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Experimentally Determining Optimal Mass and Frequency of Pendulum Type Tuned Mass Damper

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***Abstract*—Tuned Mass Damper (TMD) is a passive structural vibration control device which consists of a moving secondary mass connected to the main structure via springs and dampers. Pendulum Type Tuned Mass Damper (PTMD) is a type of TMD in which the secondary mass is suspended from the main structure. To design a PTMD, its optimal mass, optimal frequency and optimal damping are needed. In the current investigation, a model of G + 3 framed structures is considered and its response under sinusoidal base excitation is compared with and without PTMD. The main objective is to reduce the response of structure under resonant condition by using a PTMD. The different PTMD parameters are considered and analysed using software to determine their performance in reducing maximum displacement of structure due to dynamic loading. An actual model of framed structure with PTMD is then tested for base excitation by shake table analysis. Considering different PTMD parameters, the reduction in response of the structure is experimentally determined. The software and experimental results are compared and optimal parameters are determined.**

***Index Terms*—Pendulum type Tuned Mass Damper, Resonance, Seismic resistance, Shake table analysis, Time history analysis**

I. INTRODUCTION

A. Background

Today's building sector has experienced substantial expansion, resulting in the development of several tall and lighter structures which possess higher flexibility and lower inherent damping. Also many older structures were only designed to withstand gravity loads. For such structures, factors like earthquake and wind can induce dynamic forces to the structure which will cause significant vibration problems to such structures. Different intensities of external vibration can lead to issues ranging from annoyance for the occupants to significant structural damage or complete collapse [1]. The earthquake vibrations are random and its amplitude and frequency keeps changing with time, at the instances when the frequency of the vibration matches or is very close to the natural frequency of the structure, structure's dynamic response increases. In some instances, resonance can occur if earthquake's frequency is constantly near the natural frequency of the structure [2]. The wind effects like vortex shedding can also cause resonance if the frequency of vortices is same as natural frequency of the structure [3]. Hence vibration control systems have become increasingly necessary to help mitigate the effects of vibration for older structures and augment the dynamic effectiveness of newer structures. Different systems like base isolators, TMD, linear dampers, etc. are commonly used to mitigate the effects of structural vibrations. One of such system is a Tuned Mass Damper (TMD). The TMD designs first patented by Frahm [4] and optimum parameters were first determined by Den Hartog [5].

B. Tuned Mass Damper

TMD fundamentally consists of a secondary mass attached to a primary mass connected via a set of spring and damper. The secondary mass is allowed to translate with respect to the main structure. Since it is a passive system, the structural motion will impart relative motion to the TMD which in turn generate restoring forces which are out of phase to the driving forces [6]. When the natural frequency of the TMD is very close to the frequency of the dominant mode of the primary structure, a large reduction in the maximum displacement, base shear and base moments of the primary structure around the natural frequency of this dominant mode can be achieved [7]. The Pendulum Type Tuned Mass Damper (PTMD) is one type of TMD in which, the secondary mass is suspended from the main structure like a pendulum. Dampers are also provided which connects the main structure to the mass of PTMD. One example of PTMD is the one attached in one of the tallest buildings Taipei 101 which has a 726 ton of PTMD suspended at the top of the structure [8]. In the current study a PTMD is considered for analysis.

The mass, frequency and damping of the TMD are important parameters which are needed to be determined to achieve optimal performance in reducing response of the structure [9]. Hence numerical and experimental studies are important to figure out optimal parameters. In this study, the variation in frequency and mass of the provided PTMD is considered to determine the best combination of the parameters in reducing the response of a G+3 frame structure model.

