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Response Control of Structures Subjected to Multi-Hazards of Earthquake and Wind Using Base Isolators and Absorbers

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ABSTRACT

Short structures when they are designed using base isolation, dynamic wind effects may be more, and it may govern the design. This issue is taken care to some extent using Lead plug bearings. This puts the limits on effective seismic performance only for design basis or beyond. At lower seismic excitation levels, it may not be that effective. In view of this a suitable passive control system using the knowledge of isolators and absorbers is developed and analysed. Five storey shear building models with fixed base, base isolated separately supported on laminated rubber bearing (LRB), lead plug bearing (LPB) and isolated with LRB and install with tuned mass damper (TMD) are developed. These structures are numerically analysed considering six Indian earthquakes and dynamic wind load. TMD used in LRB supported building is provided in LPB supported building and responses of building models also observed under wind load which is more than design basis. Results of all cases are compared. Combined passive isolation along with absorber found suitable for multi-hazards like earthquakes where peak displacement increases by 0.76 times to 38 times, peak acceleration decreases by 73% to 99%, maximum inter-storey drift decreases by 71% to 99% when comparing with fixed base structure and for wind, values of peak displacement, peak acceleration, maximum inter-storey drift decreases by 45%, 46%, 44% when comparing with LRB provided structure.

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1. Introduction

Urban row houses, apartment buildings, bungalows, malls, factories and hospitals etc are generally reinforced cement concrete frame structures. Due to their fundamental frequency which lies in the range of earthquakes with the highest energy content, these structures are prone to experiencing major stresses and have large inter-storey drifts.

In an earthquake, the forces acting on the structure are proportional to its acceleration. The acceleration is also proportional to the time period and the structure's damping. As seen in Fig. 1, this relationship is represented in the form of spectra for hard soil case [1]. Most low to medium-rise structures have a frequency between 1 to 10 *Hz* (i.e., 0.1-1 *secs* time period) [2]. Accelerations in this region are greater than those of the ground. Structures with a fundamental frequency lower than 0.5 *Hz* (i.e., more than 2 *secs* time period) are susceptible to much lower accelerations.

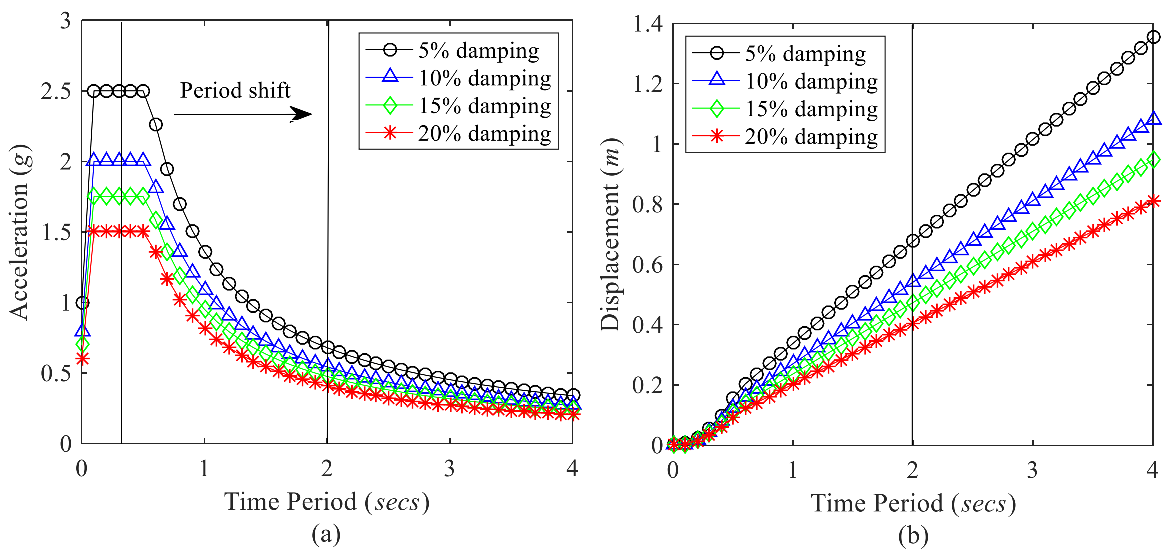


Fig. 1. (a) Acceleration spectra (b) Displacement spectra for 5, 10, 15 and 20% damping.

Generally, the natural period of structure supported on isolation will be kept around 2 *secs* [3]. As a result, the acceleration and hence the earthquake induced force in the structure reduces and also deformation across the isolation system increases as seen in spectra shown in Fig. 1. Due to the long period of base isolated structures, fluctuating wind forces can govern the design of the structure. Some of international codes for design of buildings on base isolators are MRIT [4], ASCE 7 [5], EN 1998-1 [6] and NTC 08 [7]. Indian code for base isolated buildings is currently in draft stage.

A dynamic absorber can be placed at the highest amplitude location to minimize the dynamic response of a structure that's subjected to dynamic loading, such as earthquakes and wind. These have a lower mass than the main structure's mass and are tuned to the main structure's fundamental frequency. It reduces resonance of main structure under dynamic loading. Tuned mass damper (TMD) and tuned liquid damper (TLD) are dynamic absorbers generally used for reducing the dynamic responses of high-rise structures, bridges, and other structures.

Base isolated structures responses without absorber are studied by Jangid [8], Providakis [9], Tavakoli et al [10] under earthquake load and Henderson and Novak [11], Saha et al [12], Ubertini et al [13] under wind load. Vulcano [14], Liang et al [15], Ju et al [16] studied responses of base isolated structures without absorber under earthquake and wind loads. Base isolated structures responses with absorber are studied by Sinha and Li [17], Tsai [18], Stanikzai et al [19,20], Matteo et al [21] under earthquake load and Kareem [22] under wind load. Shahabi et al [23] has given state of the art review of several base isolation systems based on their mechanisms. Also, Zhai et al [24] studied damper failure such as metallic damper in steel moment resisting frames for large intensity earthquake. Behaviours of steel bar hysteretic dampers are studied by Jahangir et al [25] and shape memory alloy (SMA) equipped bar hysteretic damper by Farhangi et al [26] with isolators under cyclic load. Babaei and Moniri [27] used TMD for controlling vibration in vertical irregularity of mass steel structures under earthquakes.

Base isolation systems are designed by considering some design basis such as target natural period desired for the isolated supported structure, so when external excitation equal to or more than design basis then isolation system will effectively counteract it. However, there can be a case when external excitation can be lower than design basis for which isolation system will not be effective. This issue can be counteracted to some extent by using lead plug bearing which has two stiffnesses, initial stiffness and post yield stiffness however this is not case with laminated rubber bearing which has one stiffness. Absorber like tuned mass damper can be use with laminated rubber bearing to resolve this issue.

There are literatures which has studied effect of wind and earthquake load on base isolated structure (Vulcano [14], Ju et al [16]), studied along wind (Henderson and Novak [11], Kareem [22]) and across wind (Saha et al [12]) and both along and across wind (Liang et al [15]) on base isolated structure and also used absorbers for reducing the along wind induced response of base isolated structure (Kareem [22]). So far there is no literature which study combination of passive isolation system and absorber where isolation system is provided for resisting earthquake and absorber is use for resisting vortex induced wind load.

Therefore, scope of present study are (a) to design laminated rubber and lead plug bearings and provide separately at the base of low rise structures; (b) to design tuned mass damper and provide at the top of LRB provided structure; and (c) to numerically investigate dynamic responses of fixed base structure, isolated with LRB structure, isolated with LRB and TMD structure and isolated with LPB structure under earthquake and vortex induced wind loads (d) to install same TMD use in LRB supported structure in LPB provided structure and analyse these structures under wind load which is more than design basis.

2. Theoretical basis of modelling and analysis of buildings

In this section, building models, seismic isolator like laminated rubber bearing and lead plug bearing, vibration control device like tuned mass damper and also method for analysis of these building models are explained.

2.1. Building model

A shear building is one in which the floors will not rotates. To have shear building model, it is assumed that: (a) the structure's total mass is concentrated at the floor levels; (b) the slabs or girders on the floors are infinitely rigid in comparison to the columns; and (c) the structure's deformation is independent of the axial forces present in the columns [28]. So, the masses are lumped at floor levels and degree of freedoms are consider at mass locations. Fig. 2 (a) shows five storey shear building model with fixed base.

Consider the forces equilibrium at each degree of freedom to obtain the governing equation of motion for an N storey shear building model with N lateral degrees of freedom at the floor levels. The equations of motion for this building are given by

$$[M]\{\ddot{u}(t)\}+[C]\{\dot{u}(t)\}+[K]\{u(t)\}=\{F(t)\} \tag{1}$$

where $[M]$, $[C]$ and $[K]$ are the mass, damping and stiffness matrices given by

$$[M]=\begin{bmatrix} m_1 & 0 & 0 & \cdots & 0 \\ 0 & m_2 & 0 & \cdots & 0 \\ 0 & 0 & m_3 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & m_N \end{bmatrix}; \tag{2}$$

$$[C]=\begin{bmatrix} c_1+c_2 & -c_2 & 0 & \cdots & 0 \\ -c_2 & c_2+c_3 & -c_3 & \cdots & 0 \\ 0 & -c_3 & c_3+c_4 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & c_N \end{bmatrix}; \tag{3}$$

$$[K]=\begin{bmatrix} k_1+k_2 & -k_2 & 0 & \cdots & 0 \\ -k_2 & k_2+k_3 & -k_3 & \cdots & 0 \\ 0 & -k_3 & k_3+k_4 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & k_N \end{bmatrix} \tag{4}$$

and $\{u(t)\}$, $\{\dot{u}(t)\}$, $\{\ddot{u}(t)\}$ and $\{F(t)\}$ are displacement, velocity, acceleration and force vectors given by

$$\{u(t)\}=\begin{Bmatrix} u_1 \\ u_2 \\ u_3 \\ \vdots \\ u_N \end{Bmatrix};\quad \{\dot{u}(t)\}=\begin{Bmatrix} \dot{u}_1 \\ \dot{u}_2 \\ \dot{u}_3 \\ \vdots \\ \dot{u}_N \end{Bmatrix};\quad \{\ddot{u}(t)\}=\begin{Bmatrix} \ddot{u}_1 \\ \ddot{u}_2 \\ \ddot{u}_3 \\ \vdots \\ \ddot{u}_N \end{Bmatrix};\quad \{F(t)\}=\begin{Bmatrix} f_1 \\ f_2 \\ f_3 \\ \vdots \\ f_N \end{Bmatrix} \tag{5}$$

