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Seismic Resistant Design of Structures with Passive Energy Dissipation Devices

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ABSTRACT: Supplemental damping through passive energy dissipation (PED) devices is often used for enhancing the seismic performance of a seismically deficient structure to reduce the seismic response during seismic events.In conventional seismic resistant design of structures using PED devices, two methods namely; dual system method for rate independent PED devices and modal strain energy method for rate dependent PED devices are used to design PED devices for improving the seismic performance of seismically deficient framed structures. However these two methods only provide design guidelines for designing the PED devices in a particular story of the framed structure without giving much emphasis to the performance level design objective. To overcome this, an alternative design philosophy named "displacement-based design" can be adopted. Displacement-based design (DBD) approach focuses on displacement as the key design parameter, which is considered to be an effective parameter for implementing performance based seismic design.This paper presents a methodology based on the 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 test of sweep sine, conducted on a single bay-three storey reinforced concrete (RC) frame structure incorporated with designed visco-elastic PED devices.

KEYWORDS:Passive energy dissipation devices, displacement-based design, supplemental damping, ductility, yield displacement.

I.INTRODUCTION

One of the principal current challenges in structural engineering concerns the development of innovative concepts to protect structures, along with their occupants and 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. 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. 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. 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 drawback 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.Alternative seismic performance enhancement methods(Kelly et al. [1]; Soong and Dargush [2]; Constantinou et al. [3])adopting passive energy dissipation systems have been developed which incorporate earthquake protective systems in the structure. 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 viscoelastic action in polymeric materials. In addition to increasing the energy dissipation capacity per

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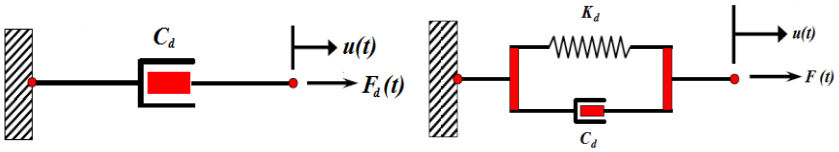
unit drift of a structure, some energy dissipation systems also increase the strength and stiffness. Such systems include the following types of energy dissipation mechanisms: yielding, extrusion, friction, viscous and viscoelastic action.

II. MODELING OF PED DEVICES

A typical viscoelastic PED device consists of thin layers of viscoelastic material bonded between steel plates. In practice, the dynamic behaviour of viscoelastic 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 viscoelastic PED device, the stiffness $K_d$and the damping coefficient $C_d$are obtained as follows:

$$K_d=\frac{G'(\omega)A}{t};C_d=\frac{G''(\omega)A}{\omega t} \quad (1)$$

Where, $G'(\omega)$ and $G''(\omega)$ are the storage shear modulus and loss shear modulus respectively; A and t are total shear area and the thickness of the material respectively; and ω is forcing frequency for which the fundamental natural frequency of the structure is generally utilized in time domain analysis.



(a) (b)

Figure 1. Mathematical models representing (a) viscous and (b) viscoelastic PED devices

With this spring-damper idealization, as shown in Figures 2 (a) and 2 (b), the dynamic system matrices of the structure with added viscoelastic PED devices can be constructed by superposing the damper properties to the stiffness and damping matrices of the structure.

III. PERFORMANCE EVALUATION USING DISPLACEMENT SPECTRUM AND CAPACITY CURVE

The Displacement based design (DBD), which focuses on displacement as the key design parameter(SEAOC Blue Book[4]), is considered to be an effective method for implementing performance based seismic design utilizing deformation capacity and ductile detailing standards. In this paper, the general procedure of the DBD documented in the SEAOC Blue Book [4] 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(FEMA [5]; ATC-40 [6]; Freeman [7])in that performance point is determined as a location where the displacements 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 dampers. 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 [8] respectively, are proposed for seismic performance evaluation of structures (without PED devices). The two procedures are summarized as follows:

Step by step procedure

1. Obtain base shear versus roof storey displacement capacity curve for the frame structure from pushover analysis. 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 $\Delta_R$and post-yield stiffness ratio α (Figure 3).
2. Transform the roof storey displacement coordinate into pseudo-displacement coordinate S_d using the following relation:

$$S_d=\frac{\Delta_R}{\Gamma\phi_R} \quad (2)$$

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Where, $\Delta_R$is the roof displacement and Γ andϕ_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.

