VIBRATION CONTROL OF A MULTI-STOREY BUILDING HAVING MASS IRREGULARITY USING SINGLE TUNED MASS DAMPER (STMD) AND MULTIPLE TUNED MASS DAMPERS (MTMDS).

MS STRUCTURES THESIS DISSERTATION

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THESIS ACCEPTANCE CERTIFICATE

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Date: _____________________________

DEDICATION

I dedicate this research to my supervisor

Dr. Muhammad Usman, My Parents, Uncles

and specially my elder brother

Mr. Inam Ullah khan.

ACKNOWLEDGEMENTS

All praise be to Allah Almighty alone

With immense gratitude, I would like to thank my mentor and advisor Dr. Muhammad Usman for his endless support, patience and knowledge which kept me in the right direction throughout my research work.

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Abstract

Tall buildings are necessary need of modern world due to shortage of land in commercial areas. Earthquake and wind loads produce undesirable vibrations in these buildings. There are several vibration control techniques available for mitigation of undesirable vibrations. Provision of an additional tuned mass damper at top of the structure is one of the classic techniques being used in several high-rise buildings. Tuned mass damper is a passive control technique used for vibration mitigation of high-rise structures subjected to wind and seismic loadings. Basic principle of tuned mass damper is to dissipate the energy produced from vibration of structures with help of out of phase vibrations of tuned mass damper with the structure. Irregularity in structure increases the vibrations produced from these loadings. In this study, a detailed experimental work is carried out for vibration mitigation of a 4-storey structure having mass irregularity at its 4th floor using single tuned mass damper (STMD) and multiple tuned mass dampers (MTMDs) against different harmonic and seismic loadings. Positions of STMD and MTMDs were varied along each floor and all possible configurations of STMD and MTMDs were tested against these loadings. For comparison acceleration response of each storey measured with help of portable accelerometer for all configurations of STMD and MTMDs were compared with that of the uncontrolled structure. It is found that under all types of loadings STMD reduces acceleration response of all floors of uncontrolled structure similarly all configuration of MTMDs shows further reduction in acceleration response showing the efficiency of MTMDs over STMD in irregular structures.

Key words: STMD, MTMDs, vibration control, irregular structure.

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CHAPTER 01

1 INTRODUCTION

1.1 BACKGROUND

Dampers are devices which absorb and dissipate energy produced in structures due to vibrations created from earthquake loadings. Damper enhances energy dissipation in structures due to which resistance to earthquake loadings is increased and vibration occurs due to these loadings are decreased.

When earthquake occurs the base of building starts moving due to inertia the buildings tries to come back to its original position. Due to which the building suffers distortion and a distortion wave travels along height of building. Dampers are used to dissipate the distortion wave by absorbing energy thus reduces distortion and controls vibration.

Different types of dampers are used for this purpose:

In viscous dampers a viscous fluid is used inside a cylinder for energy dissipation. Also it consists of piston as shown in Figure 1.1. This piston moves when the main structure applied force on damper and absorbs the energy produced from the structural vibrations. Viscous dampers are used in high rise buildings to reduce vibrations of building.

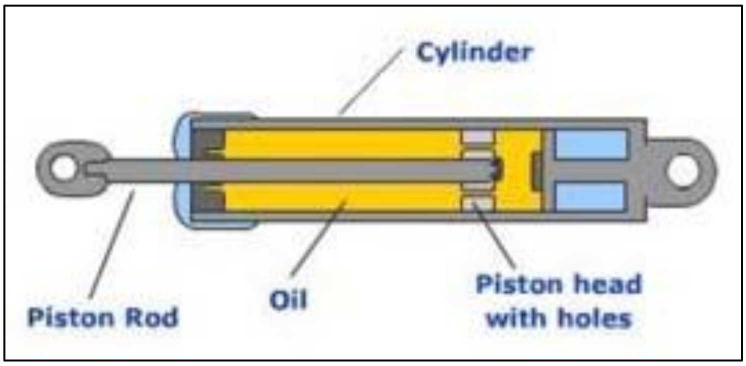

Figure 1.1: Viscous damper

In friction dampers the energy is absorbed by friction occurs between metals or surfaces in friction. Typically friction damper consist of several steel plates sliding against each other in opposite direction to absorb the energy.

Another type visco-elastic damper have a combination of metal with an elastomer is placed for the absorption and dissipation of energy. Main difference from viscous damper is that here instead of viscous fluid a visco-elastic fluid or an elastomer is used as shown in Figure 1.2 . Mainly energy is absorbed by utilizing controlled shearing of solids.

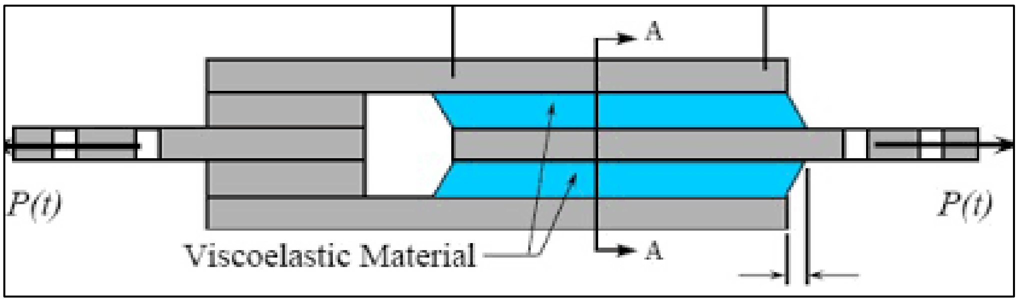

Figure 1.2: Viscoelastic dampers

Tuned mass damper is a device consists of a mass, spring and a damper that is attached to a structure without any other support to reduce vibration produces from earthquake in a structure. For the reduction of vibrations tuned mass dampers can be used in two ways single tuned mass dampers and multiple tuned mass dampers. Generally they are used in high rise buildings practical implication of tuned mass dampers includes:

- Taipei 101 (Taiwan)-have World’s largest tuned mass damper.
- Burj Al Arab (Dubai).
- Shanghai World Financial center (China).
- Tehran international tower (Iran).
- Shanghai tower. (China) e.t.c.

The Taipei 101 tuned mass damper has world largest tuned mass damper having mass 660 metric tons. It is placed openly for attraction of tourists shown in Figure 1.3.

Similarly the shanghai world tower has also a unique design of tuned mass damper shown in Figure 1.4 which is also connected with music for attraction of tourists.

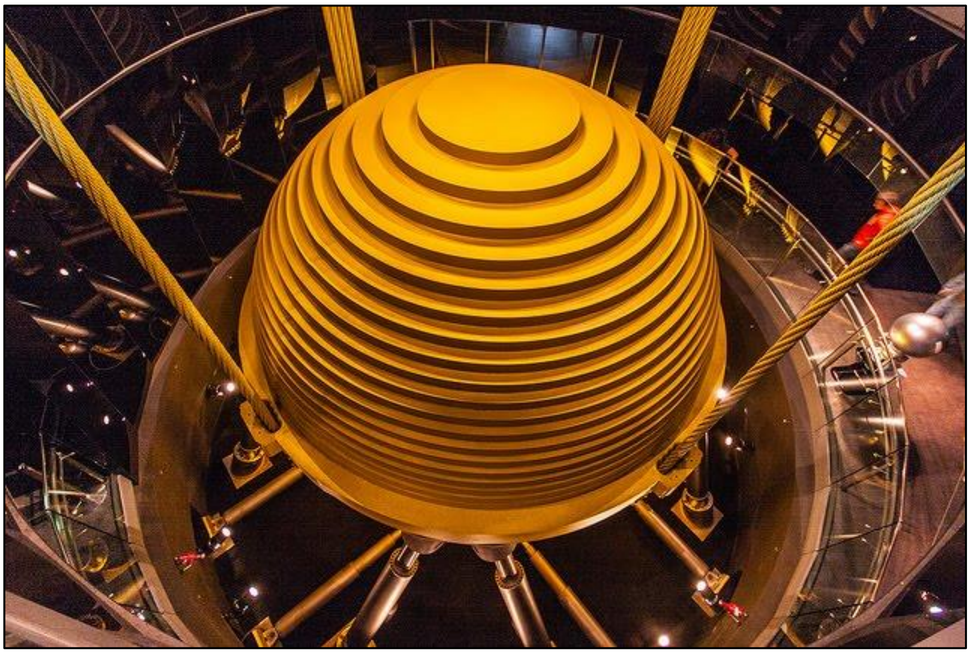

Figure 1.3: Taipei 101 Tuned mass damper

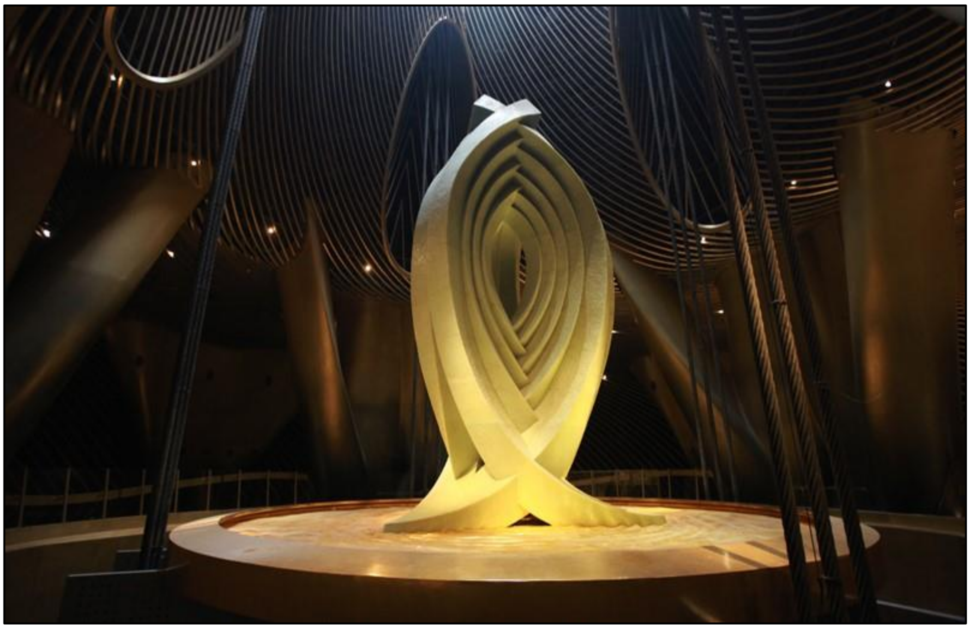

Figure 1.4: Shanghai tower tuned mass damper

1.2 PROBLEM STATEMENT

Mass irregularity in structure increases the vibrations produced due to earthquake and wind loadings. In irregular structures location optimization of TMDs should be carried out to obtain efficient response reduction in vibrations.

1.3 RESEARCH OBJECTIVES

- To investigate how TMD reduces response of the steel frame having mass irregularity.

- To investigate effect of STMD and MTMDs on a steel frame having mass irregularity at its top floor.

- To investigate all possible configurations of STMDs and MTMDs for steel frame having mass irregularity against different harmonic and seismic loadings.

1.4 RESEARCH SIGNIFICANCE

Since construction of tall buildings is basic need of present era due to shortage of land in commercial area. These tall buildings show prominent response to earthquake loadings due its height and irregularities. Many methods were used for the mitigation of these responses like base isolations, tuned mass dampers, tuned liquid column damper, tuned liquid column ball dampers etc.

In this research we will study how tuned mass damper reduces the response of a structure subjected to harmonic and earthquake loadings. We will also discuss how single tuned mass damper and multiple tuned mass dampers reduce responses in building. Previously studies have been carried on use of STMD and MTMDs for regular structure only. This study will also explain how we can use STMD and MTMDs for building having mass irregularities.

1.5 RESEARCH METHODOLOGY

Previously work has been done on use of TMD for mitigation responses of regular structure only. Now in this study we will focus how the STMD and MTMDs reduces response of an irregular structure.

Research Methodology includes following steps:

We have considered an example of a structure having mass irregularity at its top floor.

Three types of cases were considered for the dynamic response of the building

- Building without tuned mass damper
- Building with single tuned mass damper
- Building with multiple tuned mass dampers

For finding the dynamic response of the structure experimental work is being carried out in laboratory using a uniaxial shake table and response of main structure is measured in terms of accelerations. Three types of harmonic loadings having 0.5 Hz, 1 Hz, and 1.5 Hz frequencies, a chirp wave having 0.15cm amplitude, Northridge and Kobe earthquake are used as base excitation for the main structure in laboratory.

1.6 THESIS ORGANIZATION

Chapter 01 gives general introduction to the thesis topic.

Chapter 02 includes literature review carried out related to the research.

Chapter 03 includes research methodology the procedure used for the occurrence of research work.

Chapter 04 includes discussion about the results came from the project.

Chapter 05 includes conclusion.

CHAPTER 02

2 LITERATURE REVIEW

2.1 GENERAL

Studies have been carried out about tuned mass dampers. Tuned mass dampers are used in structures to reduce vibrations produced from earthquake loadings. Basic principle of tuned mass damper is to tune the damper frequency with main structure frequency so that when this frequency is excited the tuned mass damper will resonate out of phase to main structure vibration thus reduces the main structure vibrations. For this purpose single tuned mass dampers and multiple tuned mass dampers are used.

2.1.1 SINGLE TUNED MASS DAMPER

In majority cases single tuned mass dampers are used in buildings to reduce vibration against earthquake. In case of single tuned mass damper a single mass attached to main structure with help of spring in a specific floor at specific position where preferable and properly tuned with fundamental frequency of main structure and thus reduces undesirable vibrations produced from earthquake and wind loadings.

