18th Australasian Wind Engineering Society Workshop
McLaren Vale, South Australia
6-8 July 2016

Hybrid Tuned Liquid Column and Sloshing Damper: Design, Testing and Commissioning

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Abstract

The design process for a Hybrid TLCD/TLSD system for the 289m tall Gama Tower, located in Jakarta, as well as details of the commissioning process, are discussed in this paper. This hybrid design was driven by the need to maximize the mass of water for the auxiliary damper system within the volume allocated.

A comparison is presented of the damping and water level for tuning between that predicted using the theoretical calculations, the measured values from the shake table tests, as well as a comparisons against the full-scale prototype.

Introduction

Tuned Liquid Column Dampers (TLCDs) and Tuned Liquid Sloshing Dampers (TLSDs) are efficient and cost effective methods of supplementing the inherent damping of tall buildings and thus reducing the wind-induced response of the structure. TLCDs typically consist of a U-shaped tank (when viewed in elevation), whereas basic TLSDs are uniform rectangular-plan tanks. In both systems the natural frequency of the oscillation of the water within the tank is tuned to the natural frequency of the building, and tuning is achieved through the selection of the overall dimension of the tank and water depth.

Although the theoretical basis of TLCDs and TLSDs are well understood, each practical implementation requires custom design and testing. This is largely due to uncertainties in the non-linear viscous energy dissipation mechanisms, caused by the motion of the water within the tanks.

Due to limitations regarding the location and volume available to install the auxiliary damper system within the tower, a hybrid design of a TLCD and TLSD was determined to be the most effective and efficient solution.

The design and commissioning procedure involved:

- Assessment of the amplitude of response of the building from wind tunnel results.
- Onsite natural frequency measurements of the partially and fully constructed building.
- Design of the TLCD damper tank using non-linear empirical models of Wu et al (2005, 2009), and with reference to the work of Hitchcock et al (1997) and Vickery (2006).
- Design of the TLSD damper tank in accordance with the methodology of Vickery (2006).
- Testing of a scale model of the TLCD damper tank and Hybrid TLCD/TLSD system using a shake table.
- FEA modelling of the final structure including the damper.
- Testing of the full-scale damper prior to installation.
- Testing of the installed system.

Wind Tunnel Testing

Wind tunnel testing was undertaken in October 2010 during the design development phase of the tower to determine the wind-induced structural loads and building motion effects. Testing was undertaken using a 1:500 scale model in Windtech's boundary layer wind tunnel facility using the High-Frequency Force Balance (HFFB) technique. A photograph of the wind tunnel test model is provided in Figure 1.

The results of the study indicated that the ultimate peak base moment of the tower would be governed by a cross-wind response when the prevailing winds were from the north or south. Whilst this result is not unusual for a tower with an aspect ratio of 8.0:1.7:1.0 and a constant floor plan across the full height of the tower, a generally smooth façade and no corner treatment, the tower was to be constructed on a structural raft due to the site being located on a marsh.

The wind tunnel study indicated that the ultimate peak base moment would exceed the limitation of the structural raft. Hence it was necessary to investigate measures to mitigate the cross-wind response and thus reduce the magnitude of the ultimate peak base moment.

Initially, mitigation options such as altering the tower form, or modifying the dynamic properties of the structure to increase stiffness were discussed. However, it quickly became apparent that altering the building form was not an option that the client would entertain, and it was not possible to increase the Mode 1 natural frequency sufficiently to mitigate the cross-wind response (the Mode 1 response was found to be the driver of the cross-wind excitation). Hence an auxiliary damping system was considered.

Further investigation showed that the auxiliary damper system is required to provide approximately 1.5% to 2.0% additional damping to the system for the Mode 1 translation motion response.

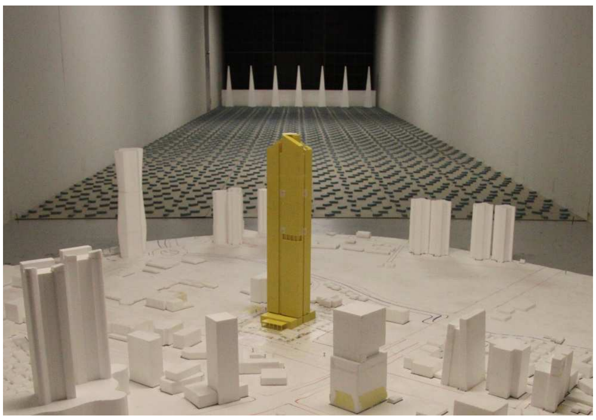

Figure 1. The wind tunnel test model (October 2010) in Windtech's Boundary Layer Wind Tunnel Facility.