3. Assume the first trial value for the maximum displacement $S_{dm}$of the equivalent structure, and determine the ductility factor $\mu = S_{dm}/S_{dy}$. The equivalent damping ratio ξ_{eq}can be obtained as:

$$\xi_{eq}=\frac{2(\mu-1)(1-\alpha)}{\pi\mu(1+\alpha\mu-\alpha)} \quad (3)$$

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

$$\xi_{eff} = \xi_{eq}+\xi_i \quad (4)$$

Where, $\xi_i$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:

$$T_{eff} = T_e\sqrt{\frac{\mu}{1+\alpha\mu-\alpha}} \quad (5)$$

Where, $T_e$is the fundamental period of the structure.

4. 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}.

5. 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 Equation (2). Carry out pushover analysis until the roof displacement reaches the maximum value computed above to estimate the maximum inter-storey drifts.

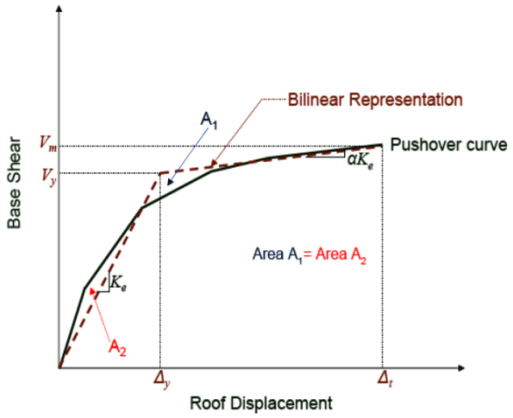

Figure 2. Bi-linear representation of a push-over curve

Graphical procedure

1. Step 1: The same as those of the step by step procedure.
2. Step 2: Draw displacement response spectra with various damping ratios.
3. Step 3: For a series of ductility ratios, obtain maximum displacements (S_{dm}= μS_{dy}), effective periods$T_{eff}(\mu)$[Equation (5)] and effective damping ratios (ξ_{eff}) [Equations (3)&(4)].
4. Step 4: Find out the point at which the effective damping ratio corresponding to a ductility ratio, obtain in step 3, is equal to the equivalent damping ratio of a displacement spectrum crossing the point [$T_{eff}(\mu)$, $S_{dm}(\mu)$].
5. Step 5: 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.

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IV. DESIGN PROCEDURE FOR PED 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, this paper 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.

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 ξ_{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 ξ_i, equivalent damping of the structure contributed from inelastic deformation of the structural members $\xi_{eq}$and the damping required to be added by PED devices ξ_d. The equivalent damping of the structure is obtained from the following equations (FEMA [5]):

$$\xi_{eq} = \frac{1}{4\pi}\frac{E_{DS}}{E_S} = \frac{V_y S_{dt} - S_{dy} V_{dt}}{\pi V_t S_{dt}} \text{ for viscous PED devices} \quad (6a)$$

$$= \frac{V_{yd} S_{dt} - S_{dy} V_{dt}}{\pi V_{dt} S_{dt}} \text{ for Viscoelastic PED devices} \quad (6b)$$

