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Building vibration mitigation employing partial floor loads coupled with several tuned mass dampers

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Abstract

When it comes to shielding tall structures from vibrations, tuned mass dampers (TMDs) are the go-to control device. Due of their ease of use and effectiveness, they have been used in many skyscrapers all around the globe. This study recommends a novel approach to distribute partial floor loads as various TMDs on a constrained number of floors. This method avoids problems caused by the loading up of a structure with excessive mass for response control, and it does so without compromising the original structure's mass. The vibration response of structures is studied in relation to wind and earthquakes, and the impacts of applying partial loads of restricted floors beginning from the top as TMDs are examined. The implications of using the proposed method on structures of varying heights and types are also studied. This paper presents the results of a parametric analysis that shows how the number of floors in a building and the percentage of each level devoted to TMDs impact its behaviour. The results show that the proposed control method improves the response of structures to wind and earthquakes in terms of drift, acceleration, and force. Buildings' responses to wind and earthquakes were shown to improve with higher story-mass ratios and more floors used as TMDs.

Introduction

Tuned mass dampers (TMDs) are the most often used devices for regulating the dynamic response of buildings [1,2] due to their efficiency, durability, and relative simplicity of set up. Due of TMD systems' effectiveness, they have been incorporated into a wide variety of man-made structures all throughout the globe, including houses and bridges [1-3]. The CN tower in Toronto, Canada (1975) and the Shanghai Global Financial Center in Shanghai, China (2008) both contain TMDs, but the 660-ton TMD atop the Taipei Tower in Taiwan (2004) is the biggest and most well-known TMD in the world [2]. Research on TMDs as a control tool was conducted, with a particular emphasis on the future of structural control studies in the United States. Mathematical formulations, numerical implementations, and the resulting behaviour of TMD-controlled systems have been the subject of several studies [4,5]. TMDs are utilized in buildings for a variety of reasons, including regulating the dynamic response under lateral loads and reducing the torsional behaviour of very torsion ally linked structures [6,7]. Large-scale parametric studies were conducted to determine the optimal values for the parameters of a TMD system, such as the location of the added mass damper, tuning frequency ratio, tuning mass ratio, and tuned damping ratio [6], in order to mitigate the seismic response of severely torsion ally coupled buildings. One research found that, given a variety of design parameters, systems with multiple TMDs (MTMDs) were more successful than single TMD systems for damping the response of a torsion ally coupled system [7]. Nevertheless, when the eccentricity ratio becomes larger, the benefits of using many TMDs instead of a single TMD begin to diminish.

Besides passive TMDs, researchers have looked at semi-active variable stiffness TMDs (SAIVS-TMDs) [9], bidirectional and homogeneous TMDs (BH-TMDs) [10], and hybrid mass dampers

(HMDs) controlled by a fuzzy logic controller (FLC) [8]. Results showed that the top-floor dis placement and acceleration response was decreased by 32% and 53%, respectively, compared to the similar reaction of an uncontrolled structure when subjected to wind excitation using the SAIVS-TMD, which used a single mass with a variable stiffness spring [9]. This has an impact comparable to that of an active TMD, but with lower energy requirements [9]. It has been stated that the BH-TMD may minimize the displacement reaction to earthquakes by 60% [10], since it provides vibration control in both of the primary directions. Since TMDs were found to be effective in dampening building responses, the idea of a roof-garden TMD was proposed and researched [11,12]. For this reason, TMDs with undetermined masses may be created by adjusting the system's mass ratio.

Due to their effectiveness, longevity, and ease of installation, tuned mass dampers (TMDs) are the most used devices for controlling the dynamic response of structures [1,2]. Because of how useful TMD systems are, they are now found in a broad range of man-made buildings and bridges all over the world [1-3]. The Shanghai Global Financial Center in Shanghai, China (2008) and the CN Tower in Toronto, Canada (1975) both have TMDs, but the 660-ton TMD atop the Taipei Tower in Taiwan (2004) is the largest and most well-known TMD in the world [2]. Studies on TMDs' use as a control mechanism were done, with an eye toward their potential impact on the development of structural control research in the USA.

[1]. Many research [4,5] have examined the mathematical formulations, numerical implementations, and consequent behaviour of TMD-controlled systems. TMDs are used in buildings for several purposes, including damping the dynamic response to lateral loads and damping the torsional behaviour of highly torsion ally coupled structures [6,7]. In order to reduce the seismic response of severely torsion ally coupled buildings, extensive parametric studies were performed to determine the optimal values for the parameters of a TMD system, such as the location of the added mass damper, tuning frequency ratio, tuning mass ratio, and tuned damping ratio [6]. One study revealed that the response of a torsion ally linked system may be better dampened by using a system with multiple TMDs (MTMDs) rather than a single TMD system, and this was true across a wide range of design parameters [7]. Nevertheless, the advantages of utilizing a large number of TMDs rather than a single TMD start to decrease as the eccentricity ratio increases.

Other alternatives to passive TMDs that have been studied include semi-active variable stiffness TMDs (SAIVS-TMDs) [9], bidirectional and homogeneous TMDs (BH-TMDs) [10], and hybrid mass dampers (HMDs) controlled by a fuzzy logic controller (FLC) [8]. Using a single mass with a variable stiffness spring, the SAIVS-TMD was able to reduce the top-floor dis placement and acceleration response by 32% and 53%, respectively, compared to the comparable reaction of an uncontrolled structure when exposed to wind stimulation [9]. The effect is similar to that of a functioning TMD, but with less energy expenditure [9]. As the BH-TMD mitigates vibration in both main axes, it is possible that the displacement response to earthquakes may be reduced by as much as 60% [10]. Given the success of TMDs in reducing the reverberation of buildings, the concept of a roof-garden TMD was presented and investigated [11,12]. As a result, the mass ratio of the system may be tweaked to produce TMDs of unknown masses.

Mathematical model of multiple-story TMDs

Consider the multi-storey building with multiple-story TMDs shown in Fig. 1. The building is composed of N stories with Nd TMDs located at different floor levels. The dynamic equation of motion of the building modelled as a shear building with lumped masses can be expressed as

$$M\ddot{x} + C\dot{x} + Kx = F \tag{1}$$

where M, C, and K are the mass, damping, and stiffness matrices of the building, respectively, considering the effect of TMDs; these matrices are defined as

$$M = M_s + M_d \tag{2}$$

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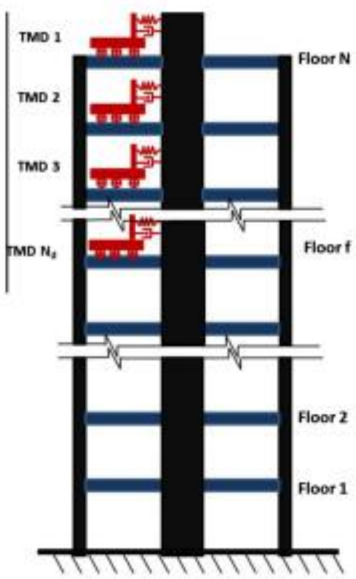