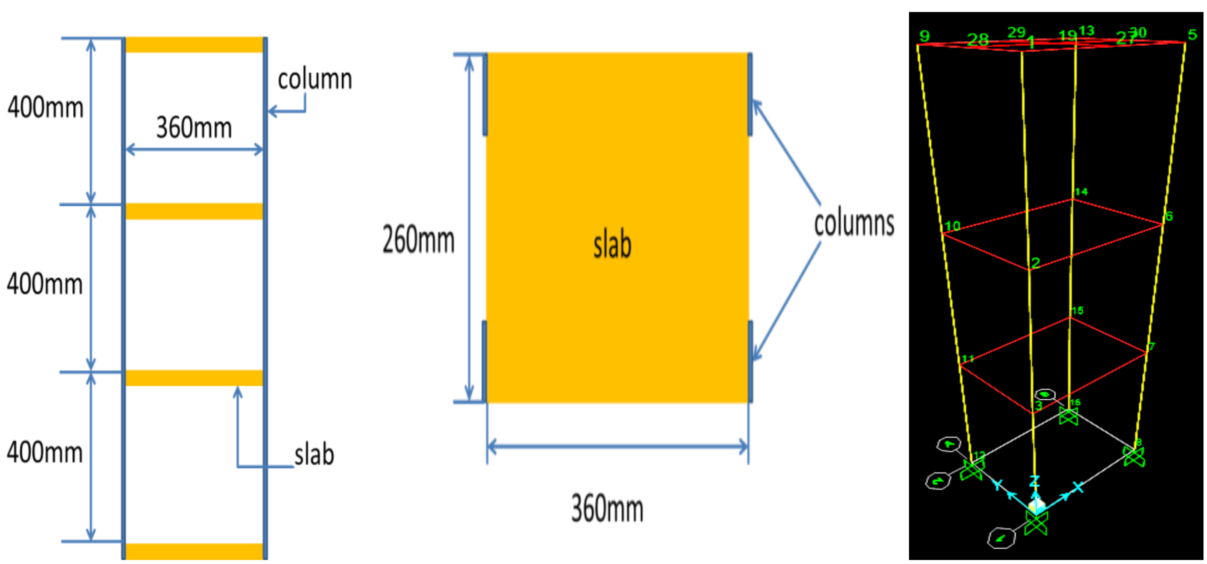
II. METHODOLOGY

A. Model Details

A model of G+3 frame structure without infill wall was considered with and without PTMD to be tested experimentally and analysed using software for harmonic base excitation to find out optimal PTMD parameters for vibration reduction. Software analysis was carried using SAP2000. The model consists of rigid slabs supported by 4 columns which are fixed at the base. The columns are arranged as shown in Fig. 1. The material properties are shown in Table I, which were taken to match the material properties of the actual experimental model.

Table I Model Properties

Slab Properties	Material = Plywood, Dimensions: Length= 360 mm, Width = 260mm, Thickness = 12mm, Density = 8.458 KN/m^3, Longitudinal Modulus of Elasticity = 10800 MPa, Longitudinal Poisson's ratio = 0.3, Longitudinal Modulus of Rigidity = 4154 MPa.
Column Properties	Material = Aluminium, Dimensions: Width = 19 mm, Thickness = 2 mm, Density = 27.1 KN/m^3, Modulus of Elasticity = 70000 MPa, Poisson's ratio = 0.32, Modulus of Rigidity= 26516 MPa.



(a) (b) (c)

Figure 1 Model Dimensions and Software Model Perspective View

Floor to floor height was taken 400mm. The total mass of software model was 3344gm. The longer slab span was placed along the global X axis and the columns were oriented such that longer width was along the global Y axis direction.

III. SOFTWARE ANALYSIS

A. Modal Analysis

The vibrations along the X direction (along the longer span) were considered for testing. The first three dominant translational modes along global X direction were determined based on the Modal Mass Participation Ratio as shown in Figure 2.