Initial Design

A Hybrid TLCD/TLSD system was selected since it provides the most efficient use of the space allocated for the system. The suggestion to install a Visco-Elastic Damper (VED) was ruled out due to the much higher cost when compared to a TLCD or TLSD system, even factoring in the cost of the long-term monitoring.

An initial concept design of the Hybrid TLCD/TLSD system was developed in July 2011. This was based on the Mode 1 natural frequency estimate from the latest FEA model of the tower structure available at that time, since Mode 1 was the mode of motion which governed the excessive wind-induced building motion observed from the wind tunnel study. A perspective section of the initial design of the Hybrid TLCD/TLSD system is shown in Figure 2.

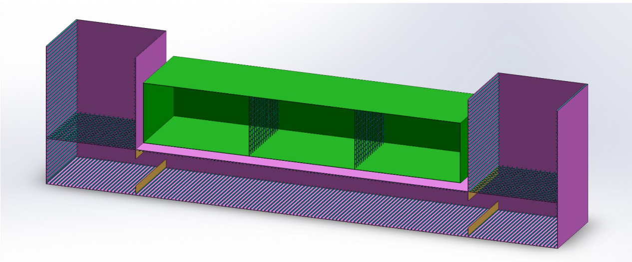

Figure 2. Perspective section view of the initial design of the Hybrid TLCD/TLSD system. The TLSD sits within the U-shape of the TLCD.

Since the auxiliary damper is relied upon for the ultimate design loads of the tower structure, great care must be taken to ensure that it will remain effective for the duration of the design wind event, since during that event there is an increased likelihood of a power failure or similar. Hence it is necessary for the system to be passive rather than active, and require minimal ongoing maintenance. A long-term monitoring system for the performance of the Hybrid TLCD/TLSD damper was considered essential even in the early design stages of the system.

The space for the system, which was allocated by the client, is located at either end of Level 44 of the tower. Each space is only 3.26m wide and 5.80m high, but over 30m long. A photograph of one of the allocated spaces within the tower is shown in Figure 3 during construction. A Hybrid TLCD/TLSD system is to be placed within each space on Level 44. The TLCD tank provides the most efficient use of the space with regards to effective water mass. A TLCD does not require as much freeboard volume for the water sloshing action, compared to a standard TLSD tank. Nonetheless, a TLSD tank is also included within the "U-tube" of the TLCD to provide the additional mass necessary to achieve the required total auxiliary system damping.

Figure 3. One of 2 allocated spaces for the Hybrid TLCD/TLSD system.

It should be noted that Level 44 is at approximately two-thirds of the total tower height. The optimum location for a TLCD and/or TLSD is at the top of the tower. Hence approximately 2.4 times more mass is required to provide the same damping effect at Level 44 compared to if the mass was placed at the top of the tower. Nonetheless, Level 44 was selected since this is the mechanical services floor of the tower, and has a larger floor-to-ceiling height compared to the typical tower levels, which is required for the TLCD.

The main TLCD damper tank was designed using the non-linear empirical models of Wu et al (2005, 2009), and with reference to the work of Hitchcock et al (1997) and Vickery (2006). The TLSD damper tank was designed in accordance with the methodology of Vickery (2006).

To extract the maximum efficiency from the TLCD tanks, they are designed to 95% of the ULS Mode 1 natural frequency (Mayol, 2004). The TLSD tanks are designed for the ULS Mode 1 natural frequency, which assists in extending the range of effectiveness from the TLCD/TLSD hybrid system. Furthermore, the tanks are designed to operate within a range of ±0.2s of the Mode 1 period simply by varying the water level within the tanks.

As detailed by Gao (1997), further energy dissipation devices are included within the TLCD tanks, including orifice panels, roughened internal surfaces, and mesh panels. These features assist in maximising the damping provided by the TLCD tanks.

Numerical Modelling of the Initial Design

The dimensions of the TLCD tank cause it to be beyond the range of empirical data provided by Wu et al (2005, 2009) The dimensions of the TLCD are driven by the height restriction of 5.80m of the available space for the tank, and also by the requirement for the tank to be able to be tuned for variations of ±0.2s for the Mode 1 period. An area ratio of 2:1 in the vertical columns of the TLCD assists in meeting these requirements.

To ensure that the initial design is designed effectively, a numerical model of the TLCD was developed. To verify the accuracy of the numerical model, standard TLCD tanks were first developed and checked to ensure that they provide the same performance parameters published by Wu et al (2005, 2009). Once this was confirmed, the performance of the specific tank required for this particular project could be determined using the numerical model.