Fig. 1 Model of building with MTMD.

$$C = C_s + C_d$$

$$K = K_s + K_d$$

Where Ms, Cs, and Ks are the mass, damping, and stiffness matrices of the structure without TMDs whereas Md, Cd, and Kd are the corresponding corrections resulting from the existence of TMDs. These matrices for a shear building with lumped masses are defined as follows:

$$M_s = \begin{bmatrix} m_1 & 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & 0 \\ 0 & m_2 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & m_3 & \cdots & 0 & 0 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & m_{i-1} & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & 0 & \cdots & 0 & m_i & 0 & \cdots & 0 & 0 \\ 0 & 0 & 0 & \cdots & 0 & 0 & m_{i+1} & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & m_{N-1} & 0 \\ 0 & 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & m_N \end{bmatrix} \quad (5)$$

$$K_s = \begin{bmatrix} k_1+k_2 & -k_2 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & 0 \\ -k_2 & k_2+k_3 & -k_3 & \cdots & 0 & 0 & 0 & \cdots & 0 & 0 \\ 0 & -k_3 & k_3+k_4 & \cdots & 0 & 0 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & k_{i-1}+k_i & -k_i & 0 & \cdots & 0 & 0 \\ 0 & 0 & 0 & \cdots & -k_i & k_i+k_{i+1} & -k_{i+1} & \cdots & 0 & 0 \\ 0 & 0 & 0 & \cdots & 0 & -k_{i+1} & k_{i+1}+k_{i+2} & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & k_{N-1}+k_N & -k_N \\ 0 & 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & -k_N & k_N \end{bmatrix}$$

$$C_s = \propto_1 M_s + \propto_2 K_S \quad (7)$$

where m_i and k_i are the mass and stiffness of story I, respectively, and ∝1 and ∝2 are constants derived using the damping ratio of the first two fundamental structural periods. For each TMD number (i) installed on a floor (f), the property matrices that account for such a TMD can be formed as follows:

$$K_{d(N+i,N+i)} = K_{di} \quad (8.a)$$

$$K_{d(N+i,f)} = -K_{di} \quad (8.b)$$

$$K_{d(f,N+i)} = -K_{di} \quad (8.c)$$

$$K_{d(f,f)} = K_{di} \quad (8.d)$$

$$M_{d(f,f)} = -\rho_i m_f \quad (9.a)$$

$$M_{d(N+i,N+i)} = \rho_i m_f \quad (9.b)$$

$$C_{d(N+i,N+i)} = 2\xi_{di} m_{di} \omega_{di} \quad (10)$$

where K_{di}, ξ_{di}, and ω_{di} are the stiffness, damping ratio, and frequency, respectively, of TMD number *i*. The mass of the TMD at floor f is defined as qi mf (Eq. (9.b)), where mf is the mass of floor f and qi is the story-TMD mass ratio for story-TMD number i:

$$\rho_i = \frac{m_{di}}{m_f} \quad (11)$$

F defined in Eq. (1) is the applied dynamic load vector, which is defined herein for wind (Fw) as a sinusoidal dynamic load and for an earthquake (FQ) using the ground acceleration record, as shown in Eqs. (12) and (13), respectively. The structure equation of motion is then solved using the Newmark-b procedure [23], which gives the nodal displacement, velocity, and acceleration vectors at each time step.

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$$F_w = A\sin(\omega t)I$$

$$F_Q = -MI\ddot{x}_g$$

where A is an arbitrary sinusoidal load amplitude, x is the frequency of wind excitation, x€g is the earthquake ground acceleration, and I is the unit direction influence vector defined here for both earthquake and wind loads as a unit vector of size N + Nd, where Nd is the number of stories used as TMDs.

Verification of numerical analysis

To verify the numerical analysis and the developed MATLAB code, the solution for a 10-story shear building previously obtained by Arfiadi and Hadi [15] (reference case) is used. The same building properties shown in Table 1 are considered, and the same TMD properties are applied (Cd = 175.033 kNs/m, Kd = 4540.369 kN/m, and a 115-ton TMD is located on the 10th floor). First, the fundamental mode shape obtained from the MATLAB code developed using the previously defined equations is compared with the results of Arfiadi and Hadi [15], as listed in Table 2. As can be seen from the table, the mode shape results are identical to the results obtained in the reference case. To verify the numerical integration procedure and the TMD effect, the time history of the top-floor lateral displacement of uncontrolled and controlled 10-story buildings (verification example) subjected to the El-Centro earthquake is obtained (Fig. 2); in the figure, the top-floor lateral displacement is plotted against time. This time history is similar to that for the reference case, with a response peak of 266.8 mm after 4.78 s for the uncontrolled building and a peak of 163.2 mm after 5.88 s for the controlled building.

Table 1 Properties of reference case (10 story building) [15].

Stories	1–2	3	4–6	7	8–9	10
Story stiffness (kN/m)	1410587.5	1410587.5	1048724.2	1048724.2	367187.5	367187.5
Story mass (ton)	572.92	567.62	562.32	548.82	535.32	489.32

Table 2 Comparison between fundamental mode shapes of present study and reference case.

Source	Fundamental mode shape										
This study	0	0.0914	0.18182	0.2686	0.37884	0.48	0.56967	0.64571	0.81979	0.9405	1.0
Ref. [15]	0	0.0917	0.1818	0.2686	0.3788	0.48	0.5697	0.6457	0.8198	0.9405	1.0

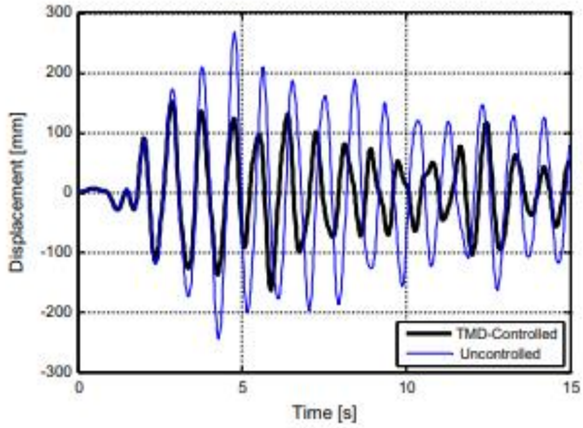

Fig. 2 Time history of top-floor lateral displacement (verification example).

The distribution of the maximum story drift along the building height is plotted in Fig. 3; again, the distribution shows the same behaviour as that for the reference case with acceptable differences. For the uncontrolled building, a peak is observed at266.8 mm, which is approximately 6.7% more than the peak observed for the reference case, and for the controlled building, a peak is observed at 163.2 mm, which is approximately 8.8% more than the peak observed for the reference case [15]. The above discussion illustrates the validity of the numerical procedure used and the acceptable accuracy of the obtained results.