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 behaviour of the structural members in the retrofitted structure respectively. Tsopelas et al., (1997) [10]provides the contribution of the added damping to the total effective damping as $\xi_d T_{eff}/T_e$, where $\xi_d$is the supplemental damping ratio. Then the required supplemental damping can be computed from the following equation:

$$\xi_d = (\xi_{eff} - \xi_{eq} - \xi_i)\frac{T_e}{T_{eff}} \quad (7)$$

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

Storey-wise distribution of PED devices

In multi-storey frame structures, the supplemental damping computed in the equivalent SDOF system using Equation (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 ξ_d. For this purpose, the expression for equivalent damping (Equation (6)) is used again except that the energy dissipated by the PED device $E_{DV}$is used in the numerator instead of E_{DS}

$$\xi_{eq} = \frac{1}{4\pi}\frac{E_{DV}}{E_S} \quad (8)$$

If the PED devices are placed as diagonal members with the inclination θ, then, the energy dissipated by the PED devices can be expressed as follows (FEMA [7])

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

Where, $T_{eff.d}$is the secant period of the retrofitted structure; $C_{di}$and $\Delta_{i-1}$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:

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$$E_S = \frac{2\pi^2}{T_{eff.d}} \sum_{i=1}^{N} m_i \Delta_i^2 \quad (10)$$

$$T_{eff} = 2\pi \sqrt{\frac{M^* S_{dt}}{V_y(1+\alpha\mu-\alpha)}} \text{ for Viscous PED devices} \quad (11a)$$

$$T_{eff} = 2\pi \sqrt{\frac{M^* S_{dt}}{V_y(1+\alpha\mu-\alpha)+K_d S_{dt}}} \text{for Viscoelastic PED devices} \quad (11b)$$

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

$$\xi_d = \frac{1}{4\pi} \frac{T_{eff.d} \sum_{i=1}^{N} C_{di} \cos^2\theta_i (\Delta_i - \Delta_{i-1})^2}{\sum_{i=1}^{N} m_i \Delta_i^2} \quad (12)$$

In Equation (12), the left hand side of the equation ξ_d is obtained from Equation (7) in the equivalent SDOF system. For viscous device, the damping coefficient of the damper device in the i^{th} storey C_{di} can be determined in Equation (12), whereas for viscoelastic device, both C_{di} and K_{di} are the variables that should be determined. This can be done by using the relation $K_d=(G'/G'')\,\omega C_d$ obtained from Equation (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 Equation (12) as:

$$C_d = \frac{1}{4\pi} \frac{4\pi\xi_d \sum_{i=1}^{N} m_i \Delta_i^2}{T_{eff.d} \sum_{i=1}^{N} C_{di} \cos^2\theta_i (\Delta_i - \Delta_{i-1})^2} \quad (13)$$

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 need to be assumed in Equations (12) and (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 dampers, design process ends here. However, for PED devices with stiffness such as viscoelastic or hysteretic dampers, 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 repeated until convergence.

V. 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 eigen value analysis of the structure to obtain natural periods and mode shapes. Using the mode shapes, perform pushover analysis to obtain top storey versus base shear curve, and transform the pushover curve into a capacity curve using Equation (6). Idealize the curve into a bilinear shape, and read the yield displacement S_{dy}.
2. Decide a desired target roof displacement, 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} (Equation (5)) and the equivalent damping (Equation (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. It would be more convenient to start the procedure with response spectra with various damping ratios. Compute the required damping for supplemental dampers from Equation (7).
4. The required damping is distributed throughout the storeys using Equation (12). The size of PED device in each storey is designed based on the required damping allocated to the storey.

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5. For structures retrofitted with viscoelastic PED devices, carry out eigen value analysis and redraw the capacity curve of the structure using the newly obtained mode shape, and repeat step 1 until convergence. Check whether the structural members, especially columns, can resist the additional axial and shear forces imposed by PED devices.