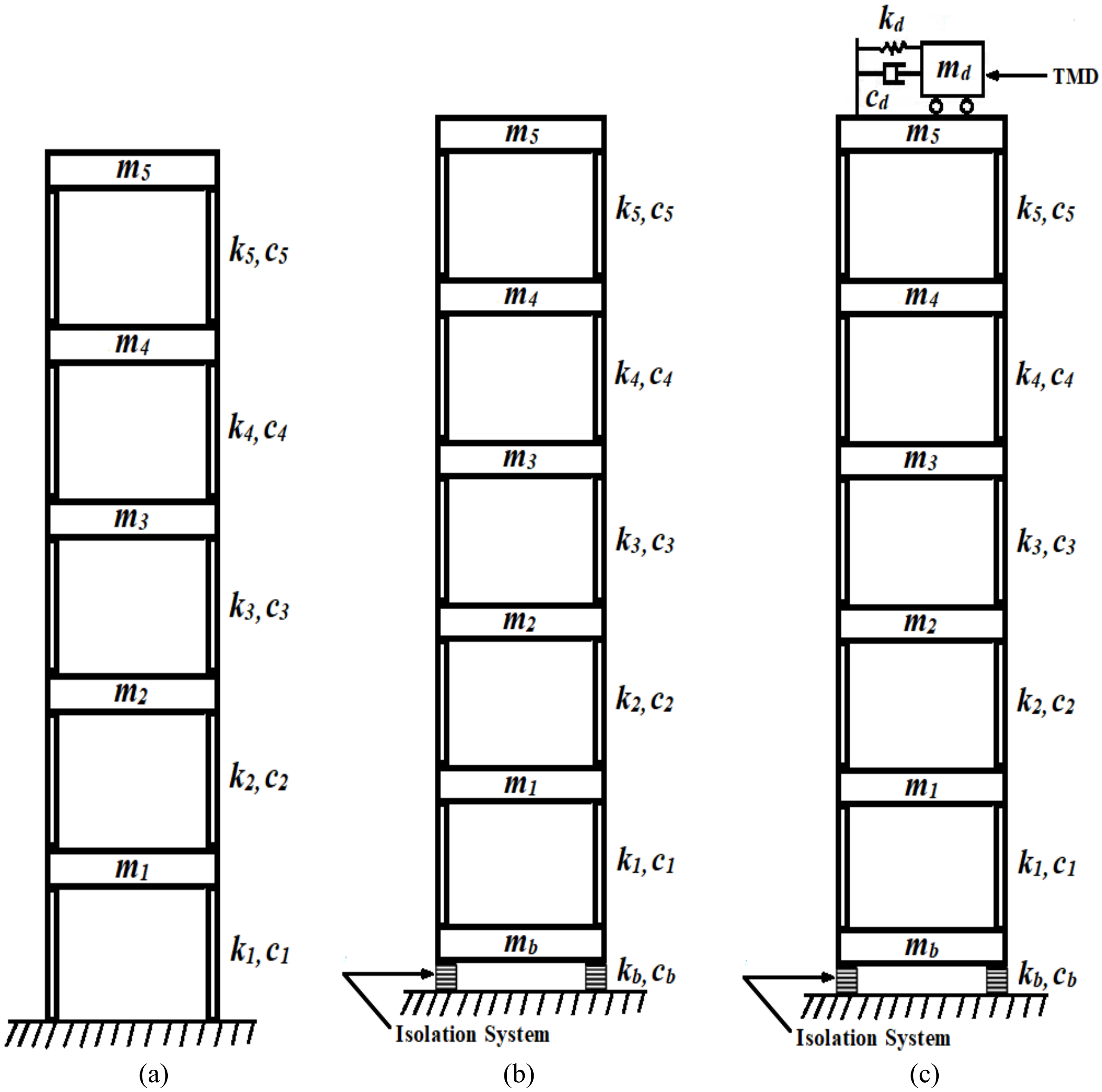


Fig. 2. Five storey shear building model (a) Fixed base (b) Supported on isolation system (c) Supported on isolation system with tuned mass damper at top.

2.2. Seismic isolators to support building

Generally, isolators like laminated rubber bearings (LRB) and lead plug bearings (LPB) are used in order to isolate the structures from earthquakes excitation. Elastomeric bearings are made up of thin elastomer layers and steel plates that are joined together to offer horizontal flexibility and vertical stiffness as shown in Fig. 3 (a). Natural rubber has a low material damping ratio of roughly 3-5% of critical, resulting in a linear force deformation relationship [2]. Laminated rubber bearings are natural rubber-based bearings with low damping. Fig. 3 (b) and (c) illustrates idealization of LRB as well as its force deformation behaviour.

Lead plug bearing (LPB) is an elastomeric bearing with a lead core as shown in Fig. 4 (a). Lead core is used in the LRB to reduce the undesirable large horizontal displacement to an acceptable level. During a strong earthquake, the lead core yields and offers extra damping [2]. The lead plug provides higher initial stiffness and hysteresis damping to deal with low strains caused by wind forces [29]. Fig. 4 (b) and (c) illustrates idealization of LPB as well as its force deformation behaviour. Fig. 2 (b) shows five storey shear building model supported on elastomeric isolators.

Mass matrix $[M]$, damping matrix $[C]$ and stiffness matrix $[K]$ for N storey shear building with elastomeric isolators at the base are given by

$$[M]=\begin{bmatrix} m_b & 0 & 0 & 0 & \cdots & 0 \\ 0 & m_1 & 0 & 0 & \cdots & 0 \\ 0 & 0 & m_2 & 0 & \cdots & 0 \\ 0 & 0 & 0 & m_3 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & m_N \end{bmatrix} \tag{6}$$

$$[C]=\begin{bmatrix} c_b+c_1 & -c_1 & 0 & 0 & \cdots & 0 \\ -c_1 & c_1+c_2 & -c_2 & 0 & \cdots & 0 \\ 0 & -c_2 & c_2+c_3 & -c_3 & \cdots & 0 \\ 0 & 0 & -c_3 & c_3+c_4 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & c_N \end{bmatrix} \tag{7}$$

$$[K]=\begin{bmatrix} k_b+k_1 & -k_1 & 0 & 0 & \cdots & 0 \\ -k_1 & k_1+k_2 & -k_2 & 0 & \cdots & 0 \\ 0 & -k_2 & k_2+k_3 & -k_3 & \cdots & 0 \\ 0 & 0 & -k_3 & k_3+k_4 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & k_N \end{bmatrix} \tag{8}$$

where m_b, c_b and k_b are mass of base slab, damping and stiffness of the isolation system.

The isolation time period (T_b) and damping ratio (ξ_b) given by

$$T_b = 2\pi\sqrt{\frac{M_t}{k_b}}\ ;\ \xi_b = \frac{c_b}{2M_t\omega_b} \tag{9}$$

where $M_t = \left(m_b + \sum_{i=1}^{N} m_i\right)$ is the total mass of the base isolated building, $\omega_b = 2\pi/T_b$ is the isolation frequency.

The textbook by Reddy et al [2] provides a step-by-step procedure for designing laminated rubber bearing and lead plug bearing.

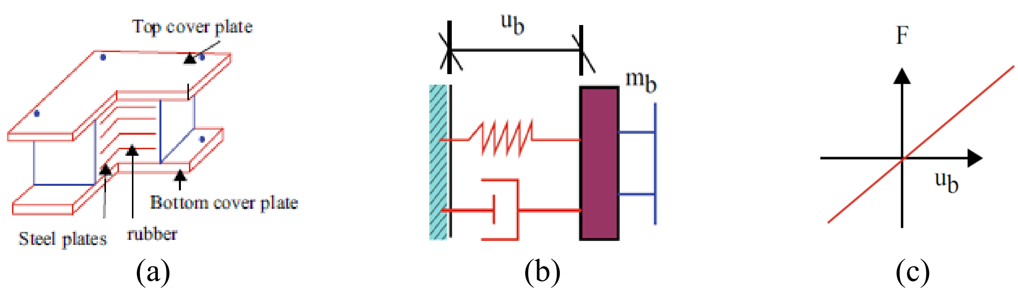


Fig. 3. (a) Laminated rubber bearing (b) Idealization of LRB model (c) Force deformation behaviour of LRB [2]

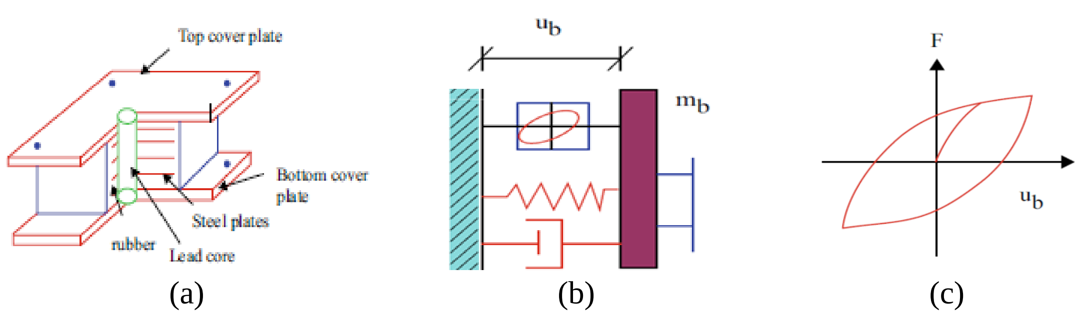


Fig. 4. (a) Lead plug bearing (b) Idealization of LPB model (c) Force deformation behaviour of LPB [2].