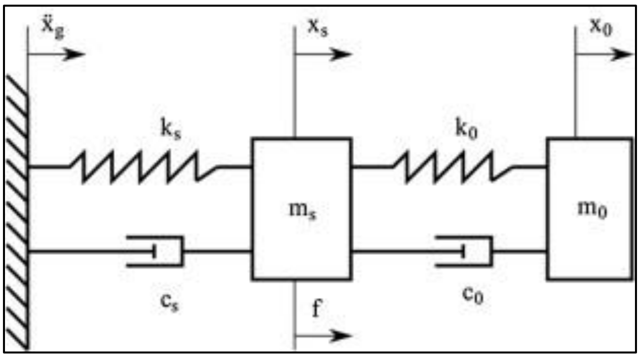

Figure 2.1: Schematic for STMD

2.1.2 MULTIPLE TUNED MASS DAMPERS

In case of multiple tuned mass dampers different TMD’s are distributed at different floors of the building with distributed frequencies, thus building responses are further reduced due to these separately placed dampers. Mostly in multiple tuned mass dampers one tuned mass damper is tuned with the fundamental frequency of main structures while other tuned mass dampers are tuned with the other higher frequencies of the main structure thus reduces the structural response in efficient way.

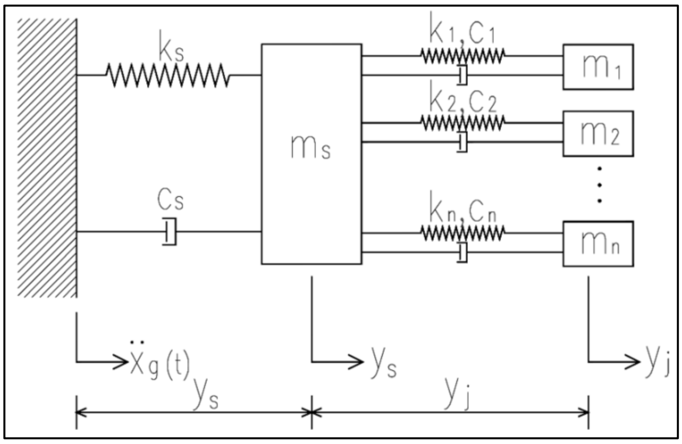

Figure 2.2: Schematic for MTMD

2.2 LEVEL OF RESEARCH ALREADY CARRIED OUT

Many methods were used for controlling unwanted vibrations in high rise buildings produced due to earthquake and wind loadings (Khante and Nirwan 2013). These methods include active mass dampers, hybrid mass dampers passive tuned mass dampers. Among these tuned mass dampers is most popular because of its simple principle and ease in practical implementation. The concept of tuned mass damper was initially given by Fraham in 1909 he used the concept of the tuned mass damper in ships to overcome ships rolling motions and its hull vibrations. Later on, Den Hertog introduced internal damping in tuned mass damper and also carried out work on optimum parameters used in the design of TMD for building structures. A semi-active tuned mass damper (TMD) is proposed to control vibrations in tall buildings due to wind loadings (Elias and Matsagar 2014). The semi-active TMD uses a small amount of external power to activate and add damping to the system. Simulation studies show the proposed system is superior to conventional passively controlled and comparable to actively controlled systems. TMD concept was initially used for reducing vibration induced from wind loadings in structures. Semi-active phenomena has been proposed showing efficiency of semi-active damper over passive active dampers (Hrovat, Barak, and Rabins 1983). In the present era, tall buildings are of great importance due to the shortage of land in commercial areas. Tall buildings are more vulnerable to seismic loadings due to its flexibility and little dampness (Farghaly and Salem Ahmed 2012). Seismic loadings induce undesirable vibrations in these tall buildings. For mitigation of these undesirable vibrations different techniques were used like base isolations (Usman et al. 2009), tuned mass dampers, tuned liquid column dampers, viscous dampers etc. (Kobori et al. 1991). One of the old, simple, economical and most common techniques used for the mitigation of undesirable vibrations is tuned mass damper. Tuned mass damper is a passive control device consisting of a mass, damper, and spring attached to the main structure reduces undesirable vibrations induced from seismic loadings. Basic principle of Tuned mass damper (TMD) is to dissipate the energy produced from structural vibrations induced from seismic and wind loadings. For this TMD frequency is tuned with fundamental frequency of the main structure so that when this frequency is excited during implication of seismic load the TMD will resonate out of phase with main structure motion and hence due to inertial effect of TMD with main structures energy of uncontrolled vibrations is dissipated from main structure to TMD. Later on, TMD was used for mitigation of vibrations produced from seismic loadings in structures showed good results (Sladek and Klingner 1983). As TMD can resonate only with fundamental frequency of main structure for its more effectiveness the concept of multiple tuned mass dampers (MTMDs) was introduced which shows better results than that of the single tuned mass damper (STMD) (Setareh and Hanson 1992).

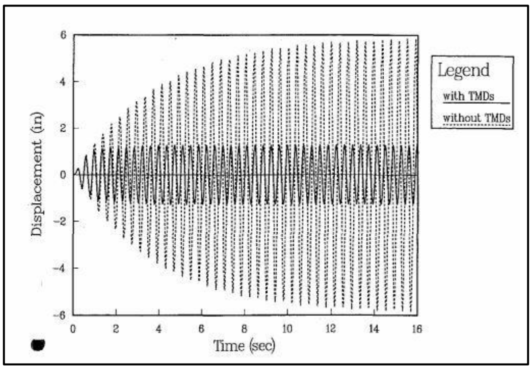

Figure 2.3: MTMD shows better response than STMD (Setareh and Hanson 1992).

Optimal parameters for MTMDs were described to overcome low-damping issues in MTMDs (Abé and Fujino 1994; Zuo and Nayfeh 2005; Özsarıyıldız and Bozer 2015). In critical conditions active tuned mass dampers and semi-active tuned mass dampers were used but mostly preference were given to passive tuned mass dampers due to its economic cost (Kwok and Samali 1995). Besides the cost issue semi-active and active tuned mass dampers were developed which shows efficient results in terms of reduction of dynamic responses (Pinkaew and Fujino 2001; Chung et al. 2013). In addition to the reduction of undesirable vibrations, TMD also reduces damage to the main structure caused by dynamic loadings and helpful in the prevention of collapse of the main structure (Domizio, Ambrosini, and Curadelli 2015). MTMDs performed significantly if they were placed at most suitable locations in the structure also it depends upon the size of MTMDs (Daniel and Lavan 2013; Chen and Wu 2001). Particle tuned mass damper installed in a structure was showing efficient results under seismic loadings (Z. Lu, Chen, and Zhou 2018).

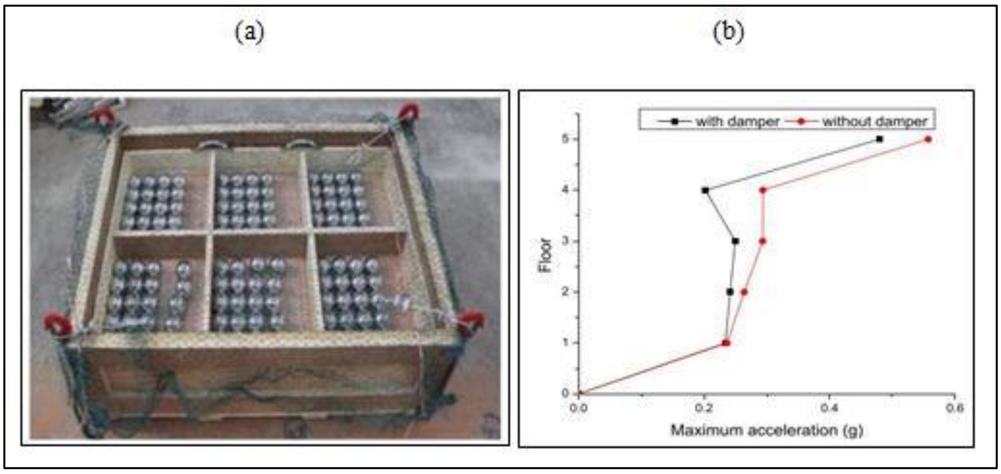

Figure 2.4: (a) PTMD (b) PTMD response (Z. Lu, Chen, and Zhou 2018).

Hybrid structures like tuned mass dampers used along with base isolations efficiently reduce floor accelerations against seismic loadings (Shi, Saburi, and Nakashima 2018). Dynamic response of the irregular structure were more than that of regular structures (Haque 2016; Nigdeli and Bekdas 2013).

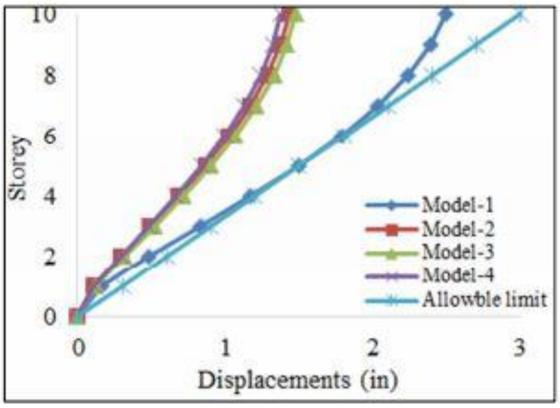

Figure 2.5: Irregular structure Model 1 is showing larger displacements (Haque 2016).

Also, dynamic response of irregular structure has a complex nature and its vibration control require some additional steps (Lei, Wu, and Lin 2012). Dynamic response of irregular high rise buildings with hybrid control system consists of tuned liquid column dampers and passive tuned mass damper was investigated under different seismic loadings (Kim and Adeli 2005).

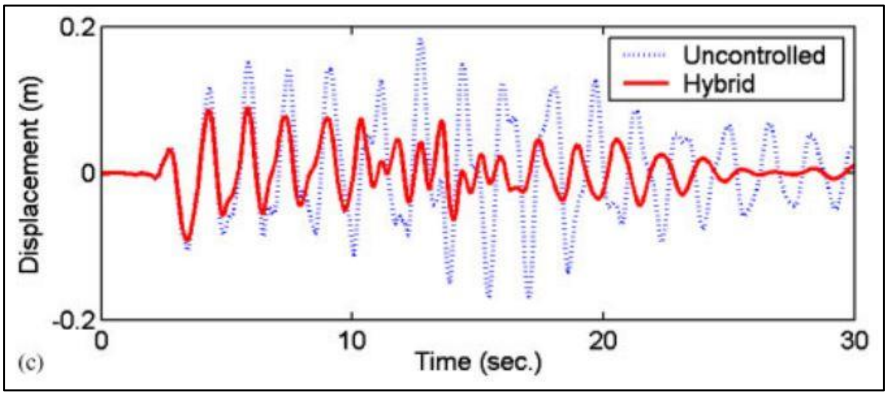

Figure 2.6: Hybrid control response for irregular structures (Kim and Adeli 2005).

Installation of more than one tuned mass damper for an asymmetric building was described showing the significance of the second TMD. Also, optimum parameters like frequency, stiffness, and locations of the tuned mass damper were described. In practical examples shanghai world financial centre one of the china tallest buildings was analysed under wind loadings using two active tuned mass damper placed on 90th floor (X. Lu et al. 2014). These TMD were employed only for wind loadings while during earthquake actuators were turned off and it behaved just like passive tuned mass dampers. Another technique use of bidirectional tuned mass damper was investigated for irregular high rise buildings under seismic loadings and proper equations were developed for tuning parameters of TMD (Soto and Adeli 2014).

2.2.1 TMD RESPONSE AGAINST WING LOAD

Semi-active tuned mass dampers for the first time to control vibrations produced in tall buildings due to wind load. Semi-active dampers need a small external force for its activation. Results show that semi-active dampers perform well than ordinary passive tuned mass dampers (Hrovat, Barak, and Rabins 1983).

2.2.2 TMD RESPONSE AGAINST EARTHQUAKE LOADING

As earlier discussed tuned mass dampers significantly reduces building vibrations when building is subjected to wind loads later on it was studied that tuned mass dampers can reduce vibrations produced from earthquake (Sladek and Klingner 1983). The prototype building having 25 storeys with and without TMD was subjected to El-Centro 1940. Both linear elastic and non-linear inelastic analysis were carried out showing that TMD not significantly affect the response due to using first mode effective mass ratio 0.026 (Sladek and Klingner 1983).

2.2.3 TUNING TMD WITH FIRST TWO MODES OF STRUCTURE

Moving towards MTMDs different TMDs were used and tuned with first and second mode of structure (because first and second modes of structure have highest possibility of excitation) and studied its response. Five different pairs of TMDs were used for the reduction of amplitude of the response. The results obtained for structure (balcony) with TMDs were highly reduced than that of the structure without TMDs (Setareh and Hanson 1992).

2.2.4 DESIGN OF MULTIPLE TUNED MASS DAMPER

Works has been carried out on design and efficiency of MTMDs. MTMDs generally consist of different no. of small oscillators with frequencies distributed around the natural frequencies of controlled mode of the structure. Effectiveness of MTMDs was analysed also an explicit formula was derived to estimate the effectiveness of MTMDs when structure is subjected to harmonic loads. MTMDs shows best response when at least one of the oscillators was coupled with any mode of the structure. Proper design of MTMDs shows better response than that of STMD. Optimal damping for MTMDs was also obtained since damping of MTMDs is smaller resulting in higher amplitude of MTMDs this becomes a drawback in application MTMDs in a structure.(Abé and Fujino 1994)

2.2.5 ACTIVE AND PASSIVE TUNED MASS DAMPERS

Work has been carried out on both passive and active tuned mass dampers both types of dampers were observed by parametric studies (Kwok and Samali 1995). On the basis of these parametric studies optimum parameters for these types of dampers were obtained. These parametric studies were also compared with experimental studies. Despite of design both passive and active control systems were installed in tall buildings reducing the building excitation to wind and earthquake loading significantly. Among active and passive tuned mass dampers selection priority is based on according to suitable condition for each of them.

2.2.6 OPTIMUM PARAMETERS FOR TUNED MASS DAMPER

Work has been carried out on obtaining optimum parameters of TMD. These parameters were used to compute the response of single and multiple degree of freedom structure with TMDs exposed to earthquake excitation.(Sadek et al. 1997) The criteria used to obtain the optimum parameters for mass ratio, frequency and damping ratio was the selection of that value which would show large damping in first two modes of vibration. These optimum parameters when used enhance the efficiency of TMD reducing displacement and acceleration response significantly.

