Experimental Study on Mitigation of Coupled Lateral–Torsional Response of an Asymmetric Scaled Structure Using Tuned Liquid and Column Tuned Liquid Dampers

Shubham Bhagwan Pancholi[1], P. V. Muley[2]
[1,2]*Department of Civil Engineering, Datta Meghe College of Engineering, Airoli, Navi Mumbai – 400 708, India*

***Abstract*—Plan-asymmetric structures exhibit coupled lateral–torsional vibration under seismic excitation due to the eccentricity between the centre of mass (CM) and the centre of stiffness (CR), resulting in amplified edge displacements and localised damage. This paper presents an experimental investigation of two passive liquid mass dampers a Tuned Liquid Damper (TLD) and a Column Tuned Liquid Damper (CTLD) for mitigating this coupled response. A G+2 asymmetric aluminium framed model (600 mm × 400 mm plan, 1200 mm height) was fabricated and tested on a 1-tonne uniaxial shake table under harmonic base excitation (amplitude 5 mm) at 1.2 Hz, 4.0 Hz and 6.0 Hz, corresponding to the first three coupled modes of the structure. Both dampers were placed at eccentric positions on the top, second and first floors, and the fluid mass ratio (ratio of liquid mass to structural mass) was varied from 5% to 80% (TLD) and 5% to 55% (CTLD). Bidirectional accelerometers mounted at the flexible and stiff edges captured the coupled translational–torsional response, and displacement time-histories were obtained by double integration. Results show that both dampers achieve maximum efficiency at a mass ratio of approximately 40%; beyond this threshold the dampers detune and performance degrades. The CTLD consistently outperformed the TLD at all frequencies, achieving a maximum displacement reduction of 37.31% versus 32.83% at the fundamental mode, and a 48.89% reduction in peak torsional rotation versus 40.00%. Efficiency was strongly frequency-dependent and was greatest when the dampers were placed eccentrically on the top floor. The study demonstrates that eccentrically placed CTLDs are a simple, low-maintenance and effective passive strategy for torsional response control of asymmetric buildings.**

***Index Terms*—Asymmetric structure, Column tuned liquid damper, Detuning, Liquid sloshing, Mass ratio, shake table testing, Torsional response, Tuned liquid damper**

I. INTRODUCTION

Modern architectural demands have produced a growing number of tall and geometrically irregular buildings. Unlike symmetric structures, plan-asymmetric buildings possess an inherent eccentricity between the centre of mass (CM) and the centre of stiffness (CR). Under earthquake ground motion, this eccentricity induces strong coupled lateral–torsional vibrations, causing non-uniform lateral force distribution and disproportionate amplification of edge deformations and drift demands in peripheral vertical elements, thereby increasing the likelihood of localised failure and progressive collapse [1].

Among the available vibration control strategies structural modification, aerodynamic modification, base isolation and supplemental damping passive liquid mass dampers have attracted wide acceptance because of their low cost, absence of mechanical wear parts, minimal maintenance and the functional reuse of the contained water for firefighting or other non-potable purposes [2]. Two principal forms exist: the Tuned Liquid Damper (TLD), in which energy is dissipated through fluid sloshing, wave breaking and boundary-layer friction in a shallow rectangular tank; and the Column Tuned Liquid Damper (CTLD), in which liquid oscillates in a U-tube and dissipates energy through orifice head loss and internal fluid friction [3], [4].

While the performance of liquid dampers in controlling purely translational modes is well documented [4]–[8], their application to the coupled lateral–torsional response of asymmetric structures remains comparatively under-explored. For torsional control, the damper must be positioned at an

eccentricity from the CR so that the sloshing force develops a restorative counter-torque, and its tuning frequency, mass ratio and geometry must account for both translational and rotational modal characteristics [9]. Experimental verification on scaled physical models using shake tables is essential, because fluid–structure interaction is strongly nonlinear and analytical models are of limited fidelity at large sloshing amplitudes [6], [7].