2.3. Tuned mass damper for isolated building

TMD is a classical device made up of a mass, spring, and dashpot that decreases the dynamic response of a vibrating system. The damper's frequency is adjusted to a specific structural frequency (typically the fundamental frequency) so that when the frequency is excited, the damper resonates out of phase and dissipates energy through inertia [2]. Fig. 2 (c) shows five storey shear building model supported on elastomeric isolators and TMD at top.

Mass matrix $[M]$, damping matrix $[C]$ and stiffness matrix $[K]$ for N storey shear building with elastomeric isolators at base and TMD at top are given by

$$[M]=\begin{bmatrix} m_b & 0 & 0 & 0 & \cdots & 0 & 0 \\ 0 & m_1 & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & m_2 & 0 & \cdots & 0 & 0 \\ 0 & 0 & 0 & m_3 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & m_N & 0 \\ 0 & 0 & 0 & 0 & \cdots & 0 & m_d \end{bmatrix}; \tag{10}$$

$$[C]=\begin{bmatrix} c_b+c_1 & -c_1 & 0 & 0 & \cdots & 0 & 0 \\ -c_1 & c_1+c_2 & -c_2 & 0 & \cdots & 0 & 0 \\ 0 & -c_2 & c_2+c_3 & -c_3 & \cdots & 0 & 0 \\ 0 & 0 & -c_3 & c_3+c_4 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & c_N+c_d & -c_d \\ 0 & 0 & 0 & 0 & \cdots & -c_d & c_d \end{bmatrix}; \tag{11}$$

$$[K]=\begin{bmatrix} k_b+k_1 & -k_1 & 0 & 0 & \cdots & 0 & 0 \\ -k_1 & k_1+k_2 & -k_2 & 0 & \cdots & 0 & 0 \\ 0 & -k_2 & k_2+k_3 & -k_3 & \cdots & 0 & 0 \\ 0 & 0 & -k_3 & k_3+k_4 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & k_N+k_d & -k_d \\ 0 & 0 & 0 & 0 & \cdots & -k_d & k_d \end{bmatrix} \tag{12}$$

where m_d , c_d and k_d are mass, damping and stiffness of the TMD.

The TMD natural frequency (ω_d), damping ratio (ξ_d), tuning frequency ratio (f) and mass ratio (μ) given by

$$\omega_d=\sqrt{\frac{k_d}{m_d}}\ ;\ \xi_d=\frac{c_d}{2m_d\omega_d};\ f=\frac{\omega_d}{\omega_s};\ \mu=\frac{m_d}{M_t} \tag{13}$$

where ω_s and M_t are structural frequency and mass.

2.4. Analysis of buildings

The step-by-step method such as Newmark Beta technique is used to solve the equations of motion in incremental form. Rajasekaran textbook [30] includes Matlab code for analyzing multi degrees of freedom (MDOF) systems using the Newmark Beta average acceleration approach. This code is modified as per steps given in the textbook by Chopra [31] and this modified code is used for analysis of multi storey shear building with isolator and TMD.

For nonlinear problem with LPB, Newmark Beta average acceleration approach along with Newton Raphson method for equilibrium or minimizing errors in nonlinear portion is adopted. Steps for doing Newton Raphson method are given in textbook by Chopra [31], Villaverde [32].

3. Validation of modelling and analysis of buildings

Djedoui et al. [33] studied performance of 5 storey building with only horizontal degrees of freedom equipped with laminated rubber bearing combined with passive or active tuned mass damper in the lowest or on the top floor (in this study, only passive tuned mass damper results are taken into account) under three strong earthquakes i.e., EI Centro, Northridge and Loma Prieta with maximum peak ground acceleration of 0.34, 0.56 and 0.36g respectively. These earthquakes are categorized as EI Centro as far field case and Northridge and Loma Prieta as near field cases. The natural frequencies of the isolated structure are 0.501, 8.267, 15.927, 22.513, 27.568 and 30.746 *Hz*. The structure parameters are same as the structure consider by Tsai [18]. Considering these data, analysis also performed with theories explained in previous section and results are compared which are shown in Fig. 5 (a) and (b) under EI Centro earthquake. The results are in good comparison with Djedoui et al [33] obtained results. Same results are observed under Northridge and Loma Prieta earthquakes.

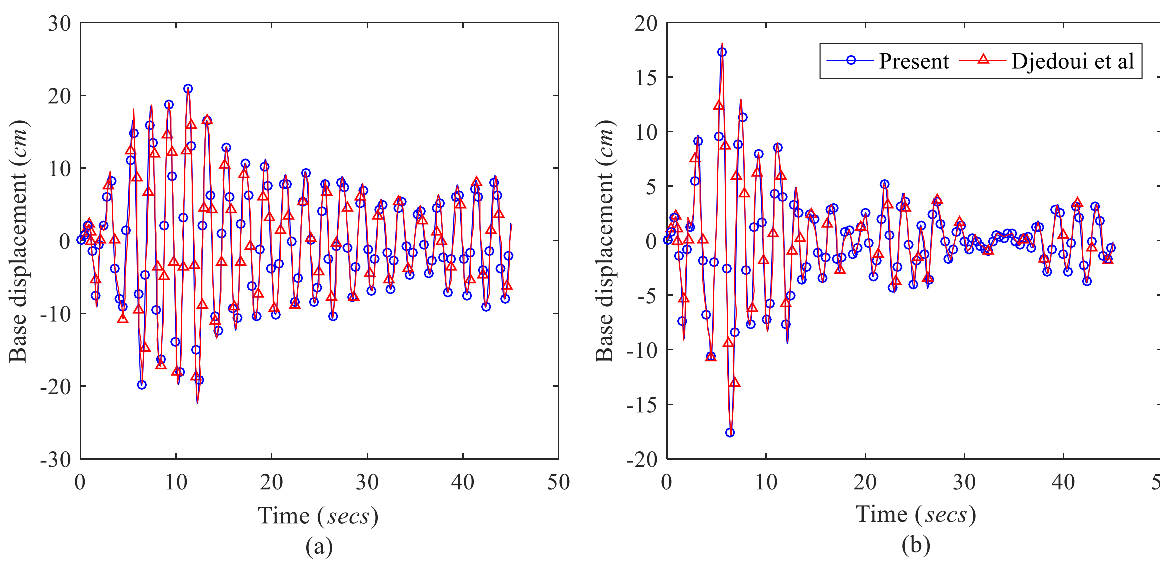


Fig. 5. (a) Base displacement of 5 storey with isolator (b) Base displacement of 5 storey with isolator and TMD under EI Centro earthquake.

Considering above understandings, the procedure has been extended to see the response variation with isolators and TMD separately for earthquake as well as wind and details are explained in successive sections.

4. Building model

The building model considered for present work is five storey shear building as illustrated in Fig. 2 (a), with a plan dimension of 6 *m* x 6 *m* and each storey height of 3 *m* in Mumbai region. Columns size 0.35 *m* x 0.35 *m* and beams size 0.30 *m* x 0.45 *m* are considered. The structure is considered as lumped mass system with each storey mass and stiffness are 20000 *kg* and 80 x 10^7 *N/m*. The Rayleigh damping matrix is created using mass, stiffness matrices, and a constant damping ratio in all modes (i.e., 5%). The natural frequencies of structure are 6.41, 18.71, 29.49, 37.89 and 43.21 *Hz*.

5. Isolators and TMD system

In the present work, laminated rubber bearing and lead plug bearing are considered separately to see reduction in the responses under earthquake and wind. The base slab is considered which has mass same as that of above floors as shown in Fig. 2 (b). As shear type structure with lateral degree of freedom at each floor level is considered so only one isolator is designed i.e., one LRB and one LPB. Isolators are designed by step-by-step procedure given by Reddy et al [2]. The effective target time periods and damping ratio of the structures with isolators are 2 *secs* and 0.1 respectively. Geometric parameters of laminated rubber bearing and lead plug bearing are presented in Table 1 and Table 2 respectively. Fig. 6 shows bilinear characteristics of LPB isolator. The natural frequency of base isolated structure in first mode is 0.48 *Hz* with LRB. In inelastic region of structure with LPB same frequency is targeted.

Table 1
Geometric parameters of laminated rubber bearing.

Quantity evaluated	Value obtained	Units
Diameter of bearing	**740**	***mm***
Thickness of rubber	**16**	***mm***
Thickness of steel shim	**4**	***mm***
Nos of rubber layers	**12**	***Nos***
Nos of steel shims	**11**	***Nos***
Thickness of top/ bottom plate	**20**	***mm***
Total height of isolator	**276**	***mm***
Vertical stiffness of bearing	**914727.52**	***N/mm***
Horizontal stiffness of bearing	**1119.44**	***N/mm***

LPB isolator has two stiffnesses (elastic stiffness and post yield stiffness) compared to LRB isolator having single stiffness, structure with LPB isolator can resist design wind load in the elastic region of LPB. However, structure with LRB having 2 *secs* time period may see oscillatory vortex wind loads. Therefore, TMD is proposed on top of the structure with LRB isolator as shown in Fig. 2 (c). TMD is tuned to the first mode natural frequency of the structure with LRB. The TMD with mass ratio of 0.05 is considered. From equation (13), the stiffness of TMD obtain is 54520 *N/m*.

The same TMD is install at the top of LPB provided structure to see effectiveness of TMD in reducing responses of structure under wind load which is more than design basis or wind load which causing yielding of LPB.

Table 2
Geometric parameters of lead plug bearing.