2.2.7 OPTIMUM PARAMETERS FOR MTMD

Work has been carried out on obtaining optimum parameters for MTMD. As optimum parameter reduces building vibrations than ordinary parameters used. These parameters include damping ratios, stiffness, and mass ratio. MTMDs were designed with constant damping and stiffness but varying mass. Main criterion selected for the optimization is to achieve minimum dynamic magnification factor (DMF) for the structure. For comparison purpose MTMD(II) having mass constant but varying stiffness and damping co-efficient, MTMD having damping co-efficient larger than that for MTMD(II) and a STMD. It was also considered that optimum frequency spacing for MTMD(II) was same as that for MTMD while damping of MTMD was little larger than that of the MTMD(II). So resulting that optimum MTMD was more efficient than optimum MTMD(II) and optimum STMD with equal mass ratio.(Li 2000)

2.2.8 SEMI-ACTIVE DAMPERS PERFORMANCE

Work has been carried out on semi-active dampers tuned with SDOF system exposed to harmonic loading. Damping of this semi-active damper was varied in a specific range. For comparison purpose its response was compared with a structure having ordinary tuned mass damper. After performing analysis it was found that semi-active dampers shows better results than ordinary passive TMD (Pinkaew and Fujino 2001). This improvement can be considered as increasing conventional TMD mass by about four times.

2.2.9 TUNED MASS DAMPER REDUCES DAMAGE RESPONSE

Generally TMD is used for displacement reduction in a structure. When TMD is unable to reduce maximum displacement in structure the structure yields and damage occurs than this TMD is helpful in reducing damage occurred to earthquake loadings. Work has been carried out on a 20-storey structure having TMD subjected to both harmonic and 1985 Mexico City ground motion. After performing numerical analysis results shows that TMD was also helpful in reducing damage occurred due to these loadings although it is failed to overcome the maximum displacement response (Pinkaew, Lukkunaprasit, and Chatupote 2003). Similarly collapse prevention can also be carried out due to application of TMD in a structure.

2.2.10 OPTIMAL ALLOCATION AND SIZING OF MTMD

Work has been carried out on the allocation and sizing of multimodal MTMDs in structure exposed to earthquake loading. TMD added stiffness and dampness to the structure providing lower response with respect to lateral loading. TMD also reduces story drifts in structure. A simple methodology of iterative analysis/redesign for obtaining optimal allocation and sizing of MTMDs for an irregular structure was carried out suggesting that all peripheral frames using any of possible damping of all modes of the structure (Daniel and Lavan 2013).

2.2.11 EFFICIENCY OF ACTIVE TUNED MASS DAMPER

Work has been carried out to show how efficiently active tuned mass dampers reduces displacement responses in buildings exposed to base excitation as compared to passive mass dampers. Although installation cost of active tuned mass dampers are high. But PTMD show good results in comparison with uncontrolled case where no TMD was installed in building especially in case when natural structure frequency was different from dominant frequency of applied earthquake. Similarly PTMD shows little reduction in shear responses while ATMD shows significantly reduction in shear responses.

2.3 GENERAL PARAMETERS

Different parameters used in this research are discussed as follow;

2.3.1 Mass ratio (μ)

It is ratio of the mass of tuned mass damper to the mass of the structure. This ratio varies from 0.02 to 0.05 represented by μ. Where μ is mass ratio, m_d is mass of tuned mass damper, and m_s is mass of the total structure.

$$\mu = \frac{\boldsymbol{m_d}}{\boldsymbol{m_s}} \qquad \textbf{(1)}$$

By increasing mass ratio of tuned mass dampers the dampers performs well and reduces main structure response efficiently. But this should be in certain limits due to serviceability and cost factor. If we increase mass ratio the cost of damper will be increased. Because of this researchers have provided a specific range.

2.3.2 Damping ratio (ζ)

It is ratio of dampness of tuned mass damper to the dampness of structure. It is generally taken as 0.02 and represented by ζ**.**

$$\boldsymbol{\zeta} = \frac{\boldsymbol{c_d}}{\boldsymbol{c_s}} \qquad (2)$$

It is independent of main structure time period and is calculated from above equation. At low damping ratios the structure shows greater response when tuned mass damper is added to main structure damping increases hence structural response decreases.

2.3.3 Tuning ratio

It is ratio of natural frequency of tuned mass damper to the natural frequency of main structure. Natural frequency of tuned mass damper is taken approximately equal to natural frequency of structure. By increasing mass ratio and damping ratio tuning ratio of structure decreases.

CHAPTER 03

3 METHODOLOGY

3.1 Model parameters

A four storey steel frame made up of stainless steel having mass irregularity at its top floor having story height of 15’’ and floor length 12’’ and width is equal to 4’’ as shown in Figure 3.1 was considered for the experimental testing carried out in this study. STMD and MTMDs dampers were placed in different cases for carrying out a comparison of all configurations of STMD and MTMDs. Mass, stiffness and dampness matrix for a specified case of main structure having STMD at its top floor are described in equation 1-3.

$$\mathbf{M} = \begin{bmatrix} \boldsymbol{m_1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{m_2} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \boldsymbol{m_3} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{m_4} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{m_d} \end{bmatrix} \tag{3}$$

$$\mathbf{K} = \begin{bmatrix} \boldsymbol{k_1 + k_2} & \boldsymbol{-k_2} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \boldsymbol{-k_2} & \boldsymbol{k_2 + k_3} & \boldsymbol{-k_3} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{-k_3} & \boldsymbol{k_3 + k_4} & \boldsymbol{-k_4} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \boldsymbol{-k_4} & \boldsymbol{k_4 + k_d} & \boldsymbol{-k_d} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{-k_d} & \boldsymbol{k_d} \end{bmatrix} \tag{4}$$

$$\mathbf{C} = \begin{bmatrix} \boldsymbol{c_1 + c_2} & \boldsymbol{-c_2} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \boldsymbol{-c_2} & \boldsymbol{c_2 + c_3} & \boldsymbol{-c_3} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{-c_3} & \boldsymbol{c_3 + c_4} & \boldsymbol{-c_4} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \boldsymbol{-c_4} & \boldsymbol{c_4 + c_d} & \boldsymbol{-c_d} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{-c_d} & \boldsymbol{c_d} \end{bmatrix} \tag{5}$$

Where $m_1, m_2, m_3, and\ m_4$ are masses of each story of the main structure. $k_1, k_2, k_3, and\ k_4$ are stiffnesses of each stroy of the main structure. $c_1, c_2, c_3\ and\ c_4$are dampness for each story of the main structure. Similarly $m_d\ , k_d\ and\ c_d$ are mass, stiffness and dampness of STMD respectively. Main structure parameters mass, stiffness, dampness and frequencies of each floor are shown in Table 3.1.

Table 3.1: Main structure parameters

Story level	Mass (kg)	Stiffness(N/m)	Dampness(N-s/m)	Natural frequency (rad/s)
1.	1.229	1505.10	1.720	9.38
2.	1.229	1505.10	1.720	30.57
3.	1.229	1505.10	1.720	50.9
4.	3.072	1505.10	2.710	64.99

The generalized form of the equation of motion for the main structure having STMD is given in equation 4.

$$\boldsymbol{M}[\ddot{\boldsymbol{u}}] + \boldsymbol{C}[\dot{\boldsymbol{u}}] + \boldsymbol{K}[\boldsymbol{u}] = -\boldsymbol{M}\{\boldsymbol{r}\}[\boldsymbol{u_g}] \qquad (6)$$

$[u]$ is displacement vector and is equal to $[u] = [u_1\, u_2\, u_3\, u_4\, u_5]^T$, $[\dot{u}] = [\dot{u_1}\, \dot{u_2}\, \dot{u_3}\, \dot{u_4}\, \dot{u_5}]^T$ is veclocity vector and $[\ddot{u}] = [\ddot{u_1}\, \ddot{u_2}\, \ddot{u_3}\, \ddot{u_4}\, \ddot{u_5}]^T$ is acceleration vector. Where {r} is influnce coefficient vector and is equal to {r}= [1 1 1 1 1 0] and $[u_g]$ is ground acceleration.

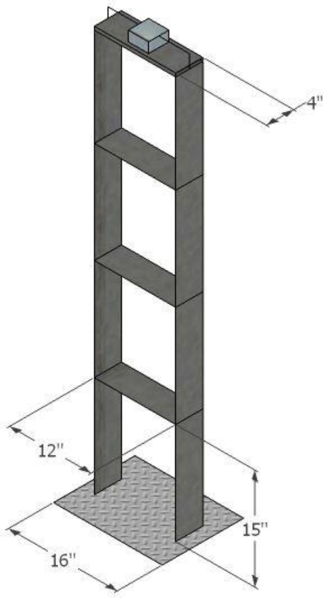

Figure 3.1: Schematic model of main structure having TMD at its top floor.

3.2 Design of STMD and MTMDs

TMD used in this study for experiments consist of a bucket mass attached to the main structure by means of two springs along both sides also TMD slides on the floor by means of bearings attached to TMD as shown in Figure 3.2. For the design of STMD, the tuned mass damper is tuned with the fundamental frequency of main structure (ω_s). For this, the frequency of STMD (ω_d) was taken approximately equal to the fundamental frequency of main structure. While for MTMDs design second TMD was tuned with the second fundamental frequency of structure. Mass, stiffness and damping coefficient of TMD were calculated using equation 5, 6, and 7 respectively.

$$\boldsymbol{m_d} = \mu \times \boldsymbol{m_s} \tag{7}$$

$$\boldsymbol{k_d} = \boldsymbol{m_d}(\boldsymbol{\omega_d})^{\mathbf{2}} \tag{8}$$

$$\boldsymbol{c_d} = \mathbf{2}\boldsymbol{\zeta}\sqrt{\boldsymbol{k_d m_d}} \tag{9}$$

Where m_d is mass of the damper, m_s is the total mass of structure and μ is the mass ratio defined as ratio of mass of Damper to the mass of main structure. In the majority of practical use mass ratios for TMD used were less than 10% (Warburton 1982), optimum mass ratios were also used but they are very high and costly. For comparison purpose, a consistent mass ratio 5% (Chang, Shia, and Lai 2018) for all configurations of STMD and MTMDs was used in this study. The fundamental frequency of the structure (ω_s) is of the main structure is found analytically.

For STMD, the frequency of damper (ω_d) was taken approximately equal to the fundamental frequency of the main structure ($\omega_d = 0.97\omega_s$) to attain the tuning phenomena so that TMD can resonate out of phase to the main structure.

In the case of MTMDs, one TMD was designed with a similar procedure used for the design of STMD while for second TMD design, TMD was tuned with the second fundamental frequency of structure (Chen and Wu 2003).

Damping ratio ζ for tuned mass damper was taken as 0.02. For comparison purpose, different cases were defined the first case is an uncontrolled structure with no TMD, 2nd case is controlled structure having STMD and the 3rd case is controlled structure with MTMDs.

Tuned mass damper is a mass attached to a building by means of only a spring to counteract against the vibrations produced from earthquake loadings applied on the structure thus reduces the vibrations in the structure.

For finding the required mass of TMD for a structure firstly total mass of structure is calculated. Using equation no 5 mass of damper can be calculated as;

$$\boldsymbol{m_d = 0.05 \times 6.76 = 0.338\, kg.} \tag{10}$$

Frequency of tuned mass damper in case of STMD can be calculated as;

$$\boldsymbol{\omega_d = 0.97 \times \omega_s = 0.97 \times 9.37 = 9.08 \frac{rad}{sec}.} \tag{11}$$

Stiffness of STMD k_d is calculated using equation no.6 where mass of damper m_d and frequency of damper $\boldsymbol{\omega_d}$ are calculated as discussed previously.

$$\boldsymbol{k_d = 0.338 \times (9.08)^2 = 27.78\, \frac{N}{m}.} \tag{12}$$

Dampness of damper c_d is calculated using equation no.7 where damping ratio ζ, stiffness of damper k_d and mass of mass damper m_d are calculated as discussed previously.

$$\boldsymbol{c_d = 2 \times 0.02\sqrt{27.78 \times 0.338} = 0.122 \frac{Ns}{m}.} \tag{13}$$

In case of MTMDs one TMD is designed with same procedure as discussed for design of STMD while for second TMD design second TMD is tuned with the second frequency of main structure and according to that frequency of the second damper ω_{d2} is calculated as;

$$\boldsymbol{\omega_{d2} = 0.97 \times 30.57 = 29.65 \frac{rad}{sec}.} \tag{14}$$

Now using equation no.6 stiffness of the second damper k_{d2} can be calculated as;

$$\boldsymbol{k_{d2} = 0.338(29.65)^2 = 296.24 \frac{N}{m}.} \tag{15}$$

Similarly dampness for second tuned mass damper is calculated using equation no.7 as;

$$\boldsymbol{c_{d2} = 2 \times 0.02\sqrt{296.24 \times 0.338} = 0.339 \frac{Ns}{m}.} \tag{16}$$

3.3 DIFFERENT CONFIGURATIONS OF STMD AND MTMDs

For the mitigation of undesirable vibration different cases were analysed separately. In the first case structure response without a tuned mass damper was investigated then structure with STMD and then structure having MTMDs. For comparison purpose location of the tuned mass damper was varied in each case. In case of single tuned mass damper a total of four configurations were defined and for MTMDs a total of six configurations were defined and are shown in Table 3.2.

Table 3.2: Different configurations of STMD and MTMDs.

	Configurations	**Description**
STMD	Case 1	STMD placed at 4th floor
	Case 2	STMD placed at 3rd floor
	Case 3	STMD placed at 2nd floor
	Case 4	STMD placed at 1st floor
MTMDs	Case I	MTMDs placed at 4th and 3rd floor
	Case II	MTMDs placed at 4th and 2nd floor
	Case III	MTMDs placed at 4th and 1st floor
	Case IV	MTMDs placed at 3rd and 2nd floor
	Case V	MTMDs placed at 3rd and 1st floor
	Case VI	MTMDs placed at 2nd and 1st floor

A STMD attached to the main structure is shown in Figure 3.2(a) while Figure 3.2(b) shows MTMDs placed at 3rd and 4th floor of the main structure. Accelerometers are also clearly visible in the picture.

