Title: **Mechanical Amplification of Relative Movements in Damped Outriggers for Wind and Seismic Response Mitigation**

Authors: Neville John Mathias, Skidmore, Owings & Merrill LLP
Francesco Ranaudo, Skidmore, Owings & Merrill LLP
Mark Sarkisian, Skidmore, Owings & Merrill LLP

Subject: Structural Engineering

Keywords: Damping
Outriggers
Seismic
Tuned Liquid Damper
Wind Loads

Publication Date: 2016

Original Publication: International Journal of High-Rise Buildings Volume 5 Number 1

Paper Type:
1. Book chapter/Part chapter
2. **Journal paper**
3. Conference proceeding
4. Unpublished conference paper
5. Magazine article
6. Unpublished

International Journal of High-Rise Buildings
March 2016, Vol 5, No 1, 51-62

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

Mechanical Amplification of Relative Movements in Damped Outriggers for Wind and Seismic Response Mitigation

Neville Mathias†, Francesco Ranaudo, and Mark Sarkisian

Skidmore, Owings & Merrill LLP (SOM)

Abstract

The concept of introducing viscous damping devices between outriggers and perimeter columns in tall buildings to provide supplementary damping and improve performance, reduce structural costs, and increase available usable area was developed and implemented by Smith and Willford (2007). It was recognized that the relative vertical movement that would occur between the ends of outriggers and columns, if they were not connected, could be used to generate damping. The movements, and correspondingly damping, can potentially be significantly increased by amplifying them using simple "mechanisms". The mechanisms also make it possible to increase the number of available dampers and thus further increase supplementary damping. The feasibility of mechanisms to amplify supplementary damping and enhance structural performance of tall, slender buildings is studied with particular focus on its efficacy in improving structural performance in wind loads.

Keywords: Viscous damping, Outriggers, Tall slender buildings, Perceptible acceleration mitigation

1. Introduction

The concept of using relatively rigid outriggers in tall buildings in conjunction with viscous damping devices to supplement damping has been excellently developed and published by Smith and Willford (Smith and Willford, 2007), and has been implemented in the 217 m tall St Francis Shangri-La Palace twin-towers in Manila, Philippines. The designers were able to use vertically mounted viscous dampers introduced into the connection between the ends of the outriggers and columns to parlay the relative vertical movements that occur at these locations into supplementary damping. The system achieved supplementary damping in 100-year winds that ranged between 5.2% and 11.2% of critical in the tower's principal directions. A diagram of the damped outrigger concept with vertically mounted viscous dampers is shown in Fig. 1.

The relative vertical movements that are harnessed to yield supplementary damping using vertically mounted dampers can, however, be small, particularly in wind events. Mechanisms to amplify the relative vertical movements can be utilized to potentially increase supplementary damping. A concept for one such mechanism is presented in Section 2 below.

The objective of the study presented in this paper is to evaluate the feasibility and efficacy of a mechanism to amplify relative movements at outrigger / column junctions with the aim of increasing supplementary damping, and to discuss various considerations associated with its use. In order to evaluate its efficacy, the proposed system is modeled using the analysis program ETABS 2015 and its performance compared to that of other lateral system options for an example structure. Particular emphasis is placed on evaluating the dynamic component of wind loads in order to estimate its effects on a building equipped with the proposed mechanism.

It has been shown (Sarkisian et al., 2015) that viscous dampers introduced into tall, flexible structures to enhance seismic performance can also serve to increase levels of supplementary damping to as much as 13.5% of critical in 20 and 50 year return wind events. The amount of supplementary damping achieved is dependent on the properties, number and locations of the dampers.

The paper by Smith and Willford (2007) provides ample explanation of the theoretical basis of the damped outrigger system along with recommendations and cautions related to the design, construction and maintenance of components of the system. It is not intended, therefore, to go into these topics in significant detail in this paper as they will also similarly apply to the system presented. A few, important points about damping as follow, however, bear mention as an introduction:

- Damping in structures under service conditions typically comprises inherent damping – the dissipation of energy that results from the use of conventional materials and construction – and supplementary damping-energy dissipation that results from the use of devices such as viscous dampers. In moderate and large earthquakes, additional energy dissipation can occur due to ductile structural

†Corresponding author: Neville Mathias
Tel: +1-415-981-1555; Fax: +1-415-398-3214
E-mail: neville.mathias@som.com

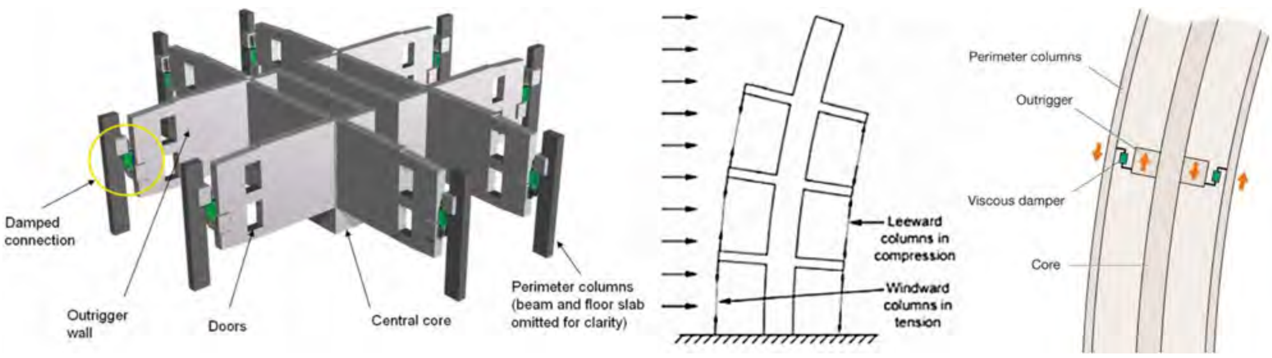

Figure 1. The outrigger concept for 60 Story Twin Towers in Manila (Smith and Willford, 2007).

deformation, increasing effective inherent damping values. Inherent damping is typically assumed by laboratories and engineers to range between 0.5% and 2%; lower values occurring in taller buildings.

- The level of damping achieved, both inherent and supplementary, is related to the level of deformation in a structure; generally increasing with increased deformation.
- When multiple damping devices are used, increased levels of deformation do not necessarily imply larger values of effective damping. The amount of damping actually achieved is dependent on the dynamic characteristics and movement of the structure and the locations of the dampers within it.

2. Proposed Mechanism

Outriggers act like the outstretched arms of skiers to provide tall buildings with core and perimeter structural systems with added lateral stiffness and stability. They are generally at least one story tall, cantilever out from the core structure and typically connect to the perimeter columns and, where they occur, belt trusses. They are provided at one or more levels over the height of the structure as needed, usually at mechanical or refuge floors. Outriggers are typically constructed to act monolithically with the floor structures at their top and bottom ends.

