

Experimental Study on Torsional Response of Asymmetric Structure with Tuned Mass Dampers on a Scaled Model

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Abstract—This experimental study explores the torsional response of an asymmetric structure through a scaled-model approach incorporating a Pendulum-type Tuned Mass Damper (PTMD). Asymmetry is a common feature in buildings and structures and can cause damaging torsional vibrations induced by external factors such as wind or seismic activity. Tuned Mass Dampers (TMDs) have demonstrated effectiveness in reducing structural vibrations, and their application to the torsional response of asymmetric structures has drawn increasing interest. The study involves designing, fabricating and testing a scaled G+2 asymmetric frame model that mimics the eccentricity present in real structures. The model was subjected to controlled dynamic (shake-table) loading to simulate torsional excitation, and its natural frequency, mass centre and stiffness centre were determined analytically and verified using ETABS software. The effect of the TMD on the torsional behaviour of the structure was then investigated by comparing the shake-table response of the model without the damper against the response with the TMD installed. The results show that installing the TMD substantially reduces the amplitude of structural vibration compared to the bare frame, with the first three modal responses reduced by 34.61%, 42.5% and 56.98% respectively. The findings advance the understanding of torsional behaviour in asymmetric structures and the benefits of TMDs in mitigating it, and can guide engineers in the design and optimisation of asymmetric real-world structures for improved stability and occupant comfort.

Index Terms—Asymmetric structure, Pendulum tuned mass damper, Scaled model, Torsional response, Tuned mass damper, Vibration control.

I. INTRODUCTION

The rapid growth of the construction industry has led to the development of numerous tall and slender structures worldwide. External dynamic actions such as wind and earthquakes cause significant vibration problems in such structures, and vibrations of varying intensity can range from occupant discomfort to serious structural damage or complete collapse [1]. Strong earthquakes may drive a structure into resonance, which can severely damage it [2]. Modern design codes provide guidelines on structural mass, ductility, shape and damping to control the amplitude and frequency of structural vibration; increasing stiffness through additional bracing is one such option [3]. Alternatively, supplementary systems connected to the main structure can be used to dissipate vibration energy, of which the Tuned Mass Damper (TMD) is one of the most widely adopted.

A TMD is a secondary mass connected to the primary structure through springs, dampers or a pendulum linkage. During excitation, kinetic energy of the main structure is transferred to the TMD and dissipated, thereby reducing the response of the main structure. The concept of the tuned-mass vibration absorber was first introduced by Frahm [4], whose undamped mass-spring absorber could reduce the vibration amplitude of the main system to zero at a single frequency; the optimum damped absorber design was later established by Den Hartog [5]. TMDs have since been installed in numerous landmark structures, including the Citicorp Center in New York, the John Hancock Tower in Boston, and the 660-tonne damper atop Taipei 101 [6].

In the Pendulum-type Tuned Mass Damper (PTMD) considered in this study, the secondary mass is suspended from the primary structure like a pendulum rather than being connected through springs. The pendulum length is tuned to the natural frequency of concern, and an auxiliary damper dissipates the absorbed energy. Because it requires no external power, a PTMD is passive, reliable and low-maintenance, although its performance is sensitive to accurate frequency tuning [3].

Most existing analytical and numerical studies of TMD optimisation idealise the structure as a single-degree-of-freedom (SDOF) system undergoing pure translation, and comparatively little experimental work has examined TMD effectiveness for the torsional response of an asymmetric, multi-degree-of-freedom (MDOF) scaled structural model. This study addresses that gap by fabricating a G+2 asymmetric frame model, experimentally and computationally determining its dynamic properties, and comparing shake-table response of the bare structure against the structure fitted with a PTMD.

II. LITERATURE REVIEW

Gerges and Vickery [7] considered a translational SDOF system with a pendulum-type TMD, derived equations of motion under dynamic force and base-acceleration excitation, and produced design charts giving optimum TMD parameters for wind and seismic loading, including the effect of inherent structural damping. Abubakar and Farid [8] extended Den Hartog's classical undamped SDOF-TMD formulation to account for structural damping, generating curve-fitted design equations (error $\approx 1.5\%$) valid for mass ratios of 0.005-0.1 and structural damping ratios of 0.0-0.05.