Quantity evaluated	Value obtained	Units
Diameter of bearing	**740**	***mm***
Diameter of lead	**65**	***mm***
Thickness of rubber	**16**	***mm***
Thickness of steel shim	**4**	***mm***
Nos of rubber layers	**14**	***Nos***
Nos of steel shims	**13**	***Nos***
Thickness of top/ bottom plate	**20**	***mm***
Total height of isolator	**316**	***mm***
Vertical stiffness of bearing	**784052.16**	***N/mm***
Ratio of initial to post yield stiffness (n)	**10**	-
Characteristic strength (Q)	**30797.77**	***N***
Elastic stiffness (K_1)	**10126.08**	***N/mm***
Post yield stiffness (K_2)	**1012.61**	***N/mm***
Displacement at yield (D_y)	**3.38**	***mm***
Yield force (F_y)	**34219.74**	***N***

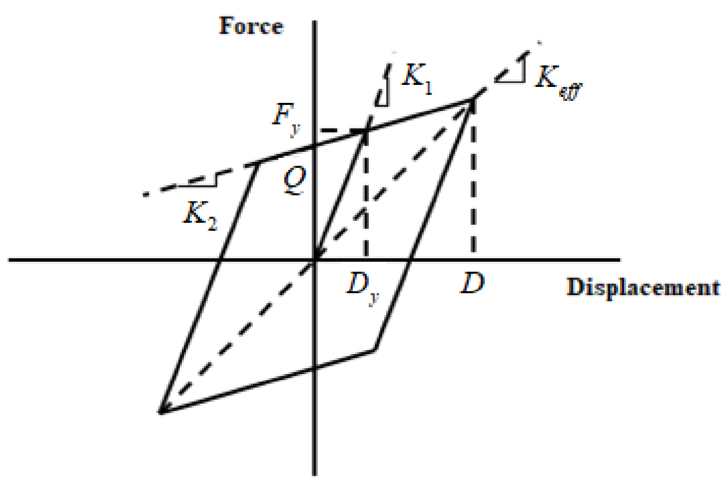


Fig. 6. Bilinear characteristics of LPB isolator [2].

6. Earthquake and wind load

The earthquakes considered for the present study are shown in Table 3 which are taken from CESMD web site [34]. Fig. 7 illustrate the ground acceleration of earthquakes. The earthquakes considered have magnitude from 4.5 to 7. These data are taken from stiff soil.

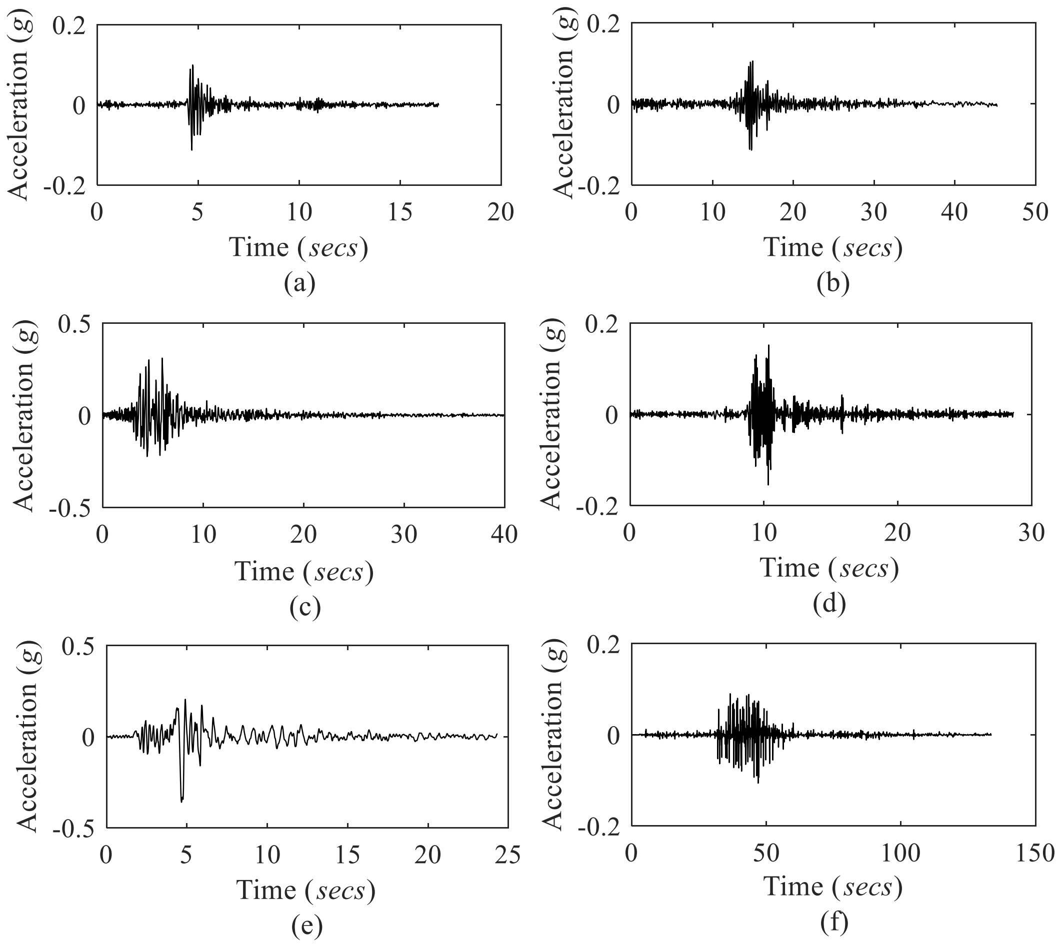


Fig. 7. Ground acceleration used in present work (a) NE-India earthquake (b) India-Bangladesh Border earthquake (c) Uttarkashi earthquake (d) India-Burma Border earthquake (e) Chamoli earthquake (f) Bhuj earthquake.

Table 3
Earthquakes considered for present study.

S.N.	Earthquake	Earthquake station	Date	Magnitude (*Mw*)	Hypocentral distance (*km*)	PGA (*g*)
1	NE-India	Ummulong	10/9/1986	4.5	44.9	0.113
2	India-Bangladesh Border	Nongkhlaw	6/2/1988	5.8	117.3	0.114
3	Uttarkashi	Uttarkashi	20/10/1991	7	34	0.31
4	India-Burma Border	Ummulong	8/5/1997	6	78.4	0.155
5	Chamoli	Gopeshwar	29/3/1999	6.6	17.3	0.36
6	Bhuj	Ahmedabad	26/1/2001	7	239	0.106

When the structure is on isolator particularly on laminated rubber bearings, frequency changes to 0.5 *Hz* and time period is 2 *secs* when compared to fixed base structure frequency of 6.41 Hz. Therefore, dynamic behaviour of structure and wind load are need to be considered as per IS 875-Part 3 [35].

When structure is subjected to wind vortices which are shed alternatively from opposite sides, this is known as vortex shedding. This results in a load that fluctuates perpendicular to the wind direction. If the frequency of vortex shedding is the same as the structure's natural frequency, resonance may develop causing larger responses.

The vortex shedding induced load acting at any location z on structure is given by:

$$F(z,t) = \frac{1}{2}\rho V^{2} C_L A \sin(2\pi f_s t) \tag{14}$$

where, p = air density in kg/m^3,

V = mean wind speed at location z in m/s,

C_L = lift force coefficient,

A = frontal area of structure at any height z in m^2,

f_s = frequency at which vortex shedding occurs in Hz, and

t = time in *secs*

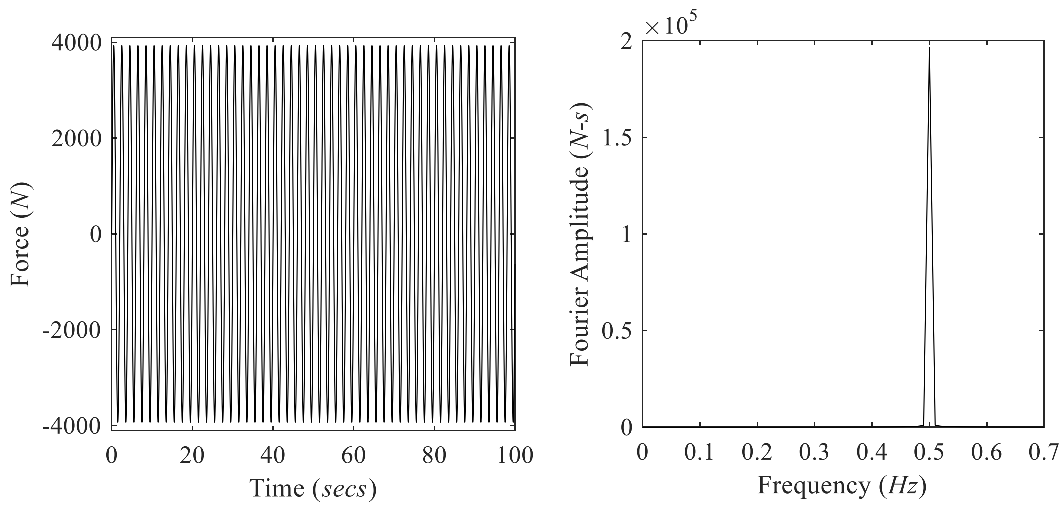
According to IS 875 [35], the vortex shedding frequency is calculated using the formula below

$$f_s = \frac{S_t V_{z,H}}{b} \tag{15}$$

where, S_t = Strouhal number,

V_{zH} = hourly mean wind speed at height z, and

b = breadth of structure or structure member normal to the wind direction in the horizontal plane



(a) (b)

Fig. 8. (a) Time history of vortex shedding induced load at top floor (b) Fourier spectrum of vortex shedding induced load at top floor.

IS 875 [35] does not give Strouhal number for square cross section structure but EN 1991 [36] has provided as S_t = 0.12. From IS 875 [35], for Mumbai region and present building structure, hourly mean wind speed at top of building obtained is 24.13 m/s. From equation (15), vortex shedding frequency obtained is 0.48 Hz. Vortex shedding induced loads are generated using equation (14) for each storey and they are applied on structures. Time history of vortex shedding induced load at top of building and its fourier spectrum are shown in Fig. 8 (a) and (b) respectively.

Wind force shown in Fig. 8 (a) has magnitude less than yielding capacity of LPB. So, to see effect of wind force which is more than design basis or wind load which causing yielding of LPB, the wind velocity increase to 72.01 *m/s* and vortex frequency obtained is 1.44 *Hz*. With this wind velocity and vortex frequency, wind forces are obtained from equation (14) and they are applied on structures.