While they are beneficial in reducing drifts and stabilizing tall structures, outriggers, particularly concrete outriggers, can complicate design and construction (Choi et al., 2012). This is due the fact that core and perimeter structural systems tend to vertically deform and shorten differentially due to the actions of elastic shortening and creep under gravity loads, and shrinkage. Connecting these systems with relatively rigid outriggers often results in very high forces being induced in the outriggers. Addressing this issue often requires the use of delayed construction techniques that complicate construction. By disengaging the outriggers from the floor structures at their top and bottom edges, and from the columns at their ends, it is possible to create a condition of relative vertical movement between the outrigger ends and the columns when towers are subjected to lateral loads and displacements that can be captured to generate damping. In the damped outrigger system developed and implemented by Smith and Willford in the Philippines, the vertically mounted viscous dampers respond to wind movements providing supplementary damping. Additionally and beneficially, due to their viscous nature, viscous dampers release force build-up in outriggers caused by the effects of differential vertical shortening as they occur gradually over an extended period of time.

The relative dynamic movements between outrigger ends and columns can, particularly in wind load situations, be relatively small. To increase the efficacy of the damped outrigger system and create larger amounts of damping in these situations, the use of a mechanism to amplify movements before imparting them to the dampers is proposed. Fig. 2 below shows the concept for a mechanism that can be used to amplify relative movements between the end of an outrigger and a column and diagrammatically shows suggested components of the amplification mechanism in a structure with a concrete outrigger system. Similar details can be developed for use with steel outrigger systems.

The geometric amplification factor ψ of the system proposed in Fig. 2 is $\psi = L / l$. The designer should keep this ratio as high as possible in order to increase the displacement in the dampers: $\Delta = \psi \cdot \delta$

3. Damping of Wind Loads

3.1. Control of wind induced structural response

In designing a structure (especially a tall building structure), there are three main ways in which the designer can control and mitigate the wind-induced response (Tamura and Kareem, 2013):

- Aerodynamic / aeroelastic shape tailoring
- Static stiffness and mass distribution modification
- Dynamic stiffness modification

There are, however, pros and cons to each of these methods and the best solution for a specific project may be

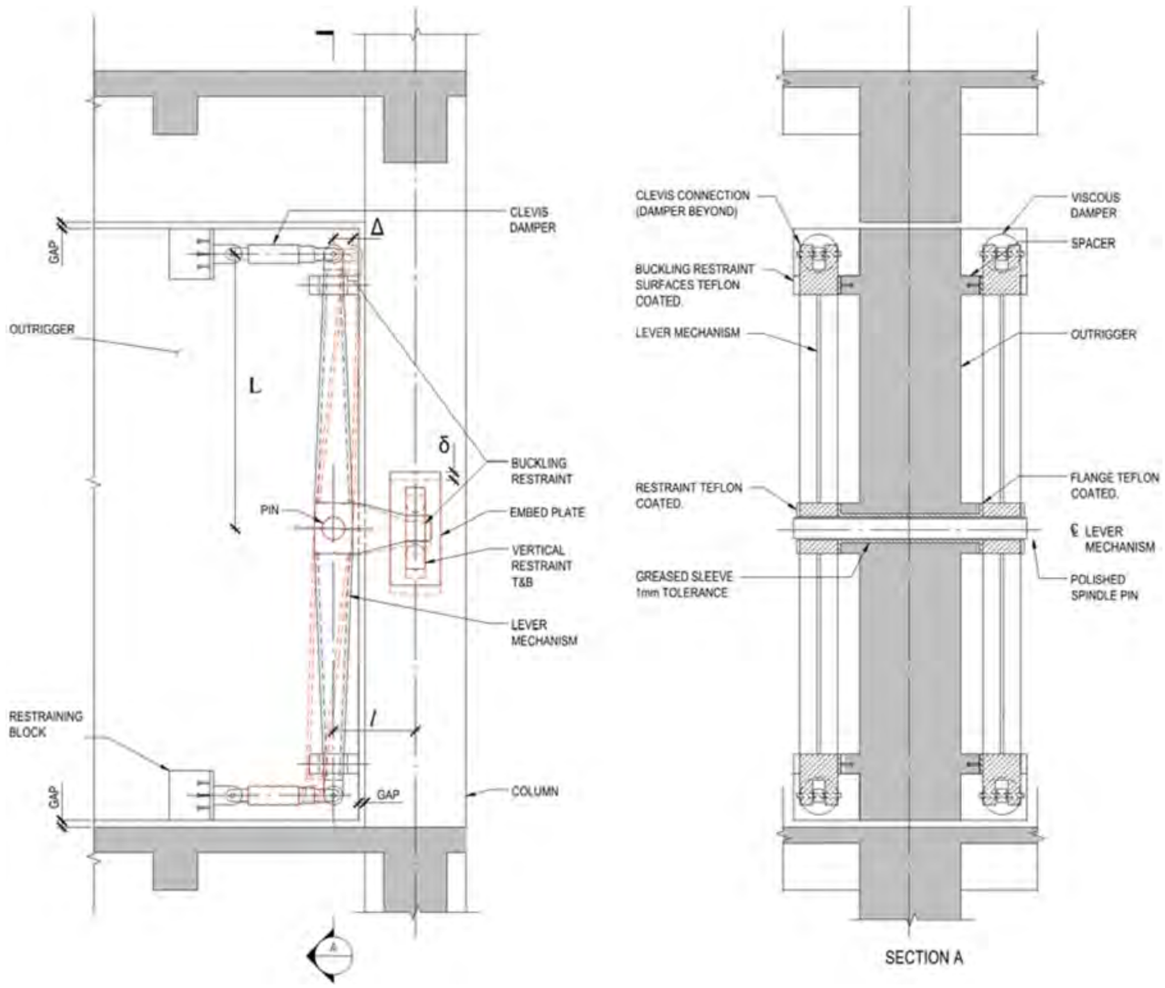

Figure 2. Schematic components the amplification mechanism (displaced configuration of the system shown in red).

not the correct one for another one. Shaping a building in order to minimize wind forces seems to be the most logical solution, but this may result in significant architectural impact that may be not suitable for the project. Alternatively, the structural designer may choose to leave the overall shape of a building unchanged and modify the dimensions of the structural members in order to make the building stiff enough to resist wind action and meet the code response requirements. Although this solution is usually the most commonly adopted solution, it often results in more material and less usable space, thus increasing costs. A third option for the designer is to modify the dynamic properties of the building by adding specific devices in order to dissipate input energy and mitigate the response of the building. The advantages of this solution are that it does not have a strong impact on the shape of the building and usually results in cost savings. The drawback is that it requires much more sophisticated analyses than the other two options. This paper will focus on the last of the three options, and in particular on the use of viscous dampers to achieve motion mitigation.

