Damped outriggers for tall buildings

Rob Smith Michael Willford

The St Francis Shangri-La Place development at Manila in the Philippines incorporates the first use of the damped outrigger concept, developed by Arup for safer, more comfortable, and more economical tall buildings.

Introduction: the dynamic response of tall buildings

For buildings of about 40 storeys and more, dynamic resonance in wind starts to have a significant effect on the design. A building's dynamic resonance is similar to that of a tuning fork – the higher the building, the lower the frequency. Unfortunately the lower the frequency, the more the building is "excited" or "resonated" by the wind, which has two effects:

- The occupants start to feel the movement, potentially leading to complaints or even panic.
- The design loading due to wind needs to be increased.

The dynamic response of a tall building is governed by several factors, including shape, stiffness, mass, and the damping. While engineers can predict with reasonable certainty the effect of the first three, it is more difficult to do this for the level of damping.

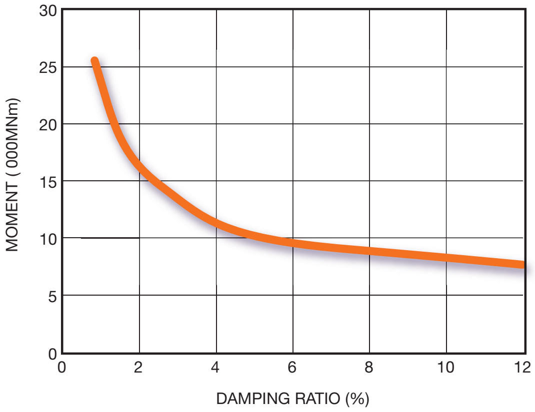
Damping is the degree of energy dissipation that a structure can provide, helping to reduce build-up of the resonant response. It comes from two main sources: intrinsic and supplementary. All buildings have intrinsic damping - from the structural materials, the foundations, the cladding, etc - but it is very difficult to predict as it depends on so many factors. Supplementary damping is added by the engineer and is only currently used in a small minority of buildings. As it is engineered, however, predicting it is much easier. The degree to which damping affects structural loading can be seen in Fig 2, which shows the global overturning load in a 400m high building. By increasing the level of damping from a typical intrinsic level of 1%, it is possible to reduce this overturning load by a factor of three.

By adding an engineered supplementary damping system to a building, it is possible to remove dependence on the low and uncertain intrinsic damping. This improves the reliability of dynamic response predictions and, by supplying higher levels of damping, substantially reduces the required stiffness of the building while at the same time improving the performance.

This article describes a new method – the damped outrigger - by which high levels of dependable damping may be introduced into high-rise building structures, and the benefits that may be realised. The towers of St Francis Shangri-La Place in Manila incorporate the first use of Arup's damped outrigger design. These twin towers, at 217m, are the highest residential buildings in the Philippines. They are within 2km of an active seismic fault, and in an area subject to strong typhoons.

As well as making the buildings safer and more comfortable, the use of the damped outrigger both reduced the capital cost of the towers and increased their floor area.

1. St Francis Shangri-La Place.



2. How overturning moment varies with damping in a tall building.

Intrinsic damping in tall buildings

To predict the likely level of damping in a tall buildings, Arup collated data on the measured values for buildings from around the world. Taken from various published academic sources, the data are shown in Fig 3. Three conclusions can be made:

- The measured values show a lot of scatter.
- There is a clear downward trend with increasing height.
- There is no clear difference in levels of damping between steel, concrete, and composite construction.

The decreasing levels of damping with increased building height can be explained by considering the non-structural elements – cladding, partitions, etc – the relative effects of which reduce as buildings increase in height. These non-structural components add significantly to damping for smaller buildings, but not for tall ones.

A common misconception is that damping always increases with amplitude of motion. If this were the case, then the measured values in low and moderate winds could be seen as "lower bound", with expected values in stronger (ie 50-year) winds being higher. However, research has shown that, for tall buildings, this is not always the case, with damping actually decreasing with amplitude in some instances (Fig 4).

