eq. (5)) and the equivalent damping x_{eq} (Eq. (6)) at the target displacement.
3. Find out the effective damping ratio corresponding to the displacement response spectrum that crosses the point of the target displacement and the effective period. This corresponds to the total demand on damping imposed by the earthquake (Figure 4). It would be more convenient to start the procedure with response spectra with various damping ratios.
4. Compute the required damping for supplemental dampers from Eq. (7).
5. The required damping is distributed throughout the stories using Equation 12. The size of PED device in each storey is designed based on the required damping allocated to the storey.
6. For structures retrofitted with visco-elastic PED devices, carry out eigenvalue analysis and redraw the capacity curve of the structure using the newly obtained mode shape, and repeat step 1 until convergence.
7. Check whether the structural members, especially columns, can resist the additional axial and shear forces imposed by PED devices.

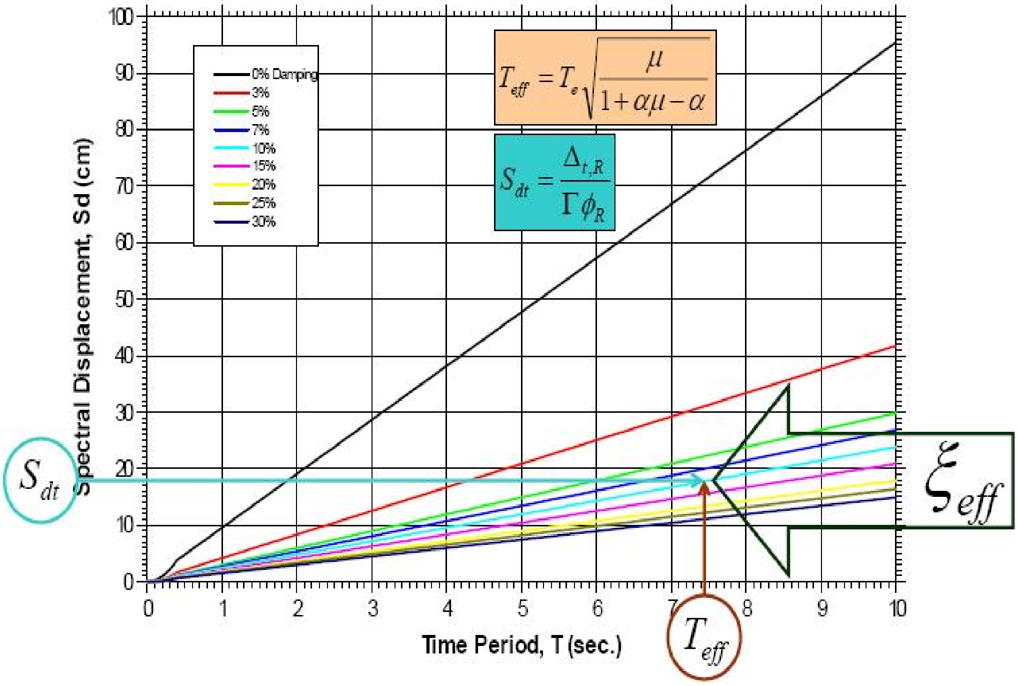


Figure 4. Typical displacement response spectrum for various damping values

5. EXPERIMENTAL STUDY

In order to validate the proposed displacement based design (DBD) methodology, an experimental study consisting of shake table tests was carried out on a single bay-three storey RC frame structure. Initially, the frame structure was designed for gravity loads only. Then the required visco elastic PED devices were designed based on the proposed direct displacement based design methodology described earlier for retrofitting the chosen RC frame structure to meet a desired performance level objective of 'Immediate Occupancy'. As per *ATC-40* [11], for Immediate Occupancy, the