3.2. Wind loads components

Wind is a dynamic and random phenomenon in both time and space. Wind effects can be described as a mean value, $\overline{U}$, constant in time, upon which random fluctuations (gusts), $u(t)$, are superimposed:

$$U=\overline{U}+u(t) \tag{1}$$

The average wind speeds tend to increase with height, while gustiness tends to decrease. There is no obvious correlation, however, between the fluctuations at different heights. Wind speeds at any time can be described statistically but not predicted exactly (Boggs and Dragovich, 2006). Mean wind speeds and corresponding pressures on buildings at different heights can be computed with any of the numerous equations provided by national building codes, which are usually based on a logarithmic law. Code formulations typically provide total load, the combination of quasi-static and resonant components. The resonant component of code wind loads, which can be manipulated using damping devices, is hard to estimate and usually re-

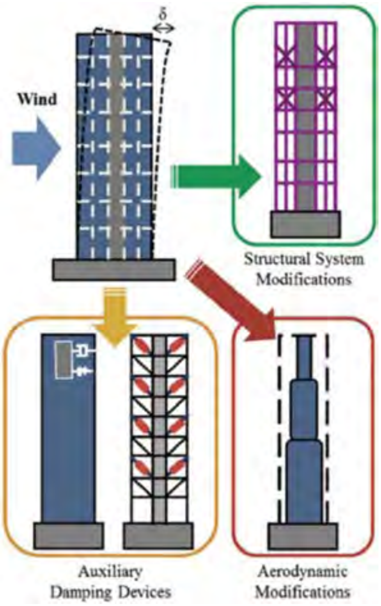

Figure 3. Wind response mitigation strategies (Tamura and Kareem, 2013).

quires wind tunnel tests or use of concepts of random vibration analysis.

Cross-wind oscillation effects are essentially resonant, and are well understood and addressed in references (e.g., Equation 18 of Commentary I of the Canadian National Building Code (CNBC, 2005)). Formulations in the references can be used to determine accelerations and forces at different levels of a structure in the cross-wind direction under wind events of a specified recurrence.

When the velocity history of a wind event is known, it is straightforward to get the pressures or forces acting on a structure by applying the following equation:

$$F(z,t)=\frac{1}{2}\rho\cdot C_D(x)\cdot A(z)\cdot[\overline{U}(z,t)+u(z,t)]^2 \tag{2}$$

where, ρ is the air density, C_D is the drag coefficient and A is the tributary area.

3.3. Using wind tunnel tests for damper design

It is very common, if not mandatory, for tall buildings (particularly those over 200 m tall) to be wind tunnel tested in order to determine their behavior under wind loads. Upon request, it is possible to obtain wind loads and structural accelerations for several values of damping ratio from the wind tunnel lab. An example of these reports is shown in Fig. 4 (Sarkisian et al., 2015), where the total, static and dynamic (resonant) components of wind load on a structure are reported for three different damping ratio values. As can be seen from these graphs, by increasing the damping ratio from 1.5% to 6% a 10% reduction of maximum equivalent static total wind load on the structure is achieved.

In order to choose the appropriate sets of wind loads (function of the damping ratio) to be provided by the wind tunnel laboratory, the engineer must first analytically study the dynamic behavior of the structure in order to obtain the additional damping required to be provided by the damping system. The additional damping system that yields the desired level of damping can be defined using a variety of methods (e.g., using the modal properties of the structure, the logarithmic decrement method, the half power bandwidth method, etc.), as described in Sarkisian et al. (2015).

3.4. Time-history analysis of wind loads

The method described in the preceding section is relatively easy to apply but it relies on the availability of appropriate wind tunnel test results. These results are not always available, especially in the early stages of design

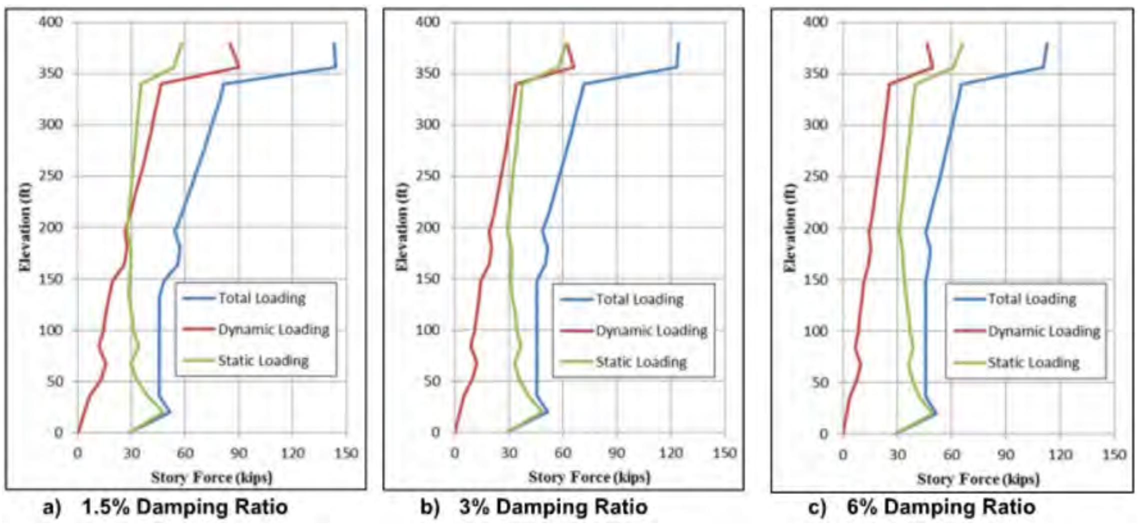

Figure 4. Static and dynamic components of wind loads for the San Diego Courthouse project (Sarkisian et al., 2015).

when the shape and structure of a building is often in flux. An alternative method is to assess the performance of a structure directly by applying expected wind load time histories to the structure. In the case of structures with added damping, and nonlinear structures in general, their characteristics will vary with the amplitude of the response and hence with time (for time-dependent actions). This means that the designer will need the time-variation of wind loads in order to run nonlinear time-history analyses and study the behavior of the damped structure. While it is common to have ground motion records at different seismic hazard levels as input for seismic analysis, it is not common to have the relevant time-history data to simulate the variation in time of wind action.