Designing for safety

The uncertainty and variability in the data present risks for building design. The measurements suggest that in common practice damping is often overestimated, with the consequence that design wind loads may be underestimated. This leaves the engineer with a choice:

- Be cautious, choose a low level of damping, and design for higher forces.
- Add supplementary damping to remove uncertainty and increase damping.
- Find other methods to reduce sensitivity to dynamic loading.

For most tall buildings, the second option will often be the most economic method of controlling wind resonance.

Supplementary damping systems

Tuned mass dampers

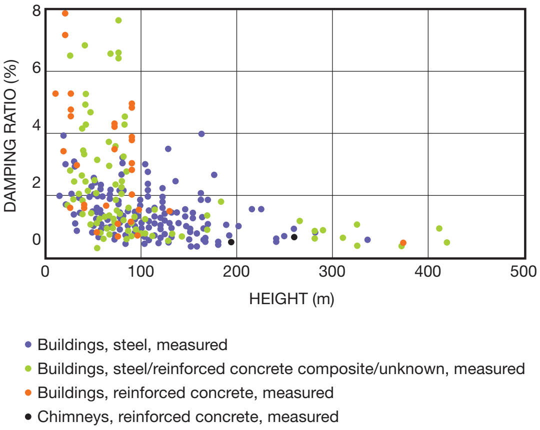
Tuned mass dampers (TMDs) or their variation, tuned liquid dampers, are an established and proven method of adding damping to a building. However, they have several drawbacks.

- They are large, heavy, and take up valuable space at the top of the building.
- They have to be "tuned" closely to the measured natural frequency of the building mode of concern; if there are several modes of concern, then several sets of differently tuned devices are required.
- They are usually introduced at the end of a design, and so form an additional cost. No offset in the structural cost can be made.
- They have no redundancy - there is only one TMD (per mode) and if it fails, resonance will increase. For this reason, TMDs are not relied upon in ultimate wind loads or seismic events.

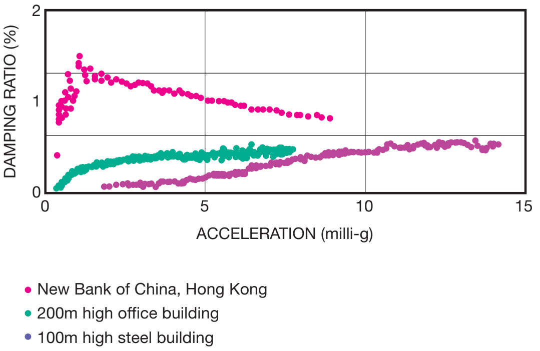
Viscous/visco-elastic dampers and similar devices

An alternative supplementary damping approach is to add discrete damping elements, such as viscous or visco-elastic dampers, which behave much in the same way as shock absorbers in cars, albeit with much less movement and significantly more durability.

Viscous dampers are commonly used in both new-build and retrofitting of buildings and bridges in areas of seismic activity. Their use to control wind response is less established – the project which forms the subject of this article shows a crossover of technologies between different disciplines within structural engineering.



3. Measured intrinsic damping of tall buildings.



4. Examples of measured damping vs response level.

The damped outrigger concept

How it works

Outriggers are a common method of stiffening and strengthening tall buildings. They work by connecting the inner core to the outer perimeter columns, much as a skier uses his arms and shoulders to hold onto ski-poles, providing extra stability. The method is very effective, and favoured by many structural engineers.

The damped outrigger works by the insertion of viscous dampers between the outriggers and the external columns (Figs 5, 6). When this is done, there is a smaller increase in stiffness of the building, but a significant increase in damping.

For a high-rise building, where resonant wind loading is significant compared to static, this is a huge benefit. The dynamic response of the building to the wind is reduced dramatically, along with the lateral accelerations (which can cause discomfort in building occupants) and the design wind forces.