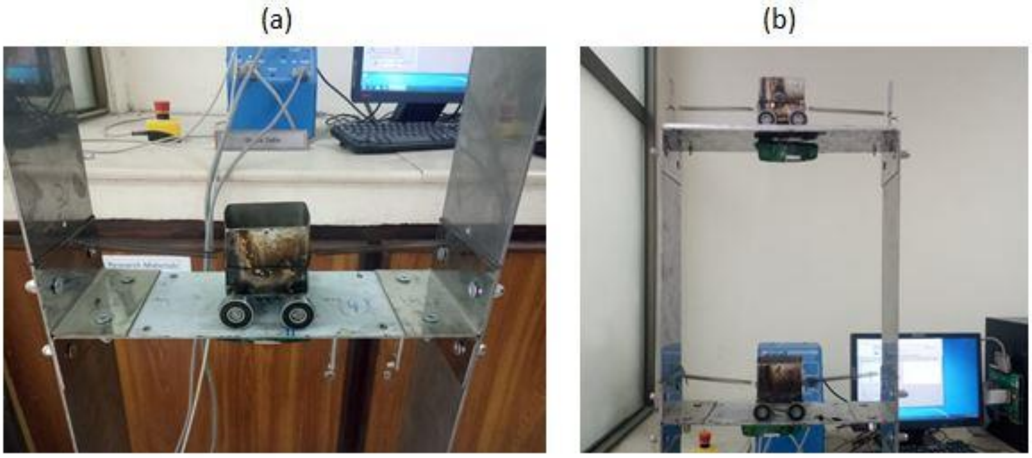

Figure 3.2: Actual TMD model (a) STMD attached to the main structure (b) MTMD placed at 3rd and 4th floor

3.4 EXPERIMENTAL PROGRAM

Experiments were being carried out in the laboratory on a uniaxial shake table has 18”x18” dimension which has maximum payload of 7.5 kg with a maximum ground acceleration of 2.5g shown in Figure 3.7. Experimental setup also includes a universal power module (UPM), Q-8 terminal board and a PC having Quarc software to run the shake table shown in Figure 3.3. The UPM 180-25-B is power amplifier designed for driving actuators of various Quanser experiments. This type of UPM is used in high powered applications like shake table usage.

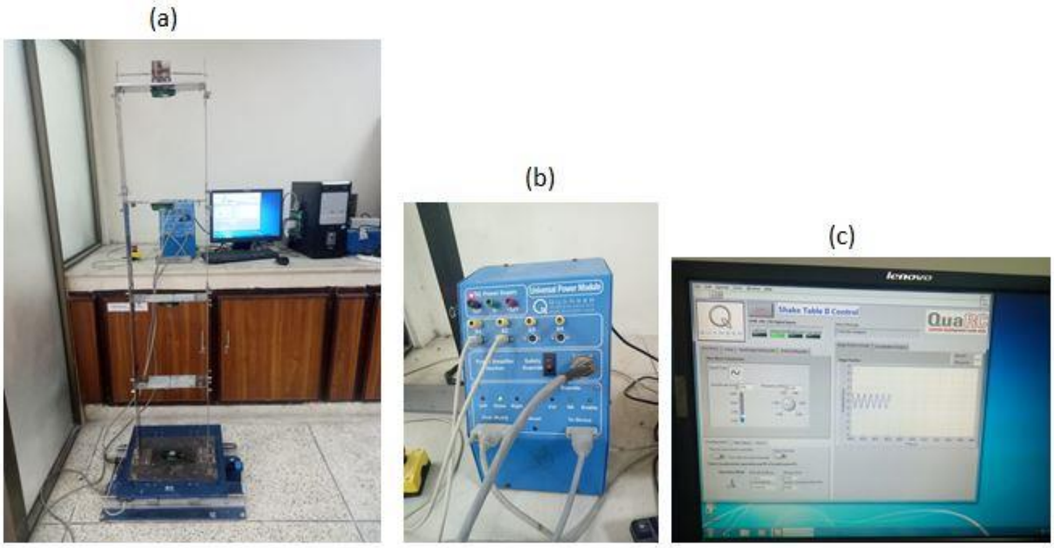

Figure 3.3: Experimental setup (a) model placed on the shake table having STMD at the top (b) universal power module (UPM) (c) QuaRC software window.

The input ground acceleration to shake table includes three types of harmonic loadings, a chirp wave and two time histories of Northridge and Kobe earthquake as shown in Figure 3.4 and Figure 3.5. Harmonic loadings are having 0.5 Hz, 1 Hz and 1.5 Hz frequency as shown in and amplitude of harmonic load is kept constant and equal to 1cm. chirp wave has 0.15 Amplitude. Northridge and Kobe earthquakes are used as scaled down by shake table II accordingly by Q-scale of shake table. In which acceleration of a given earthquake is remained unchanged while its displacement are scaled down to the limits of shake table II stroke i-e ±7.5 cm.

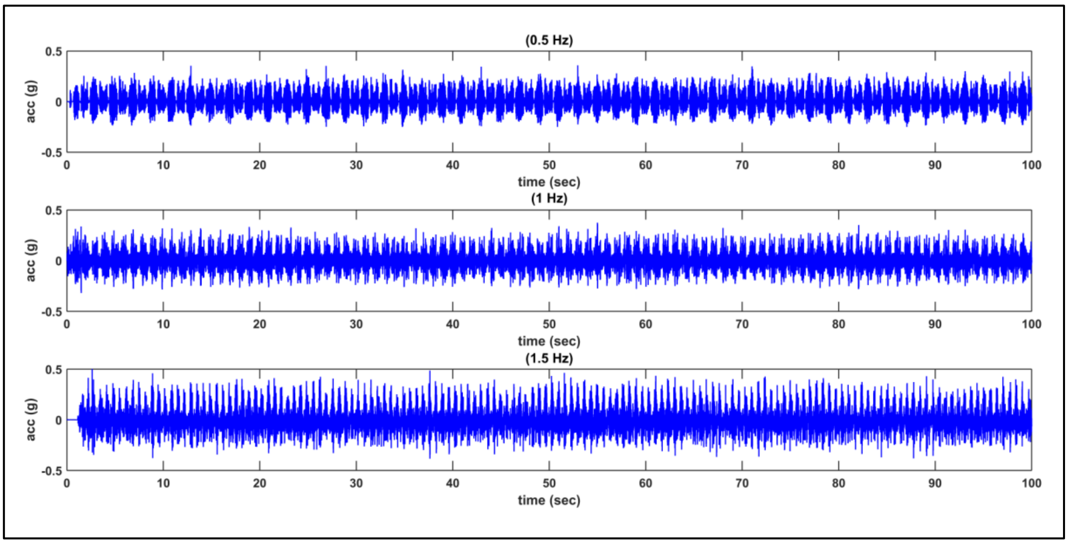

Figure 3.4: Input ground acceleration for 0.5 Hz, 1 Hz and 1.5 Hz harmonic loadings

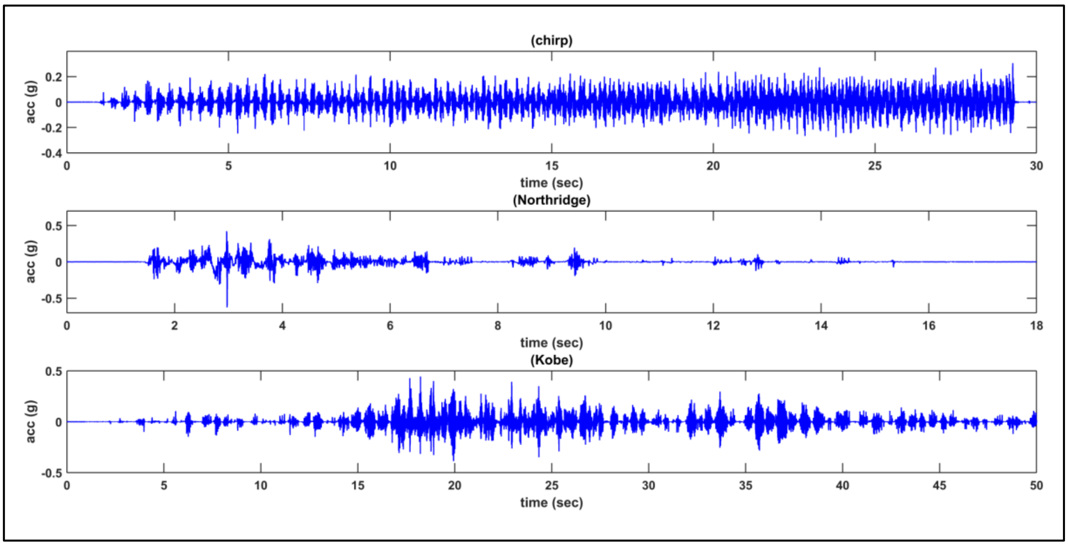

Figure 3.5: Input ground acceleration for chirp, Northridge and Kobe earthquake.

In this study, a four-story steel structure having mass irregularity at its 4th floor was investigated under experimental testing against above discussed six types of loadings.

The columns and beams of main structure were fabricated from stainless steel sheet and structural integrity is carried out with help of bolts, also main structure is bolted on the base plate with help of which it is bolted to shake table in the laboratory.

Acceleration of each storey level was measured with help of X2-02 accelerometer as shown in Figure 3.6 pasted below each floor with help of double tap. Acceleration of each sotrey level was meausred and stored in terms of signals in the portable accelerometer. This accelerometer was kept at ‘low gain’ having capacity of measuring ± 2.0 g accelerations. Although this X2-02 has the ability of measuring tri axial accelerations i-e can measure accelerations in X-axis, Y-axis and Z-axis with sample rate upto 512 Hz. But we are interested only in X-axis accelerations as shake table is un-axial and can move only in X-axis. The acclerometer contains a lithium-polymer battery which can provide a backup of upto 10 hours for recording data at 512 Hz rate. For every case of application of load each accelerometer was reset with real time clock by setting configuration file of each accelerometer. The data was stored in form comma spereated values (CSV) files and contains signals recorded against time. The accelerometer when connected to a PC apperead as mass storage device where the signals stored in accelerometer were later on converted to accelerations by dividing it with a factor 6554 shown in user mannual of accelerometer when are kept in ‘low gain’ and values of acceleration in terms of ‘g’ were obtained.

Figure 3.6: X2-02 Accelerometer

Each round of experiment includes application of all six types of loadings to a speicfic case of the structure. First of all uncontrolled structure was tested against all six types of loadings. Then all four configuration of STMD i-e case 1, case 2, case 3, and case 4 for main structure were subjected to all six types of loadings and response for each floor was measured with help of accelerometer for each case.. After that all six configurations of MTMDs were subjected to each type of loading for comparison with all configurations of STMD. Similar procedure is used for measuring the accelration of each floor of the main structure for each configurations of MTMDs. Each type of input accelrations was given by the PC to shake table with help of Quarc software.

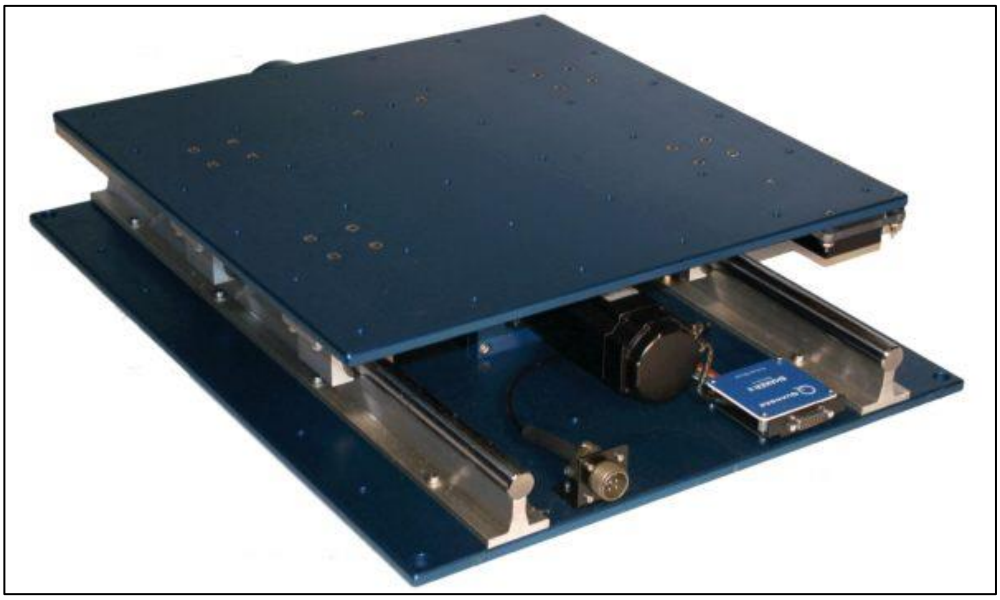

Figure 3.7: Quanser Shake Table II

CHAPTER 04

4 RESULTS AND DISCUSSIONS

4.1 Uncontrolled Structure Response

The main structure without a damper was subjected to all six types of loadings as ground accelerations. Root mean square (RMS) accelerations of all four storeys against each type of load were calculated with accelerometers as discussed above and are tabulated in Table 4.1. The uncontrolled structure shows maximum acceleration responses to 1.5 Hz harmonic loadings and Northridge earthquake especially for the top floor of irregular structure which are 0.1619 g and 0.1453g respectively. Acceleration responses of 2nd and 4th storeys were selected for comparison purpose as they show maximum responses in majority of input ground accelerations.

Table 4.1: Uncontrolled RMS accelerations (g).

	0.5hz	**1hz**	**1.5hz**	**0.15chirp**	**Northridge**	**Kobe**
1	0.0988	0.0936	0.0866	0.1167	0.0736	0.0691
2	0.1135	0.1172	0.1606	0.1187	0.0958	0.0918
3	0.1112	0.1051	0.1405	0.132	0.1147	0.1012
4	0.1198	0.1083	**0.1619**	0.1438	**0.1453**	0.1179

4.2 Response of Structure with STMD

According to the location of STMD, All four configurations case 1, case 2, case 3, and case 4 as defined were also subjected to the same six types of loadings as ground accelerations and RMS accelerations for each storey were calculated with help of accelerometer and are plotted as shown in the Figure 4.1. In the case of 0.5 Hz harmonic loading case 4 of STMD were showing good results and reduces all storeys RMS accelerations significantly as shown in Figure 4.1 (a). In case of 1Hz harmonic loading case 1 of STMD shows significant reduction in RMS accelerations of all storeys except for the first storey where case 3 is showing good results in reduction as shown in Figure 4.1 (b). In case of 1.5 Hz harmonic and chirp loading almost every configuration of STMD was showing approximately equal efficiency in the reduction of all storeys RMS acceleration shown in Figure 4.1 (c),(d). In the case of Northridge earthquake case 1 shows good results as shown in Figure 4.1 (e). In the case of Kobe earthquake, STMD shows good results for case 4 of STMD Figure 4.1 (f).