This study addresses this gap through a comprehensive shake-table experimental programme on a scaled asymmetric structure, comparing rectangular TLDs and CTLDs placed eccentrically at different floor levels over a wide range of fluid mass ratios and excitation frequencies. The specific objectives are: (i) to identify the coupled natural frequencies of the asymmetric model; (ii) to evaluate the influence of fluid mass ratio on damper efficiency; (iii) to compare the torsional mitigation capability of the TLD and CTLD; and (iv) to establish the optimal placement and mass ratio for maximum counter-torque generation.

II. LITERATURE REVIEW

Liquid dampers have been studied since the 1980s. Vandiver and Mitome [5] demonstrated the use of liquid tanks to reduce the vibration of offshore platforms. Balendra et al. [4] showed that TLCDs can effectively suppress wind-induced vibration of towers, with an optimal orifice opening ratio between 0.5 and 1.0. Sadek et al. [10] established design parameters for single and multiple TLCDs for seismic applications, reporting response reductions of up to 47%. Banerji et al. [11] found that a TLD with a mass ratio of 4% and depth ratio of 0.15 can reduce the response of a single-degree-of-freedom structure by approximately 30%. Bhattacharjee et al. [8] showed experimentally that rectangular TLDs outperform square TLDs under harmonic excitation. Saha and Debbarma [12] studied multiple TLDs on a scaled structure and confirmed that maximum response reduction occurs at tuning. Ashasi-Sorkhabi et al. [13], using real-time hybrid simulation, found that TLD effectiveness improves with mass ratio up to about 3%, beyond which no considerable gain occurs. Pabarja et al. [14] achieved a 45% reduction in RMS displacement of a vertically irregular structure using TLDs tuned to the first two modes.

Critically, most published experimental studies consider symmetric or vertically irregular models under unidirectional excitation, and direct experimental comparisons of TLDs and CTLDs for the coupled lateral–torsional response of plan-asymmetric structures are scarce. The present work fills this gap.

III. EXPERIMENTAL PROGRAMME

A. Structural Model

A G+2 (three-storey) plan-asymmetric, rigid-jointed framed model was fabricated from aluminium, as shown in Fig. 1. The L-shaped floor slabs measured 600 mm × 400 mm × 12 mm, supported on columns of 19 mm × 2 mm rectangular section at a floor-to-floor height of 400 mm (overall height 1200 mm). The plan asymmetry produces the desired mass–stiffness eccentricity. The model was bolted to the shake table base with four 10 mm diameter bolts to simulate fixed supports, and excitation was applied along the minor (weak) axis of the columns to induce maximum lateral–torsional coupling. The total mass of the model was 3.5 kg.



Fig. 1. Asymmetric G+2 framed model mounted on the shake table.

B. Damper Configurations

Two dampers were fabricated from 3 mm acrylic sheet (Fig. 2): (a) the TLD, with interior dimensions 200 mm × 140 mm × 180 mm (mass 846 g), operating as a shallow sloshing tank; and (b) the CTLD, a U-tube configuration with 200 mm overall length, 140 mm width, 40 mm high bottom channel, 40 mm wide vertical columns and 180 mm overall height (mass 797 g), with a small vent hole at the top of each column to maintain atmospheric pressure on the free surface. The

dampers were rigidly attached at eccentric positions (near the flexible edge, away from the CR) on the floor under test, so that the sloshing inertial force acted with a maximum lever arm to generate counter-torque.

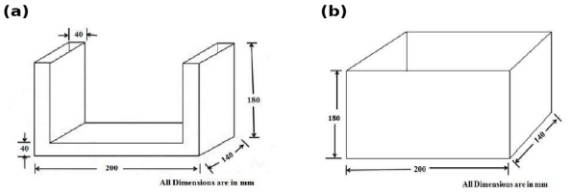


Fig. 2. Damper geometries (dimensions in mm): (a) TLD; (b) CTLD.