7. Results and discussion

The analysis of structures is done in Matlab R2016a version. The soil structure interaction and structure-structure interaction are not considered in the analysis. Fig. 9 to Fig. 14 demonstrate the time history of roof relative displacement and roof absolute acceleration due to the Chamoli earthquake, wind load and wind load which is more than design basis. Fig. 15 (a) and (b) depict force deformation behaviour of LRB and LPB under Chamoli earthquake. The roof peak relative displacement and roof peak absolute acceleration of fixed base, isolated base with LRB, isolated base with LRB and TMD and isolated base with LPB under six earthquakes are shown in Table 4, Table 5 and also presented in Fig. 16 under earthquakes. The peak relative displacement and peak absolute acceleration of TMD provided in LRB isolated structure under six earthquakes and wind load are shown in Table 6. The peak displacement and peak acceleration of roof under wind load and wind load causing yielding of LPB are shown in Table 7 and values of maximum inter-storey drift of structures are shown in Table 8. Following are the results

- The peak relative displacement of 5^{th} floor of isolated structure with LRB increase by 91.34%, 5.41 times, 6.48 times, 2.18 times, 41.39 times, 30.03 times and 482.15 times and for isolated structure with LPB increase by 16.48%, 1.26 times, 3.81 times, 1.94 times, 27.82 times, 21.22 times and 15.96 times under NE-India, India-Bangladesh Border, Uttarkashi, India-Burma Border, Chamoli, Bhuj earthquakes and wind load when comparing with fixed base structure which can be seen in Table 4. When comparing LPB provided structure with LRB provided structure, the peak relative displacement of 5^{th} floor decrease by 39.13%, 64.70%, 35.63%, 7.62%, 32%, 28.39% and 96.49% under NE-India, India-Bangladesh Border, Uttarkashi, India-Burma Border, Chamoli, Bhuj earthquakes and wind load. So, with base isolation peak relative displacement increases when compared with fixed base structure. Also structure isolated with LPB has reduce peak relative displacement compare with LRB provided structure. Therefore, LPB is more effective than LRB when comparing peak relative displacement because of its higher initial stiffness.

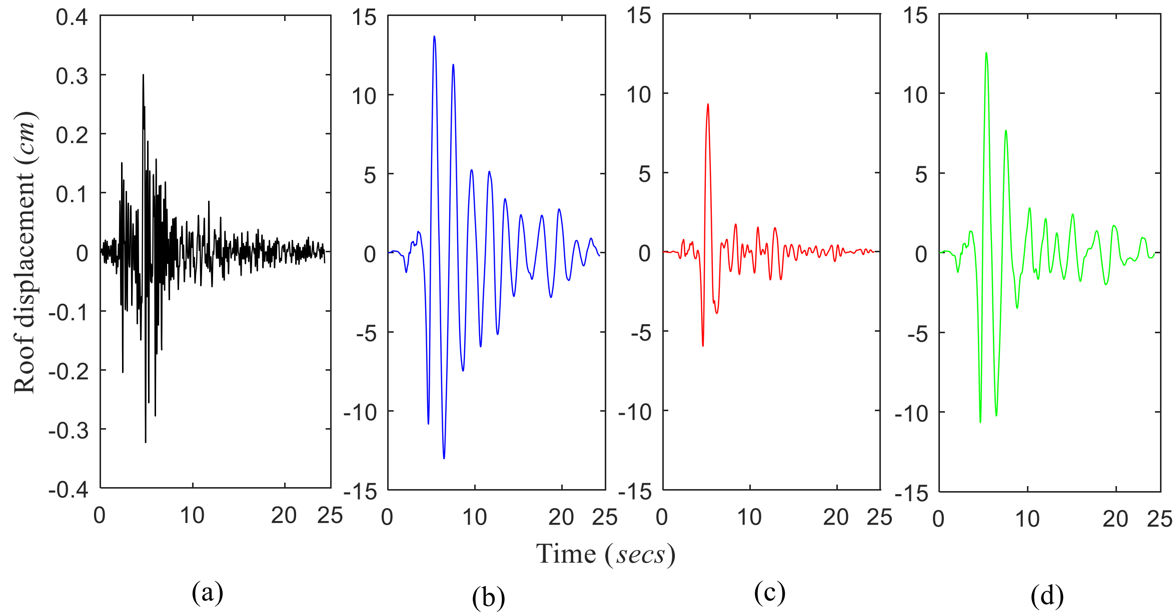


Fig. 9. Time history of roof relative displacement of (a) Fixed base (b) Isolated base with LRB (c) Isolated base with LPB (d) Isolated base with LRB and TMD structures under Chamoli earthquake.

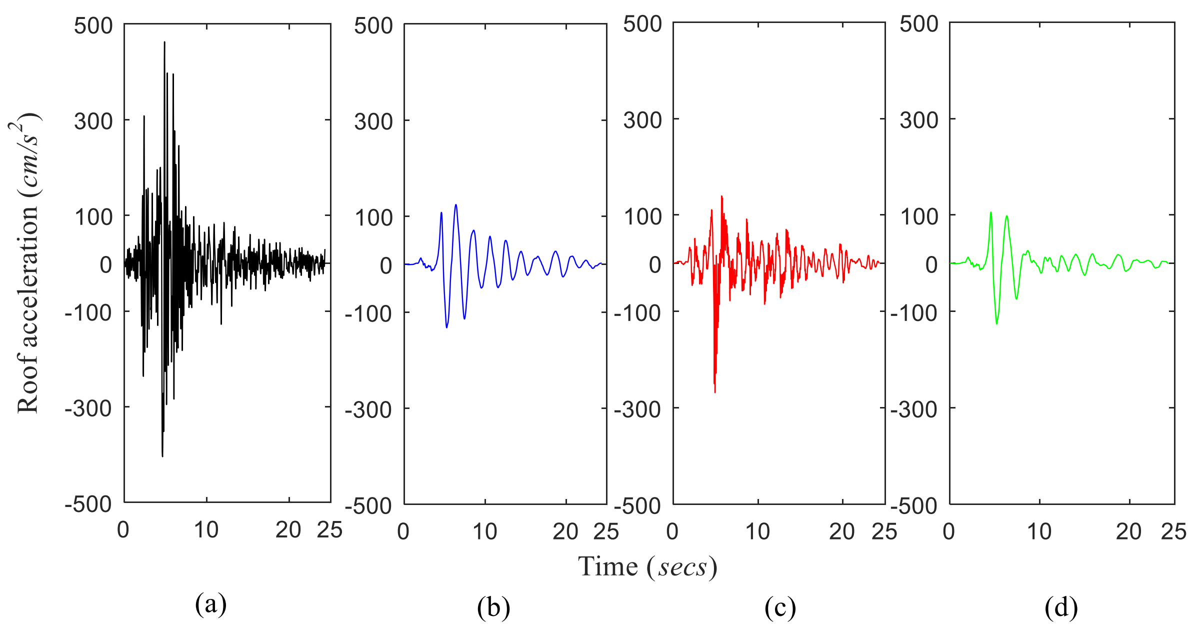


Fig. 10. Time history of roof absolute acceleration of (a) Fixed base (b) Isolated base with LRB (c) Isolated base with LPB (d) Isolated base with LRB and TMD structures under Chamoli earthquake.

- The peak absolute acceleration of 5th floor of isolated structure with LRB decrease by 98.93%, 95.29%, 94.76%, 97.77%, 71.35%, 79.7% and increase by 39.8 times and for isolated structure with LPB decrease by 92.93%, 86.53%, 76.11%, 83.09%, 41.99%, 51.98% and increase by 2.68 times under NE-India, India-Bangladesh Border, Uttarkashi, India-Burma Border, Chamoli, Bhuj earthquakes and wind load when comparing with fixed base structure which can be seen in Table 5. This shows that design of low-rise building is govern by earthquake load and base isolated building is sensitive to vortex induced load. When comparing LRB provided structure with LPB provided structure, the peak absolute acceleration of 5th floor decreases by 84.9%, 65%, 78.07%, 86.83%, 50.62%, 57.73% and increase by 10.09 times under NE-India, India-Bangladesh Border, Uttarkashi, India-Burma Border, Chamoli, Bhuj earthquakes and wind load. So, with base isolation peak absolute acceleration decreases under six earthquakes and increases under wind load when comparing with fixed base structure. Also structure isolated with LRB has lower peak absolute acceleration under six earthquakes and more value under wind load when comparing with LPB provided structure. Therefore, LRB is more effective than LPB when comparing peak absolute acceleration under six earthquakes whereas LPB is more effective than LRB under wind load.

- The peak relative displacement of 5th floor of isolated structure with LRB and TMD decrease by 8.02%, 18.4%, 5.49%, 5.7%, 8.36%, 4.83% and 44.72% under NE-India, India-Bangladesh Border, Uttarkashi, India-Burma Border, Chamoli, Bhuj earthquakes and wind load when comparing with LRB provided structure which can be seen in Table 4. When comparing LRB and TMD provided structure with LPB provided structure, the peak relative displacement of 5th floor increase by 51.09%, 1.31 times, 46.83%, 2.08%, 34.77%, 32.9% and 14.75 times under NE-India, India-Bangladesh Border, Uttarkashi, India-Burma Border, Chamoli, Bhuj earthquakes and wind load. So, TMD found to be little effective in reducing peak relative displacement of LRB provided structure under earthquakes whereas it is found to be more effective under wind load. The effect of variation of frequency of TMD on roof displacement of LRB provided structure under wind load are shown in Fig. 17 (a).