maximum total drift is limited to 0.01 or the roof drift ratio is limited to 1%. In the present study, to design the PED devices, a target roof drift ratio of 0.01 (1%) to meet the desired performance level and design acceleration response spectrum given in Indian Standard Code of Practice (IS 1893: Part 1)[15] for Design Basis Earthquake (DBE), Zone IV, 5% Damping, Medium Soil condition as shown in Figure 5 was used. Based on this exercise, the number, capacity and the sizes of the PED devices required to retrofit the frame structure to meet the desired performance objective (10% Target total effective damping x_{eff}) were arrived. Four numbers of visco elastic PED devices of size 5cm x 10cm x 2cm made of high damping rubber (Storage shear modulus *G'*: 1.73MPa, Loss shear modulus *G"*: 1.89MPa & Loss modulus η_d: 1.10) were added for retrofitting the chosen RC frame structure through a pair of non-structural infill walls in the first storey only.

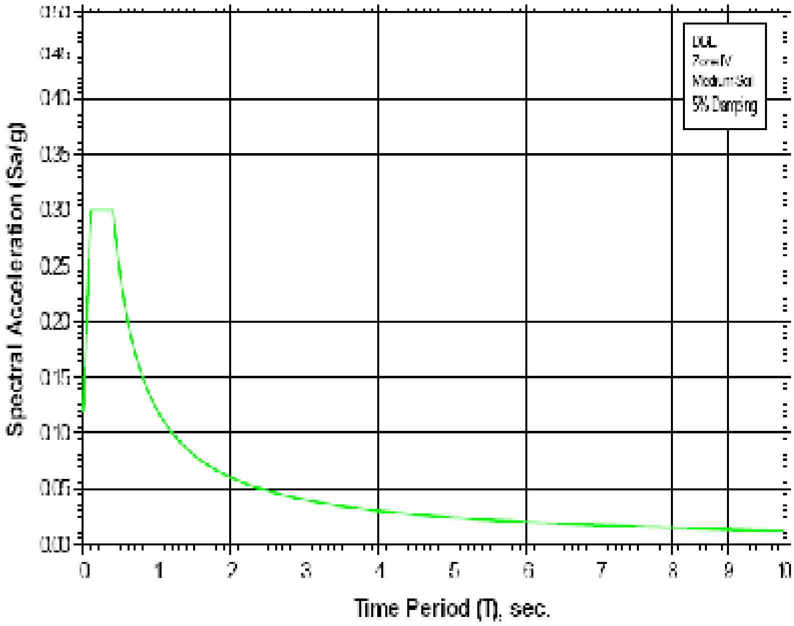


Figure 5. Design acceleration response spectrum (DBE) as per IS1893-2002 used in the present study, for 5% damping, zone IV, medium soil case

Figure 6 shows the details of the frame structure studied. Figure 7 shows the photographic view of the retrofitted RC frame chosen in the present study. Then the retrofitted RC frame was subjected to shake table tests of sweep sine, steady state dynamic and seismic type in its linear range. The basic dynamic characteristics of the frame structure like natural frequencies, mode shapes and modal damping were evaluated from the sweep sine tests. The energy dissipation capacity of the retrofitted ground storey was evaluated using the force-displacement hysteretic curves obtained from the steady state dynamic tests.