In this paper, two different approaches to simulating wind effects with time on structures are suggested[1]:

- Employing code formulae
- Performing random vibration analyses

The first approach consists in determining the dynamic component of wind forces using one of the formulae provided in national codes (e.g., NBCC, 2005) or in the literature to estimate the expected acceleration at the top of a structure for the desired wind return period, and then to proportionally vary it along the structure's height using the primary sway mode shape of the building in the direction of interest. The force distribution along the structure's height can be directly computed knowing the mass at each floor ($F = ma$). Once the force distribution is obtained, the next step is to apply the forces dynamically to the structure by assuming a sinusoidal function with a period equal to the fundamental period of the structure in that direction. The force amplitudes are scaled and the duration of the loading selected so that the rooftop acceleration does not exceed the value determined from the code formulae. The major assumption of this method, reasonable as it relates to resonant response, is to consider the structural behavior to be dominated by its response in the primary mode in the direction of interest. Despite the simplicity of this method, the equations in the codes are usually very empirical and determined for medium-height buildings. This could lead to incorrect or overly conservative results and misdirect design choices. Because of this concern, this procedure is not explored below further in this paper and further discussions and analyses will be based on a second option.

As previously discussed in section 3.2, a wind field is traditionally represented by a velocity vector (Eq. (1)) and its law of variation in time. While the mean value of the wind velocity varies only with site conditions and height of the point, the fluctuating part of the wind velocity is a random event. However, because wind can be considered to possess stationary characteristics (Buchholdt, 1997), it is possible to describe it in statistical terms. In particular, numerous studies (Kareem, 98) (Rossi et al., 2004) have shown that it is reasonable to represent the fluctuating component as a zero mean random process. The velocity at a specific point is influenced by the velocities at other points and the field must be considered as a whole, rendering the fluctuating wind velocity a multivariate multidimensional random process.

There are basically two families of time domain simulation of multivariate random processes (Tamura and Kareem, 2013): one based on wave superposition techniques (Spectral Based Schemes); and the other based on digital filtering (Time-Series Approach). The former is the traditional and most common approach, and consists of simulating the process through the superposition of trigonometric functions with random phase angles in order to approximate the energy spectrum of the original event. The second approach is based on simulating the random quantity at successive time increments. In other words, the signal at a given time is expressed through a linear combination of the previous events to which a stochastic component is added. An example of the use of these families of methods in structural analysis and their comparison can be found in the design of the Montreal Olympic Stadium fabric roof (Rossi et al., 2004).

In both cases, the generation of loading histories is a very onerous task in terms of CPU time and memory and requires concepts of random vibrations analysis not common in the background of structural engineers. Fortunately, the University of Notre Dame has made a free web-based tool available (Kwon and Kareem, 2006) to generate several types of multivariate wind fields starting from basic user inputs about wind features (3-sec gust wind speed, site conditions, etc.) and geometry of the field (location in which simulate the process). As explicitly disclaimed on the main page of their website, this tool is not meant to be a substitution for wind tunnel tests.

Once the fluctuating wind component is estimated, it is possible to obtain the total along-wind load at points of interest acting in time on the building using Eq. (2). These loads are then applied to the structure as time history load cases and run simultaneously.

4. Damping of Seismic Loads

While the main objective of adding damping using devices such as viscous damping devices (VDD) for wind load cases is to reduce building motion and enhance occupant comfort, when it comes to seismic excitation, damping is usually added to help reduce earthquake damage. The great benefit of using VDD is that their response is 90° out of phase with the forcing function. In other words, when the forces induced in a structure by the forcing function are at their maximum, the force caused by the damper is zero. This is because the dynamic forces induced by the forcing

[1]A third way could be the use of Computational Fluid Dynamics Analysis, but this method is not addressed in this paper.

function reach their peak at the maximum displacement and at that instant the velocity and, therefore, the force in the damper, are both zero.

From the analysis point of view, the evaluation of the performance of damping systems in structures under seismic loads is more straightforward than in the case of wind loads. Structural engineers are indeed much more familiar with ground motion functions and this data is easier to obtain. For these reasons, no additional information is provided in this paper about the modeling for seismic loads.

5. Viscous Damper Characteristics

By adding fluid viscous dampers, the energy input from a transient load is absorbed not by the structure itself but rather by the supplemental dampers (McNamara et al., 2003). The energy stored in the devices is then dissipated through heat exchange with the external environment.

The general force-displacement relationship for a VDD takes the following form:

$$F = C \cdot U^{\alpha}$$

where, F is the force, C is the damping constant and α the velocity exponent. The values of C and α are device specific characteristics.

There are several types of VDD available in the market and the designer can choose among numerous products and configurations. A Taylor device (Fig. 5) with the characteristics shown in Table 1 and Fig. 6 is selected for the study conducted for the purpose of this paper.

The curve in Fig. 6 shows that the behavior of the selected VDD is linear at small velocities, such as the ones expected in normal wind conditions, and nonlinear for velocities greater than approximatively 0.6 in/s (0.015 m/s), which can be expected in moderate and rare seismic events.

The design of a damping system consists of selecting the right type of device to provide the amount of damping required for the specific project. It is usually an iterative process because the effective damping depends on the amplitude of the response, which, itself, depends on the behavior of the damping system.

Assuming that there are no other sources of energy dissipation other than the dampers, the equivalent damping ratio, ζ_{eq}, of a structure can be evaluated by the following equation:

$$\zeta_{eq} = \frac{1}{4\pi} \frac{\sum_{i=1}^{n} E_{D_i}}{E_{S_0}} \tag{3}$$

where E_{S_0} is the available potential energy at a given displacement, E_{D_i} is the energy dissipated by a single device in one cyclic displacement of corresponding amplitude and n is the number of devices. The total effective damping ratio would become: $\zeta_{eff} = \zeta_{inherent} + \zeta_{eq}$.

Computing the effective damping of a structure can be a good index of the general behavior of the system and, as explained in Section 3.2, can be used for its design under

Table 1. Viscous damper properties

Force	1957 N
Spherical Bearing Bore Dia.	8.89 cm
Mid-stroke Length	157.4 cm
Stroke	12.7 cm
Clevis Thickness	8.89 cm
Clevis Width	22.86 cm (Max)
Clevis Depth	20.32 cm
Cylinder Dia.	28.57 cm
Weight	408 kg

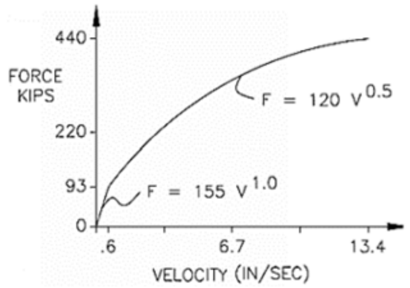

Figure 6. Nominal force-velocity relationship of the selected VDD (Taylor Devices).