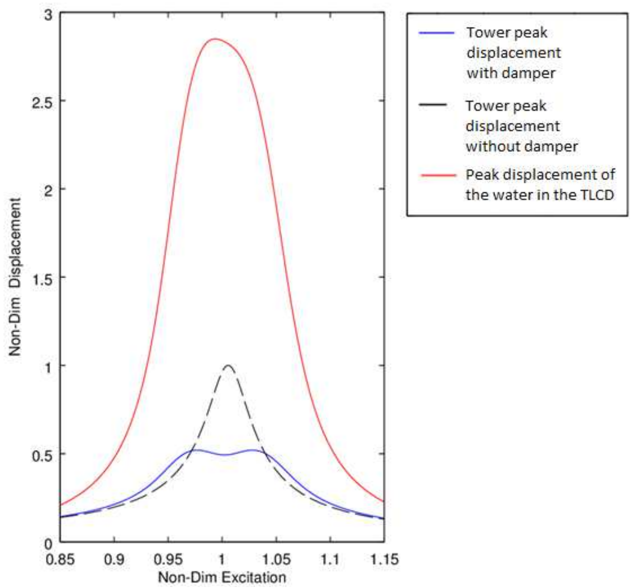

Figure 4. TLCD tank performance, obtained from the numerical model.

The performance of the TLCD tank, and a comparison of the displacement of the tower with and without the TLCD installed, is presented in Figure 4.

The numerical model is also used to obtain an estimate of the displacement of the water slosh within the vertical columns of the TLCD tank, and to ensure that sufficient freeboard is provided in the tank.

The study confirmed that the initial design of the system would achieve approximately 2.0% additional damping to the tower structure, which would be sufficient to provide adequate ultimate design loads and base moments for the tower structure.

On-Site Testing for the Natural Frequency of the Tower

The results of the wind tunnel study, and the initial design of the Hybrid TLCD/TLSD system, were based on estimates of the natural frequencies of the tower structure obtained from a detailed FEA model. It is known that the natural frequencies of completed tower structures can vary somewhat from those estimated by FEA models (Kim et al, 2011), and hence since the design of an effective TLCD and/or TLSD is sensitive to even relatively minor variations to the natural frequencies, it was necessary to obtain more accurate natural frequencies. This was achieved by undertaking on-site testing during the construction process.

The first on-site test was undertaken near to top-out of the structure construction, and with approximately 25% of the façade installed. This was undertaken in March 2015. The results of this test were then used by the structural engineer to fine-tune the modal response behaviour of the FEA model, and to then provide a more accurate prediction of the ULS natural frequencies. It should be noted that only the SLS natural frequencies can be measured on-site, so an assumption for the behaviour of the structure under ULS conditions is still necessary to be undertaken.

As part of the first on-site tests, the damping characteristics of the structure were also measured. The tower structure was excited using crane drops, which caused a measured peak building acceleration of 2.0milli-g (close to the annual peak acceleration for this tower). The resulting damping from the structure was determined to be 1.3% of critical, which confirms that the assumed levels of inherent damping used for the wind tunnel study were appropriate (2.0% of critical assumed for the ULS scenario, 1.0% of critical for the acceleration calculations).

A second on-site test was undertaken in October 2015 once construction of the tower structure was complete and the façade fully installed. This was used to further fine-tune the structural engineer's FEA model and the estimates of the ULS natural frequencies of the structure.

The evolution of the ULS Mode 1 natural frequency estimates throughout the course of the project are summarised as follows:

- October 2010: 0.117Hz, from the FEA model. Used for wind tunnel study.
- June 2011: 0.108Hz, from a refined FEA model. Wind tunnel results updated, and used for the initial design of the Hybrid TLCD/TLSD system.
- July 2015: 0.119Hz, after the first set of on-site measurements. Wind tunnel results updated, and used for design development of the Hybrid TLCD/TLSD system.
- October 2015: 0.130Hz, after the second set of on-site measurements. Wind tunnel results updated, and used for further design development of the Hybrid TLCD/TLSD system.

Scale Model Shake Table Testing and FEA Modelling

Once the initial on-site test for the natural frequencies of the tower structure was complete, estimates of the ULS natural frequencies were revised and the design of the Hybrid TLCD/TLSD system was refined to maximise efficiency. This refined design was then modelled physically at 1:10 scale and tested at the University of Technology Sydney shake table facility. This test is necessary to verify non-linear effects of the water in the TLCD, and to verify the effectiveness of the additional energy dissipation devices which have been included within the TLCD.

Initially, the TLCD tank was tested in isolation without the TLSD and without the mesh panels. This was considered the base case, and further testing was undertaken with various configurations of mesh panels, TLSD, etc, to determine the optimum configuration. Varying levels of water within the TLCD and TLSD were also investigated. A photograph of the scale model on the shake table is provided in Figure 5.

Figure 5. Shake table test of the 1:10 scale TLCD model (without TLSD, without mesh panels).

Each shake table test was undertaken for a sweep of natural frequencies, which not only enabled confirmation of the tuning frequency of the system, but also enabled the determination of the damping performance of the damper system using the half-power bandwidth method and by fitting the theoretical response curve of Wu et al (2005, 2009). This is demonstrated in Figure 6.