VI. PUSHOVER ANALYSIS OF THE TEST STRUCUTRE

The test framed structure is a three storey RC framed structure with plan dimensions of 1.44m x 0.75m. Each storey height is 1.2m. Beam and column members have similar dimensions of 75mm x 75mm with four members of 12mm diameter bars. Lateral ties in the column and beam are 6mm diameter two legged stirrups at a spacing of 100c/c. Materials used are M20 grade concrete and Fe415 steel. The thickness of the slab is 25mm. An additional mass of 100kg is added on each floor. Pushover analysis of the test framed structure is carried out using SAP2000 Version 17. The beams and columns are modelled as 3D frame elements and restraints at foundation are taken as fixed. Slab is modelled as a rigid diaphragm. Slab dead load and additional mass load are applied on beams. The SAP model of the chosen RC framed structure is shown in Figure 3. Initially modal analysis is performed and the first three modal time periods are 0.364, 0.109 and 0.061 seconds respectively. Then the pushover analysis is performed in the longer direction using the first mode shape of the structure. The obtained pushover curve is shown in Figure 4. Then the obtained pushover curve is converted to Acceleration Displacement Response Spectrum(ADRS).

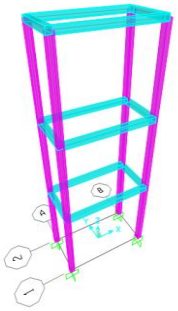

Figure 3. SAP Model of the test structure

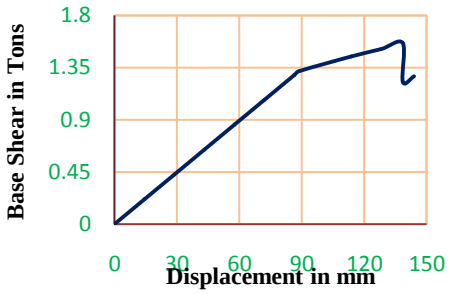

Figure 4. Pushover curve of the test structure

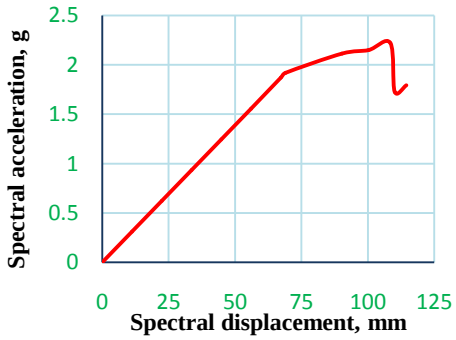

Figure 5 Capacity curve of the test structure

VII. ESTIMATION OF TOTAL EFFECTIVE DAMPING

The target roof drift Δ_R as per *ATC-40* for the chosen three storey RC framed structure of height 3.6m for meeting the performance level objective 'Immediate Occupancy' is 36mm. Converting this value into spectral displacement using Equation (2). The modal participation factor Γ of the chosen RC framed structure is calculated as 1.20. The evaluated mode shape coefficient of the roof is 1.42. For this modal participation factor of the first mode of the test structure and mode shape value of the roof in the first mode, the corresponding spectral displacement demand S_d is calculated as 21.13mm. From the capacity curve as shown in Figure 5, it is observed that the test structure still remains in the elastic range. Hence the effective period T_{eff} is taken as the natural period *T*of the test structure which is about 0.364sec (2.75 Hz). The displacement response spectra corresponding to the selected design acceleration spectra for DBE, seismic

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zone IV, medium soil condition plotted for various damping values are shown in Figure 6. From this figure it is observed that for the effective time period T_{eff} of the test structure and the spectral displacement demand S_d for meeting the target performance level objective of 'Immediate Occupancy' meet at a total effective damping value ξ_{eff} of 10 percent damping.