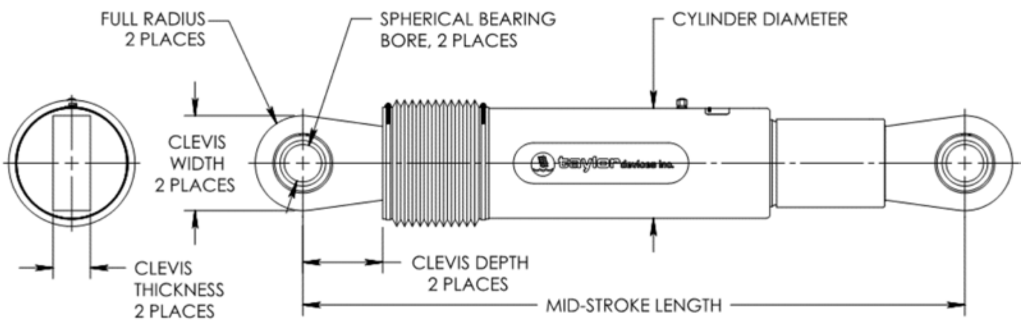

Figure 5. Taylor device geometric and mechanical properties.

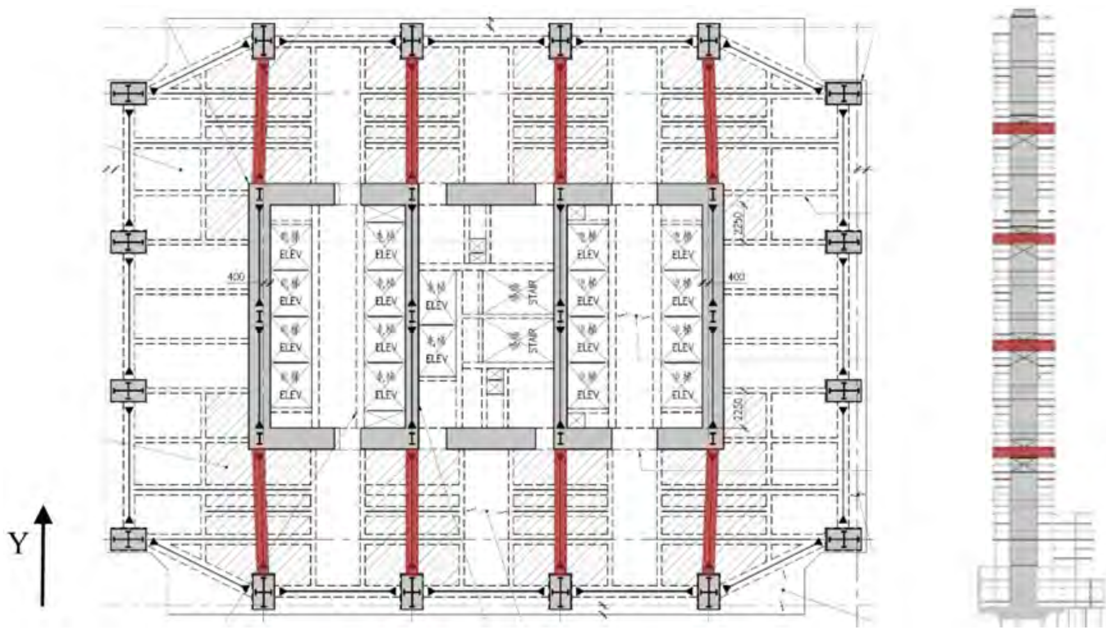

Figure 7. Typical outrigger floor and section of the example structure (position of the outriggers/dampers shown in red).

wind loads.

6. Application of Concepts

6.1. Description of study models

The concepts described in Section 2 are implemented in the analysis of an example structure using the analysis software CSI ETABS 2015 to study their efficacy. The example structure is a 320 m high skyscraper assumed to be located in the city of Shenzhen, China, and designed initially with outriggers connecting the core to the perimeter columns in order to increase the lateral stiffness in the short direction. A typical floor plan and elevation of the structure are shown in Fig. 7.

In order to evaluate the effectiveness of the proposed mechanism in mitigating the structure's response under wind and seismic loads, the system is evaluated in relation to other alternative lateral system options and also in relation to several configurations of the mechanism option itself.

The first set of analyses involves the comparative evaluation of the proposed system as an alternative to or improvement upon other possible lateral resisting system options. For consistency of comparison, the same basic structure described earlier is modified in order to obtain a total of four structural options with different lateral resisting systems:

1. Outrigger system: this is the original configuration, in which the core is connected to the perimeter frame using four pairs of walls each at four levels in the Y direction in order to increase the lateral stiffness of the building;
2. Frame-core system: in this system the lateral loads are distributed between the core and the perimeter frame, but there is no outrigger connection between the two;
3. Vertically Damped Outrigger system: the model replicates the configuration proposed in Fig. 1, in which viscous dampers are added in the connections between the outriggers and the perimeter columns;
4. Horizontally Damped Outrigger system: in this model, the proposed solution shown in Fig. 2 is implemented. The mechanism as modeled in ETABS is shown in Fig. 10.

The displacement amplification system in the horizontal damper configuration is modeled as a rigid element pin and roller (vertical restraint) connected to the outrigger and adjacent column respectively in order to capture vertical displacements. The amplification factor introduced in Section 2 is set equal to 2.5. Both in the vertical and horizontal-dampers configurations, the outrigger wall is fixed to the core but completely detached for the surrounding floor and column structures.

As already mentioned, the sizes of the structural elements common to all the configurations (originally designed for the outrigger system) are kept the same for all the models for consistency of comparison. In a real-life project, the main structural element sizes and the damper characteristics would be iteratively optimized throughout the design process in order to obtain the desired behavior of each option. This assumption is consistent with the objectives of this paper, which is to study the relative benefits of the proposed systems when compared to other solutions.

In this study, the location of the damping system along

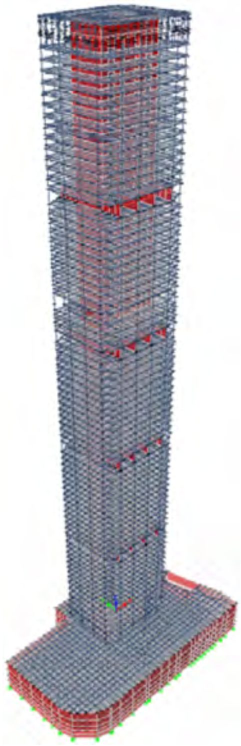

Figure 8. ETABS General Model.

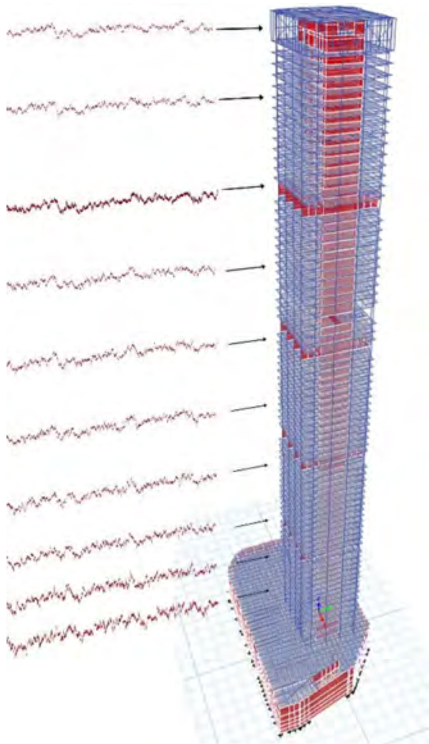

Figure 9. Wind loads as applied on the model.