Examples and loads

To illustrate the proposed idea and explore its effect on building response, three example structures were considered to represent low-, mid-, and high-rise buildings. The buildings have 5, 25, and 50 stories with uniform properties along the

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height as shown in Table 3. For each example, first, TMDs are employed in a few uppermost stories as shown in Fig. 1 because previous studies reported that the optimum response of buildings can be obtained if TMDs are located in the upper floors [24]. Each example building is first subjected to sinusoidal loads with different excitation frequency ratios, and the effect of the existence of story-TMDs on the peak dynamic response and resonance frequency is investigated. Using the frequency that generates the peak response of the building, a relation is derived between the story-TMD mass ratio (qi) and the main response parameters when different number of stories are used as TMDs. The building response to earthquakes is investigated by using three major known earthquakes: El-Centro, Parkfield, and Loma Prieta. The average response is studied in terms of qi to show how the seismic response of a building is affected by different TMD arrangements.

Results and discussion

Dynamic response of low-rise building

To investigate the response of the five-story low-rise building to dynamic loads, the TMD is located at the uppermost storyand the uppermost two, three, and four stories; in addition, the case of the original building without TMDs is considered. Dynamic sinusoidal loads are applied with different excitation frequency ratios rx, which is defined as the ratio of the applied load frequency x to the natural fundamental period xn0 of the original building:

Table 3 Main properties of building examples.

Example	Story stiffness (kN/m)	Story mass (ton)	Fundamental period (s)
Five story	1.20×10^6	900	0.60
Twenty-five story	1.80×10^6	1000	2.40
Fifty stories	2.60×10^6	1200	4.33

$$r_\omega = \frac{\omega}{\omega_{n0}}$$

$$r_\omega = \frac{\omega}{\omega_{n0}} \qquad (14)$$

The story-TMD mass ratio pi defined in Eq. (11) is taken as 25% for all the cases as a guide value, which indicates that one quarter of the story mass of the selected stories is used as TMDs. The response of the five-story building to sinusoidal loads with different excitation frequencies is illustrated in Figs. 4–9. In Fig. 4, the maximum top drift ratio rd is plotted against rx. rd is defined as the top-story maximum drift normalized with respect to the top-story maximum drift of the original building subjected to excitation with rx = 1. The case of the original building and those with one-, two-, and fourstory TMDs at the uppermost floors are shown in the figure. It is observed that the maximum drift of the original building varies with rx such that the peak response is located at rx = 1, and as this ratio moves away from unity, the drift response tends to decrease. This peak response is too much as compared to the response for rx much more or less than unity such that the peak response exceeds 3.56 times the response for rx is only 10% more or less than unity. The case in which the uppermost floor is used as a TMD shows a different response from the other cases; that is, the peak response is greatly reduced, and its location is slightly moved toward a higher value of rx. The peak response of rd for the case of a one-story TMD is approximately 18.55% of that for the original building, and resulting value of rx equals 1.08. It should be noted that this case corresponds to the TMD mass ratio of 5% of the overall building mass. Adding more TMDs at the uppermost stories of the building gives similar results. The peak drifts of two- and four-story TMDs are recorded to be 13.73% and 12.11% of the reference value, respectively, and are located at rx = 1.16 and 1.24, respectively. At rx = 1, the maximum top drift is reduced to 15.87%, 10.21%, and 7.88% of that of the originalbuilding for one-, two-, and four-story TMDs, respectively.

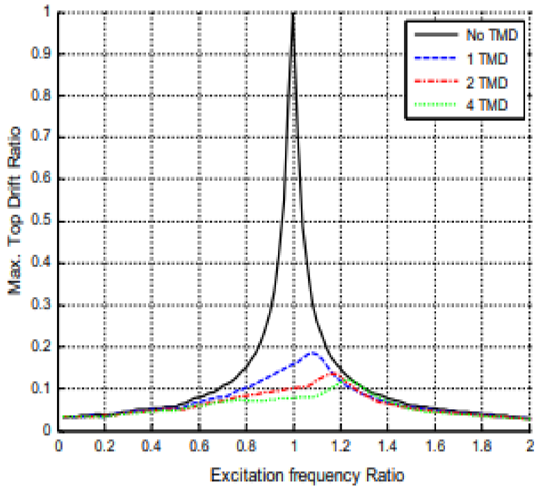

Fig. 4 Relation between maximum top drift and r_ω for five-story building subjected to sinusoidal loads (ρ_i = 25%).

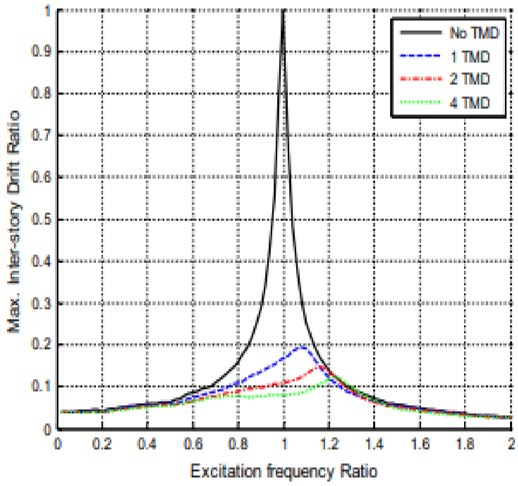

Fig. 5 Relation between maximum inter-story drift and r_ω for five-story building subjected to sinusoidal loads (ρ_i = 25%).

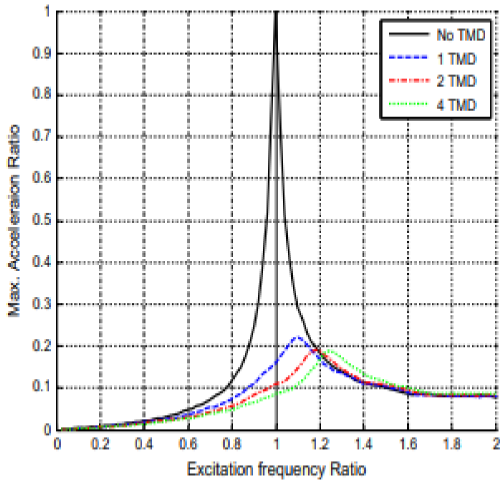

Fig. 6 Relation between maximum acceleration and r_ω for five-story building subjected to sinusoidal loads (ρ_i = 25%).

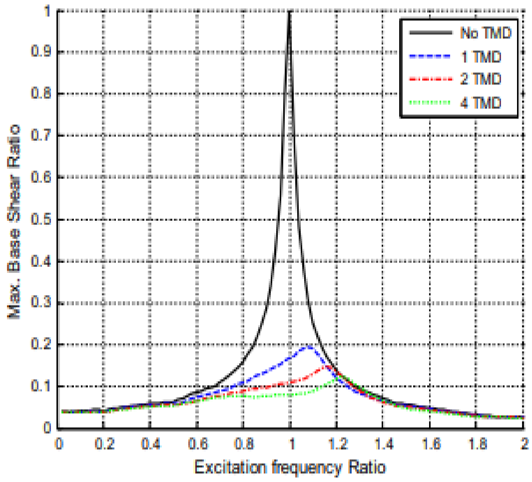

Fig. 7 Relation between maximum base shear and r_ω for five-story building subjected to sinusoidal loads (ρ_i = 25%).