Roffel et al. [9] investigated the three-dimensional motion of a nonlinear pendulum TMD coupled to an MDOF structure and found that a planar (linearised) PTMD model predicts the in-plane response well at low mass ratios but shows up to 9% error in the orthogonal direction, with accuracy degrading as the mass ratio increases. Fallahpasand et al. [10] used a nonlinear pendulum absorber to control the resonance peak of a horizontally excited primary system, deriving optimum damping and frequency ratios through numerical minimisation of the steady-state response. Gutierrez Soto and Adeli [11] reviewed

advances in TMD, PTMD, tuned-liquid-damper (TLD) and tuned-liquid-column-damper (TLCD) systems, along with real-world implementations. Mohite and Patil [12] evaluated a symmetric moment-resisting frame with TMDs at several storey levels under the Bhuj earthquake record and reported satisfactory drift and displacement reduction at most storeys, recommending multiple or active TMDs where a single passive damper was insufficient. These studies confirm the effectiveness of TMDs/PTMDs for translational vibration control, but few provide experimental modal-wise quantification of TMD effectiveness for a scaled asymmetric structure, which is the focus of the present work.

III. METHODOLOGY

A. Aim and Objectives

The aim of this project is to design and analyse a Tuned Mass Damper for a proposed asymmetric three-storey structure using both software simulation and experimental testing on a scaled model. The specific objectives were: (1) prepare a 3-storey asymmetric scaled model in ETABS; (2) fabricate the model and test it in the laboratory; (3) determine the natural frequency and time period of the fabricated structure; (4) determine the mass centre and stiffness centre analytically and verify them using ETABS; (5) integrate the PTMD with the fabricated structure at the designated height; (6) set the shake-table excitation frequency to match the modal frequencies of the structure; (7) test the structure without and with the PTMD; and (8) quantify the reduction in vibration amplitude achieved by the damper for each mode.

B. Model Details

The scaled model was a G+2, rigid-jointed plane frame with an asymmetric plan of 6000 mm $\times$ 4000 mm, floor-to-floor height of 400 mm and overall height of 1200 mm. Floor slabs were 12 mm thick aluminium (unit weight 26.98 kN/m³, $E = 10\,800$ MPa, $\nu = 0.3$), and columns were aluminium of 19 mm $\times$ 2 mm cross-section (density 27.1 kN/m³, $E = 70\,000$ MPa, $\nu = 0.32$). Idealisation assumed lumped floor masses, single-direction lateral translation per floor, rigid floor/beam members relative to columns, and combined column stiffness at each storey level.

C. Determination of Natural Frequency

Modal (eigenvalue) analysis was used to obtain the natural frequencies of the idealised 3-DOF shear-frame model by solving $[[K] - \omega^2[M]] = 0$, where $[K]$ and $[M]$ are the structural stiffness and mass matrices. Using a slab mass of 1.5 kg per floor, an inter-storey column mass of 0.172 kg and a storey stiffness of 635.04 N/m, the analysis yielded natural frequencies of $f_1 = 1.73$ Hz, $f_2 = 3.00$ Hz and $f_3 = 6.00$ Hz, corresponding to time periods $T_1 = 0.787$ s, $T_2 = 0.282$ s and $T_3 = 0.196$ s for the first three modes.

D. Time-History Analysis

Forced-vibration (time-history) analysis was carried out in SAP2000 by applying a base acceleration corresponding to a simple-harmonic displacement of amplitude 5 mm at the first modal frequency ($T = 0.7406$ s), i.e. $x(t) = 5 \sin(2\pi t/0.7406)$ mm, differentiated twice to obtain the input acceleration function. A nonlinear time-history load case was defined with modal damping of 0.016 to match the physical model, and the top-floor displacement response was extracted for each mode.

E. Experimental Set-Up

The fabricated model was mounted on a shake table and tested in two configurations: Test 01 without the TMD, to establish the baseline dynamic response, and Test 02 with the PTMD installed at the designated height, allowed to respond dynamically along with the structure. The oscillation amplitude at each of the first three modal frequencies was recorded for both configurations to quantify the vibration reduction achieved by the damper.