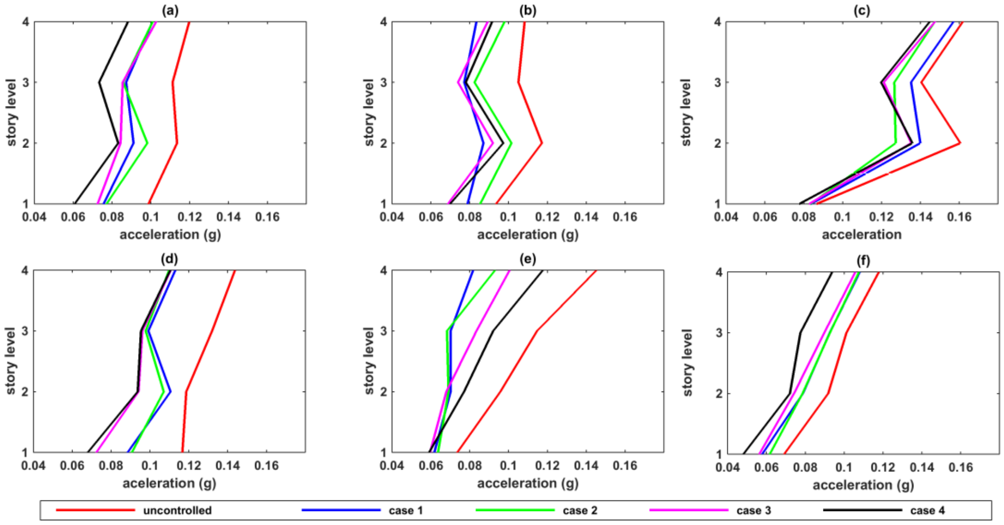

Figure 4.1: Comparison of RMS accelerations for STMD configurations against (a) 0.5 Hz, (b) 1Hz, (c) 1.5Hz, (d) chirp, (e) Northridge earthquake and (f) Kobe earthquake excitations.

For comparison with uncontrolled structure percentage reduction of all storeys acceleration for every configuration of STMD against each loading were shown in Table 4.2. Due to the mass irregularity of structure response against STMD were variable. For each loading case, 2nd storey shows different percentage reductions at different locations. For 0.5 Hz harmonic, chirp and Kobe earthquake loadings 2nd storey and 4th storey acceleration show a better reduction for case 4 of STMD. For higher harmonic loadings (1 Hz and 1.5 Hz) for 2nd floor response STMD shows better efficiency for case 1 and case 2 respectively. For 2nd storey RMS acceleration, max percentage reduction against Northridge earthquake is shown by case 3 of STMD. Similarly, maximum reduction for 4th storey RMS acceleration has been shown by case 1 of STMD. This maximum reduction in RMS acceleration is because of the position of STMD as placed at that floor where the main structure is showing maximum response confirming results from the past research (Jabary and Madabhushi 2018). In case of Kobe earthquake, case 4 of STMD shows better efficiency for both in case of 2nd and 4th floor.

For the better understanding of results average percentage reductions of acceleration response against all loading were studied in which 2nd storey maximum average percentage reduction was 21.97 % by case 3 of STMD against all loadings because STMD performs well when it is placed at that floor where the structural response is maximum. And the minimum average percentage reduction was 16.61 % shown by case 2 of STMD against all types of loadings. Similarly, the maximum average percentage reduction for the 4th storey was 19.17 % shown by case 1 of STMD against all loadings and minimum average percentage reduction was 17.04 % shown by case 2 of STMD against all loadings.

Table 4.2: Percentage reductions for all configurations of STMD.

Floor no.	**STMD location**	**0.5hz**	**1hz**	**1.5hz**	**chirp**	**Northridge**	**Kobe**	**Average**
1	Case 1	23.38	15.71	3.35	24.16	16.03	16.35	16.50
	Case 2	21.86	8.76	3.58	22.28	13.45	10.71	13.44
	Case 3	26.52	26.50	4.39	37.96	19.02	18.52	22.15
	Case 4	38.46	25.32	10.28	41.73	19.70	30.39	27.65
2	Case 1	19.74	**25.68**	12.83	6.82	26.72	14.16	17.66
	Case 2	13.48	13.40	**20.73**	9.77	**27.87**	14.38	16.61
	Case 3	25.64	21.50	15.75	20.72	29.02	19.17	**21.97**
	Case 4	**26.70**	16.98	15.38	**21.06**	19.52	**21.46**	20.18
3	Case 1	21.49	26.55	3.77	24.85	38.80	8.50	20.66
	Case 2	22.84	21.50	9.89	25.91	40.45	8.40	21.50
	Case 3	23.11	29.59	13.74	27.20	27.20	11.26	22.02
	Case 4	33.99	25.78	14.73	27.73	19.70	23.42	24.23
4	Case 1	15.78	**22.90**	2.96	21.35	**43.70**	8.31	**19.17**
	Case 2	15.69	9.51	8.89	23.57	35.93	8.65	17.04
	Case 3	14.19	17.54	8.83	23.02	30.76	10.26	17.44
	Case 4	**26.29**	15.42	**10.50**	**23.16**	19.00	**20.36**	19.12

4.3 Response of structure with MTMDs

Similar load application procedure was used for the structure having different configurations of MTMDs on different floors. The response of all six combinations of MTMDs in terms of RMS accelerations of each storey against each loading is shown in Figure 4.2. For all types of loading all cases of MTMDs controlled the main structure response more than that of the structure having STMD. In the case of 0.5Hz loadings case V of MTMDs shows good results for all storeys especially for 2nd and 4th storeys. For 1 Hz loadings, 2nd storey and 4th storey RMS accelerations show an efficient reduction for case II of MTMDs. In the case of 1.5 Hz loading, 2nd storey response is showing an efficient reduction for case II of MTMDs while 4th storey response is showing a significant reduction for case VI of MTMDs. Also, case VI reduces 2nd storey response approximately equal to that of case II of MTMDs. In the case of chirp loading case IV of MTMDs is showing an efficient reduction for 2nd storey RMS acceleration while case III of MTMDs is showing an efficient reduction for 4th storey RMS acceleration. For Northridge earthquake loading case IV of MTMDs is showing good results in the reduction of RMS accelerations for the 2nd storey while case III of MTMDs is showing good results in RMS acceleration reduction for the 4th storey. In the case of Kobe earthquake for both 2nd and 4th storey case VI of MTMDs shows efficient reductions than all other cases of MTMDs.

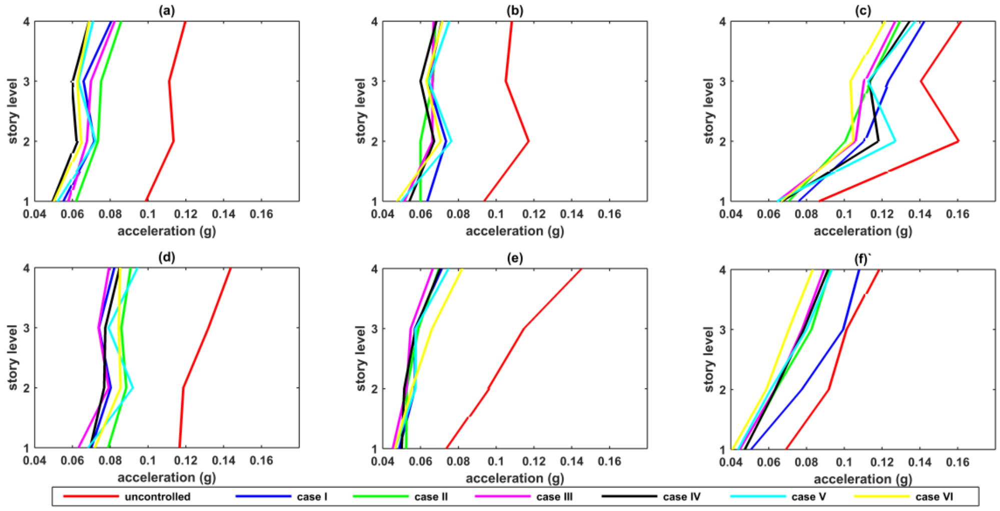

Figure 4.2: Comparison of RMS accelerations for MTMD configurations against (a) 0.5 Hz, (b) 1Hz, (c) 1.5Hz, (d) chirp, (e) Northridge earthquake, and (f) Kobe earthquake excitations.

All configurations of MTMDs gave better response reduction than STMD configurations. Acceleration percentage reduction for the 2nd storey is showing more reduction for case V of MTMDs confirming results obtained by(Chen and Wu 2003) that MTMDs shows better results when placed at that storey or adjacent to the storey which shows maximum response. While in case of 1 Hz and 1.5 Hz harmonic loadings MTMDs are showing good results for case II of MTMDs. More or less in the majority of cases like 1 Hz harmonic, chirp and Northridge earthquake loadings, 4th storey response is showing efficient reductions in case III of MTMDs. In case of 1.5 Hz harmonic and Kobe earthquake loadings, MTMDs gave good percentage reductions for case VI of MTMDs.

To elaborate results more average percentage reductions of all six types of loadings were calculated against each configurations of MTMDs as shown in Table 4.3. In the case of 2nd storey, two cases of MTMDs were found to be efficient for case III showing 37.87 % reduction and for case IV showing 37.80 % reduction. Similarly for 4th storey maximum average percentage reduction is 35.89 % by case VI of MTMDs.

Table 4.3: Percentage reductions for all configurations of MTMDS.

Floor no.	**MTMDs positioning**	**0.5hz**	**1hz**	**1.5hz**	**chirp**	**Northridge**	**Kobe**	**Average**
1	Case I	44.13	32.05	12.47	40.02	33.83	26.77	31.55
	Case II	37.35	35.90	18.48	32.39	28.80	31.69	30.77
	Case III	41.50	45.09	25.40	45.84	38.45	35.31	38.60
	Case IV	49.90	42.20	22.63	40.53	32.07	31.40	36.46
	Case V	47.17	46.90	25.75	41.47	36.68	36.61	39.10
	Case VI	49.19	49.25	22.98	38.47	36.82	40.96	39.61
2	Case I	36.92	37.29	31.26	32.35	40.40	15.58	32.30
	Case II	35.24	**48.81**	**37.42**	25.44	44.99	30.39	37.05
	Case III	40.35	43.43	34.00	33.28	45.09	31.05	**37.87**
	Case IV	**45.20**	42.66	26.46	**35.30**	**46.35**	30.83	37.80
	Case V	36.39	34.90	20.86	22.49	40.19	28.00	30.47
	Case VI	43.08	39.68	34.74	27.97	42.17	**36.06**	37.28

3	Case I	40.74	39.20	12.24	43.94	50.31	1.78	31.37
	Case II	32.37	36.63	19.00	34.92	48.65	18.38	31.66
	Case III	37.23	36.92	21.42	44.09	52.22	23.32	35.87
	Case IV	46.40	42.91	19.36	41.36	49.96	22.43	37.07
	Case V	43.17	38.82	19.86	40.08	49.96	20.95	35.43
	Case VI	43.71	39.96	26.48	35.98	42.37	30.24	36.46
4	Case I	32.72	34.26	12.04	42.84	50.93	8.48	30.21
	Case II	28.38	37.40	20.01	36.86	51.96	21.46	32.68
	Case III	31.22	**38.23**	21.93	**44.78**	**54.23**	24.26	35.77
	Case IV	**43.07**	36.84	16.86	40.89	51.55	22.48	35.28
	Case V	40.82	30.56	15.01	34.28	48.52	20.78	31.66
	Case VI	42.49	33.98	**25.26**	40.75	43.50	**29.35**	**35.89**

4.4 Comparison of STMD and MTMDs

Responses of 2nd and 4th floor were maximum and are considered as severe cases as it shows maximum responses. For better comparison, percentage reductions for all configurations of STMD and MTMDs were shown on the bar charts for both 2nd and 4th storey.

In Figure 4.3 percentage reduction of all configurations of STMD for 2nd storey were compared against harmonic loadings. In load case of 0.5 Hz case 4 of STMD shows better reduction similarly in load case of 1 Hz case 1 of STMD shows better results. While in load case 1.5 Hz case 2 of STMD shows efficient results.

In Figure 4.4 percentage reductions for all configurations of MTMDs for 2nd storey were shown against harmonic loadings. As compared to that of STMD configurations all configurations of MTMDs shows almost double efficiency than that of STMD for all loading cases. Among MTMDs configurations case II of MTMDs shows maximum percentage reductions which is against 1 Hz harmonic load case. Lowest percentage reduction was shown by case V of MTMDs which is against 1.5 Hz harmonic load case.

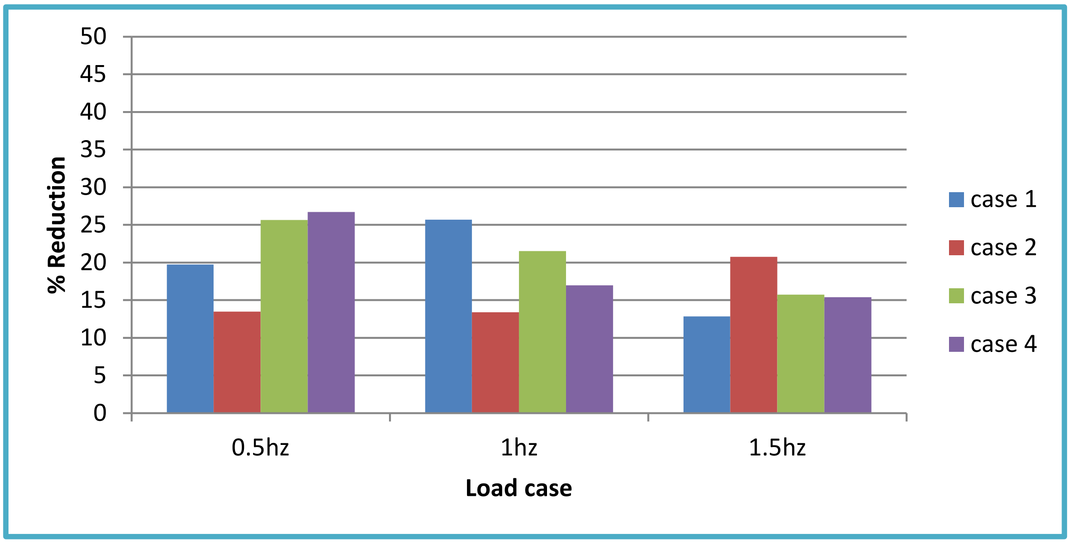

Figure 4.3: % Reduction of 2nd floor using STMD configurations against harmonic loadings.