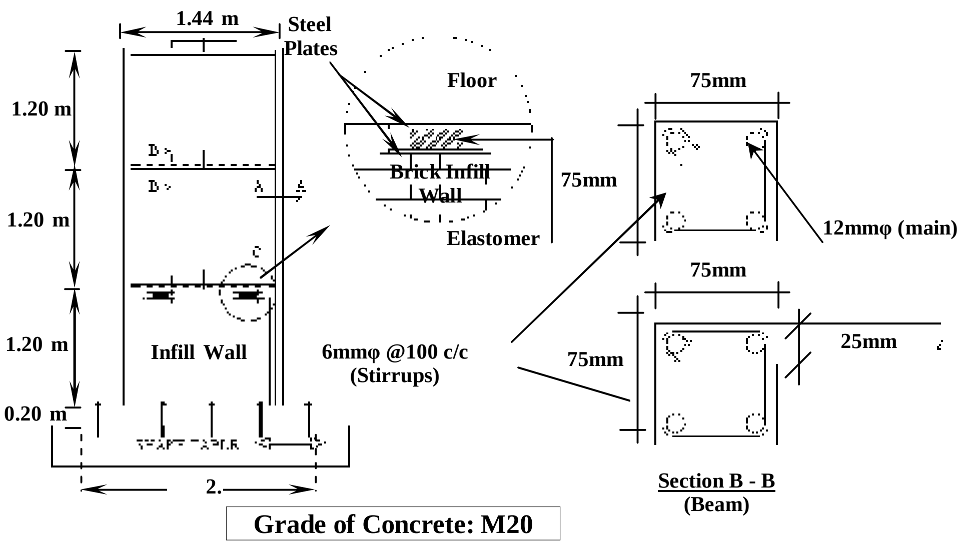


Figure 6. Details of the RC frame structure chosen in the study

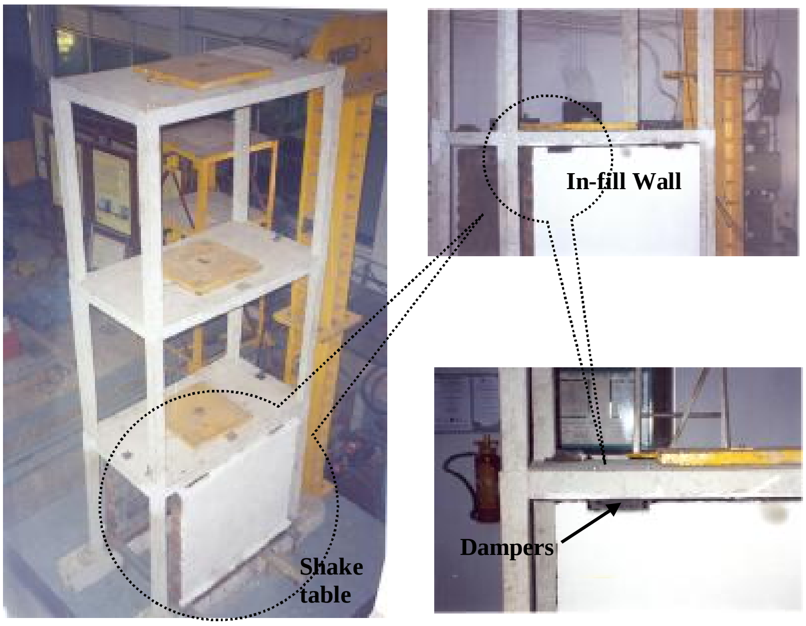


Figure 7. View of the retrofitted RC frame structure fixed on the shake table

Similarly, the seismic performance was evaluated from the seismic tests. For the seismic tests a spectrum compatible displacement time history compatible to the design acceleration response spectrum given in IS 1893 [15] was generated and applied to the frame structure through the shake table. Then the entire exercise was repeated after removing the PED devices and the test results were compared against the test results obtained on the retrofitted frame structure to evaluate the supplemental damping provided by the visco-elastic PED devices. Through this study the proposed displacement based design methodology was validated.

5.1 Shake table testing

Shake table testing (Kausel [16]; Kausel [17]; Antony Jayasehar et al. [18]) is one of the experimental methods adopted for seismic performance evaluation of structures subjected to simulated earthquake motions. This shake table method is towards developing and validating new design and construction methodologies with improved seismic resistance and also for bench-marking new analytical tools and software (Helen Santhi et al., [19]). Essentially in shake table testing, the three basic dynamic forces namely inertial, elastic and damping forces are induced in the tested structure. Such a pure experimental seismic performance evaluation of structures necessitates the use of sophisticated and expensive dynamic actuators and control systems. However, it is difficult to design large shake tables capable of reproducing actual ground motions, particularly when simulating multi axial earthquakes. Among the reasons limiting the simulation of realistic effects are the deformability and inertia of the shake table, its characteristic modes of vibration, the devices needed to carry the dead load of test specimen and overturning moments without impeding the table’s motion, the friction of the bearings, the physical capabilities of the hydraulic actuators, and to a lesser extent the limitations in the control devices.