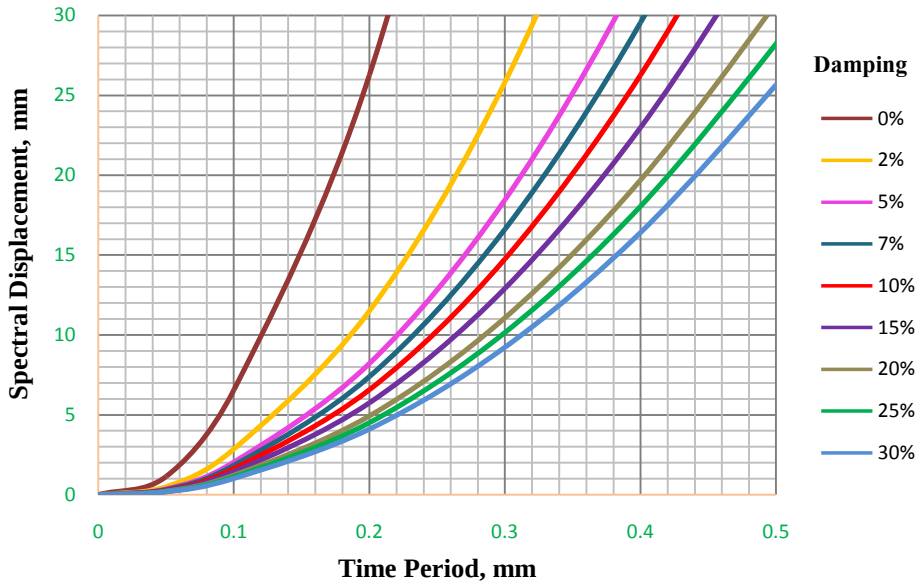

Figure 6. Displacement response spectrum for different damping values

VIII. DESIGN OF PED DEVICES FROM SUPPLEMENTAL DAMPING

From the target effective damping ξ_{eff} of 10 percent and evaluated first mode damping of the test structure ξ_i of 3.54 percent the supplemental $\xi_d$to be provided by the PED devices is calculated as 6.46 percent.The displacement amplitude corresponding to the first floor level where the PED devices are placed, arrived from the target roof displacement (Δ_R= 36mm) through first mode shape coefficient for the selected performance level as 25.32mm. Using this supplemental damping ξ_d, effective mass m_{eff}, effective period T_{eff} and first mode shape value in first mode $\Delta_{1,1}$ and assuming PED devices are provided in the first story only, then the total damping coefficient C_d of all the PED devices using Equation (13) is calculated as 4481.55Nsec/mm. Assuming four number of PED devices are provided through a pair of non-structural infill walls, the damping coefficient per device C_{di} is calculated as 1120.38Nsec/mm.. Adopting high damping rubber (HDR) having shore hardness IRHD of 40 degress; loss modulusG'' of 1.89 MPa;G' of 1.73 MPa; loss factor $\eta_d$of 1.10and allowable shear strain $\gamma_{max}$of 200 percent the dimensions of the individual PED devices is obtained. The required thickness of the rubber layer t in the PED devices is calculated to be 20.282mm for the expected displacement amplitude of 25.352mm and an allowable shear strain of 125 percent and thus rounded to the nearest value of 20mm. Using this thickness t of 20mm, loss modulus G'' of 1.89 MPa, natural period of the test structure T of 0.364sec and damping coefficient per device C_{di} of 1088Nsec/mm, the required area of the rubber layer using Equation (1) is calculates ad 5120mm^2. Hence the dimensions of 50mm x 100mm is arrived for the rubber layer in the individual PED device.

IX.EXPERIMENTAL STUDY

In order to validate the proposed displacement based design (DBD) methodology, anexperimental study consisting of shake table test was carried out on a single bay-threestorey 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 directdisplacement based design methodology described earlier for retrofitting the chosen RCframed structure to meet a desired performance level objective of 'Immediate Occupancy'. Asper *ATC-40* [6], for Immediate Occupancy, the

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maximum total drift is limited to 0.01 or theroof drift ratio is limited to 1%. In the present study, to design the PED devices, a target roofdrift ratio of 0.01 (1%) to meet the desired performance level and design accelerationresponse spectrum given in Indian Standard Code of Practice (IS 1893: Part 1)[9] forDesign Basis Earthquake (DBE), Zone IV, 5% Damping, Medium Soil condition as shownin Figure 7 was used. Based on this exercise, the number, capacity and the sizes of the PEDdevices required to retrofit the frame structure to meet the desired performance objective(10% Target total effective damping ξ_{eff}) were arrived. Four numbers of visco elastic PEDdevices 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 forretrofitting the chosen RC frame structure through a pair of non-structural infill walls in thefirst storey only.