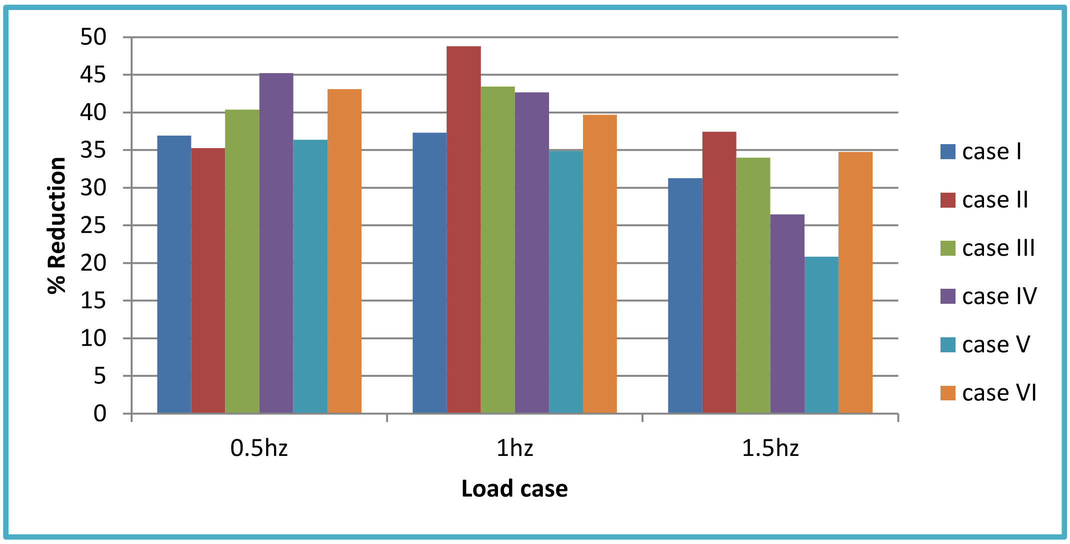

Figure 4.4: % Reduction of 2nd floor using MTMD configurations against harmonic loadings.

In Figure 4.5, Figure 4.6 percentage reduction for all configurations of STMD and MTMDs were compared against chirp, Northridge and Kobe earthquake loadings. These percentage reductions are also plotted for the 2nd floor response. In case of chirp loading for all configurations of STMD and MTMDs the percentage reductions were quite less as compared to other loadings cases. In case of Northridge earthquake loading case 3 of STMD while case IV of MTMDs were showing maximum percentage reductions for 2nd floor response. Similarly in case of Kobe earthquake percentage reductions for all configurations of STMD and MTMDs were less because amplitude of Kobe earthquake is high and TMD dampers performed not so well in this conditions. Although MTMDs percentage reductions were quite high as compared to percentage reductions of STMD confirming the efficiency of MTMDs over STMD in case of Kobe earthquake as well.

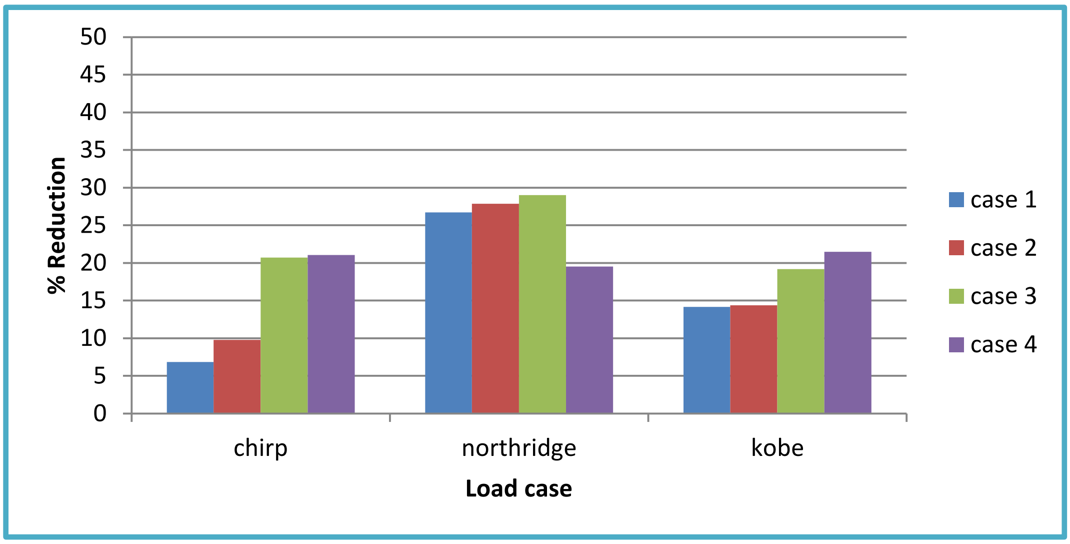

Figure 4.5: % Reduction of 2nd floor using STMD configurations against chirp, Northridge and Kobe earthquake.

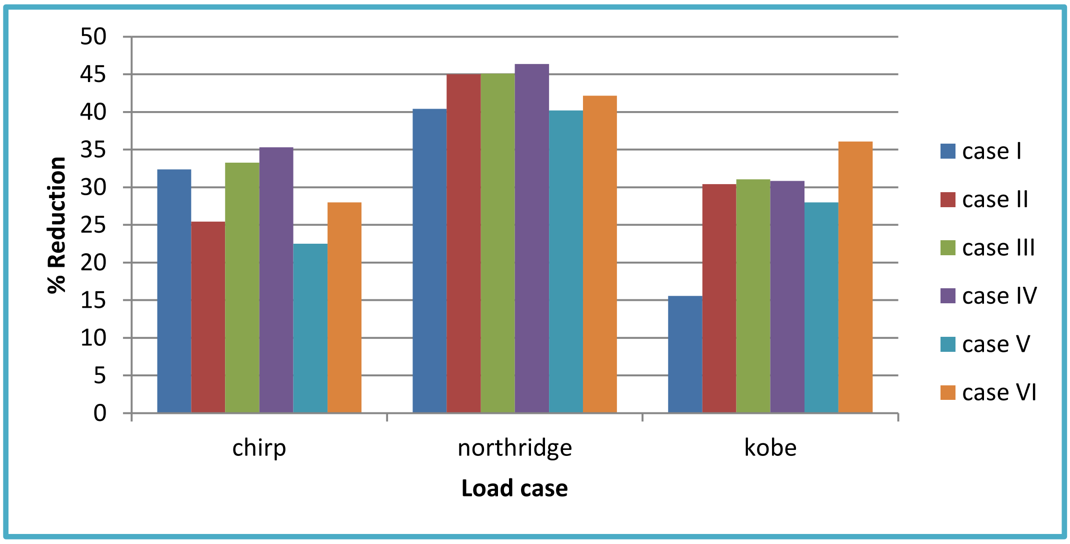

Figure 4.6: % Reduction of 2nd floor using MTMDs configurations against chirp, Northridge and Kobe earthquake.

Similarly percentage reductions for all configurations of STMD and MTMDs for 4th floor response against harmonic loadings are shown in Figure 4.7, Figure 4.8. Among harmonic loadings maximum percentage reductions were shown in case of 0.5 Hz harmonic loading for both STMD and MTMDs configurations. Similarly MTMDs configurations for all cases of harmonic loadings show greater percentage reductions as compared to that of STMD configurations percentage reductions. In case of 0.5Hz harmonic loading case 4 of STMD and case IV of MTMDs were showing maximum percentage reductions. In case of 1 Hz harmonic loading case 1 of STMD and case III of MTMDs were showing maximum percentage reduction for 4th floor acceleration response. In case of 1.5 Hz harmonic loading case 4 of STMD and case VI of MTMDs were showing maximum percentage reduction for 4th floor acceleration response.

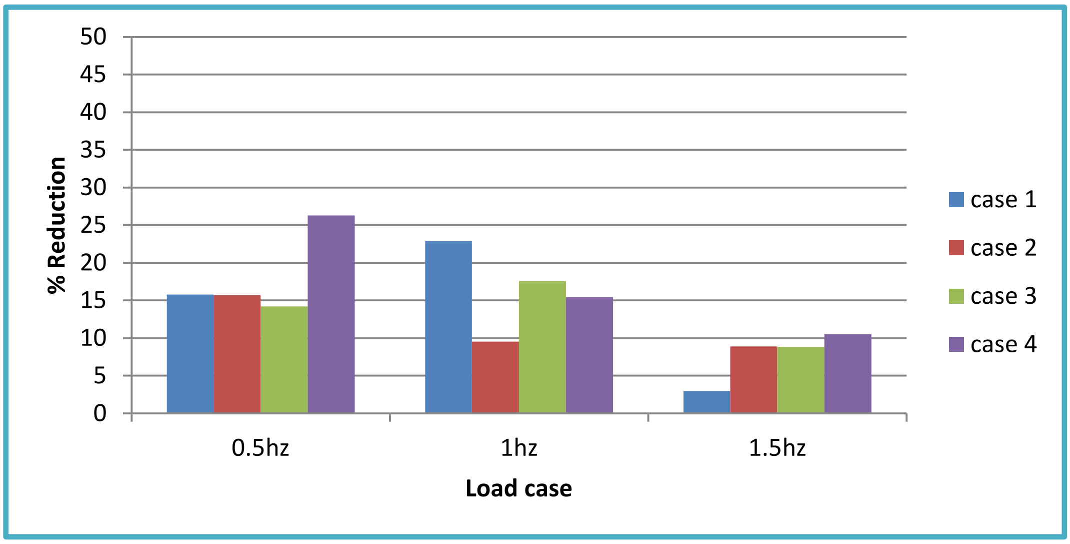

Figure 4.7: % Reduction of 4th floor using STMD configurations against harmonic loadings.

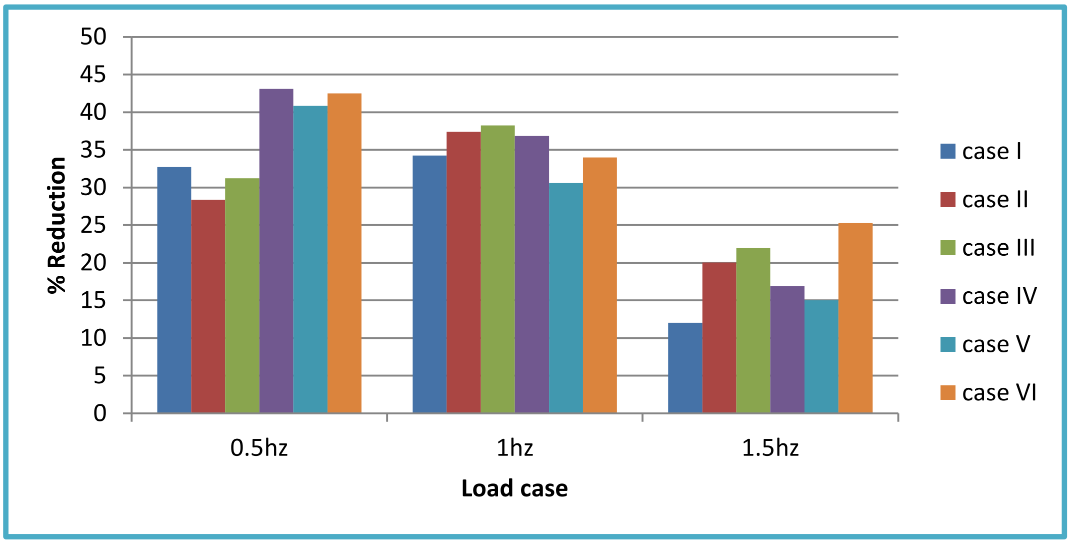

Figure 4.8: % Reduction of 4th floor using MTMDs configurations against harmonic loadings.

Percentage reductions for all configurations of STMD and MTMDs against chirp, Northridge and Kobe earthquake loadings for 4th floor acceleration response are shown in Figure 4.9, Figure 4.10 Similar trend has been shown in these loading cases that all configuration MTMDs were showing efficient results than all configurations of STMD. In case of Chirp loading almost all configurations of STMD and MTMDs were showing equal percentage reductions. In case of Northridge earthquake case 1 of STMD and case III of MTMDs were showing maximum percentage reductions. While in case of Kobe earthquake case 4 of STMD and case VI of MTMDs were showing maximum percentage reductions. Against Kobe earthquake both STMD and MTMDs show maximum reduction at lower floor.

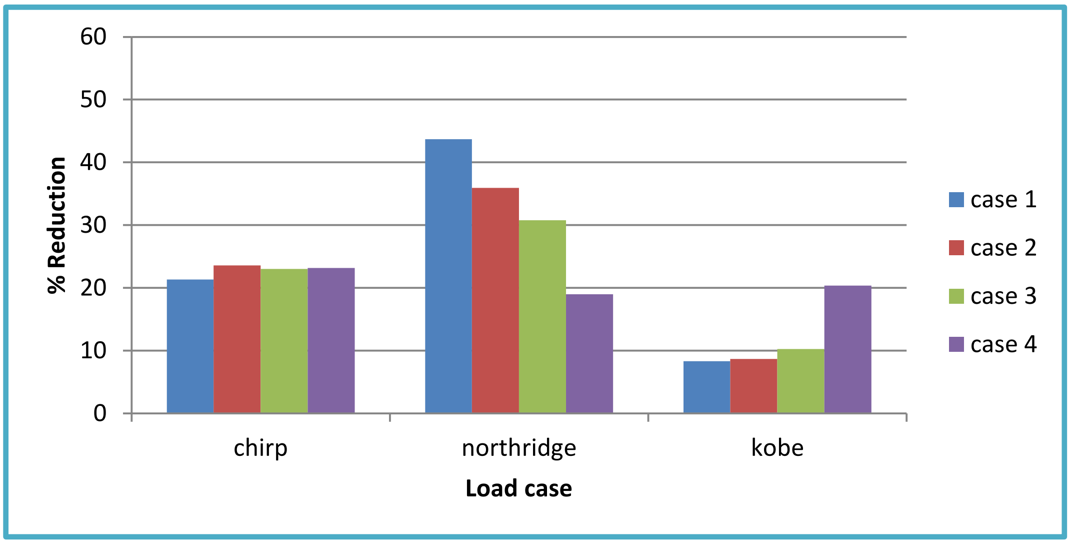

Figure 4.9: % Reduction of 4th floor using STMD configurations against chirp, Northridge and Kobe earthquake.