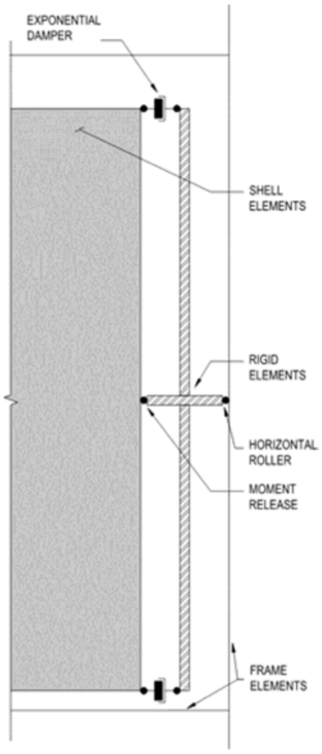

Figure 10. Horizontal dampers as modeled in ETABS.

the building's height is set by the location of the outriggers in the initial example structure. These locations were constrained by the need for a refuge floor every 15 floors.

The general model upon which these configurations are generated is shown in Fig. 8.

As described in Section 3.4, the wind velocity field is simulated as a multivariate stochastic process for 50 and 10 year events. Specific parameters for the simulation are reported in Table 2. The pressures obtained with Eq. (2) are applied as variable point forces approximately every 30 meters (10 locations) along the height of the building, as shown in Fig. 9. The number of locations was limited in order to reduce computational time, but it can be increased in order to increase the accuracy of the analysis.

Seismic forces are applied on the structure using a single set of time-history ground motions related to the seismicity of the area: frequent (50-year return period), moderate (475-year return period) and rare (2475-year return period) intensity. A larger number of ground motions sets as required by the codes should be considered in an actual building design.

Table 2. Wind analysis parameters

Basic Wind Speed (50y wind)	34.6 m/s
Basic Wind Speed (10y wind)	26.8 m/s
Time Step	0.125 s
Number of Frequencies	1024
Exposure Category	C
Cut-off Frequency	4 Hz
Air density	1.226 kg/m^3
Drag Coefficient	1

The results of this set of analyses are shown in Fig. 11 to Fig. 15. In Figs. 16 and 17, typical force-displacement relationships are presented for a damper in the vertical and horizontal mechanism configurations for the moderate earthquake ground motion. The increase in damping and reduction in displacement in the latter configuration are evident.

A second set of analyses is carried out only on the horizontal-damper (mechanism) lateral system option in order to assess the dependency of the proposed solution on the number and the locations of the dampers. Specifically, the system is tested with damped outriggers removed at different levels to assess the sensitivity of structural response to their presence. This study is also useful for understanding the behavior of the structure in the unlikely event that some of the dampers should fail. The results of this set of analyses are presented in Fig. 20.

7. Summary of Results and Findings

7.1. Comparison of the horizontally damped outrigger mechanism system with other lateral system options

The results for the first set of analyses comparing system option performance show that the proposed mechanism

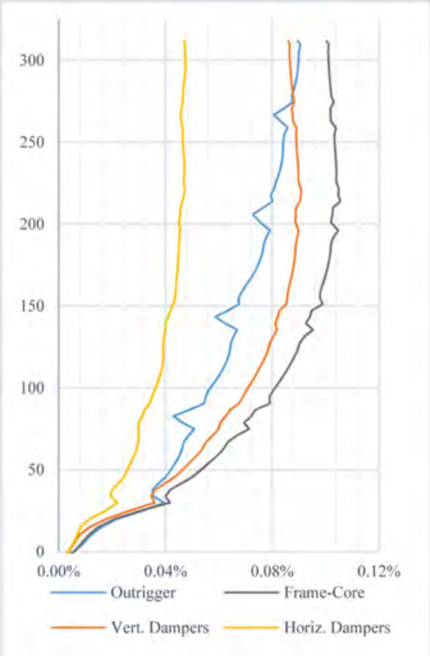

Figure 11. Drift results for Frequent Earthquake load case.

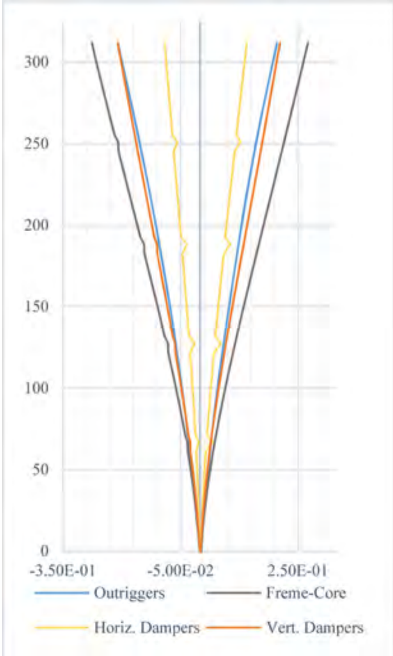

Figure 12. Story displacement results for Frequent Earthquake load case.

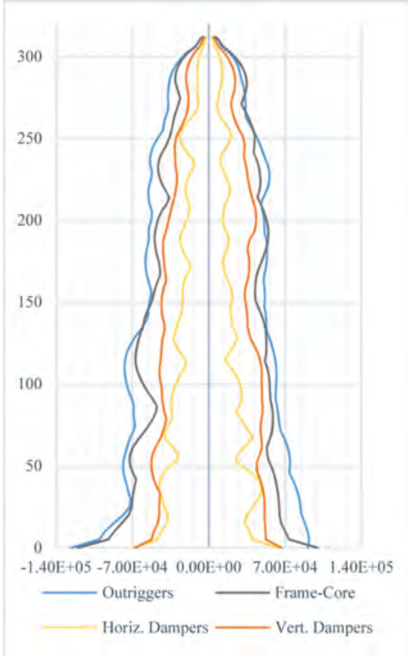

Figure 13. Story Shear results for Moderate Earthquake load case.