5.2 Sweep sine tests

Shake table tests of sweep sine type are normally conducted on a test structure to evaluate the dynamic characteristics namely natural frequencies and their associated mode shapes and damping. Such sweep sine tests should be conducted with an optimum linear or logarithmic sweep rate so that the amplitude error parameter and frequency error parameter are kept low (Ewins [20]). Based on the earlier experimental studies (Gopalakrishnan et al. [21; Rama Rao et al. [22]) an optimum logarithmic sweep rate of 1 Octave/minute was adopted in the present shake table study for both forward sweep and backward sweep. Acceleration responses were measured using accelerometers (B&K type 4370 accelerometers coupled with B&K type Nexus 2692-A-0I4 signal conditioners) at all the four elevation levels namely ground floor level, first floor level, second floor level and roof level for arriving at frequency-response functions. Three separate sweep sine test were conducted for each of the three levels namely first floor level, second floor level and roof level and in each of the sweep tests acceleration responses from the respective floor level and ground floor level were acquired and fed into a dual channel FFT analyzer (AND type 3524). From the acquired and averaged acceleration responses in the dual channel FFT analyzer the final frequency response function (FRF) curve was obtained for the floor under consideration. Using these FRF curves the real and imaginary parts of the FRF curves were arrived by way of mathematically splitting inside the FFT analyzer. Finally from the real part of the FRF curve the natural frequencies and damping values for all the identified modes of the test structure were arrived. Similarly from the imaginary part of the FRF curve the mode shape information for all the identified modes of the test structure was gathered.

5.3 Steady state dynamic tests

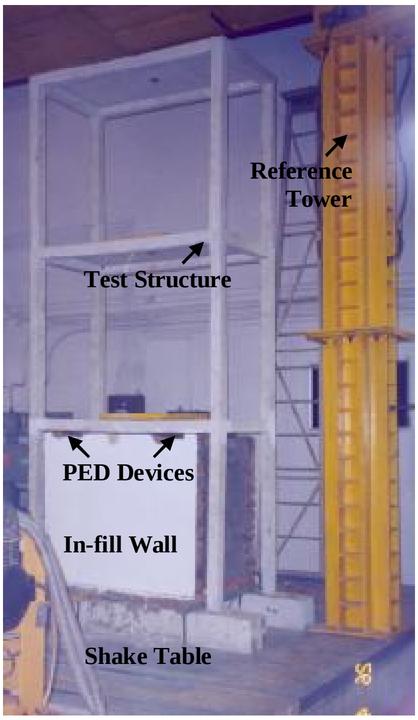
Shake table tests of steady state dynamic type are normally conducted on a test structure to evaluate the energy dissipation ability through force-displacement energy dissipation hysteretic curves. Such steady state shake table tests involve application of a small acceleration value at the fundamental resonant frequency to the base of the structure. During steady state tests, acceleration and displacement responses were measured respectively using accelerometers (B&K type 4370 accelerometers coupled with B&K type Nexus 2692-A-0I4 signal conditioners) and LVDTs (HBM type W-100TS LVDTs coupled with HBM type MVD2555 signal conditioners) at every floor level (three in the present study) and simultaneously acquired on a 16 Channel Data Acquisition System (Dewtron type DEWE-2010) where post processing of the measured response signals were done. In the post processing stage in the data acquisition system the displacement responses were numerically multiplied with the total column stiffness to arrive at the elastic forces generated in the test structure. Similarly, by numerical multiplication of acceleration responses with floor mass, the inertial forces generated in the test structure were arrived. Using these computed inertial and elastic forces, the base storey shear forces were arrived. Inter-storey drift responses of the test structure were obtained as the difference in the displacement responses of the successive floors. Finally by plotting the base shear force against inter-storey drift response, the energy dissipation hysteretic curves were arrived for every floor. From the area of the energy dissipation hysteretic curve the energy dissipation ability of the test structure was evaluated.