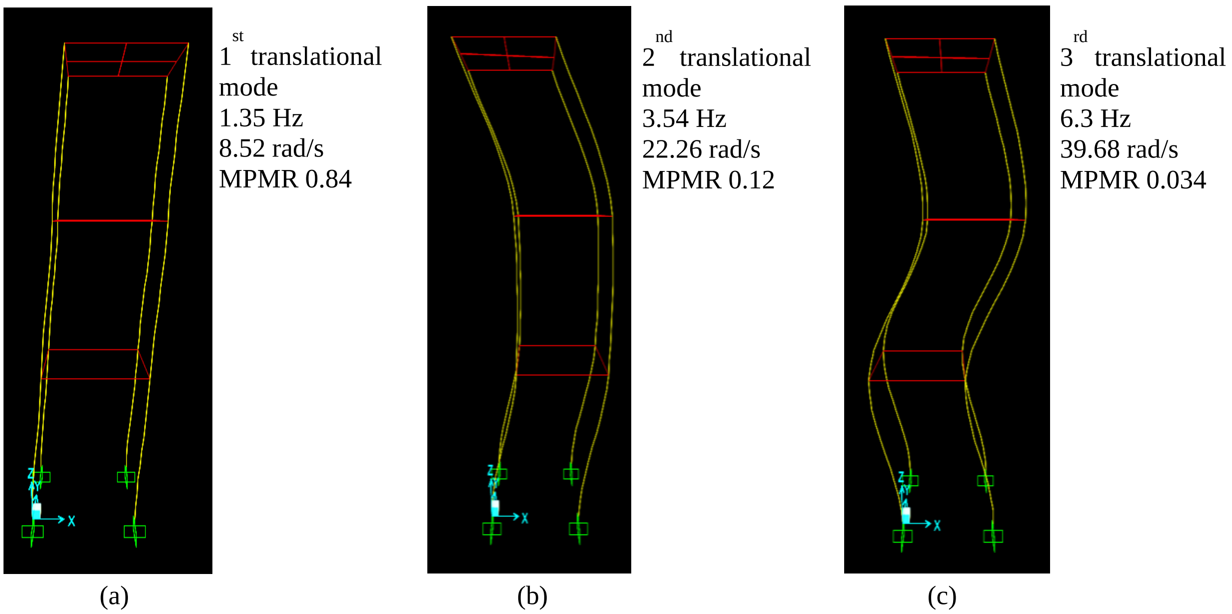


Figure 2 Mode Shapes

B. Forced Vibration Analysis (Without PTMD)

A sinusoidal time history load case was defined and the frequency was kept 1.35 Hz. Ground motion of 5mm amplitude was applied for 15 seconds. Without PTMD, under the time history load case, the maximum displacement occurring at top floor was 170.5mm.

C. Forced Vibration Analysis (With PTMD)

The PTMD was modelled as a simple harmonic oscillator using a linear link element. The PTMD was connected to the top floor as shown in Figure 3 and combinations of different mass ratio and frequency ratio were considered. The structure with PTMD was analysed for the time history load case and maximum displacement of top floor was recorded.

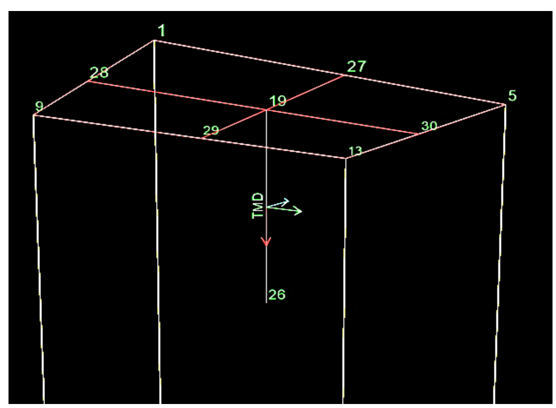
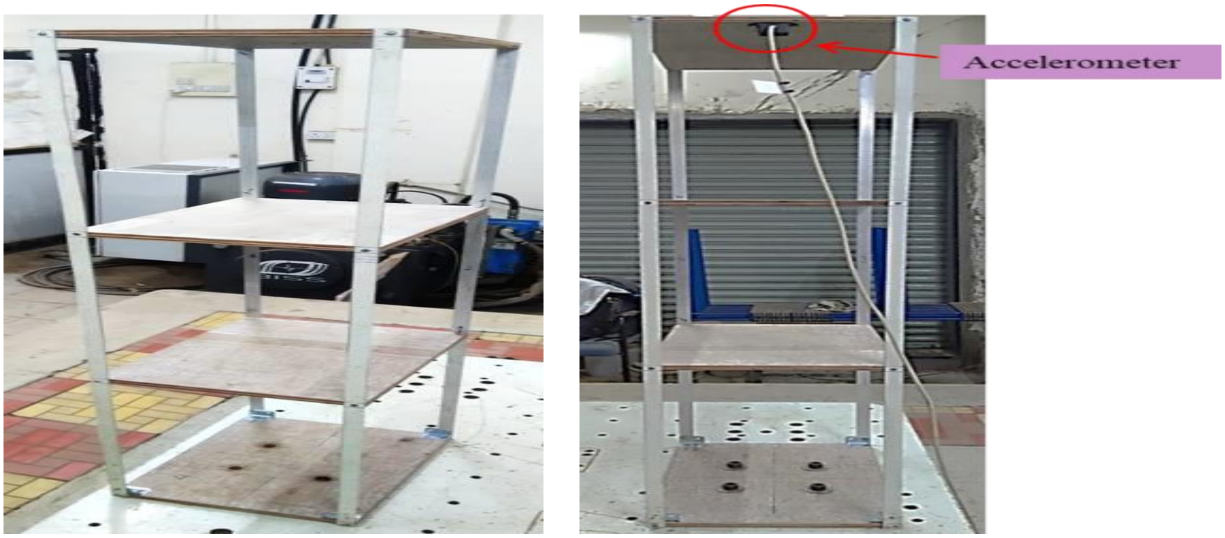


Figure 3 PTMD on Top Floor Using Link Element

IV. EXPERIMENTAL ANALYSIS

A. Free Vibration Test

An actual model, as shown in Figure 4, was fabricated which had the dimensions and material properties which are given in Table I and Fig. 1. The mass of actual model was measured to be 3500gm. The free vibration test was conducted on the actual model. An accelerometer was attached at the top floor of the structure to measure the acceleration. Fast Fourier Transform was carried out on the acceleration vs time data to find out the frequency domain response. The peaks in the frequency domain graph correspond to the modal frequency of the structure. Figure 5 shows the graph of recorded acceleration vs time data and Figure 6 shows its frequency domain response.