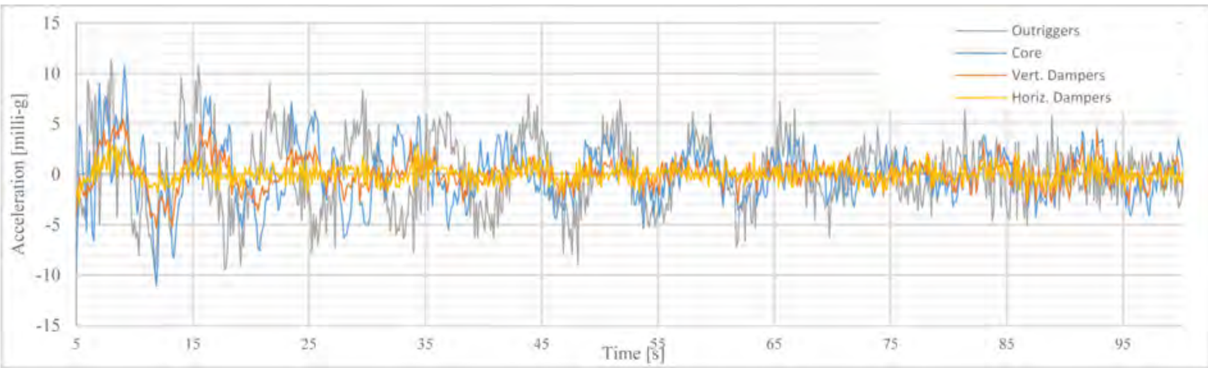

Figure 14. Acceleration history at the roof level for the 10-year Wind load case (along-wind direction).

solution (yellow line in the charts) provides increased levels of damping and performs better than the other systems in all the performance indexes compared (drift, roof displacement and acceleration); for seismic and wind loads. In particular, in a frequent seismic event it was able to reduce the inter-story drift by up to 50% when compared to the outrigger system, while the maximum roof displacement was reduced from approximately 20 cm for both the outrigger system and the vertical damper system to 11 cm using the horizontal damper mechanism. For all indexes studied, it can be seen that the mechanism option with horizontal dampers performs better than the system with only vertical dampers, not. demonstrating the efficacy of the proposed system.

In terms of wind response, the benefits are somewhat less but still appreciable: the maximum roof displacement under a 50-year return period wind dropped from approximatively 25 cm for the frame-core and vertical-damper systems to approximatively 20 cm (Fig. 15) for the mechanism system. As shown in Fig. 14, the accelerations at the roof level under a 10-year return period wind are reduced from the 10 milli-g for the outriggers system and 5 milli-g for the vertical damper system to a maximum of 3.5 milli-g using the mechanism system.

Values of the effective damping ratio for the two damper configurations studied are computed using Eq. (3) and the

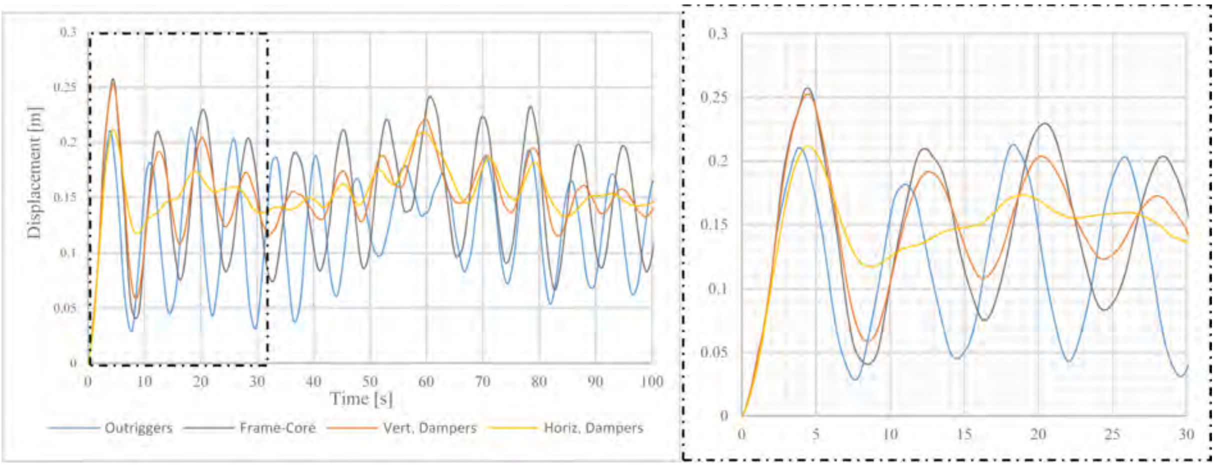

Figure 15. Displacement history for 50-year return period Wind load case. Full history (left) and enlargement (right).

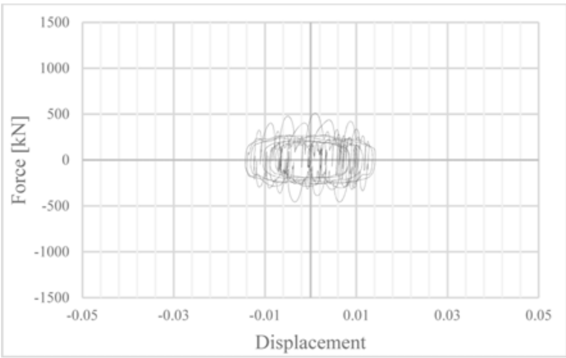

Figure 16. Typical force-displacement loop for a damper in the vertical configuration (Moderate Earthquake).

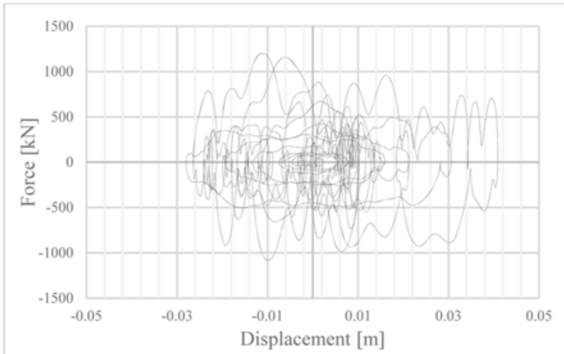

Figure 17. Typical force-displacement loop for a damper in the horizontal configuration (Moderate Earthquake).

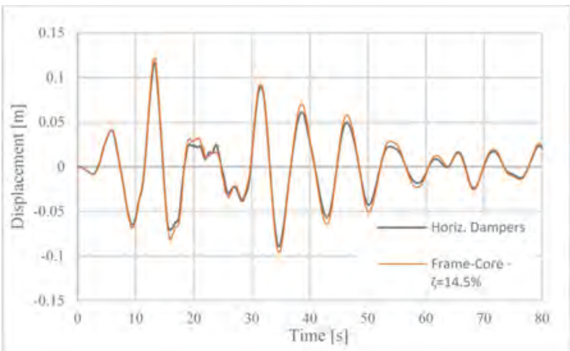

Figure 18. Displacement response comparison for computed damping ratio validation (horizontal dampers) - Frequent Earthquake.