There are many variations on this concept, but the principle lies in adding and/or connecting structural elements with components primarily to develop damping, rather than primarily to develop additional stiffness.

Damping FAQs

What is damping?

Damping is the physical phenomenon of the reduction of motion through energy dissipation, eg the control of vibration in a car's suspension system, or the vibration of a piano string slowly dying away on its own.

Why is it important to tall buildings?

Tall buildings oscillate with long natural periods (or low frequencies). This makes them particularly susceptible to dynamic resonance in wind, as wind energy is highest at low frequencies. In addition to responding to the natural gustiness of wind, in tall buildings a common form of dynamic response in wind is caused by vortex shedding. This creates movement perpendicular to wind direction.

Where does damping come from?

Tall buildings have two principal sources of damping:

(1) *Intrinsic damping:* this comes from the structural material, connections, cladding, foundation, friction caused by interior fit-out and, in the case of seismic movement, damage to the structure.

(2) *Supplementary damping:* engineered devices such as tuned mass dampers, slosh dampers, viscous dampers, and friction devices.

Why should I worry?

For very tall and slender buildings, dynamic wind response will often dominate lateral loading and the design wind load can be up to three times the static wind loading (ie a dynamic amplification factor of three). Estimates from most wind loading codes will underestimate the dynamic response, and if this happens, it will leave a building susceptible not only to increased acceleration (in the serviceability state), but also to fatigue loading and understrength design in the ultimate wind loading.

Wind tunnel tests enable the dynamic response to be calculated more accurately, but the wind tunnel consultant still needs to make an assumption about what the structural damping is – it cannot be measured before the building is built.

How can dynamic wind response in tall buildings be controlled?

There are three broad methods:

(1) *Shape or sculpt the building:* Vortex shedding is reduced significantly when a building has an irregular shape, is tapered, or has built-in obstructions (eg strakes on chimneys). All these have the effect of breaking up vortices or preventing them from "locking in" simultaneously over the whole building. This may not be appropriate for all buildings, and may increase the cost of construction as well as losing space efficiency.

(2) *Stiffen the building:* This is the traditional approach to controlling wind response and is often appropriate for shorter buildings. However, for taller buildings it can be extremely expensive to provide enough stiffness.

(3) *Add damping:* This is often the most cost-effective method of controlling dynamic response. In addition, by adding supplementary damping, the consequences of uncertainty about intrinsic damping are reduced.

Usually two or three of these approaches are taken in parallel – each project is different.

How do I know what intrinsic damping to assume?

Traditionally a damping level of 1-2% of critical has been assumed for tall buildings. However, recent research and review of measured data shows 0.5-1% to be more appropriate for buildings over 250m tall. Several factors determine the damping, but as yet, there is no foolproof method of predicting damping of a tall building with any accuracy. A cautious approach (say assuming 0.5%) risks overestimating wind loads and increasing the cost of the project. A more conventional approach (say 1.5%) runs the risk of underestimating wind load. Adding supplementary damping removes some uncertainty as the response of an engineered damping system can be predicted with more (although not total) accuracy.

Why is damping in earthquakes bigger?

Damping ratios listed in codes for structures in earthquakes are typically around 5% for concrete structures and 2% for steel. These figures are higher than for wind since they take in energy absorption through damage. It is not possible to consider this energy dissipation in wind (even ultimate wind loading) since wind storms are much longer than earthquakes, and prolonged inelastic behaviour would lead to fatigue failure.

What types of dampers are there?

(1) *Tuned mass damper (TMDs):* These are giant pendula at the tops of buildings. They work by oscillating out of phase with the movement of the building. TMDs are established proven technology and have been used on many buildings around the world. However they have several drawbacks: they are expensive, complicated mechanisms, take up the most valuable part of a building (the top), and have no redundancy so are not usually used to damp earthquakes or ultimate winds.

(2) *Tuned liquid or slosh dampers:* These use the same principle as TMDs but with sloshing water instead of a mass. They are cheaper but bulkier than TMDs.