(a) (b)

Figure 4 Actual Model and Accelerometer Position

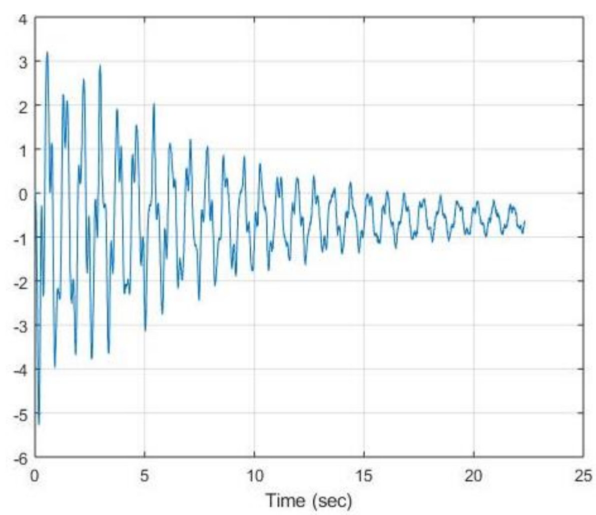


Figure 5 Acceleration Vs Time Data

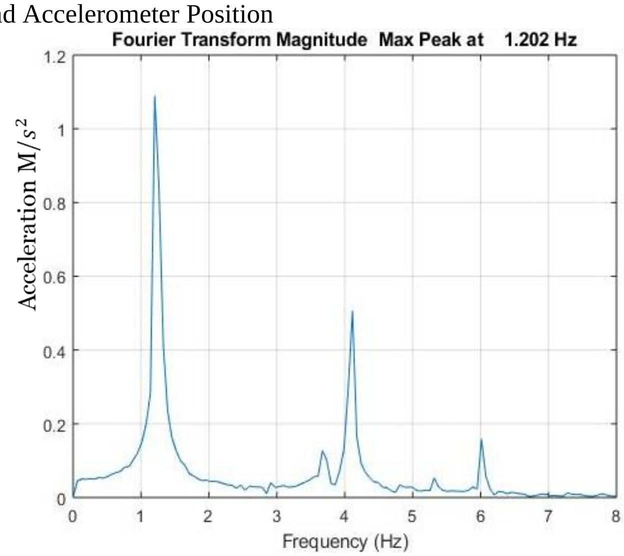


Figure 6 Frequency Domain Response

The natural frequencies obtained were 1.2 Hz, 4 Hz and 6 Hz which corresponds to the 1st, 2nd and 3rd translational mode. The natural frequencies of the experimental and software model were identical.

B. Shake Table Test (Without PTMD)

Sinusoidal base excitation was given to the model using the shake table machine. The model was tested without PTMD for excitation frequencies 1.2Hz and 4 Hz which are the 1st and 2nd natural frequencies of the model. The amplitude of vibration was kept as 5mm. The acceleration of top floor and the acceleration of shake table were measured using accelerometers. Using these acceleration vs time data the relative displacement between base and top floor was calculated. The maximum relative displacement for 1.2 Hz was 80.23mm and for 4 Hz it was 17.46mm. The graphs of relative displacements of the tests are shown in Figure 7 and Figure 8 respectively.

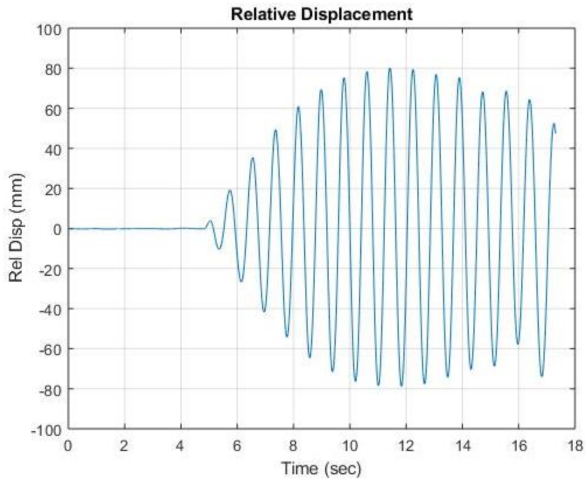


Figure 7 Relative Displacement (1.2 Hz Base Excitation)