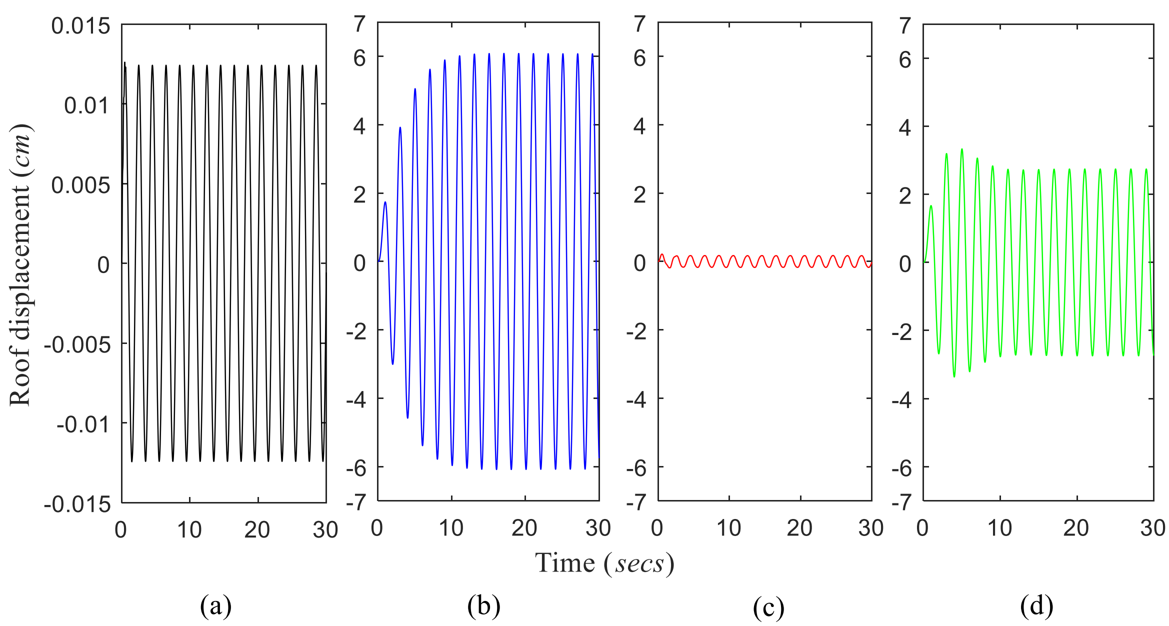


Fig. 11. Time history of roof displacement of (a) Fixed base (b) Isolated base with LRB (c) Isolated base with LPB (d) Isolated base with LRB and TMD structures under wind load.

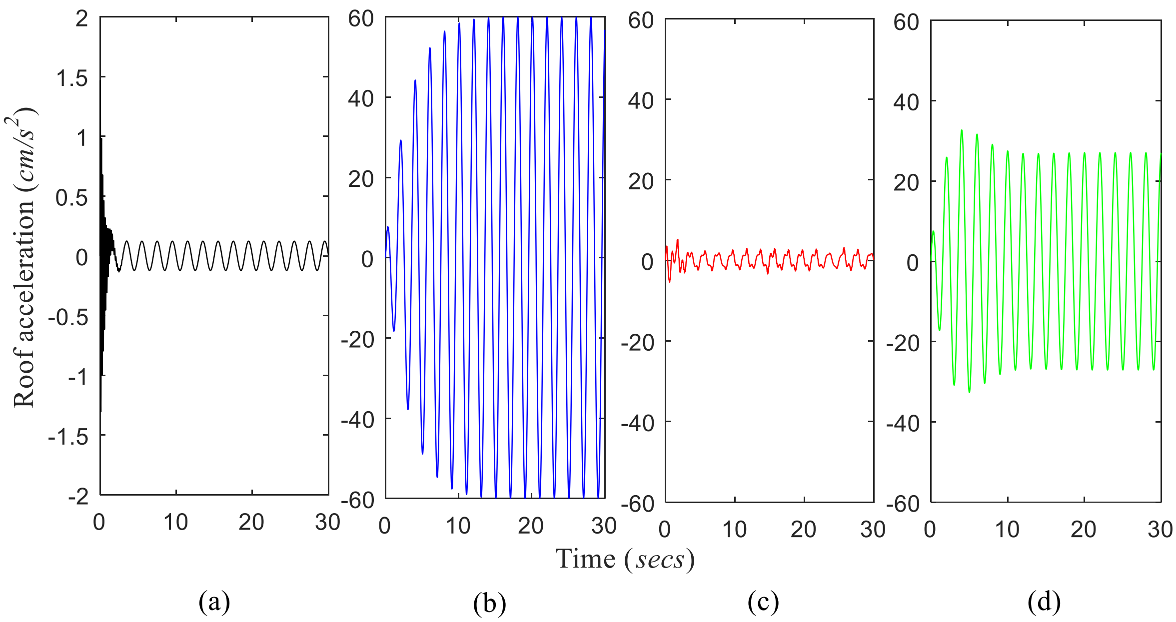


Fig. 12. Time history of roof acceleration of (a) Fixed base (b) Isolated base with LRB (c) Isolated base with LPB (d) Isolated base with LRB and TMD structures under wind load.

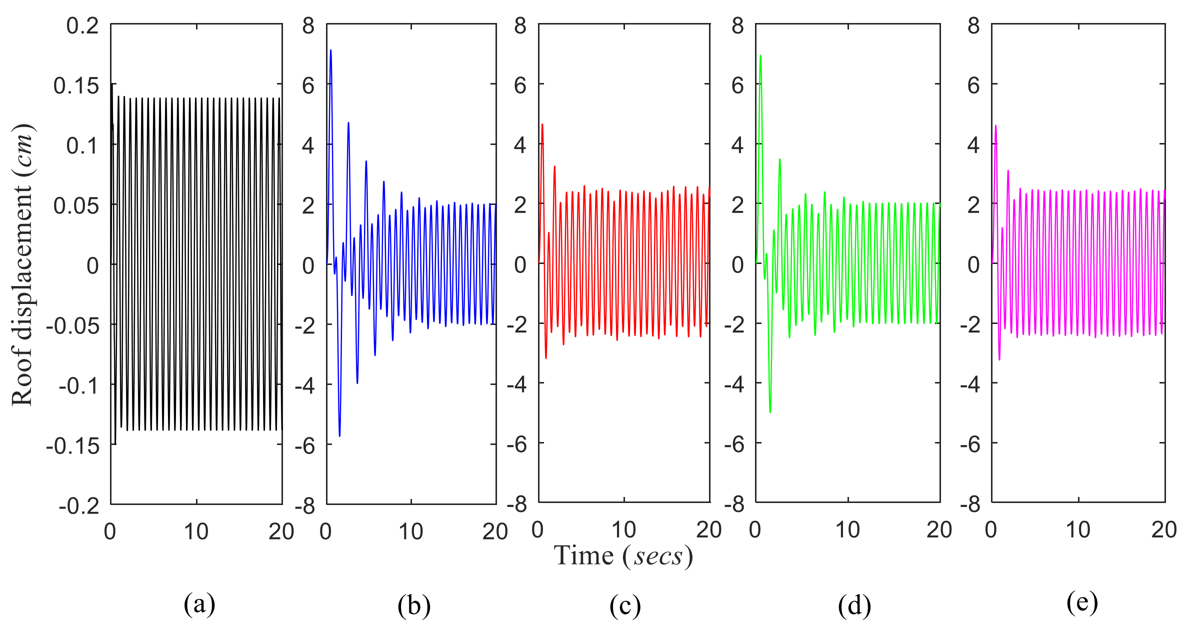


Fig. 13. Time history of roof displacement of (a) Fixed base (b) Isolated base with LRB (c) Isolated base with LPB (d) Isolated base with LRB and TMD (e) Isolated base with LPB and TMD structures under wind load causing yielding of LPB.

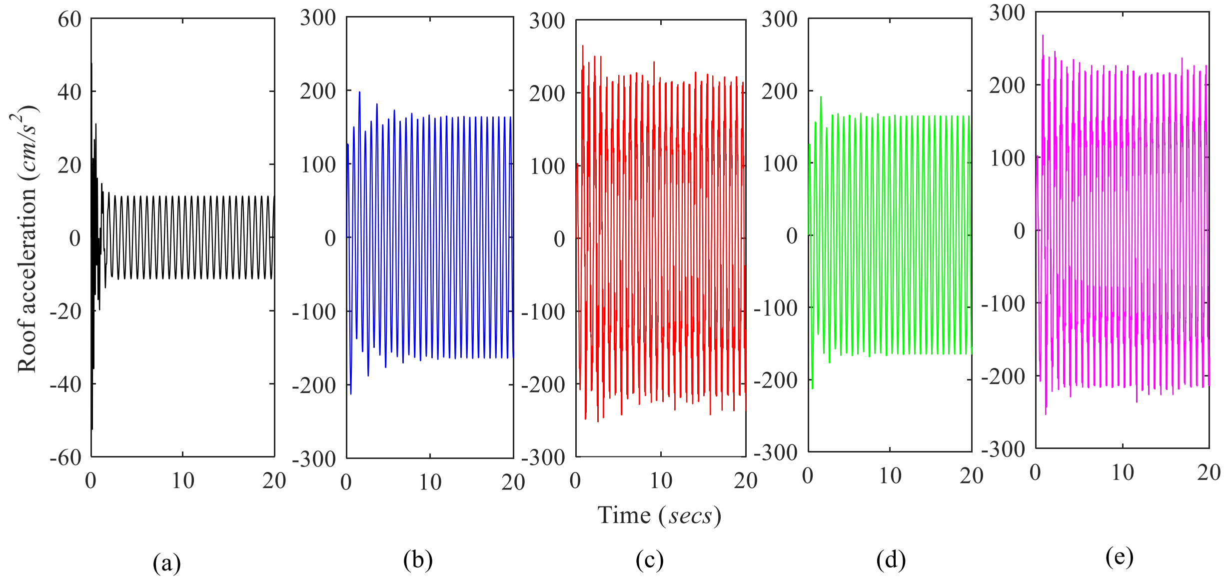


Fig. 14. Time history of roof acceleration of (a) Fixed base (b) Isolated base with LRB (c) Isolated base with LPB (d) Isolated base with LRB and TMD (e) Isolated base with LPB and TMD structures under wind load causing yielding of LPB.