(3) *Viscous dampers:* These giant shock absorbers dissipate energy by relative movement in them. They have been used to reduce seismic response for many years - many buildings in Japan use distributed viscous dampers. The damped outrigger concept uses viscous dampers.

(4) *Viscoelastic dampers:* These can be used but tend to be temperature-sensitive, and so will lose efficiency as they generate heat in a storm. The best example of their use was in the New York World Trade Center where thousands were installed throughout the buildings to supplement low intrinsic damping.

Can I use a swimming pool as a slosh damper?

Not really. Efficiency is very dependent on the depth, length, shape, and presence of baffles within the water. It would not be an ideal swimming pool.

How stiff should I make my building?

A rule of thumb is to restrict a building's total deflection to height/500 during the 50-year wind. This is a reasonable starting point, but this limit is not absolute. In some cases, where no supplementary damping is added, the stiffness may need to be increased.

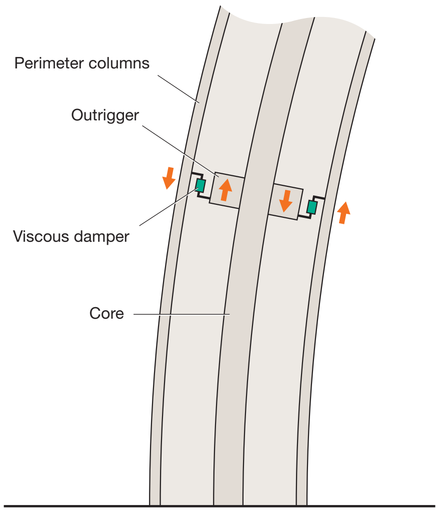
How do I know if I "need" dampers?

Rarely is it a question of whether damping is needed, rather if it is economic. Early in the design stage, the benefit of damping vs stiffness can be estimated and a judgment made of how stiff the building should be. Once wind tunnel testing is complete, the stiffness and damping can be optimised to get the most cost/efficient solution. The wind tunnel testing specification should allow for several design iterations from the structural engineer.

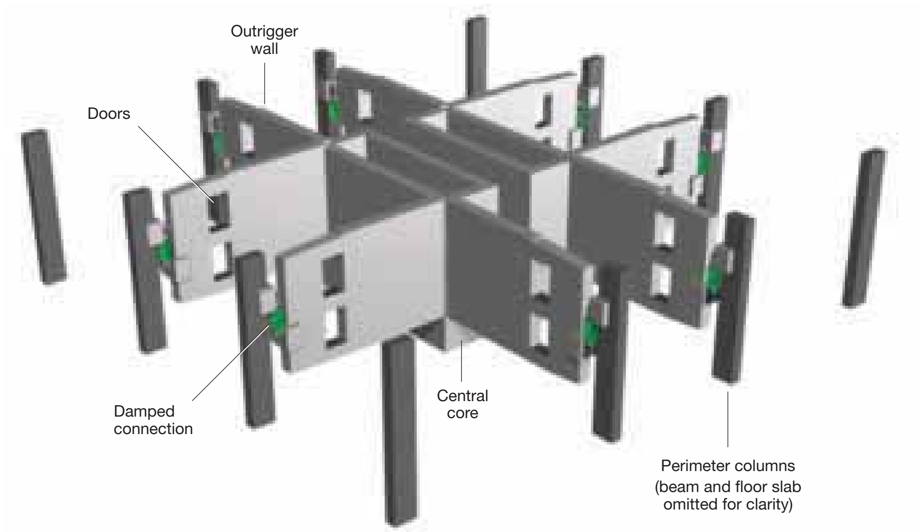
Aren't dampers an extra cost to a building?

If supplementary damping is added late in design, it can be seen as an additional cost. However, the alternative is usually to stiffen the building, which will often cost more. By considering damping early on in the design process, it is possible to exploit its value to the full and optimise the balance of stiffness and damping.