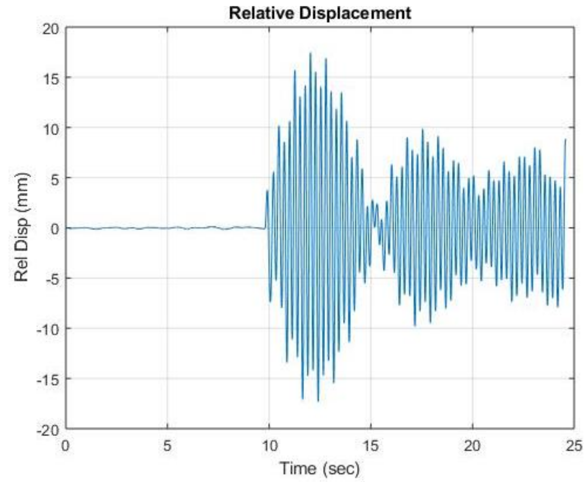
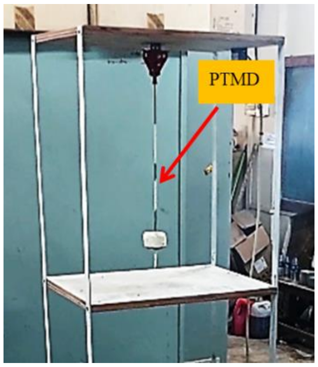


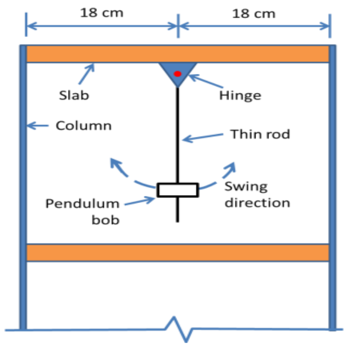
Figure 8 Relative Displacement (4 Hz Base Excitation)

B. Shake Table Test (With PTMD)

Fig. 9 shows the PTMD setup on the actual model. Combinations of different mass ratio and frequency ratio were considered and tested for sinusoidal base excitation of frequency 1.2 and 4 Hz both having 5mm amplitude. The acceleration of top floor and base were measured during the tests with 1.2 Hz base excitation. For the tests where the base excitation frequency was 4 Hz the maximum displacement was observed to be occurring on the 2nd floor.



(a)



(b)

Figure 9 PTMD Attached at the Top Floor

V. RESULTS AND DISCUSSION

A. Software Analysis Results

The maximum displacement of top floor obtained from software analysis is shown in Table II. The Figure 10 shows the variation of displacement of top floor against change in frequency ratio. The figure 11 shows the variation of displacement against the change in mass ratio.

Table II Maximum Displacement of Top Floor (in mm)

Mass Ratio \ Frequency Ratio	0.5	0.8	1	1.1	1.3	1.5
0.05	127.73	44.43	19.96	30.3	49.9	61.77
0.07	110.35	35.58	17.11	24.64	38.44	48.53
0.1	91.67	27.47	15.49	20.53	31.16	38.02
0.12	81.48	24.34	15.34	19.04	28.17	34.05
0.15	71.48	19.82	13.9	16.9	25.07	28.65

0.17	65.239	18.51	14.34	16.45	23.68	26.66
0.2	56.81	16.73	12.525	15.06	21.068	24.46