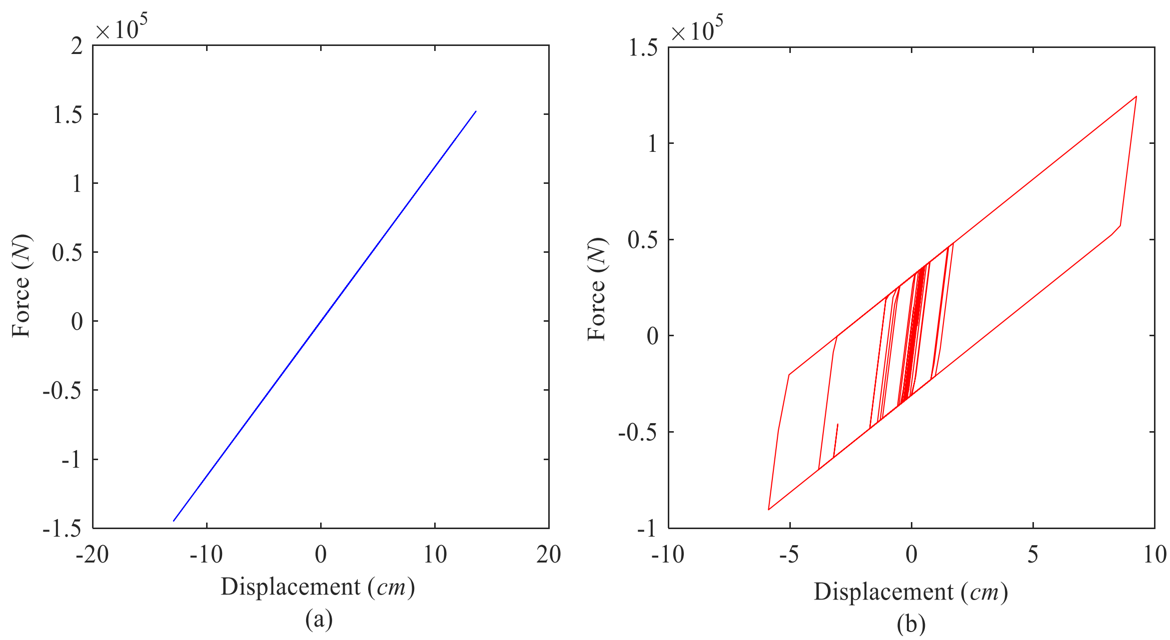


Fig. 15. (a) Force deformation behaviour of LRB (b) Force deformation behaviour of LPB under Chamoli earthquake.

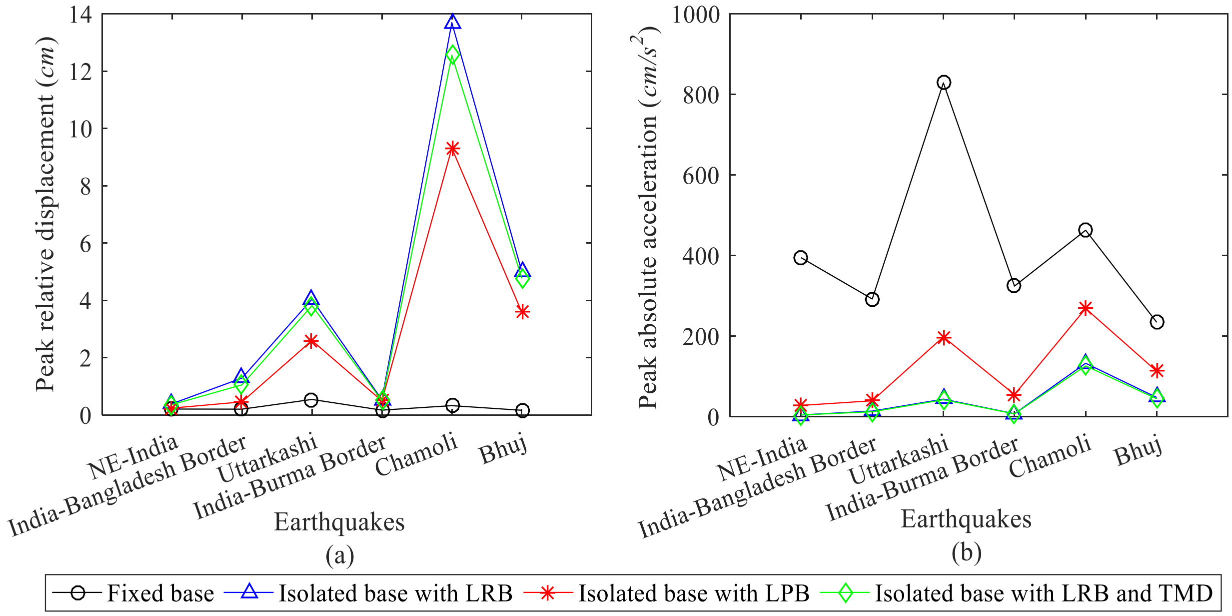


Fig. 16. (a) Roof peak relative displacement (b) Roof peak absolute acceleration of structures under earthquakes.

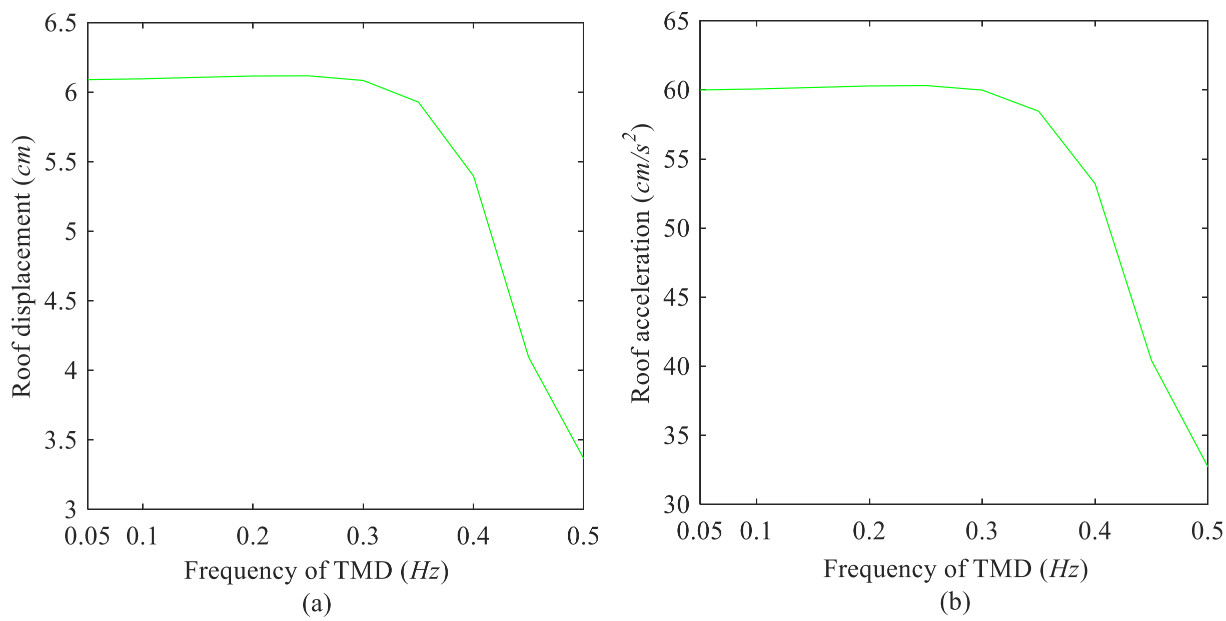


Fig. 17. Effect of variation of TMD frequency on (a) Roof displacement (b) Roof acceleration under wind load.

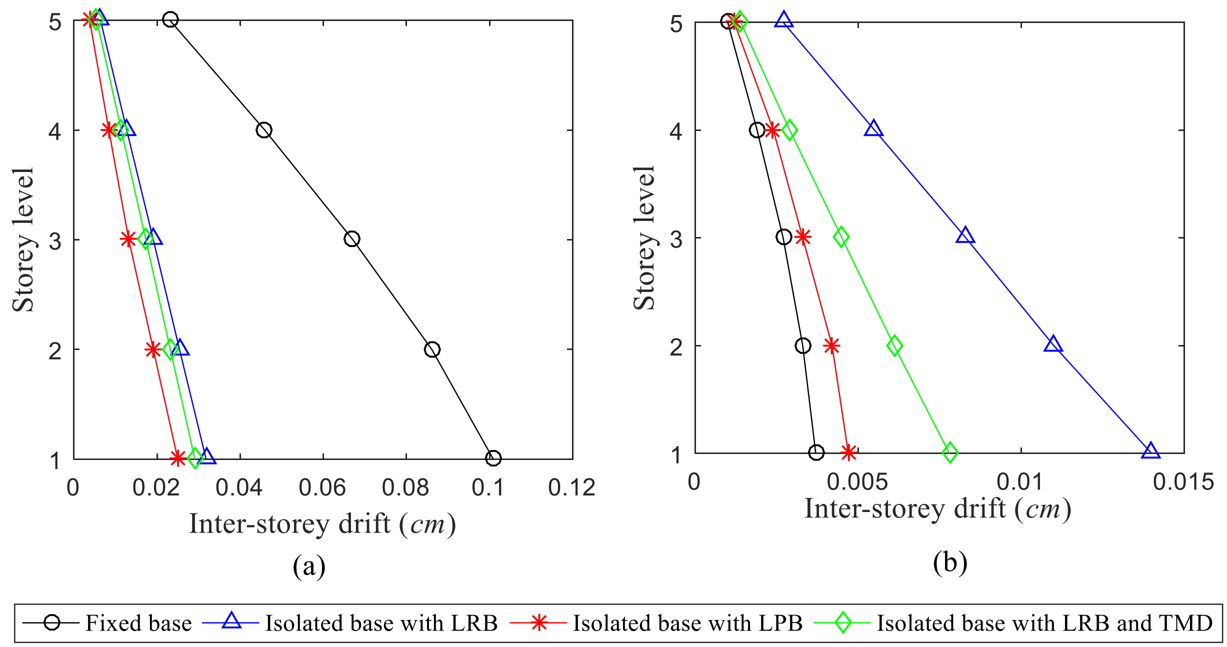


Fig. 18. Inter-storey drift under (a) Chamoli earthquake (b) Wind load.

- The peak absolute acceleration of 5th floor of isolated structure with LRB and TMD decrease by 0.24%, 12.06%, 3.5%, 4.02%, 4.91%, 7.26% and 45.45% under NE-India, India-Bangladesh Border, Uttarkashi, India-Burma Border, Chamoli, Bhuj earthquakes and wind load when comparing with LRB provided structure which can be seen in Table 5. When comparing LRB and TMD provided structure with LPB provided structure, the peak absolute acceleration of 5th floor decreases by 84.94%, 69.22%, 78.84%, 87.36%, 53.04%, 60.8% and increase by 5.05 times under NE-India, India-Bangladesh Border, India-Burma Border, Uttarkashi, Chamoli, Bhuj earthquakes and wind load. So, TMD found to be little effective in reducing peak absolute acceleration of LRB provided structure under earthquakes whereas it is found to be more effective under wind load. The effect of variation of frequency of TMD on roof acceleration of LRB provided structure under wind load are shown in Fig. 17 (b).