5.4 Seismic tests

Shake table tests of seismic type are normally conducted on a test structure to evaluate the realistic seismic performance under a simulated earthquake loading. Such tests need mathematical algorithms (Sathish Kumar et al., [23]) for generating spectrum compatible acceleration time history (SCDTH) so that the shake table driven by displacement/position controlled servo hydraulic actuators imparts the desired seismic motion to the base of the test structure. Through similar instrumentation procedure explained in the steady state dynamic tests, the post processing of the seismic responses were done for evaluating the seismic performance. In the present study a SCDTH compatible to the design acceleration response spectrum given in Indian Standard Code of Practice (IS 1893-2002: Part 1 [15]) for Design Basis Earthquake (DBE), Zone IV, 5% Damping, Medium Soil condition (Figure 5) was generated and used for evaluating the seismic performance of the test structure on the shake table.

5.5 Test results and observations

Figures 8 (a), 8(b) & 8(c) respectively show the retrofitted RC frame structure fixed on the shake table, typical instrumentation scheme consisting of accelerometer and LVDT adopted for response measurements during shake table tests and control panel for controlling the shake table & data acquisition using the 16 channel data acquisition system.



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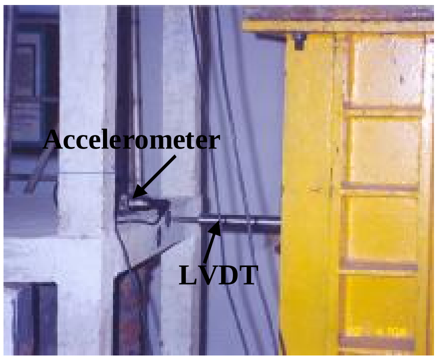

(b)

(c)

Figure 8. (a) The retrofitted RC frame structure fixed on the shake table, (b) typical instrumentation consisting of accelerometer and LVDT adopted for response measurements during shake table tests and (c) shake table controller & data acquisition using the 16 channel data acquisition system

It was observed from the sweep sine tests that the retrofitting measure carried out through providing supplemental damping using PED devices enhanced the first mode damping ratio of the RC frame structure under study. Table 1 gives the comparison of dynamic characteristics of the RC frame structure under study in bare and retrofitted conditions obtained from the sweep sine tests. Close match observed between the achieved total damping of 9.69% which is evident from the sweep sine test results as against the targeted total effective damping of 10% shows the validity of the proposed PED damper design methodology using direct displacement based design (DBD) approach. Figure 9 shows a typical comparison of first three experimental mode shapes of the RC frame structure in bare and retrofitted conditions obtained from the sweep sine tests. This overall increase in the damping resulted in reduced base shear, storey displacement, inter storey drift at all storey levels.

Table 1: Results of sweep sine tests on the RC frame structure

Resonant frequency (Hz)			
Description of the frame	1st mode	2nd mode	3rd mode
Bare frame	2.75	10.25	15.50
Retrofitted frame	3.00	10.75	16.25
Damping ratio (%)			
Description of the frame	1st mode	2nd mode	3rd mode
Bare frame	3.54	2.65	2.24
Retrofitted frame	9.69	4.19	3.87