5. The damped outrigger concept.



6. Isometric of core, columns, outriggers, and dampers.



7. The London Millennium footbridge.

8. Viscous damper under bridge deck.

9. Diagonally braced viscous damper under abutment.

Where the idea came from

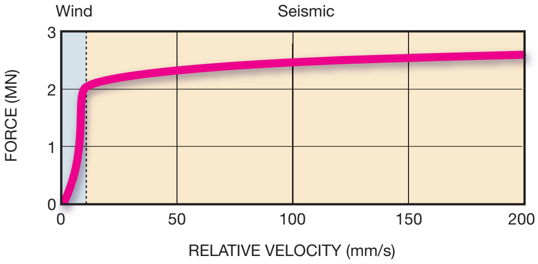
The London Millennium footbridge opened in 2000 but was soon closed following its widely-publicised lateral movement[1]. The solution Arup developed to reduce this movement used damping devices and was extremely effective (Figs 7-9). At the time, Arup was also concerned with a number of tall building projects that were predicted to vibrate in the wind. The ideas put into place on the horizontal bridge were turned around for the use of vertical buildings.

The design

Seismic performance

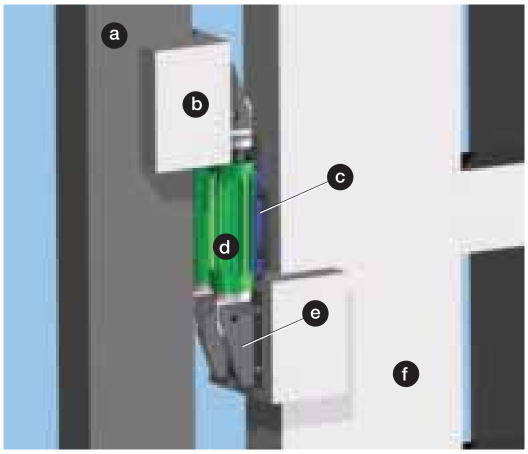
The specification for the dampers on the St Francis Towers needed to consider the effect of earthquakes. Manila is in the same seismic “zone” as California and this being the case, careful attention to the performance of the building and dampers in an earthquake was required.

The dampers were designed to work at optimum level in the “ultimate” wind (31m/s). The velocity of the piston in the damper is up to 10mm/s in wind loading, and up to 200mm/s in an earthquake (Fig 10). Because the force in the damper is a function of the velocity of the piston, the dampers were designed to restrict the force that they would generate by use of a pressure release value (Fig 11). In the unlikely event that this valve fails, the outrigger walls are designed to yield in a ductile manner, but still remain intact. Even if the whole outrigger/damper system failed, the building would remain standing after the most extreme earthquake, although it would be damaged more than if the dampers had worked.



10. Performance of damper under wind and seismic action.

11. Damped connection showing: (a) column, (b) connection block, (c) pressure release valve, (d) damper with cooling fins, (e) steel connection, (f) outrigger wall.



12. Testing the dampers.

Manufacture and testing

The dampers for the St Francis Towers were manufactured and tested by FIP Industriale, based in Italy. The damper design was based on a modification of a standard product produced by FIP with a performance specification written by Arup. A rigorous testing procedure was specified and witnessed by Arup, including a full-scale simulation of the forces induced by earthquakes (Fig 12). This involved a 400kW peak power input into the testing rig, which put a significant strain on the local electricity grid.