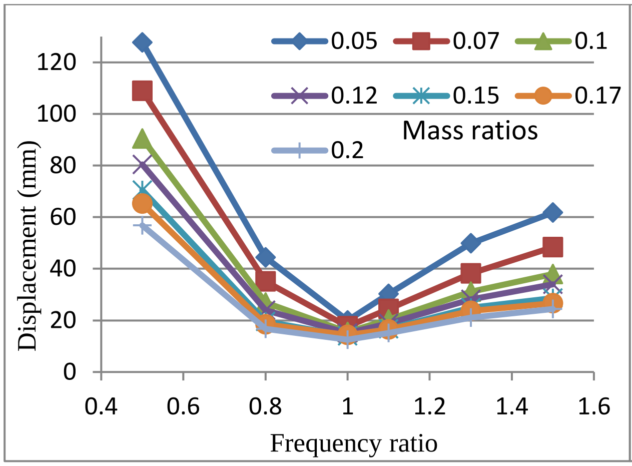


Figure 10 Displacement Vs Frequency Ratio

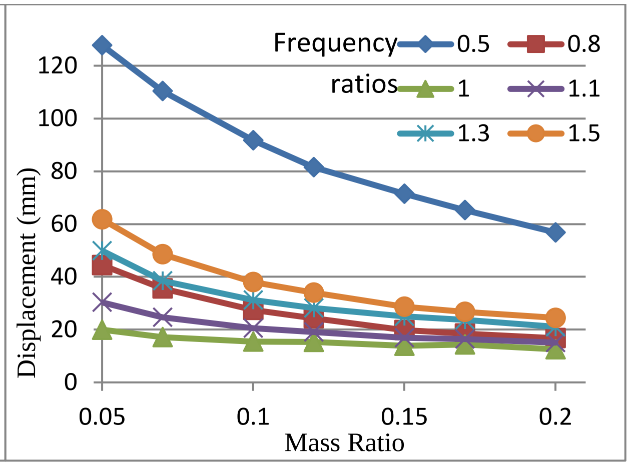


Figure 11 Displacement Vs Mass Ratio

From Figure 10 we can observe that for all mass ratios, the optimum frequency ratio is always 1. And from Figure 11 it is observed that for any frequency ratio initially up to 0.1 mass ratio, the slope of graph is steeper compared to the slope of the graph after 0.1 mass ratio. For frequency ratio of 1, more mass ratios were considered to get more data points in between of maximum displacement which are shown in Figure 12.

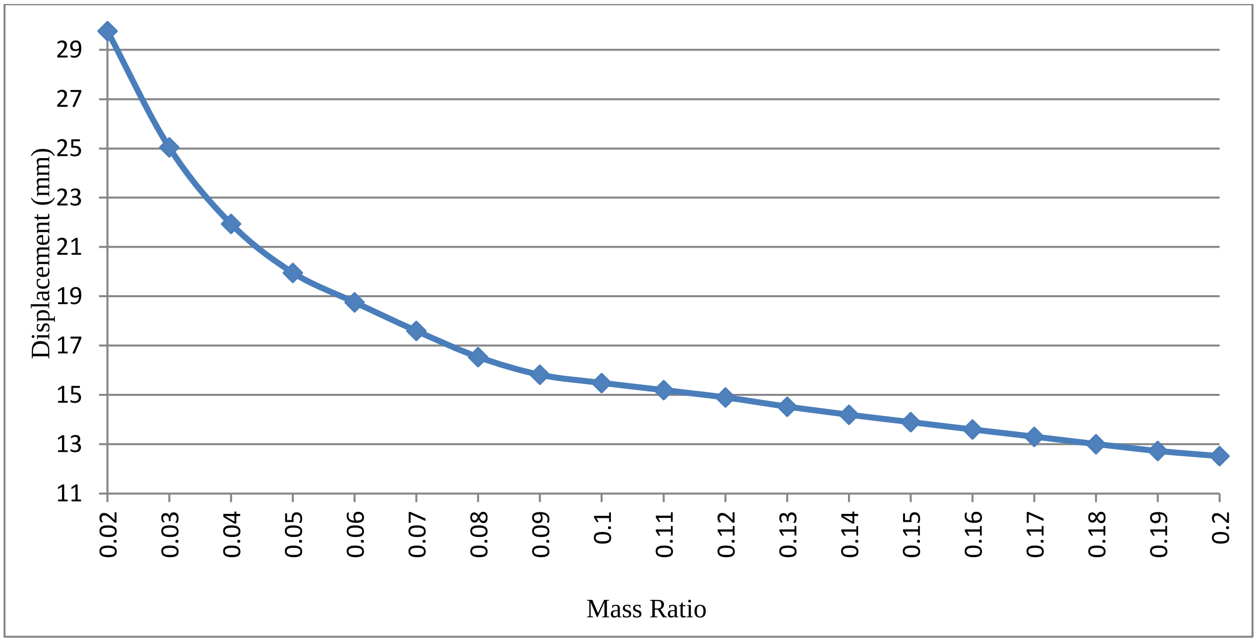


Figure 12 Maximum Displacement for Different Mass Ratio (Frequency Ratio = 1)

B. Experimental Test Results

Table III and Table IV shows the maximum displacements from shake table tests with PTMD.