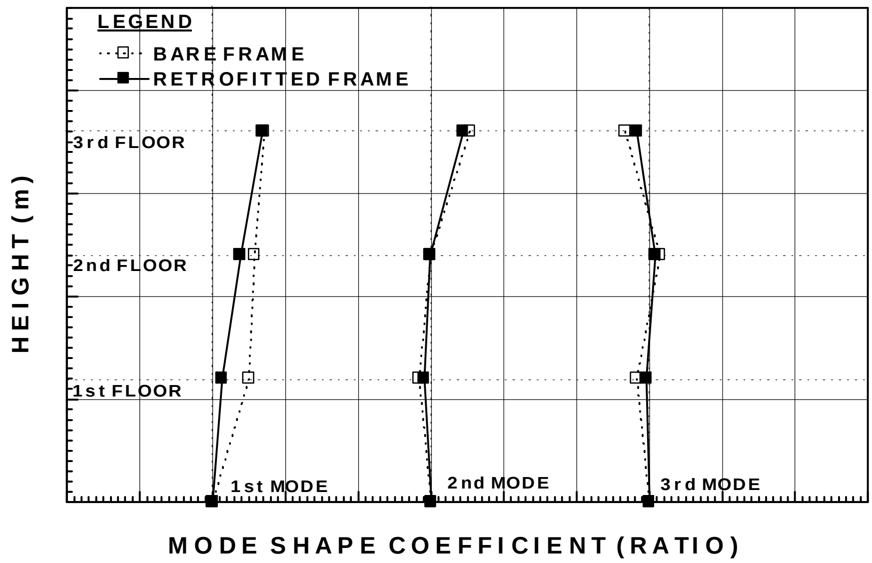

Figure 9. Comparison of experimental mode shapes of the bare and retrofitted RC frame structure from sweep sine tests

It was also observed that, from the steady state dynamic tests conducted on the RC frame at the fundamental frequency, a considerable increase in the energy dissipation ability of the first storey due to the provision of PED damper devices through in-fill walls, which in turn resulted in a considerable reduction in the base shear and inter storey drift especially at the first storey level. However reductions in these parameters at the higher storey levels were found to be only marginal. Similar trend was observed in the seismic tests also. Figure 10 shows a typical comparison of force-displacement hysteretic curves obtained from the steady state dynamic tests conducted on the RC frame structure evaluated at the fundamental frequency demonstrating the enhanced energy dissipation ability due to supplemental damping provided by the PED devices. Figure 11 shows the photographic view of the energy dissipation hysteretic curves as observed from the steady state dynamic test on the RC frame structure under study. Similarly, Figure 12 shows a typical comparison of seismic performance of the bare and retrofitted RC frame obtained from seismic tests under specified earthquake loading.