Table 4
Roof peak relative displacement under earthquakes.

Loads	Roof peak relative displacement (*cm*)			
	Fixed base	LRB	LPB	LRBTMD
NE-India EQ	0.2045	0.3913	0.2382	0.3599
India- Bangladesh Border EQ	0.2006	1.2861	0.454	1.0495
Uttarkashi EQ	0.5397	4.0349	2.5973	3.8135
India- Burma EQ	0.1666	0.5301	0.4897	0.4999
Chamoli EQ	0.3231	13.6953	9.313	12.5507
Bhuj EQ	0.1613	5.0053	3.5843	4.7634

Table 5
Roof peak absolute acceleration under earthquakes.

Loads	PGA (cm/s^2)	Roof peak absolute acceleration (cm/s^2)			
		Fixed base	LRB	LPB	LRBTMD
NE-India EQ	110.85	394.6	4.21	27.89	4.2
India- Bangladesh Border EQ	111.83	292.07	13.77	39.34	12.11
Uttarkashi EQ	304.11	828.63	43.42	197.99	41.9
India- Burma EQ	152.06	324.1	7.22	54.82	6.93
Chamoli EQ	353.16	462.77	132.57	268.46	126.06
Bhuj EQ	103.99	234.11	47.52	112.43	44.07

Table 6
Peak relative displacement and peak absolute acceleration of TMD.

Loads	Peak relative displacement (cm)	Peak absolute acceleration (cm/s^2)
NE-India EQ	0.8699	7.33
India- Bangladesh Border EQ	2.0385	17.24
Uttarkashi EQ	7.385	61.37
India- Burma EQ	1.0432	8.62
Chamoli EQ	32.7375	272.79
Bhuj EQ	11.9461	103.86
Wind load	13.0172	127.93

Table 7
Peak displacement and peak acceleration of roof under wind loads.

Loads	Roof peak displacement (cm)				
	Fixed base	LRB	LPB	LRBTMD	LPBTMD
Wind load	0.0126	6.0877	0.2137	3.3654	-
Wind load causing yielding of LPB	0.1501	7.1349	4.6539	6.9563	4.6103
	Roof peak acceleration (cm/s^2)				
Wind load	1.47	59.98	5.41	32.72	-
Wind load causing yielding of LPB	52.55	212.97	264.89	212.98	268.01

- The peak displacement, peak acceleration of 5^{th} floor of isolated structure with LRB increase by 46.53 times, 3.05 times and for isolated structure with LPB increase by 30.01 times, 4.04 times under wind load which is causing yielding of LPB when comparing with fixed base structure which can be seen in Table 7. When comparing LPB and TMD provided structure with LPB provided structure the peak displacement, peak acceleration of 5th floor decreases by 0.94%, 1.18% under wind load which is causing yielding of LPB. So, under wind load which is more than design basis, both isolated structures have responses more than fixed base structure. Also, TMD provided in LPB supported structure which has frequency same as first mode natural frequency of LRB provided structure is not found to be effective under wind load which is more than design basis in reducing peak displacement and peak acceleration of LPB provided structure.

- The maximum inter-storey drift of isolated structure with LRB decrease by 98.35%, 95.11%, 94.15%, 97.44%, 68.48%, 77.48% and increase by 2.78 times and for isolated structure with LPB decrease by 91.58%, 88.44%, 92.28%, 85.9%, 75.22%, 71.84% and increase by 27.03% under NE-India, India-Bangladesh Border, Uttarkashi, India-Burma Border, Chamoli, Bhuj earthquakes and wind load when comparing with fixed base structure which can be seen in Table 8. When comparing LRB and TMD provided structure with LPB provided structure, the maximum inter-storey drift decreases by 82.61%, 64.79%, 27.42%, 81.82%, increase by 16.4%, decrease by 23.45% and increase by 65.96% under NE-India, India-Bangladesh Border, Uttarkashi, India-Burma Border, Chamoli, Bhuj earthquakes and wind load. So, with base isolation maximum inter-storey drift decreases under six earthquakes and increases under wind load when comparing with fixed base structure. Also, LRB and TMD provided structure has little lower inter-storey drift under six earthquakes and more value under wind load when comparing with LPB provided structure. Therefore, LRB is little effective than LPB when comparing maximum inter-storey drift under six earthquakes whereas LPB is more effective than LRB under wind load. Fig. 18 (a) and (b) showing inter-storey drift under Chamoli earthquake and wind load.

Table 8
Maximum inter-storey drift.

Loads	Storey drift (*cm*)			
	Fixed base	LRB	LPB	LRBTMD
NE-India EQ	0.0546	0.0009	0.0046	0.0008
India- Bangladesh Border EQ	0.0614	0.003	0.0071	0.0025
Uttarkashi EQ	0.1607	0.0094	0.0124	0.009
India- Burma EQ	0.0468	0.0012	0.0066	0.0012
Chamoli EQ	0.1009	0.0318	0.025	0.0291
Bhuj EQ	0.0515	0.0116	0.0145	0.0111
Wind load	0.0037	0.014	0.0047	0.0078

Thus, with base isolation roof peak relative displacement increases under all six earthquakes and wind load whereas roof peak absolute acceleration, maximum inter-storey drift decreases under all six earthquakes and increases under wind load. LPB found to be more effective than LRB in terms of peak relative displacement under earthquakes and wind load whereas LRB found to be more effective in terms of peak absolute acceleration under earthquakes and less effective under wind load. Installation of TMD at the top of LRB provided structure reduces much responses under wind load but the values are higher than LPB provided structure. Same TMD install at the top of LPB supported structure is found to be ineffective in reducing responses of structure under wind load which is more than design basis. Therefore, TMD can be use with LRB where LRB reduces structure response under earthquakes load and TMD reduces response under wind load.

8. Conclusions

In this paper, five storey shear building model having first mode natural frequency of 6.41 *Hz* located in Mumbai region is considered. Rayleigh Damping matrix is constructed from mass and stiffness matrices of structure by considering constant damping ratio in each mode. Laminated rubber bearing and Lead plug bearing are designed and provided separately at base of structure. Tuned mass damper is designed and provided at the top of LRB and LPB supported structure separately. Under six Indian earthquakes (NE-India, India-Bangladesh Border, Uttarkashi, India-Burma Border, Chamoli and Bhuj earthquakes) and Wind load (Vortex induced load), the peak relative displacement and peak absolute acceleration of fixed base, isolated with LRB, isolated with LRB and TMD, and isolated with LPB structures are observed. Also, TMD used at the top of LRB supported structure is install at the top of LPB supported structure and responses of structures are observed under wind load which is more than design basis. These responses of structures are evaluated using Newmark Beta integration method. The limitation of this method is that it leads to errors when adopted for nonlinear system like in LPB provided structure. So, to counteract nonlinearity Newton Raphson iteration is used within time step in LPB provided structure. Computer programs are written on Matlab R2016a version. Following are the conclusions of this study

- With base isolation, roof peak relative displacement increases when comparing with fixed base structure under all six earthquakes and wind load, however LPB supported structure roof peak relative displacement found to be lower than LRB provided structure and LRB and TMD provided structure. This is because of high initial stiffness of LPB.
- With base isolation, roof peak absolute acceleration and maximum inter-storey drift decreases when comparing with fixed base structure under all six earthquakes and increases under wind load however LRB provided structure roof peak absolute acceleration found to be lower than LPB provided structure. This shows that design of low-rise building is govern by earthquake load and base isolated building is sensitive to vortex induced load.
- The roof peak relative displacement found to be little lower by installing TMD at the top of LRB provided structure under earthquakes and about 44.72% lower under wind load when comparing LRB provided structure however the values are higher than LPB provided structure.
- The roof peak absolute acceleration found to be little lower by installing TMD at the top of LRB provided structure under earthquakes and about 45.45% lower under wind load when comparing LRB provided structure however the values are higher than LPB provided structure. So, TMD tuned to natural frequency of LRB provided structure (0.48 *Hz*) found to be little effective under earthquakes and more effective under vortex induced load in reducing the responses.

- Under wind load which is more than design basis, responses of both isolated structures increase when comparing with fixed base structure. TMD installed at the top of LPB provided structure tuned to natural frequency of LRB provided structure found to be ineffective in reducing responses of LPB provided structure. Therefore, TMD effectively reduce responses of structure when it is tuned to natural frequency of structure on which it is installed at resonance.

Thus, the base isolation reduces acceleration response and inter-storey drift of five storey building and found to be effective under all six Indian earthquakes. LRB provided structure found to be more effective about 51% to 87% reduction of roof acceleration when comparing with LPB provided structure under earthquakes. Under vortex induced load, base isolated structure has more responses than fixed base structure. LPB provided structure found to be more effective about 96.49% reduction in peak displacement, 90.98% reduction in peak acceleration and 66.43% reduction in inter-storey drift when comparing with LRB provided structure under vortex induced load due to its high initial stiffness. However, responses of both LRB isolated, LPB isolated structures increases about 46.53 times, 30.01 times in peak displacement values and about 3.05 times, 4.04 times in peak acceleration values when comparing with fixed base structure under wind load which is more than design basis. When TMD installed on top of LRB provide structure, peak displacement increases by 0.76 times to 38 times, peak acceleration decreases by 73% to 99%, maximum inter-storey drift decreases by 71% to 99% under earthquakes when comparing with fixed base structure and under wind values of peak displacement, peak acceleration, maximum inter-storey drift decreases by 45%, 46%, 44% respectively when comparing with LRB provided structure. Therefore, combining a passive isolation system with an absorber was found to be beneficial in decreasing responses of five storey building model, with the isolator reducing earthquake responses and the absorber reducing wind induced responses.

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