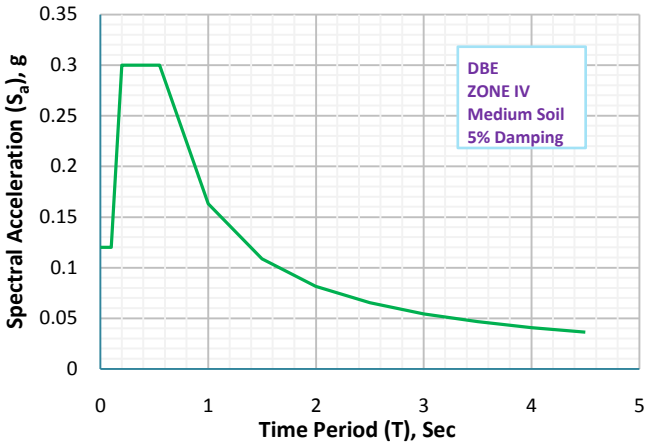

Figure 7. Design acceleration spectra (DBE)

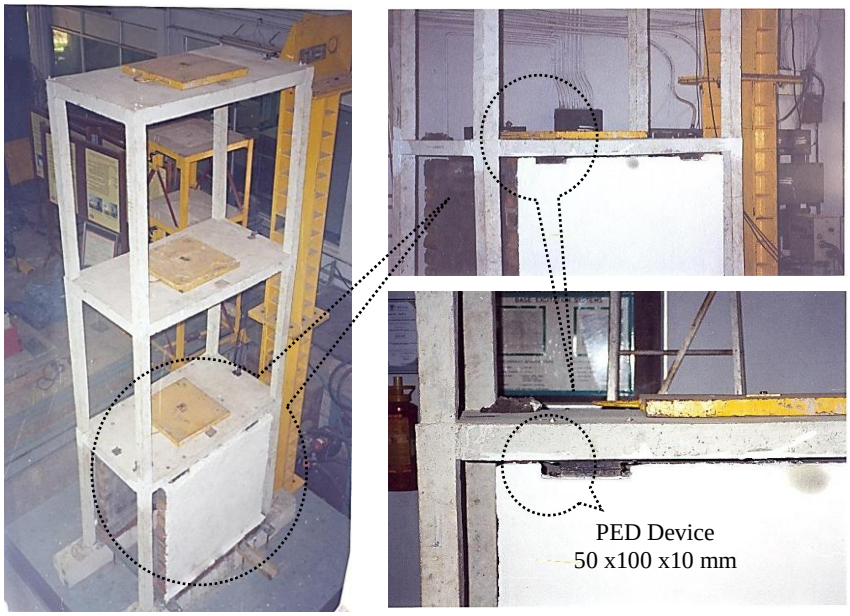

Figure 8. View of the retrofitted RC frame structure fixed on the shake table

Figure 8 shows the photographic view of the retrofitted RC frame chosen in the present study. For the seismic test a spectrum compatible displacement time history compatible to the design accelerationresponse spectrum given in IS

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1893 [9] was generated and applied to the frame structurethrough the shake table. Then the entire exercise was repeated after removing the PED devicesand the test results were compared against the test results obtained on the retrofitted framestructure to evaluate the supplemental damping provided by the visco-elastic PED devices.Through this study the proposed displacement based design methodology was validated.