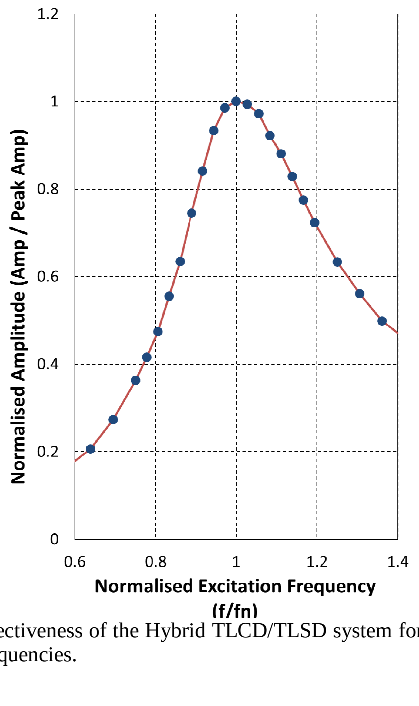

Figure 6. Effectiveness of the Hybrid TLCD/TLSD system for a range of excitation frequencies.

The shake table test confirmed that the design of the Hybrid TLCD/TLSD system had an effective characteristic damping of 16% of critical. The measured performance properties of the auxiliary damper system from the shake table test were used in conjunction with a FEA model of the full tower to account for the effect of the mass ratio. This confirmed that the total additional damping that the auxiliary damper provides to the tower ranges from 1.6% of critical (for Mode 1 = 7.6s period) to 1.9% of critical (for Mode 1 = 8.0s period). These values of additional damping were demonstrated to be capable of reducing the ULS cross-wind response of the tower structure and consequent loading on the raft foundation system by a sufficient amount.

Design Development

The second on-site measurement of the natural frequencies of the tower, which were undertaken after the completion of the shake table test, indicated that the natural frequency would be a little higher than previously estimated. However, since the results of the shake table test confirmed that the numerical model provides accurate performance estimates of the TLCD/TLSD hybrid system, the design could be modified without the need for further shake table testing.

The final design for the TLCD tanks are that they will be 18.20m long, 3.26m wide, and 5.80m tall. The effective tuning range will accommodate the desired ±0.2s of the Mode 1 period, and tuning is achieved by varying the water level. To avoid minimise water loss in the tanks due to evaporation, the tanks are sealed. However, to enable the sealed TLCD tank to function correctly, a horizontal duct connecting the freeboard volumes at the top of each vertical column is included and sized such that the cross-section area of the duct is sufficient to not throttle the efficiency of the TLCD.

The total mass of water on Level 44 of the tower is 315,000kg (for Mode 1 = 7.6s period), or 400,000kg (for Mode 1 = 8.0s period). Note that the mass is split to each TLCD/TLSD hybrid damper system, located at either end of the Level 44 floor plate.

Pre-Installation and Commissioning

The final on-site test for the natural frequencies of the tower, which was necessary to finalise the design of the Hybrid TLCD/TLSD system, has been undertaken after completion of construction of the main tower structure. Hence no major construction cranes are available on-site for the installation of a pre-fabricated tank system into Level 44 of the tower. Hence it is necessary to construct the tanks in-situ from smaller parts which could be delivered to Level 44 using the service elevator. To minimise the risk of on-site fabrication issues, a mock-up of the tanks were constructed off-site. This also enabled any issues relating to maintenance access, drainage, etc, to be identified prior to the on-site construction. A photograph of the mock-up tanks constructed off-site is shown in Figure 6.

Figure 6. Testing of full-scale damper prior to installation in the tower.

Once installed to the tower and filled with water to the correct levels, the performance of the auxiliary damper system is monitored remotely in real-time. This is achieved using several accelerometers located permanently atop the tower to measure the natural frequencies of the structure, and also sensors within the tanks to monitor the water levels. The local wind speed is determined from recorded data obtained from the meteorological observation station located at the local airport. The water level within the tanks can be altered to maintain maximum efficiency of the system at all times.

Conclusions

An effective auxiliary damper system has been designed and developed for the 289m tall Gama Tower, located in Jakarta. The effectiveness has been estimated using empirical and numerical modelling, and verified using shake table laboratory testing. Combined with results of wind tunnel testing for the wind-induced loads acting on the total tower structure, the analysis confirms that the auxiliary damper system is effective in mitigating the excessive cross-wind induced response for the ULS scenario. Furthermore, the implementation of a long-term monitoring system for the performance of the auxiliary damper ensures that the system will remain effective throughout the life of the structure.

Acknowledgments

Prof. Bijan Samali of Western Sydney University assisted with the testing and numerical modelling of the damper.

Marten Eddy of TTW Indonesia for providing the necessary structural engineering input.

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