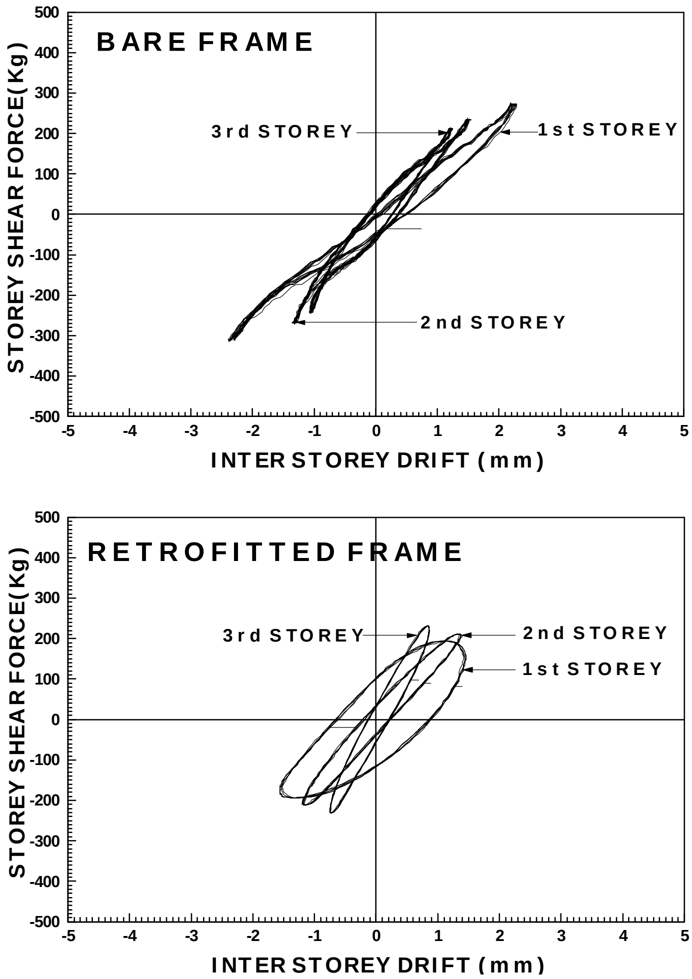

Figure 10. Typical comparison of force-displacement hysteretic curves from steady state dynamic tests on the bare and retrofitted RC frame structure

Figure 11. View of the energy dissipation hysteretic curves as observed from the steady state dynamic test on the RC frame structure under study

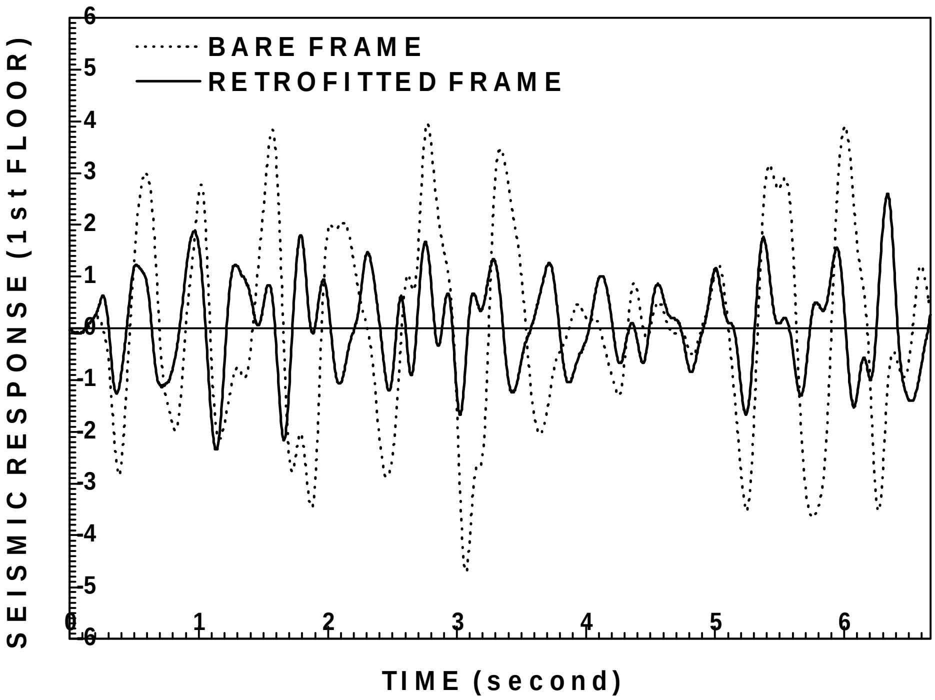

Figure 12. Typical comparison of seismic responses from seismic tests on the bare and retrofitted RC frame structure

7. SUMMARY AND CONCLUSIONS

The general procedure of the direct displacement based design (DBD) documented in the *SEAOC blue book* is applied in reverse order for evaluating the seismic performance of an existing frame structure. Based on this approach a methodology is proposed for designing PED devices of viscous and visco-elastic types for providing supplemental damping to enhance the overall energy dissipation ability of multi-storey frame structures to achieve a desired performance objective level as per *ATC-40* subjected to a specific earthquake loading. The proposed PED design methodology is validated through an extensive shake table experimental study consisting of sweep sine, steady state dynamic and seismic type shake table tests conducted on single bay - three storey reinforced concrete frame structure incorporated with visco-elastic PED devices. The study also demonstrates the enhanced energy dissipation ability of the retrofitted RC frame due to supplemental damping provided through designed PED devices to achieve the desired performance objective under a simulated earthquake loading as per *IS1893-2002* design code.

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