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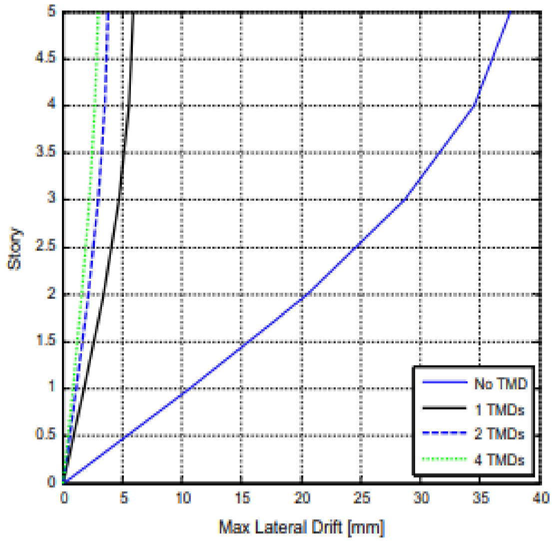

Fig. 8 Maximum story drift distribution for five-story building subjected to sinusoidal loads (ρ_i = 25%).

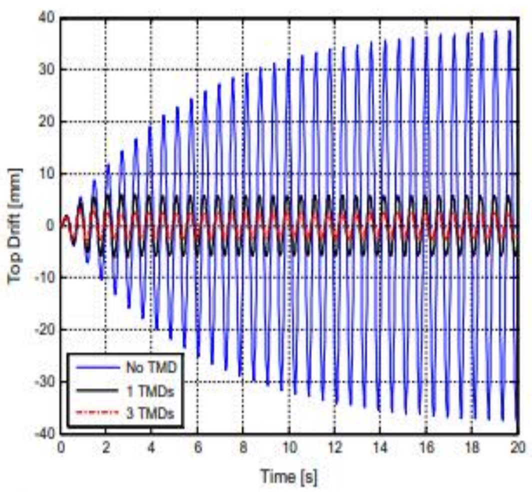

Fig. 9 Time history of top drift for five-story building subjected to sinusoidal loads (ρ_i = 25%).

These cases correspond to TMD mass ratios of 5%, 10%, and 20%. The relation between the excitation frequency ratio and the maximum inter-story drift ratio is plotted in Fig. 5. The maximum inter-story drift ratio ri is defined here as the maximum inter-story drift normalized with respect to that of the original building excited by a sinusoidal load with rx = 1. The inter-story drift is selected because it is a major indicator of story shear identified by design and limited by codes. The peak of the maximum inter-story drift for the original building is observed at rx = 1; the use of TMDs reduces such peaks considerably and shifts their locations to higher values of rx. The peaks for one-, two-, and four-story TMDs are observed to be 19.48, 14.78, and 12.35% of the reference value, respectively, and are located at rx = 1.08, 1.16, and 1.22, respectively.

The acceleration and base shear response of buildings without and with TMDs are shown in Figs. 6 and 7; in these figures, the maximum acceleration ratios and base shear ratiofor all the cases are plotted against rx. The behaviours of acceleration and base shear are similar to that of drift in terms of the peak values and resonance criteria. The existence of TMDs reduces the peak maximum acceleration by 22.15% at rx = 1.1, 19.07% at rx = 1.18, and 18.78% at rx = 1.24 for the cases of one-, two-, and four-story TMDs, respectively, compared to the original case in which the maximum acceleration is observed at rx = 1. It is clear that the acceleration response improves for the one-, two-, and four story TMDs much better than the original building. On the other hand, the base shear ratio significantly improves because of the existence of TMDs, with the peak excitation frequency ratio shifting toward higher values. The base shear ratio is reduced to 19.48% at rx = 1.08, 14.78% at rx = 1.16, and 12.35% at rx = 1.22 for the cases of one-, two-, and four-story TMDs, respectively, compared to the original case in which the maximum acceleration is observed at rx = 1.

An overview of the improvements in the drift response for buildings with multiple-story TMDs is shown in Fig. 8; here, the variation in the maximum lateral drift with the building height is shown for different cases. As discussed before, the existence of TMDs enhances the drift distribution significantly at all heights and reduces the top drift to 18.55%, 13.73%, and 12.11% of that of the original building because of the addition of the one-, two-, and four-story TMDs. Fig. 9 shows the time history of the top-floor lateral displacement of the five-story building for different cases of multiple-story TMDs. In the plot, the lateral drifts at the top of the building are plotted against time for qi = 25% andrx = 1. For the original building with no TMD, the resonance response is clear; that is, the lateral drift continues to increase with time until the

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excitation stops. On the other hand, the existence of TMDs at one or more stories changes the behaviour considerably toward stable vibration with relatively small amplitudes. Although oneand three-story TMDs show such improvement and stability, the values of the maximum lateral drift in the case of the three-story TMDs are reduced by 53.2% compared to that in the case of the one-story TMD. It can be concluded that by considering 25% of the top floor as a TMD, the response of the lateral top drift can be reduced to 15.87% of the original building while considering the same for two extra levels (fourth and third stories) improves this reduction to 7.88%.

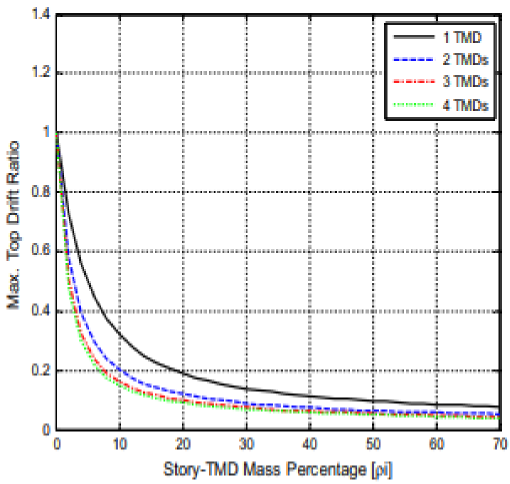

Fig. 10 Variation of maximum top drift with ρ_1 for five-story building subjected to sinusoidal loads ($r_\omega = 1$).