Table III Maximum Displacement of Top Floor (mm) (TMD Position Top Floor) (1.2 Hz base excitation)

Table IV Maximum Displacement of 2nd Floor (mm) (TMD Position Top Floor) (4 Hz base excitation)

Frequency Ratio \ Mass Ratio	0.05	0.1	0.15
0.8	43.22	29.24	20.35
1	17.74	14.11	12.72
1.3	68.72	34.43	26.37

Frequency Ratio \ Mass Ratio	0.05	0.1	0.15
0.8	15.41	13.14	13.68
1	14.86	13.58	12.86
1.3	14.68	14.32	12.65

C. Comparison of Experimental and Analytical Data

Experimental PTMD data and its corresponding analytical data are shown from Figure 15 through Figure 26.

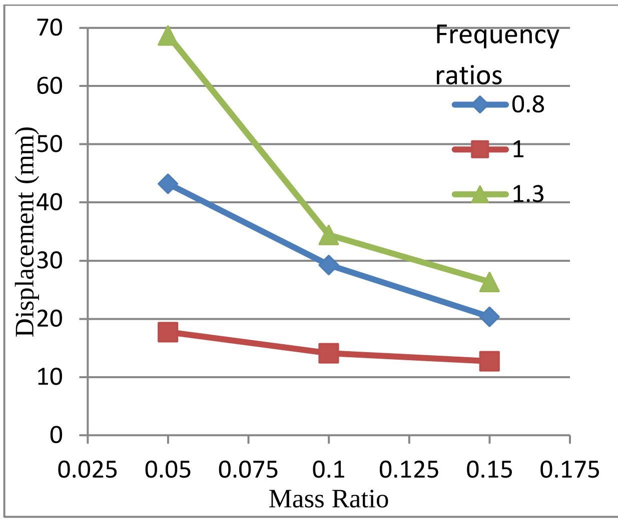


Figure 13 Experimental Displacement vs Mass Ratio (PTMD Position Top Floor) (1.2 Hz base excitation)

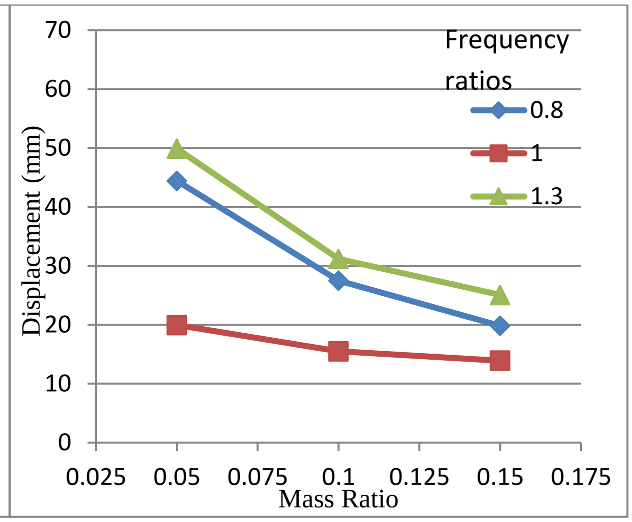


Figure 14 Analytical Displacement vs Mass Ratio (PTMD Position Top Floor) (1.2 Hz base excitation)

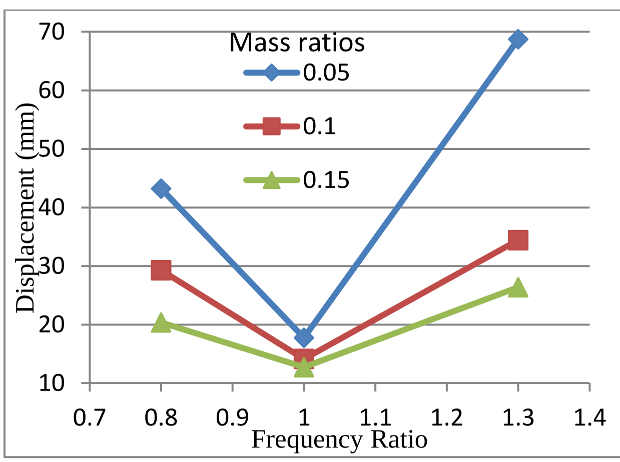


Figure 15 Exp. Displacement vs Frequency Ratio (PTMD Position Top Floor) (1.2 Hz base excitation)