Sweep sine tests

Shake table tests of sweep sine type are normally conducted on a test structure to evaluatethe dynamic characteristics namely natural frequencies and their associated mode shapes anddamping. Such sweep sine tests should be conducted with an optimum linear or logarithmicsweep rate so that the amplitude error parameter and frequency error parameter are kept low(Ewins [10]). Based on the earlier experimental studies (Gopalakrishnan et al. [11]; Rama Rao et al [12]) an optimum logarithmic sweep rate of 1 Octave/minute was adopted in thepresent shake table study for both forward sweep and backward sweep. Accelerationresponses were measured using accelerometers (B&K type 4370 accelerometers coupledwith B&K type Nexus 2692-A-0I4 signal conditioners) at all the four elevation levelsnamely ground floor level, first floor level, second floor level and roof level for arriving atfrequency-response functions. Three separate sweep sine test were conducted for each of thethree levels namely first floor level, second floor level and roof level and in each of thesweep tests acceleration responses from the respective floor level and ground floor levelwere acquired and fed into a dual channel FFT analyzer (AND type 3524). From theacquired and averaged acceleration responses in the dual channel FFT analyzer the finalfrequency 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 wayof mathematically splitting inside the FFT analyzer. Finally from the real part of the FRFcurve the natural frequencies and damping values for all the identified modes of the teststructure were arrived. Similarly from the imaginary part of the FRF curve the mode shapeinformation for all the identified modes of the test structure was gathered.

Table 1. Results of sweep sine tests on the RC framed structure

Resonant Frequency(Hz)			
Condition of the structure	**1st Mode**	**2nd Mode**	**3rd Mode**
Bare condition	2.75	10.25	15.50
Retrofitted condition Percentage increase	3 (+9.09%)	10.74 (+4.88%)	16.25 (+3.23%)
Damping Ratio (Percent)			
Description of the frame	**1st Mode**	**2nd Mode**	**2nd Mode**
Bare condition	3.53	2.65	2.24
Retrofitted condition Percentage increase	9.69 (+173.73.09%)	4.19 (+58.11%)	3.87 (+72.77%)

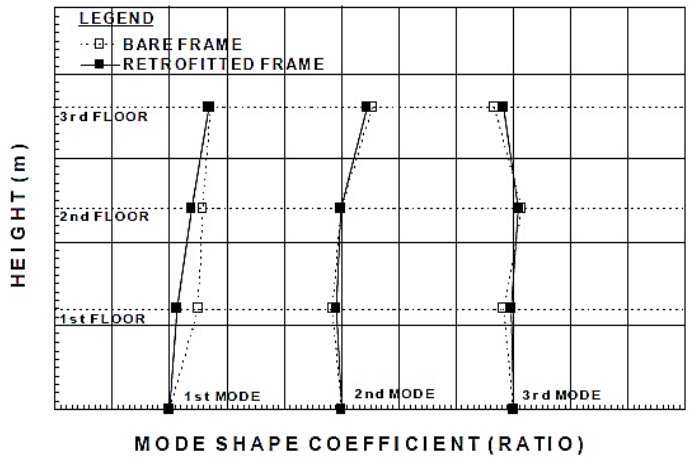

Figure 9. Comparison of experimental mode shapes of the bare and retrofitted RC frame structure from sweep sine tests

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X. SUMMARY AND CONCLUSIONS

The general procedure of the displacement based design (DBD) documented in the*SEAOC blue book* is applied in reverse order for evaluating the seismic performance of anexisting frame structure. Based on this approach a methodology is proposed for designingPED devices of viscous and viscoelastic types for providing supplemental damping toenhance the overall energy dissipation ability of multi-storey frame structures to achieve adesired performance objective level as per *ATC-40* subjected to a specific earthquakeloading. The proposed PED design methodology is validated through a shaketable experimental study consisting of sweep sine typeconducted on single bay three-storey reinforced concrete frame structureincorporated with viscoelastic PED devices.

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