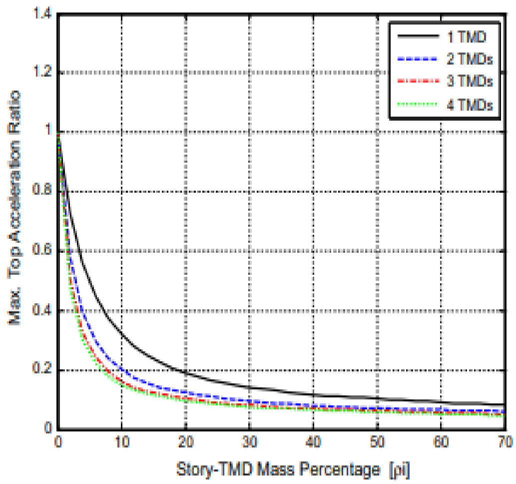

Fig. 11 Variation of maximum top acceleration with ρ_1 for five-story building subjected to sinusoidal loads ($r_\omega = 1$).

Owing to the importance of the share of the floor load reserved as TMDs, the effect of qi on the maximum top lateral drift and maximum top acceleration is examined for the case of rx =1(Figs. 10 and 11). Fig. 10 shows that as qi increases, the lateral top drift of the building decreases for any number of stories used as TMDs. This increase can be simply attributed to the increase in the overall TMD mass ratio, which produces more response enhancements [3,11]. The rate of reduction in the maximum top drift decreases with increasing qi such that in the case of a one-story TMD, the first 30% of qi reduces the top drift by approximately 86.1% whereas the latter 70% of qi increases the reduced value only by 6.1%. The same effect is observed for the cases of two-, three-, and four-story TMDs with greater reduction in the response. The greatly enhanced value of the maximum inter-story drift was only 7.8%, 5.2%, 4.3%, and 3.9% of that of the original building for the cases of the one-, two-, three-, and four-story TMDs, respectively, at qi = 70%. The acceleration response of the five-story building to sinusoidal loads is shown in Fig. 11; in the figure, the top acceleration ratio is plotted against qi. The top acceleration is observed to decrease sharply with increasing qi for small values of qi and continues to decrease at a lower rate for higher values of qi. In all the cases, the acceleration response of the building with TMDs is much lower than that of the original building. The top acceleration reaches its least values of 8.4%, 6.1%, 5.1%, and 4.7% of that of the original building for the cases of the one-, two-, three-, and four-story TMDs, respectively, at the maximum qi value. Approximately 94% of the acceleration enhancements are observed for the first 30% of qi; that is, 85.9% reduction in the top acceleration is observed for qi = 30%, whereas 91.5% reduction in the top acceleration is observed for qi = 70%.

Earthquake response of low-rise building

As discussed earlier, for the low-rise building subjected to sinusoidal loads and having multiple-story TMDs located at the uppermost story and uppermost two, three, and four stories for any value of qi, considerable enhancement in its displacement and force behaviour was observed. To investigate the response of the building to earthquakes, time history analysiswas carried out on the building using three known earthquake records. El-Centro, Parkfield, and Loma Prieta were selected as known earthquakes with different characteristics. The average response was compared to indicate how the response of a building is affected by earthquakes in general. Fig. 12 shows the seismic average maximum top drift response of the fivestory building to the selected earthquakes. The figure plots the relation between the average top drift ratio and qi for buildings with one-, two-, three-, and four-story TMDs subjected to the ground acceleration of the selected earthquakes. It is clear from the plot that the top drift response of the building is enhanced (decreased) when qi is increased, for any number of stories used as TMDs. The decrease in the top drift with increasing qi continues in the case of a one-story TMD, whereas for more TMDs, this decrease continues up to a specific value of qi. It is also observed that the for two-, three-, and four-story TMDs, no response enhancement is gained after qi = 60%, 45% and 45%, respectively which can be attributed to the simultaneous increase of the number of TMDs and the mass ratio leading to the least possible reduced response. In all the cases, the drift of the low-rise building with multiple-story TMDs is less than that of the original building. The optimum values of the top drift reach 53% at qi = 70% for the onestory TMD, 46% at qi = 60% for the two-story TMDs, 45% at qi = 70% for the three-story TMDs, and 44% at qi = 70% for the four-story TMDs. A similar response can be observed in Fig. 13 for the maximum inter-story drift, which is plotted against qi, for buildings with one-, two-, three-, and four-story TMDs subjected to the ground acceleration of the selected earthquakes. The average value of the maximum inter-story drift is also observed to be enhanced when more number of stories are used as TMDs and for higher values of q. The rate of enhancement is observed to be more for lower values of qi. For a one-story TMD, the decrease in the top drift with increasing qi continues, whereas for more TMDs, this decrease continues up to a specific value of qi. The response tends to increase after this qi value, which is 60%, 45%, and 40% for the two-, three-, and four-story TMDs, enhancement can take place. In all the cases, the maximum inter-story drift of the low-rise building with multiple-story TMDs is less than that of the original building. The optimum values of the maximum inter-story drift reach 56% at qi = 70% for the one-story TMD, 50% at qi = 60% for the two-story TMDs, 51% at qi = 45% for the three-story TMDs, and 48% at qi = 55% for the four-story TMDsrespectively. This trend can be attributed to the large increase in the overall mass ratio, which reaches 48%, 36%, and 32% for the above-mentioned cases beyond them noenhancement can take place. In all the cases, the maximum inter-story drift of the low-rise building with multiple-story TMDs is less than that of the original building. The optimum values of the maximum inter-story drift reach 56% at qi = 70% for the one-story TMD, 50% at qi = 60% for the two-story TMDs, 51% at qi = 45% for the three-story TMDs, and 48% at qi = 55% for the four-story TMDsThe top-story acceleration response of the five-story building to earthquakes is shown in Fig. 14; in the figure, the maximum top-story acceleration ratio is plotted against qi. It can be clearly observed from the plot that the acceleration response of the building is significantly enhanced when TMDs are present and when the values of qi are increased. The rate of enhancement is initially sharp at low values of qi and then decreases as qi increases. The values of the top acceleration reach their minimum values of 74%, 69%, 66%, and 66% of the original building response for the one-, two-, three-, and four-story TMDs with qi = 70%. The base shear response to earthquakes of the low-rise building is shown in Fig. 15. For one- and two-story TMDs, the maximum base shear ratiostend to decrease with increasing qi, whereas for three- and four-story TMDs, the base shear ratios decrease up to a certain value of qi, after which the base shear ratios increase with further increase in qi. Thus, for one- and two-story TMDs, the minimum response occurs at qi = 70% and is 55% and 47%, respectively, of the base shear of the original building. The minimum values of the base shear for three- and fourstory TMDs are observed to be 47% and 48%, respectively, of the base shear of the original building at values of qi = 45% and 40%, which are the inflection points after which the base shear increases. It is also noted from the above values that the two- or three-story TMDs have the same values of minimum base shear but at different values of qi and these base shear values are more optimized compared to the cases of oneor four-story TMDs.