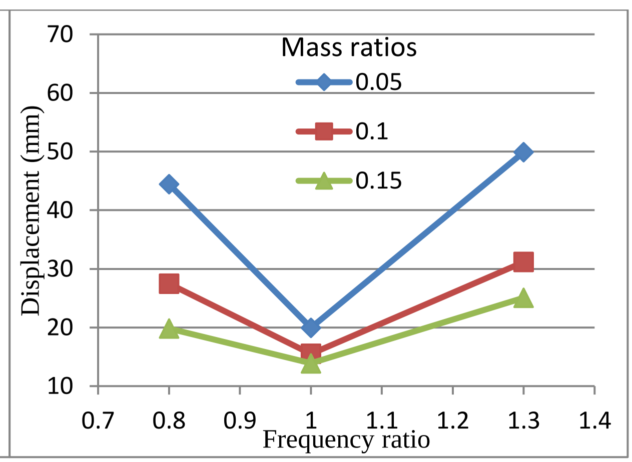


Figure 16 Analytical Displacement vs Frequency Ratio (PTMD Position Top Floor) (1.2 Hz base excitation)

The results show that there is a decrease in maximum displacement as the mass ratio increases. Comparing maximum displacements at mass ratios 0.05 and 0.1 the experimentally found percentage difference in maximum displacement is 20.46% and analytical difference is 22% on the other hand going from mass ratio 0.1 to 0.15, the experimental percentage difference is 9.85% and analytically found difference is 10.26% hence the analytical and corresponding experimental values can be considered to be very similar. For the 4 Hz base excitation frequency, without PTMD, the maximum displacement is 78.2% less compared to the maximum displacement under the 1.2 Hz base excitation without PTMD.

VII. CONCLUSION

An actual model of G+3 frame structure was tested for harmonic base excitations with and without PTMD. The PTMD was provided on top floor and multiple tests were carried with different PTMD parameters and maximum displacements of the model for these tests were determined. A software model of G+3 structure in SAP2000 was also tested for base excitations with TMD having different parameters and maximum displacements were determined. The maximum displacements of actual model and software model were compared to see which combination of parameter provides optimal results in reducing the maximum displacements.

1. From displacement vs mass ratio graphs, it is observed that when mass ratio is below 0.1, the slope of graph is observed to be higher and a small increment in mass ratio gives a considerable improvement in reducing the maximum displacement. When mass ratio is above 0.1 the slope of graph becomes lower and a small increment in mass ratio provides smaller improvement in reducing the maximum displacement.
2. When the applied base excitation had frequency same as natural frequency of the structure, the PTMD with frequency ratio of 1 was able to greatly reduce the maximum displacements, as observed experimentally and analytically.
3. When the frequency ratio is less than 1, the PTMD becomes less and less effective and at lower frequency ratios the PTMD is very ineffective and in some case it is increasing the maximum displacement.
4. For 1.2 Hz base excitation, maximum displacement reduction of 77.8%, 82%, and 84.2%, was found with PTMD having frequency ratio 1 and mass ratios of 0.05, 0.1, and 0.15 respectively. Additionally, for 4 Hz base excitation, the PTMD with frequency ratios of 1 and mass ratios of 0.05, 0.1, and 0.15 produced reductions in maximum displacement of 14.9%, 22.2%, and 26.3%, respectively. Hence for the G+3 frame structure, frequency ratio of 1 and mass ratio in the range from 0.05 to 0.1 is considered optimal.

REFERENCE

[1] Abburu and S.a.S. - Vibration Control in High-Rise Buildings for Multi-Hazard", 2015.Master's Thesis, Civil and Environmental Engineering, LSU, Baton Rouge, Louisiana, 1991.

[2] Murty, C. V. R., et al. - Earthquake behaviour of buildings, Gujarat State Disaster Management Authority, Gandhinagar 53 (2012): 79.

[3] Mendis, Priyan, et al. - Wind loading on tall buildings, Electronic Journal of Structural Engineering (2007).

[4] Frahm, H, 1909 - Device for Damping Vibrations of Bodies, U.S. Patent No. 989958

[5] J.P. (Jacob Pieter) Den Hartog - Mechanical vibrations, McGraw-Hill, New York, 1956, (OCoLC)597567130.\

[6] Purge.edu, Structural Dynamics Document by J. Connor, Available at: https://engineering. purdue. edu/~ce573/Documents/Intro %20to%20 Structural%20Motion%20Control_Chapter4.pdf

[7] Hassani S, Aminafshar M. Optimization of pendulum tuned mass damper in tall building under horizontal earthquake excitation. Bull. la Société R. des Sci. Liège [En ligne]. 2016 Jan 1;85:514-31.

[8] Poon, Dennis C. K., Shawn Shieh, Leonard Martin Joseph and Ching-Chang Chang - Structural Design of Taipei 101, the World's Tallest Building, 2004.

[9] Samal, Prasanta Kumar and Pasha Tajmul - Numerical and Experimental Investigation of Vibration Isolation of Three storied Building Structure using Tuned Mass Damper, 2019.