IV. RESULTS AND DISCUSSION

A. Test 01: Shake Without TMD

In Test 01, the G+2 structure was subjected to controlled shaking on the shake table without installing a Tuned Mass Damper (TMD). The purpose of this test was to establish the baseline dynamic response of the structure under external excitation. During the shaking, the structure exhibited noticeable lateral movement and oscillations, particularly at the upper levels. As the shaking continued, the displacement of the structure increased due to the dynamic forces acting on it. The absence of a damping mechanism allowed the vibrations to

propagate through the structure, resulting in comparatively higher oscillations. This test provides a reference response against which the effectiveness of the TMD in the subsequent test can be evaluated.

B. Test 02: Shake With TMD

In Test 02, the same G+2 structure was subjected to similar shaking conditions after installing the Tuned Mass Damper. The TMD was positioned at the designated height and allowed to respond dynamically along with the structure. During the test, the movement of the structure was comparatively controlled, with a reduction in the amplitude of oscillations observed. The TMD works by developing an opposing dynamic response to the motion of the main structure, thereby absorbing and dissipating a portion of the vibration energy. Compared with Test 01, the presence of the TMD resulted in improved vibration control and reduced lateral movement of the structure, demonstrating its potential effectiveness in mitigating structural vibrations.

C. Quantitative Reduction in Vibration

Table I summarises the percentage decrease in vibration amplitude recorded for the first three modes of the structure after installation of the TMD, comparing Test 02 against the Test 01 baseline.

TABLE I PERCENTAGE DECREASE IN VIBRATION AMPLITUDE (TEST 01 VS TEST 02)

Mode	Decrease in Vibration (%)
Mode 1	34.61
Mode 2	42.50
Mode 3	56.98

The reduction in vibration amplitude increases progressively from the first to the third mode, with the TMD achieving a 34.61% decrease in Mode 1, 42.50% in Mode 2 and 56.98% in Mode 3. This trend indicates that the damper is increasingly effective at higher modal frequencies, likely because the higher modes involve greater relative floor displacements and torsional coupling, which the PTMD is well suited to counteract through its opposing dynamic response. The consistently high reduction across all three modes confirms that the TMD provides broadband vibration control rather than being effective only at a single tuned frequency, which is a

desirable characteristic for real structures subjected to multi-modal excitation from wind or seismic loading. Overall, the experimental results validate the SAP2000 time-history predictions qualitatively: resonant excitation at the modal frequencies produces significant response in the bare frame, and the addition of a correctly tuned PTMD substantially attenuates this response at every mode tested, improving the stability and serviceability of the asymmetric structure.

V. CONCLUSION

This chapter draws conclusions from the experimental and software studies conducted on the 3-storey framed structure fitted with a Pendulum Tuned Mass Damper (PTMD). The study determined the optimal mass ratio and optimal frequency ratio of the PTMD for reducing structural vibration due to sinusoidal base excitation, and further explored the effect of positioning the PTMD on different floors of the structure.

Based on the data and observations recorded during testing, it is evident that installing the Tuned Mass Damper had a significant positive effect on the structural vibrations. Prior to installing the TMD, the structure exhibited excessive shaking and oscillation, a condition that could lead to structural damage, occupant discomfort, or even failure under extreme conditions; such vibration typically results from dynamic forces including wind, seismic activity, or other external excitations.

After installing the Tuned Mass Damper, the vibrations were notably reduced, as seen in the comparative results, confirming the effectiveness of the TMD in mitigating the impact of these external forces. The TMD functions by absorbing a portion of the vibrational energy of the structure and dissipating it, thereby preventing excessive oscillation. By tuning the damper to the natural frequency of the structure's vibration, the system specifically targets and reduces the resonant response, which is typically where the most significant oscillations occur.

The results obtained are promising and indicate that the TMD significantly enhances the stability and performance of the structure, leading to a safer and more resilient system. This reduction in vibration not only preserves the structural integrity but also improves occupant comfort and the long-term

durability of the building. The successful implementation of the Tuned Mass Damper in this project serves as a valuable demonstration of how passive vibration-control systems can be effectively employed to address dynamic loading concerns in engineering design. In conclusion, the installation of the TMD has proven to be an effective solution for controlling excessive structural vibration, demonstrating its potential for broader application in various civil and mechanical engineering projects, particularly in high-rise buildings, bridges, and other structures susceptible to dynamic forces.

Future Scope of Work

- Investigate the effect of varying the pendulum/TMD height on the structural response.
- Extend the study from the existing G+2 structure to structures with a greater number of floors.
- Provide the PTMD with viscous dampers and test the assembly to find the optimal damping.

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