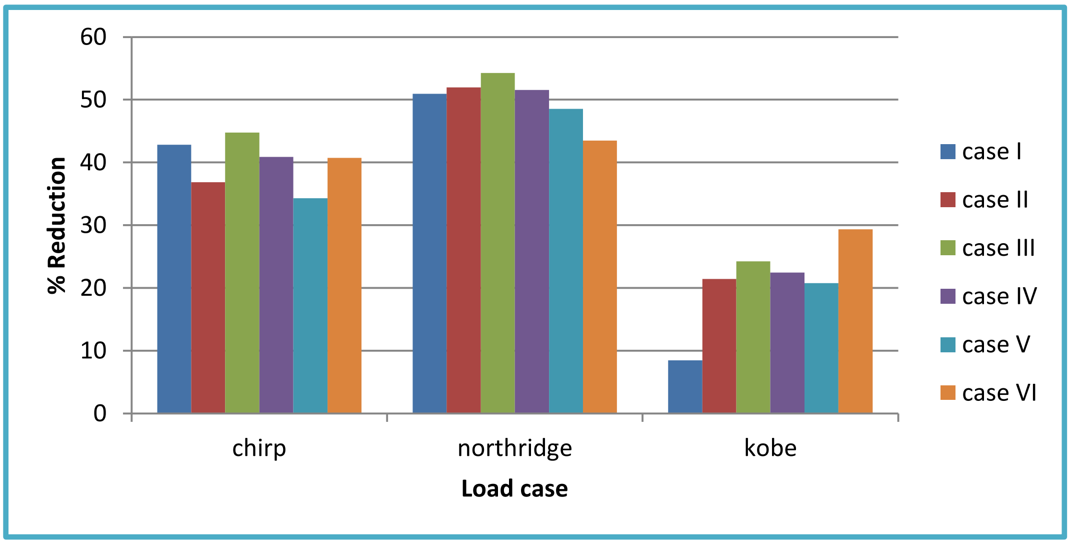

Figure 4.10: % Reduction of 4th floor using MTMDs configurations against chirp, Northridge and Kobe earthquake.

For overall comparison of the response of the uncontrolled structure, the structure with STMD and structure with MTMDs average RMS acceleration of each storey for all configurations of STMD and MTMDs are plotted against each loading. For all six types of loadings, MTMDs is showing efficient results than STMD for the irregular main structure as shown in Figure 4.11.

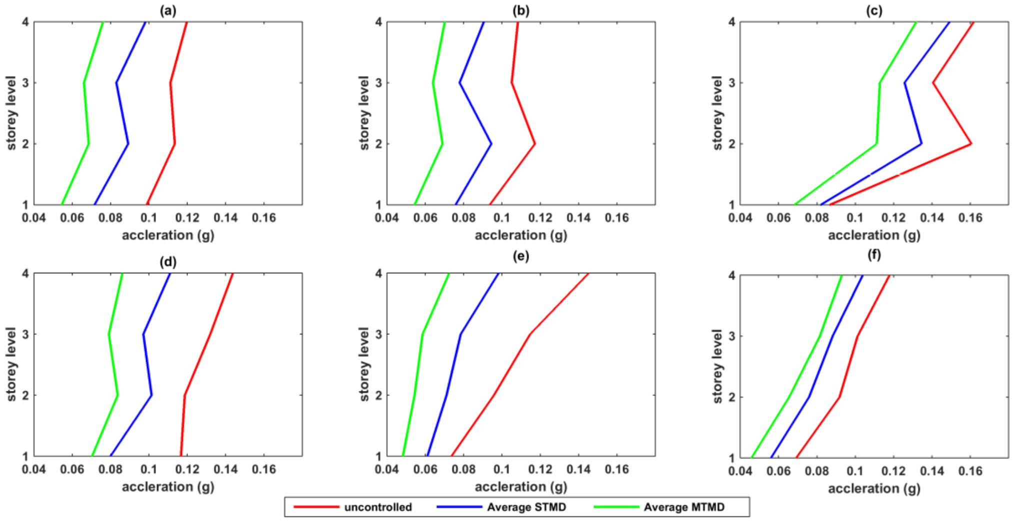

Figure 4.11: Comparison of average reduction for STMD and MTMDs configurations against (a) 0.5 Hz, (b) 1Hz, (c) 1.5Hz, (d) chirp, (e) Northridge earthquake, and (f) Kobe earthquake excitations.

Average percentage reductions of MTMDs placed at different locations are clearly greater than the average percentage reduction of STMD used on different locations against each and every load case as shown in Table 4.4. For 2nd storey acceleration response average percentage reduction of all loadings for STMD is calculated to be 19.10 % while for MTMDs this reduction increases up to 35.46 % showing the efficiency of MTMDs(Daniel and Lavan 2015). Similarly for 4th storey acceleration response average percentage reduction of STMD for all types of loadings is 18.19 % while MTMDs average percentage reduction is 33.58 %. This efficiency of MTMDs is more than that of STMD because of its tuning with multiple modes of main structure as single tuning with main structure is not that much enough for reduction of storey accelerations in irregular structures. Same phenomena of multi-mode control for distributed tuned mass dampers in the past have been used for reduction of structure response against seismic loadings. Average percentage reduction shows that MTMDs gives maximum percentage reduction against Northridge earthquake loading.

Table 4.4: Comparison of average percentage reduction of STMD and MTMDS

Floor no.		**0.5hz**	**1hz**	**1.5hz**	**chirp**	**Northridge**	**Kobe**	**Average**
1	STMD	27.56	19.07	5.40	31.53	17.05	18.99	19.93
	MTMDs	44.87	41.90	21.29	39.79	34.44	33.79	36.01
2	STMD	21.39	19.39	16.17	14.60	25.78	17.29	**19.10**
	MTMDs	39.53	41.13	30.79	29.47	43.20	28.65	**35.46**
3	STMD	25.36	25.86	10.53	26.42	31.54	12.90	22.10
	MTMDs	40.60	39.07	19.73	40.06	48.91	19.52	34.65
4	STMD	17.99	16.34	7.80	22.77	32.35	11.90	**18.19**
	MTMDs	36.45	35.21	18.52	40.07	**50.11**	21.13	**33.58**

4.5 Acceleration time history analysis

From the above discussions, most efficient configurations of STMD and MTMDs for both 2nd and 4th storey are selected against each loading. Time histories for 2nd storey for harmonic loading cases are shown in Figure 4.12. For 0.5 Hz harmonic loading case 4 of STMD is most optimum case among all configurations of STMD and case IV of MTMDs is optimum case among all configurations of MTMDs. MTMDs optimum configuration is showing more efficient reduction than that of STMD optimum configuration for 2nd storey response. For 1 Hz harmonic loading case 1 of STMD and case II MTMDs are optimum configurations among STMD and MTMDs configurations showing efficient reduction than uncontrolled structure response. For 1.5 Hz harmonic loading case 2 of STMD and case II MTMDs are optimum configurations among STMD and MTMDs configurations showing efficient reduction than uncontrolled structure response. In case of 1.5 Hz harmonic loadings the STMD and MTMDs doesn't show sufficient reductions as compared to that in case of 0.5 Hz and 1 Hz harmonic loadings.

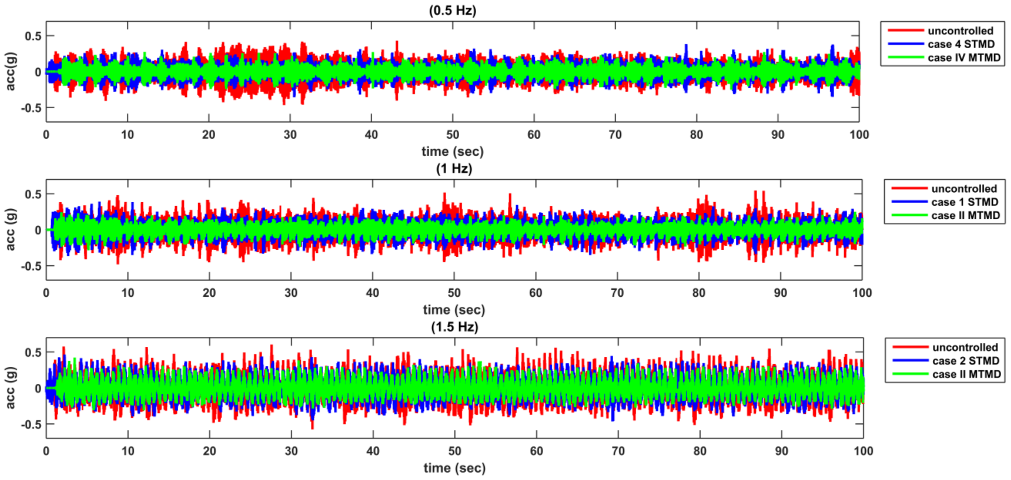

Figure 4.12: Time histories response for optimum configuration of STMD and MTMD for 2nd storey of the structure.

Time histories of 2nd storey for chirp, Northridge and Kobe earthquake loadings are shown in Figure 4.13. For chirp loading case 4 of STMD and case IV of MTMDs are optimum configurations among all configurations of STMD and MTMDs showing reductions of 2nd storey accelerations. Optimum case of MTMDs shows more reductions than that of STMD configurations. For Northridge earthquake case 3 of STMD and case IV of MTMDs are optimum configurations of STMD and MTMDs showing efficient reductions in 2nd storey accelerations. Similarly for Kobe earthquake case 4 of STMD and case IV of MTMDs are optimum configurations of STMD and MTMDs showing efficient reductions in 2nd storey accelerations.

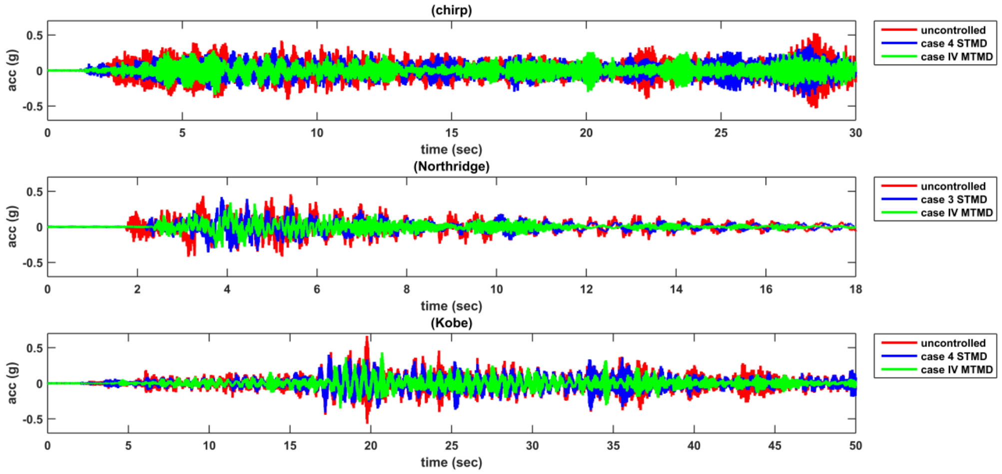

Figure 4.13: Time histories response for optimum configuration of STMD and MTMD for 2nd storey of the structure.

Similarly most efficient configurations of STMD and MTMDs are plotted for Comparison with the uncontrolled response of 4th storey accelerations against harmonic loadings are shown in Figure 4.14. For 0.5 Hz and 1.5 Hz harmonic loadings case 4 of STMD and for 1 Hz harmonic loadings case 1 of STMD shows efficient results. Overall comparison of harmonic loadings shows that STMD for 0.5 HZ shows a maximum reduction in 4th storey accelerations response as compared with 1 Hz and 1.5 Hz harmonic loadings. A similar trend is found for MTMDs but the difference is that MTMDs reduces structural response more than STMD.