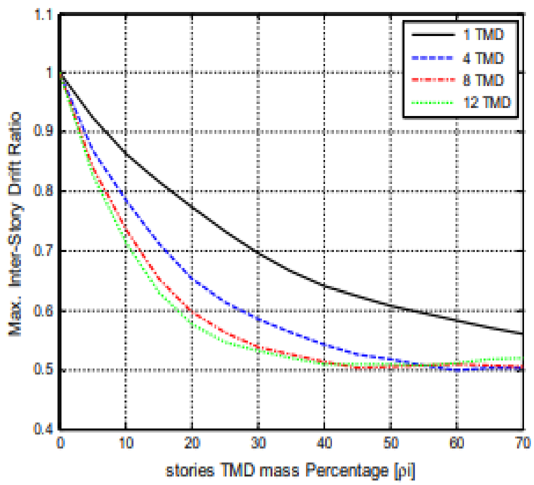

Fig. 13 Variation of maximum inter-story drift with ρ_1 for five-story building subjected to earthquakes.

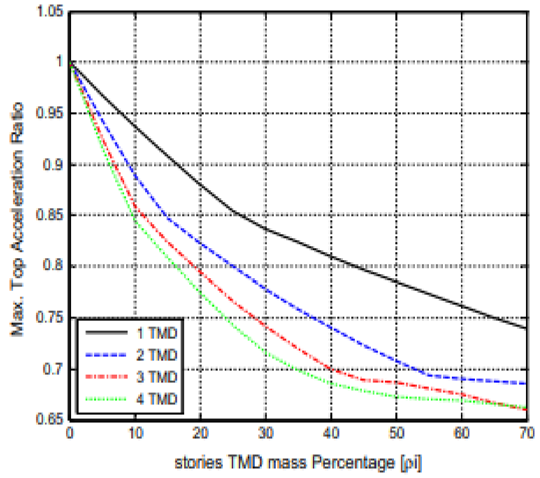

Fig. 14 Variation of maximum top acceleration with ρ_1 for five-story building subjected to earthquakes.

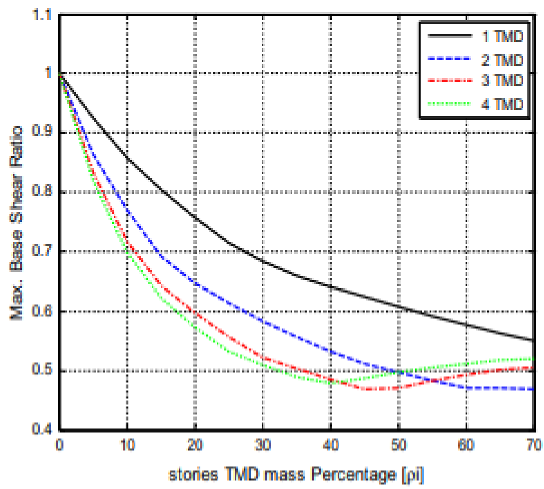

Fig. 15 Variation of maximum base shear with ρ_1 for five-story building subjected to earthquakes.

Dynamic response of mid- and high-rise buildings

As discussed earlier, the use of a portion of the floor load of limited stories as TMDs enhances the behaviour of the lowrise building subjected to sinusoidal and earthquake loads. In this section, sample results for mid- and high-rise buildings are presented. Fig. 16 shows the relation between the maximum lateral top drift and the excitation frequency ratio rx for the selected 25-story building by applying multiple-story TMDs at limited floors

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with qi = 25% for all the cases. As shown in the figure, the peak drift value of the original building is observed to be at rx = 1, and the value decreases as rx becomes more or less than unity. If the peak response frequency for the original building is changed by only 20%, the drift response for the 25-story building may reduce by approximately 47.3%. As more TMDs are used, the peak response is significantly reduced and the peak response frequency ratio shifts toward higher frequency ratios. The existence of four-, eight-, and twelve-story TMDs resulted in a reduction in the peak drift to 53.3%, 42.9%, and 39.5% respectively, at frequency ratios that are 1.08, 1.16, and 1.22 times the natural frequency of the original building. The response of high-rise building (50 stories) to sinusoidal loads is shown in Fig. 17. It can be observed that the drift behaviour of the 50-story

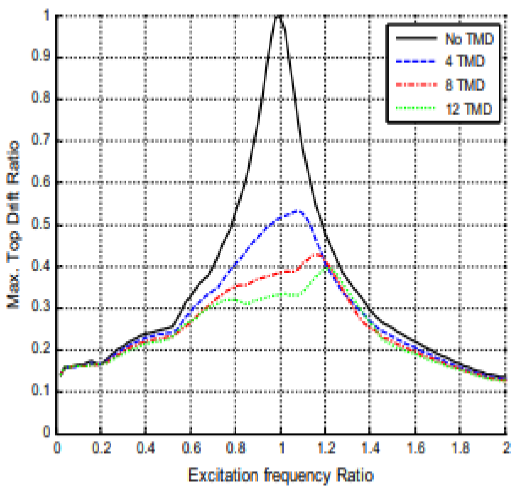

Fig. 16 Relation between maximum top drift and r_ω for 25-story building subjected to sinusoidal loads (ρ_i = 25%).

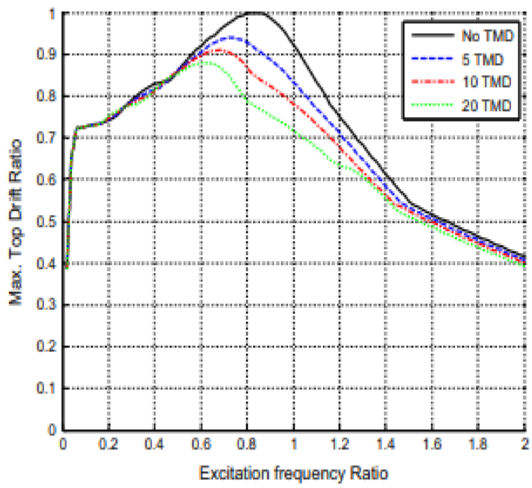

Fig. 17 Relation between maximum top drift and r_ω for 50-story building subjected to sinusoidal loads (ρ_i = 25%).

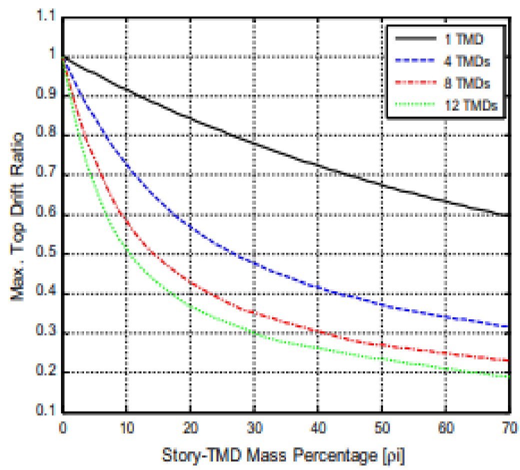

Fig. 18 Variation of maximum top drift with ρ_i for 25-story building subjected to sinusoidal loads (r_ω = 1).