C. Shake Table and Instrumentation

The tests were conducted on a 1-tonne capacity uniaxial servo-hydraulic shake table (Fig. 3) with a 1200 mm × 1200 mm table, maximum displacement of ±150 mm and a frequency range of 0.1–60 Hz. Harmonic sinusoidal base motion of 5 mm amplitude was applied at 1.2 Hz (15 cycles) and 4.0 Hz (40 cycles); additional characterisation was performed at 6.0 Hz. Bidirectional accelerometers (range ±2g) were mounted at the flexible and stiff edges of the floor slabs, enabling simultaneous capture of lateral translation and torsional rotation. Data were processed using the enDAQ Vibration Data Toolbox: modal frequencies were identified by Fast Fourier Transform (FFT) of free-vibration decay records, and displacement time-histories were obtained by double integration of the acceleration records.

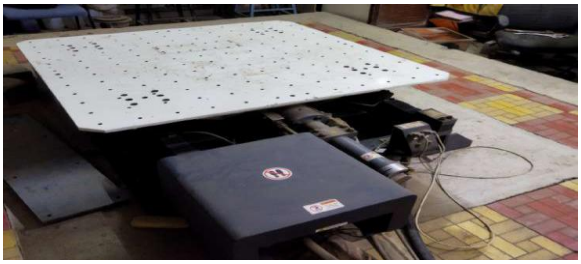


Fig. 3. Uniaxial shake table used for testing.

D. Dynamic Characterisation

Free-vibration tests with the damper attached at each floor centre yielded coupled natural frequencies of 1.2 Hz, 4.0 Hz and 6.0 Hz for the first three translational modes (Fig. 4). These agree closely with the values obtained analytically (1.26 Hz by hand calculation using the eigenvalue approach, and 1.23 Hz from STAAD.Pro modal analysis), validating the experimental model.

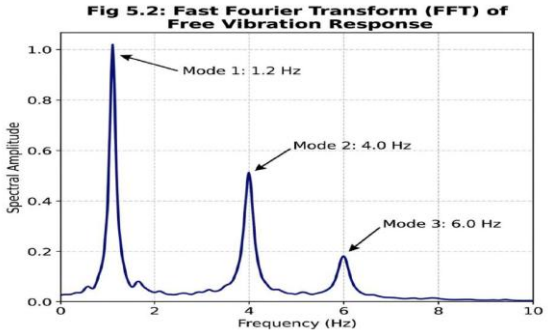


Fig. 4. FFT of the free-vibration response showing coupled modes at 1.2, 4.0 and 6.0 Hz.

E. Test Matrix

For each damper, the mass ratio was varied from 5% to 80% (TLD, at 5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 75 and 80%) and from 5% to 55% (CTLD). Each configuration was tested with the damper placed eccentrically on the top, second and first floors, at excitation frequencies of 1.2 Hz and 4.0 Hz. The bare-frame response (0% mass ratio) served as the reference.

IV. RESULTS AND DISCUSSION

A. Effect of Mass Ratio and the Detuning Phenomenon

At the fundamental frequency (1.2 Hz, resonance), the bare frame exhibited a maximum edge displacement of 55.83 mm. As the TLD mass ratio increased from 5% to 40%, the displacement reduced monotonically from 50.15 mm to a minimum of 37.50 mm (32.83% reduction). Beyond 40%, however, the displacement increased again (38.20 mm at 50%, 42.15 mm at 80%). The identical trend was observed for the CTLD and at 4.0 Hz and 6.0 Hz.

This behaviour is explained by detuning: as water is added, the fundamental sloshing frequency of the liquid decreases and approaches the structural frequency near a 40% mass ratio, maximising energy transfer and dissipation. Additional water lowers the sloshing frequency below the structural frequency, throwing the damper out of phase with the structure and sharply reducing its effectiveness. The 40% mass ratio therefore represents the practical optimum for this model, and excessive fluid mass is not merely wasteful but actively detrimental.