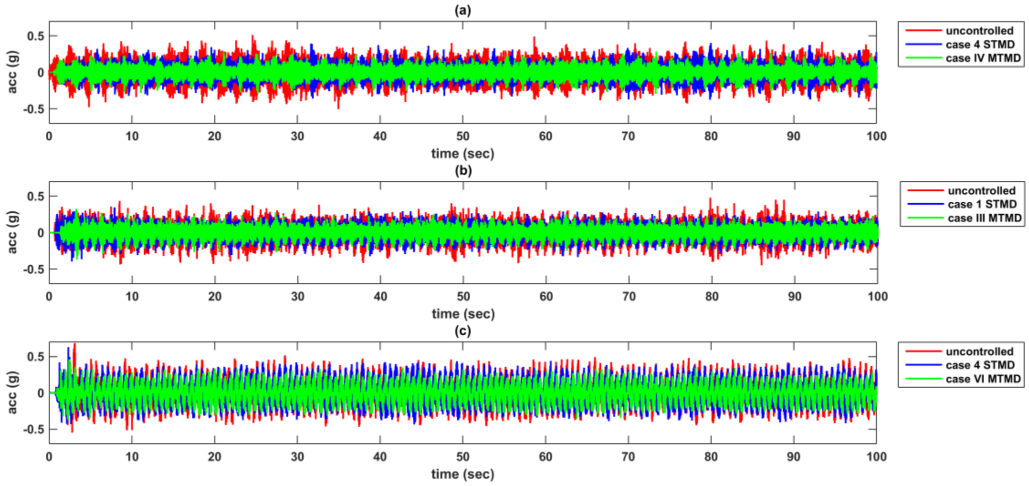

Figure 4.14: Time histories response for optimum configuration of STMD and MTMD of the top storey of the structure against (a) 0.5 Hz, (b) 1 Hz and (c) 1.5 Hz harmonic loadings

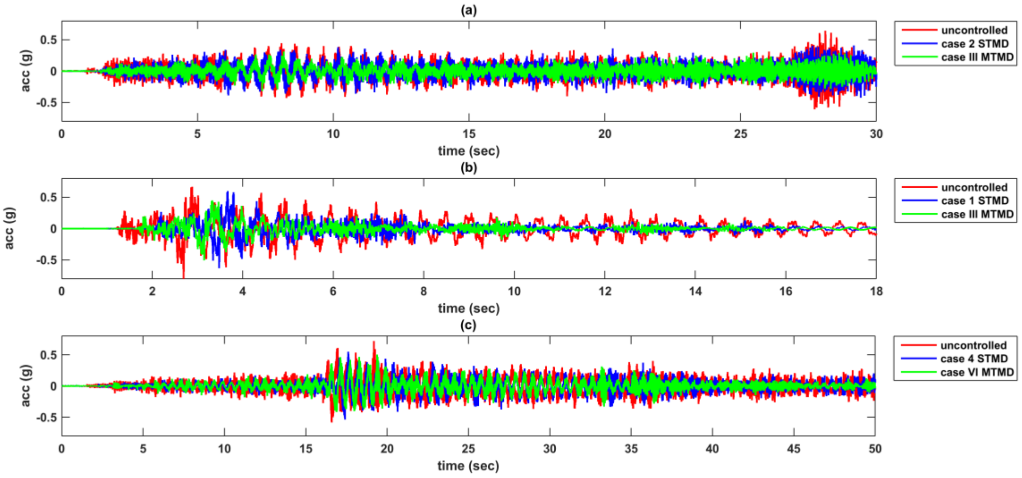

Figure 4.15: Time histories response for optimum configuration of STMD and MTMD of the top storey of the structure against (a) chirp, (b) Northridge earthquake and (c) Kobe earthquake loadings.

Time histories of 4th storey for chirp, Northridge and Kobe earthquake loadings are shown in Figure 4.15. For chirp loading, optimum configuration for STMD is case 2 and for MTMDs optimum configuration is case III. STMD case 2 is showing less reduction than MTMDs case III as MTMDs are more efficient than STMD. For Northridge earthquake STMD case 1 is optimum configuration showing an efficient reduction in 4th storey accelerations while for MTMDs case III is the optimum configuration showing an efficient reduction in 4th storey accelerations. For Kobe earthquake STMD case 4 is the optimum configuration showing an efficient reduction in top story accelerations while for MTMDs case VI is optimum configuration showing an efficient reduction in top story accelerations. For all types of loadings, top story accelerations for the irregular structure are showing the reduction in case of STMD while MTMDs shows a further reduction of these accelerations showing an efficiency of MTMDs over STMD in irregular structure.

4.6 PSD curves

Power spectral density (PSD) response curves for all six types of loadings for the top story were drawn. For comparison purpose PSD of best case of MTMD is compared with the uncontrolled structure response. In case of 0.5 Hz harmonic loadings two peaks at 0.5 Hz and 2 Hz were suppressed as shown in Figure 4.16 by adding MTMDs to main structure.

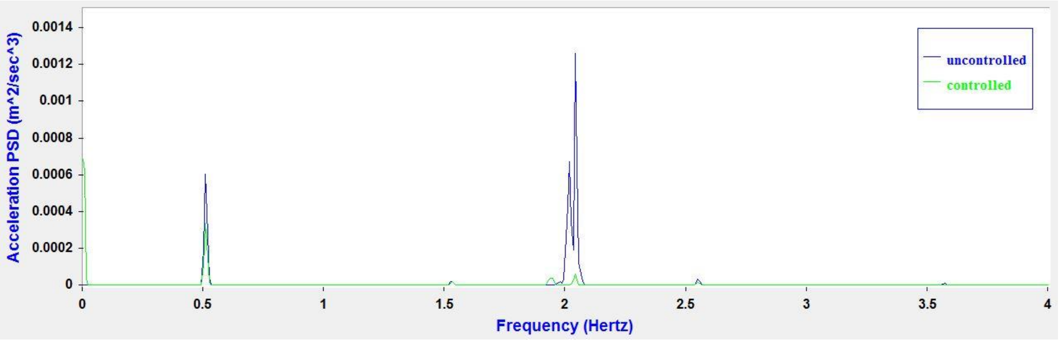

Figure 4.16: PSD Response for MTMD controlled against 0.5 Hz loading

In case of 1 Hz harmonic loading the peak occurred at around 1 Hz as shown in Figure 4.17 and in case of 1.5 Hz the peak occurred at 1.5 Hz as shown in Figure 4.18 and in controlled structure these peak were suppressed by adding TMDs to main structure in both loading cases.

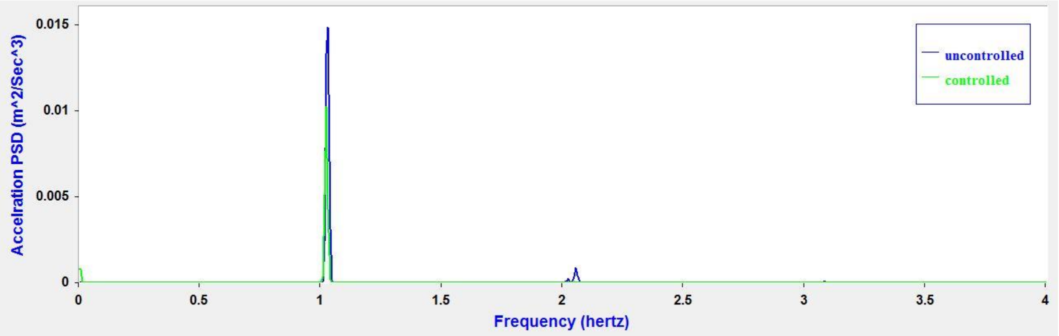

Figure 4.17: PSD Response for MTMD controlled against 1 Hz loading

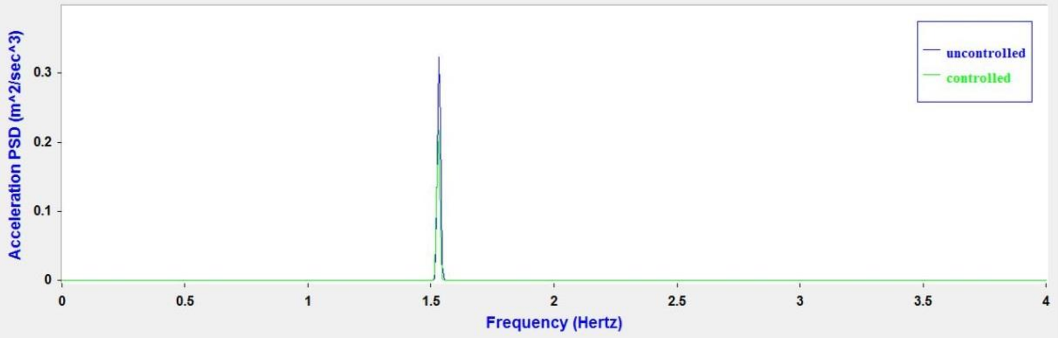

Figure 4.18: PSD Response for MTMD controlled against 1.5 Hz loading

In case of chirp loading the peak occurred at around 2 Hz and in control structure response is controlled as shown in Figure 4.19 by adding TMDs to main structure. Also a little shift of frequency in controlled structure can also be seen.

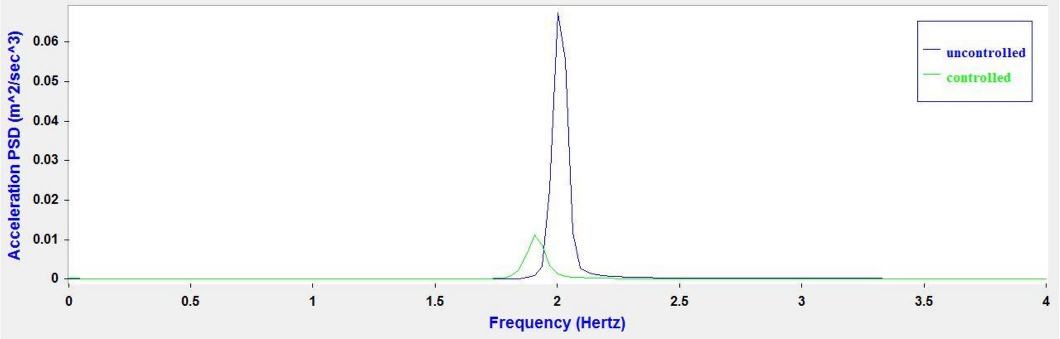

Figure 4.19: PSD Response for MTMD controlled against chirp loading

Similar PSD response for both Northridge and Kobe earthquake were shown in Figure 4.20 and Figure 4.21 . In which peak occurred at around 2 Hz and is suppressed in control structure response by adding TMDs to main structure. A slight frequency shift in control structure response in case of Kobe earthquake also occurs like in case of chirp loading.

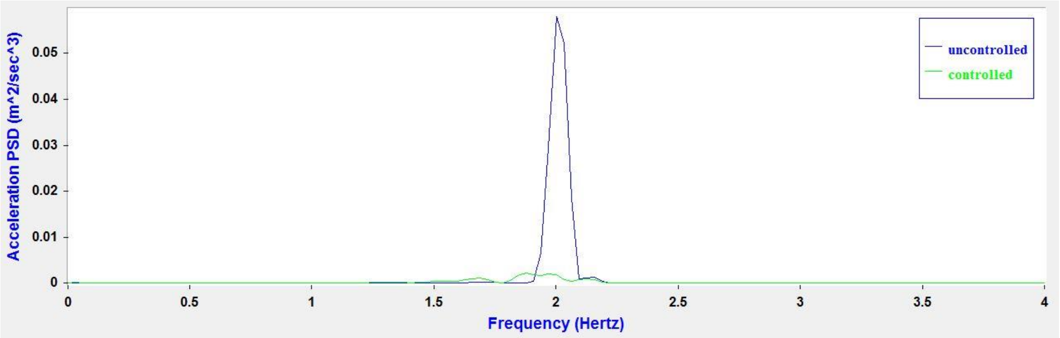

Figure 4.20: PSD Response for MTMD controlled against Northridge earthquake

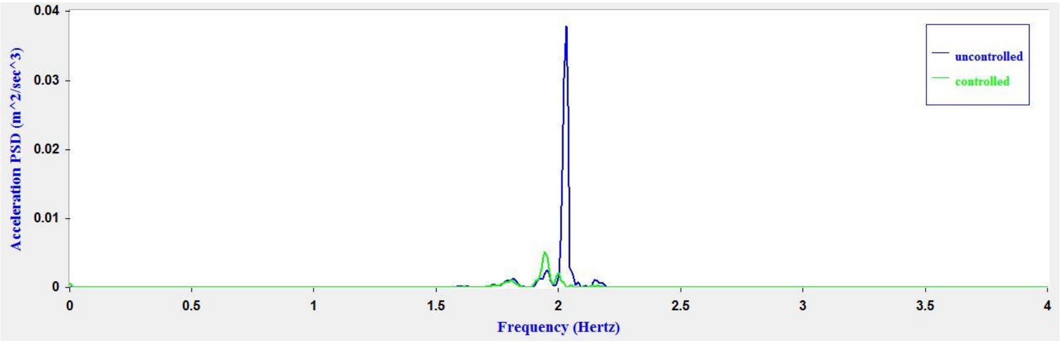

Figure 4.21: PSD Response for MTMD controlled against Kobe earthquake

4.7 Summary of results

Average % reductions for each case of STMD and MTMD for all floors against all loadings were calculated as shown in Table 4.5. For STMD case 4 is showing maximum average percentage reductions 22.79 % and is considered optimum configuration for overall main structure. For MTMD case III and case VI were showing almost equal and maximum reductions 37.03 % and 37.31 % and are considered optimum cases of MTMD for overall structure.

Table 4.5: Average % percentage reductions

	Configurations	**Average % reductions**
STMD	Case 1	18.50
	Case 2	17.15
	Case 3	20.89
	Case 4	**22.79**
MTMD	Case I	31.36
	Case II	33.04
	Case III	**37.03**
	Case IV	36.65
	Case V	34.18
	Case VI	**37.31**

CHAPTER 05

5 CONCLUSION

The effectiveness of tuned mass damper as STMD and MTMDs having varying locations along the storeys of main structure was experimentally studied on a 4-storey steel frame structure having mass irregularity at its 4th floor for harmonic, chirp and earthquake loadings. All possible configurations of STMD and MTMDs were studied for each loading case having a constant mass ratio and damping ratio. Based on this experimental study optimum locations of STMD and MTMDs were found for each loading case to reduce top storey RMS accelerations efficiently. For 0.5 Hz harmonic loading STMD optimum configuration to was found to be case 4 showing 26.29% reduction and MTMDs optimum configuration was also found to be case IV showing 43.07% reduction. For 1 Hz harmonic loading, case 1 of STMD was found to be optimum configuration showing 22.90% reduction while for MTMDs case III was found to be optimum showing 38.23% reduction. For 1.5 Hz harmonic loading, overall reduction of RMS accelerations by all configurations of STMD and MTMDs were less as compared to other loadings. The optimum configuration of STMD for 1.5 Hz harmonic was found to be case 4 showing 10.50% reduction and optimum configuration for MTMDs was found to be case VI showing 25.26% reduction. In the case of chirp loading, almost all configuration of STMD were showing equal reductions while among MTMDs configuration case III was found to be optimum showing 44.78% reduction. For Northridge earthquake, optimum configuration for STMD was found to be case 1 showing 43.70% reduction and for MTMDs case III was found to be optimum showing 54.23% reduction. In the case of Kobe earthquake STMD efficiency was less by the majority of the configurations but case 4 of STMD shows maximum reductions 20.36% similarly for MTMDs maximum reduction 29.35% was shown by case VI. Overall discussion shows that MTMDs optimum configurations are more suitable for irregular structure to reduce overall structure response especially top storey structure response in terms of RMS accelerations for all six types of input loadings.

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