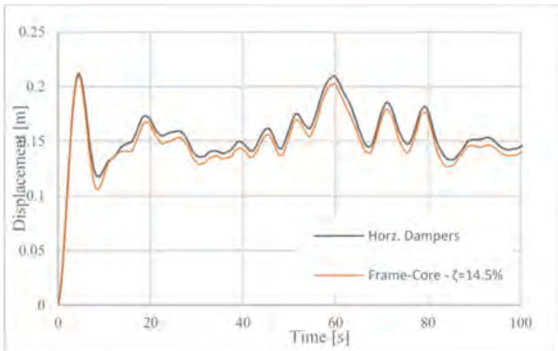

Figure 19. Displacement response comparison for computed damping ratio validation (horizontal dampers) - 50-year Wind.

energy results obtained from ETABS. The option with horizontal dampers provides a total damping ratio of approximately 14.5%, while the vertical damper option provides approximately 4.5% total damping. To validate the

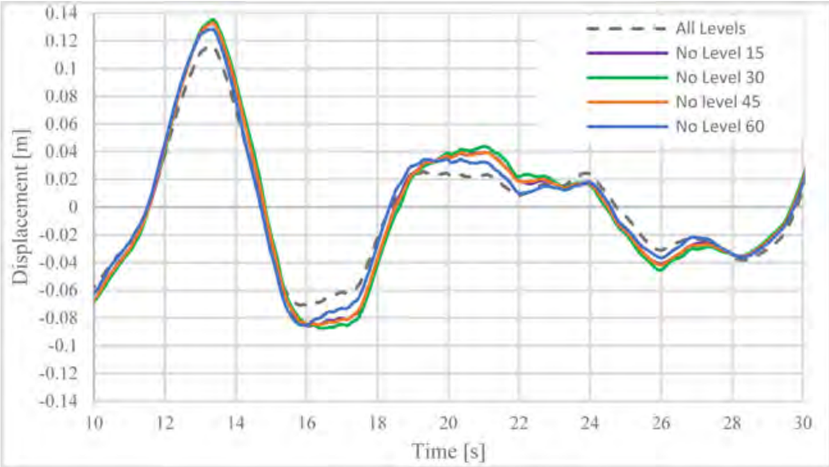

Figure 20. Roof displacement response under Frequent Earthquake of several configurations of horizontal dampers.

damping ratio thus obtained, it is applied to the frame-core system option model and the roof displacement responses are determined for the Frequent Earthquake and 50-year Wind load cases. These responses and those of the mechanism model are compared in Figs. 18 and 19. These models show a very similar response, indicating that the effective damping computed for the horizontally damped system is correct.

In both damped outrigger cases (horizontal and vertical configurations), the structure was not specifically optimized for the respective damping system used. These systems were simply added in the original frame-core system model. It is therefore reasonable to assume that an even better performance can be achieved by optimizing the design of the structure around the selected damping system.

The second set of analyses was performed to determine the relative efficacy of the horizontal damping system at different outrigger levels, not. Fig. 20 shows the roof displacement response of the model when dampers at different levels are removed. It can be seen that the dampers at level 60 have the least influence on the overall behavior of the structure, while the ones at level 30 are the most effective in damping the response of the strucure. The contribution of the devices at the other two levels is roughly equal and somewhat less than that of the outriggers at level 30. In a worst case scenario in which all the dampers at level 30 fail, the maximum displacement will increase by approximately 16%. When compared to the displacements shown in Fig. 12, however, these displacements are seen to still be lower than those of the other lateral systems, including the damped outrigger system with vertical dampers.

8. Conclusions

The idea of using mechanisms to amplify relative movements in damped outrigger systems in tall buildings to increase additional damping and mitigate the effects of wind and seismic loads was studied. Schematic details of the mechanism were presented and an example structure was used to evaluate the efficacy of such a system in comparison to other systems including one with damped outriggers but without amplifying mechanisms. The study showed that that using mechanisms to amplify relative vertical movements between the ends of outriggers and columns was very effective, increasing, for the same structure, total effective damping levels from 1.5% without mechanisms to 14.5% with horizontal mechanisms with corresponding mitigating effects on structural responses including floor accelerations, inter-story drifts and roof displacements. The relative efficacy of damped outriggers with amplification mechanisms at different levels was also studied and it was found that the uppermost level of damped outriggers in the model structure studied was least effective and the ones at a lowest level, level 30, the most effective.

Acknowledgements

The authors gratefully acknowledge and thanks Dr. Nick Isyumov, Honorary Professor at the University of Western Ontario, Canada / Research Consultant at the Boundary Layer Wind Tunnel Laboratory, and Dr. Suresh Kumar, Principal / Managing Director of RWDI India, for their advice.

References

Boggs, D. and Dragovich, J. (2006). The nature of wind loads and dynamic response. *American Concrete Institute. Special Publication*, 15-44.

Buchholdt, H. A. (1997). *Structural Dynamics for Engineers.* Trowbridge: Thomas Telford.

Choi, H. S. and Joseph, L. (2012, September). Outrigger system design considerations. *International Journal of High-*

Rise Buildings, 237-246.

Choi, H. S., Ho, G., Joseph, L., and Mathias, N. (2012). *Outrigger design for High-Rise Buildings.* Chicago: CTBUH in conjunction with IIT.

Kareem, A. (1998). Numerical simulation of wind effects: A probabilistic perspective. *Journal of Wind Engineering and Industrial Aerodynamics*, 1472-1497.

Kwon, D. and Kareem, A. (2006). *NatHaz on-line wind simulator (NOWS): simulation of Gaussian multivariate wind fields.* NatHaz Modeling Laboratory Report: Univ. of Notre Dame, http://windsim.ce.nd.edu/

McNamara, R., Taylor, D. P., and Duflot, P. (2003). Fluid viscous dampers to reduce wind-induced vibrations in tall buildings. *Structural Design of Tall Special Buildings*, 145-154.

Rossi, A., Lazzari, M., and Vitaliani, R. (2004). Wind field simulation for structural engineering. *International Journal of Numerical Methods in Engineering*, 738-763.

Sarkisian, M., Lee, P., Garai, R., and Tsui, A. (2015). Controlling Wind in Tall and Flexible Structures with Viscous Damping Devices. *SEAOC Convention.* SEAOC.

Shinozuka, M. and Deodatis, G. (1991). Simulation of stochastic processes by spectral representation. *Applied Mechanics Reviews*, 44(4), 191-204.

Shinozuka, M. and Jan, C. M. (1972). Digital simulation of random processes and its applications. *Journal of Sound and Vibration*, 111-128.

Smith, R. J. and Willford, M. R. (2007). The damped outrigger concept for tall buildings. *The Structural Design of Tall and Special Buildings*, 501-5017.

Tamura, Y. and Kareem, A. (Eds.). (2013). *Advanced Structural Wind Engineering.* Japan: Springer.