B. Comparison of TLD and CTLD

At every excitation frequency, the CTLD outperformed the rectangular TLD (Table I and Fig. 5). In the TLD, energy is dissipated primarily through surface wave breaking, which is uncontrolled and amplitude-dependent. The CTLD confines the liquid motion to two vertical columns connected by a horizontal channel; the resulting U-tube oscillation produces larger restorative forces and higher internal and orifice friction per unit liquid mass, generating a stronger counter-force and hence a stronger counter-torque given the same eccentric placement. At 1.2 Hz the CTLD reduced the peak edge displacement by 37.31% (35.00 mm) against 32.83% (37.50 mm) for the TLD, and reduced the peak torsional rotation by 48.89% against 40.00% a significant advantage for torsional control of asymmetric structures.

C. Frequency-Dependent Efficiency

Damper effectiveness decreased markedly with excitation frequency. At 1.2 Hz the slow, near-resonant sway allows the liquid sufficient time to traverse the container, build momentum and impact the far wall, fully developing the sloshing wave. At 4.0 Hz and particularly 6.0 Hz, the rapid base motion produces only choppy, partially developed surface waves, and the liquid cannot build a full sweeping slosh; momentum transfer and energy dissipation are consequently reduced. Maximum reductions therefore dropped from 37.31% (CTLD, 1.2 Hz) to 34.84% (4.0 Hz) and 25.00% (6.0 Hz). This confirms that liquid mass dampers are fundamentally low-frequency devices, most effective when tuned to the fundamental mode.

D. Effect of Damper Elevation

Positioning the dampers at the highest elevation (top floor) consistently gave the best mitigation, because the top floor experiences the largest modal displacement and provides the longest lever arm about the CR for counter-torque generation. Relocating either damper to the second or first floor reduced efficiency substantially, owing to the lower modal displacements at those levels. Eccentric placement outperformed central placement for the same reason the lever arm of the sloshing inertial force about the CR is maximised at the flexible edge.

V. CONCLUSION

Based on the free- and forced-vibration shake-table tests on the scaled asymmetric framed model, the following conclusions are drawn:

1. Both dampers achieve maximum energy dissipation at a fluid mass ratio of approximately 40% (35–40% for the CTLD at 4.0 Hz). Beyond this threshold the sloshing frequency detunes from the structural frequency and efficiency degrades excessive liquid mass is detrimental.
2. The CTLD consistently outperformed the TLD at all tested frequencies, achieving 37.31% versus 32.83% displacement reduction and 48.89% versus 40.00% peak torsional rotation reduction at the fundamental mode, owing to its confined U-tube sloshing mechanism.
3. Eccentric placement on the top floor is the most effective configuration, maximising both modal displacement participation and the counter-torque lever arm.
4. Efficiency is highest at the fundamental mode (1.2 Hz) and decreases at higher modes (25.00% at 6.0 Hz for the CTLD), because rapid excitation prevents full sloshing-wave development.
5. Passive liquid dampers are confirmed as a simple, robust, low-maintenance and cost-effective means of controlling the coupled lateral–torsional response of plan-asymmetric structures; the CTLD is the preferred configuration where torsional control is the governing requirement.

Future work may extend the excitation to real earthquake time-histories and bi-directional/multi-axis base motion; introduce baffles, screens or floating particles to modify sloshing; investigate sloped-bottom or circular (torsional) tank geometries; examine fluids of different density and viscosity, including magneto-rheological fluids for semi-active CTLDs; and incorporate soil–structure interaction and infill walls.

ACKNOWLEDGMENT

The authors thank Prof. P. V. Muley for his guidance throughout this study, and the Structural Engineering Division of Sardar Patel College of Engineering, Mumbai, for providing the uniaxial shake table facility used for the experimental work.

Table I
Maximum Efficiency of TLD and CTLD at Optimal Mass Ratio

Excitation	Mode	Damper	OptimalMass Ratio	Bare Frame (mm)	Mitigated (mm)	Reduction (%)
1.2 Hz	Fundamental coupled	TLD	40%	55.83	37.50	32.83
1.2 Hz	Fundamental coupled	CTLD	40%	55.83	35.00	37.31
4.0 Hz	Secondary coupled	TLD	40%	15.50	11.25	27.42
4.0 Hz	Secondary coupled	CTLD	35–40%	15.50	10.10	34.84
6.0 Hz	Higher-order	TLD	40%	8.20	6.56	20.00
6.0 Hz	Higher-order	CTLD	40%	8.20	6.15	25.00