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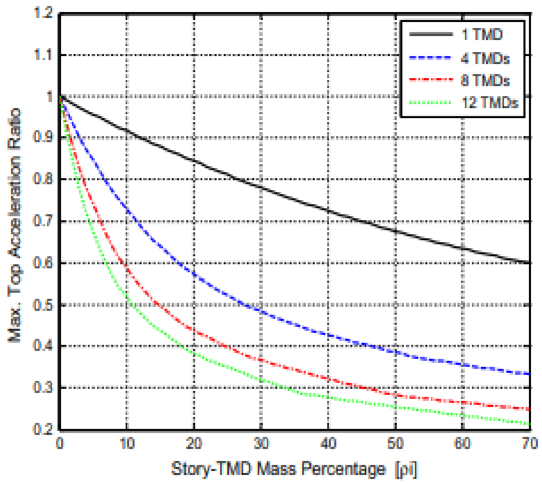

Fig. 19 Variation of maximum top acceleration with ρ_l for 25-story building subjected to sinusoidal loads (r_ω = 1).

Building is different from the behaviour of the low-rise building or the 25-story building. For the original building, the peak drift response is observed to have shifted from the unity frequency ratio such that peaks are found at rx = 0.84 for the 50-story building. Adding multiple-story TMDs reduces the peak drift response and shifts the peak frequency ratios to lower values. Adding five-story TMDs reduces the peak to 94% of that of the original building at rx = 0.74. Adding 10- or 20-story TMDs results in more reduction in the drift response and leads to the generation of two peaks, with the effective one located at a value of rx that is less than the original building peak response frequency ratio. The peak values of the top drift are 91% and 87.7% for the cases of 10- and 20-story TMDs, respectively, at frequency ratios of 0.68 and 0.62. At the frequency ratio of the peak response of the original building, the 5-, 10-, and 20-story TMDs reduced the drift response to 91.2%, 84.5%, and 77.5%, respectively.

The effects of qi on the maximum drift and acceleration of the 25-story building under sinusoidal dynamic loads are shown in Figs. 18 and 19. The top drift ratio normalized with respect to the drift of the original building is plotted in Fig. 18 against qi for buildings with 1-, 4-, 8-, and 12-story TMDs. It can be clearly observed that the drift and acceleration response of the 25-story building decreases with an increase in qi and with the use of more stories as TMDs. When only the uppermost story is used as the TMD, although the mass ratio of the TMD to the structure load is still low, the drift and acceleration responses decrease to 59.6% and 59.8% of the original drift and acceleration responses, respectively, at qi = 0.7, which is the maximum ratio examined. As the number of stories and TMDs increases, more enhancement of the drift and acceleration response is observed. For 4-, 8-, and 12-story TMDs, the drift response decreases to 31.7%, 23%, and 18.9%, respectively, of the original response and the acceleration response decreases to 33.3%, 24.9%, and 21.4%, respectively, of the original response. The same relations for the drift and acceleration for the 50-story building are shown in Figs. 20 and 21. Only minor enhancement of the drift and acceleration responses is observed for a one-story TMD. The decrease of only 6.1% and 6.5% for the drift and acceleration,

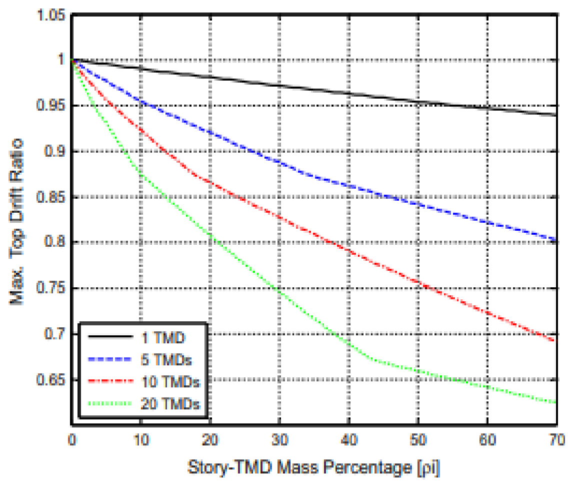

Fig. 20 Variation of maximum top drift with ρ_L for 50-story building subjected to sinusoidal loads (r_ω = 1).

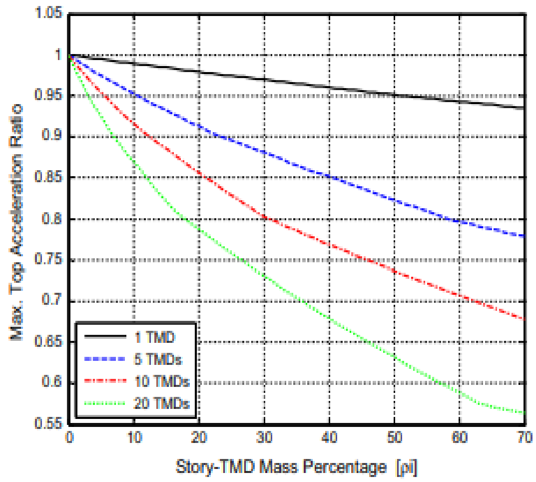

Fig. 21 Variation of maximum top acceleration with ρ_l for 50-story building subjected to sinusoidal loads (r_ω = 1).

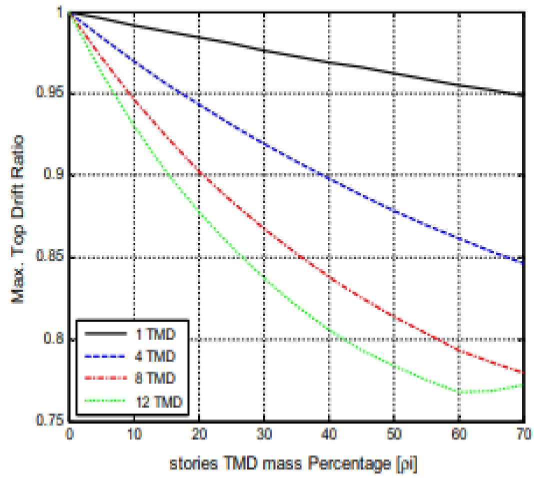

Fig. 22 Variation of maximum top drift with ρ_l for 25-story building subjected to earthquakes.

Respectively, is attributed to the small overall mass ratio in this case. As the number of stories used as TMDs increases, the enhancement increases and a decrease in the drift of 19.7%, 30.9%, and 37.6% is observed for the 5-, 10-, and 20-story TMDs, respectively. The acceleration response shows similar behaviour; for the 5-, 10-, and 20-story TMDs, a reduction in the top acceleration of 22.1%, 32.2%, and 43.7%, respectively, is observed.