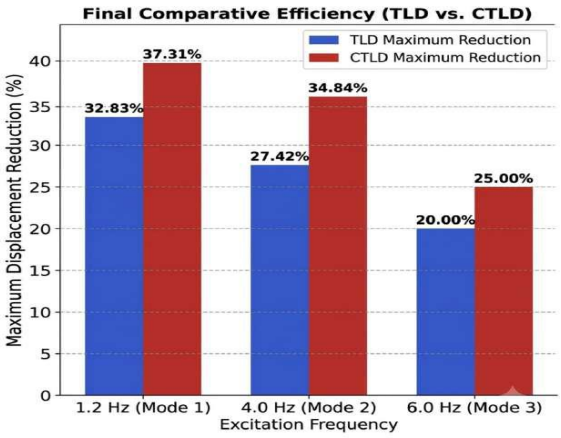


Fig. 5. Final comparative efficiency of the TLD and CTLD at the optimal mass ratio.

REFERENCES

[1] K. Chopra, *Dynamics of Structures*, 4th ed. Pearson, 2012.

[2] Nanda and K. C. Biswal, "Application of tuned liquid damper for controlling structural vibration," in *Proc. International Conference on Structural Engineering and Construction (ISEC)*, 2011.

[3] Y. Fujino, L. Sun, B. M. Pacheco, and P. Chaiseri, "Modelling of tuned liquid damper (TLD)," *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 43, pp. 1883–1894, 1992.

[4] T. Balendra, C. M. Wang, and H. F. Cheong, "Effectiveness of tuned liquid column dampers for vibration control of towers," *Engineering Structures*, vol. 17, no. 9, pp. 668–675, 1995.

[5] J. K. Vandiver and S. Mitome, "The effect of liquid storage tanks on the dynamic response of offshore platforms," *Journal of Petroleum Technology*, vol. 31, pp. 1231–1240, 1979.

[6] L. Sun and Y. Fujino, "A semi-analytical model for tuned liquid damper (TLD) with wave breaking," *Journal of Fluids and Structures*, vol. 8, pp. 471–488, 1994.

[7] J. B. Frandsen, "Numerical predictions of tuned liquid tank structural systems," *Journal of Fluids and Structures*, vol. 20, pp. 309–329, 2005.

[8] E. Bhattacharjee, L. Halder, and R. Sharma, "An experimental study on tuned liquid damper for mitigation of structural response," *International Journal of Advanced Structural Engineering*, vol. 5, 2013.

[9] M. J. Hochrainer, "Tuned liquid column damper for structural control," *Acta Mechanica*, vol. 175, pp. 57–76, 2005.

[10] F. Sadek, B. Mohraz, and H. S. Lew, "Single and multiple-tuned liquid column dampers for seismic applications," *Earthquake Engineering & Structural Dynamics*, vol. 27, pp. 439–463, 1998.

[11] P. Banerji, M. Murudi, A. Shah, and N. Popplewell, "Tuned liquid dampers for controlling earthquake response of structures," *Earthquake Engineering & Structural Dynamics*, vol. 29, pp. 587–602, 2000.

[12] S. Saha and R. Debbarma, "An experimental study on response control of structures using multiple tuned liquid dampers under dynamic loading," *International Journal of Advanced Structural Engineering*, vol. 8, 2016.

[13] Ashasi-Sorkhabi, H. Malekghasemi, A. R. Ghaemmaghami, and O. Mercan, "Experimental and numerical investigations of the dynamic interaction of tuned liquid damper–structure systems," *Journal of Vibration and Control*, vol. 21, no. 14, pp. 2707–2722, 2015.

[14] Pabarja, M. Vafaei, S. C. Alih, M. Y. M. Yatim, and S. Osman, "Experimental study on the efficiency of tuned liquid dampers for vibration mitigation of a vertically irregular structure," *Mechanical Systems and Signal Processing*, vol. 115, pp. 102–117, 2019.