Earthquake response of mid- and high-rise buildings

This section discusses the response of the 25- and 50-story buildings to earthquakes by using the three previously mentioned earthquake records. For the 25-story building, the average maximum lateral top drift is plotted in Fig. 22 against qi when different number of stories is used as TMDs. As shown in the figure, the average drift decreases as qi increases for the one-, four-, and eight-story TMDs. For the twelvestory TMDs, the average drift decreases with pi up to qi = 60%, after which the average drift ratio begins to increase. This can be attributed to the increase in the overall TMDs mass ratio in addition to the existence of twelve levels of TMDs, which complicates the behaviour of the structure in different ways. In all the cases, the increase in the number of TMDs decreases the drift response of the building to earthquakes. The minimum drift responses recorded for one-, four-, and eight-story TMDs at qi = 70% are 95%, 85%, and 78% of the drift of the original building, respectively. For the 12-story TMDs, the minimum average drift value is 76.8% of the original drift at qi = 60%. As shown in Fig. 23, the relation between the average acceleration ratio and qi exhibits similar behaviour but with different values of response ratios. The acceleration is less affected by qi, and the maximum reduction in the maximum top acceleration ratio reaches only 5% for the 12-story TMDs with qi = 70%. For the one- and four-story TMDs, the average acceleration ratio decreases with qi, reaching 98.9 and 96.6%, respectively. For the 8- and 12-story TMDs, the average maximum acceleration ratio decreases to an optimal value at qi = 55% and 40% respectively, and then increases for higher values of qi. This behaviour emphasizes the importance of selecting the proper number and properties of TMDs to avoid any adverse effects on the building behaviour.

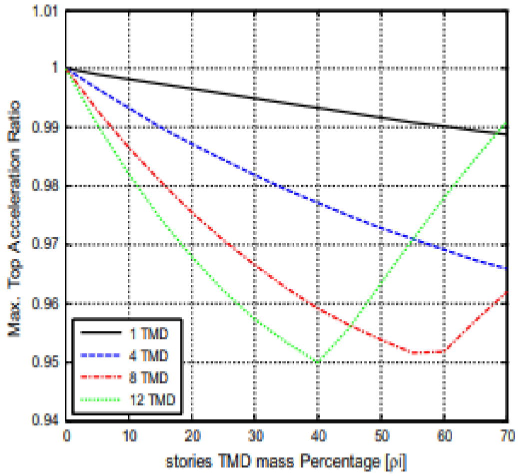

Fig. 23 Variation of maximum top acceleration with ρ_I for 25-Story Building Subjected to Earthquakes.

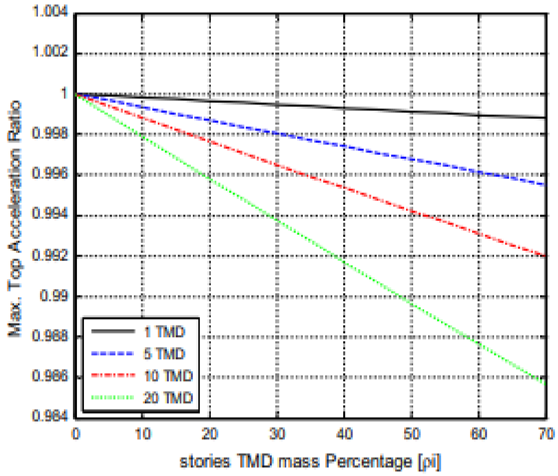

Fig. 25 Variation of maximum top acceleration with ρ_I for 50-story building subjected to earthquakes.

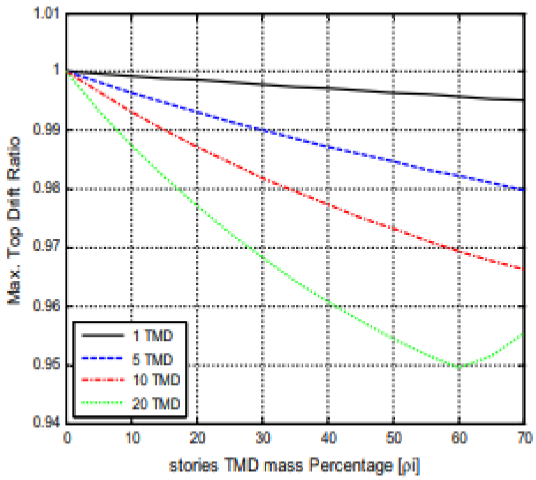

Fig. 24 Variation of maximum base shear with ρ_I for 50-story building subjected to earthquakes.

For the 50-story building, the average maximum lateral top drift is plotted in Fig. 24 against qi when different number of stories is used as TMDs. As shown in the figure, the average drift decreases as qi increases for the 1-, 5-, and 10-story TMDs. For the 20-story TMDs, the average maximum drift decreases with qi up to qi = 60%, after which the average drift ratio tends to increase. This trend can be attributed to the abnormal increase in the overall TMD mass ratio, which affects the behaviour of the building in different ways. In all the cases, the increase in the number of TMDs decreases the drift response of the building to earthquakes. The minimum drift responses recorded for the 1-, 5-, and 10-story TMDs at qi = 70% are 99.5%, 98%, and 96.6% of the drift of the original building; for the 20-story TMDs, the minimum average drift value is 95% of the original drift at qi = 60%. The relation between the average acceleration ratio and qi is plotted in Fig. 25, which shows a slight improvement in the response. In all the cases, the average top acceleration ratio is enhanced as qi increases and the number of TMDs increases. The decrease in the acceleration response is as little as 0.1%, 0.4%, 0.8%, and 1.4% of the original acceleration for the 1-, 5-, 10-, and 20-story TMDs, respectively.

Summary and conclusions

In this work, we discuss the concept and theoretical underpinnings of utilising a building's uppermost floors as numerous TMDs. After the formulation of the suggested system, the reaction of a few representative structures to wind and earthquakes is examined. To properly depict low-rise, medium-rise, and high-rise structures, 5-story, 25-story, and 50-story buildings are chosen for the study. For analysing the effects of wind, sinusoidal dynamic loads at varying frequencies are used, while whileanalysing the effects of earthquakes, data from significant quakes like El-Centro, Park field, and Loma Prieta are consulted for seismic analysis. The following evidence confirmed the viability of the suggested notion in enhancing the reaction of structures to wind and earth quakes:

The existence of multiple-story TMDs significantly reduces the drift, acceleration, and force response of all examined buildings subjected to sinusoidal dynamic loads.

- The peak response of the original buildings without TMDs to sinusoidal loads is observed at rx = 1 for the 5-, and 25- story buildings and slightly below this value for the 50-story buildings. The use of multiple-story TMDs shifts the peak toward higher excitation frequency ratios for the 5- and 25-story buildings and toward lower excitation frequency ratios for the 50-story building.
- An increase in qi and the number of stories utilized as TMDs significantly enhances the response of all types of buildings to sinusoidal loads.
- The response of buildings to earthquakes is also enhanced by the use of more number of stories as TMDs and an increase in qi, especially for low- and mid-rise buildings. For high-rise buildings, this enhancement is not substantial because of the nature of the buildings and the earthquake ground motions selected. Better selection of the building and TMD parameters might provide better results in terms of the response of buildings to earthquakes.

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