Maintenance, inspection, replacement

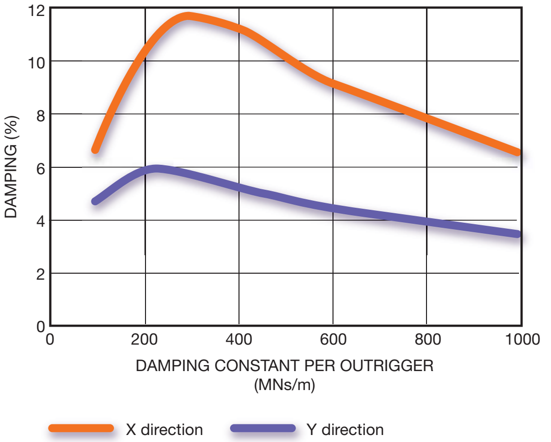
The specification for the dampers placed a big emphasis on durability, testing, and the use of high quality materials, with the intention that they be maintenance-free. The technology used in the dampers is proven, having been developed over several years for both military and civil applications. The London Millennium Bridge dampers were produced with a 35-year warranty[1] and are maintenance-free, other than repainting.

Nevertheless, it can never be said with absolute certainty that there will be no problems , so inspections are recommended to look out for the unexpected. An analogy can be made with bridge bearings – they need to be inspected, should have no planned maintenance, but will probably need to be replaced during a bridge's lifetime.

Reliability and redundancy

A significant advantage of using multiple viscous dampers to control wind response is that the damping system can be used to reduce the forces that are used in the building design. Without a damping system, the resonant wind response (and hence design forces) would be much higher. Since the ultimate wind loads are being resisted by dampers, there is a safety issue to consider and this is addressed by adding robustness and reliability to the damping system.This is done by:

- adding more dampers than are necessary for "optimum" performance. This means that if some dampers fail, then the performance does not immediately deteriorate (as more dampers fail, the performance point moves to the left on Fig 13).
- using dampers that act in parallel with each other
- physically separating the dampers from each other
- designing for the case when a number of dampers fail
- assuming that the damping system may not act at 100% efficiency
- designing such that even if all dampers fail the building would be damaged, but would not collapse.



13. Variation of global damping with viscous damper coefficient.

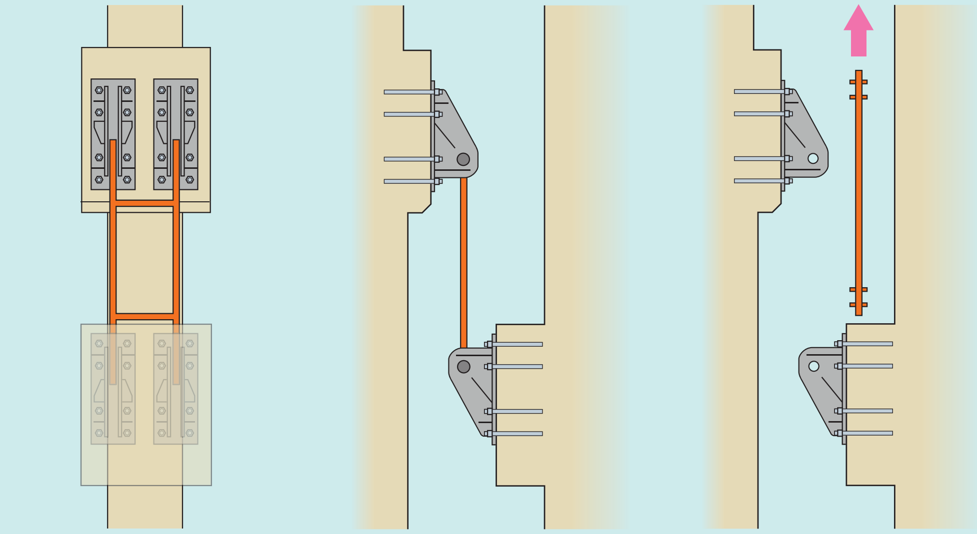
By applying this prudent approach to risk and robustness, it is justifiable to use the dampers in the "ultimate" load conditions, rather than just "serviceability" conditions, as is typically the case with mass dampers.

Installation

The dampers do not require special equipment to install. Lifting and bolting them - each weighs about 1 tonne - is within the capacity of most competent contractors (Figs 14-18).

14. The dampers do not require special equipment to install.

15. Installation procedure.

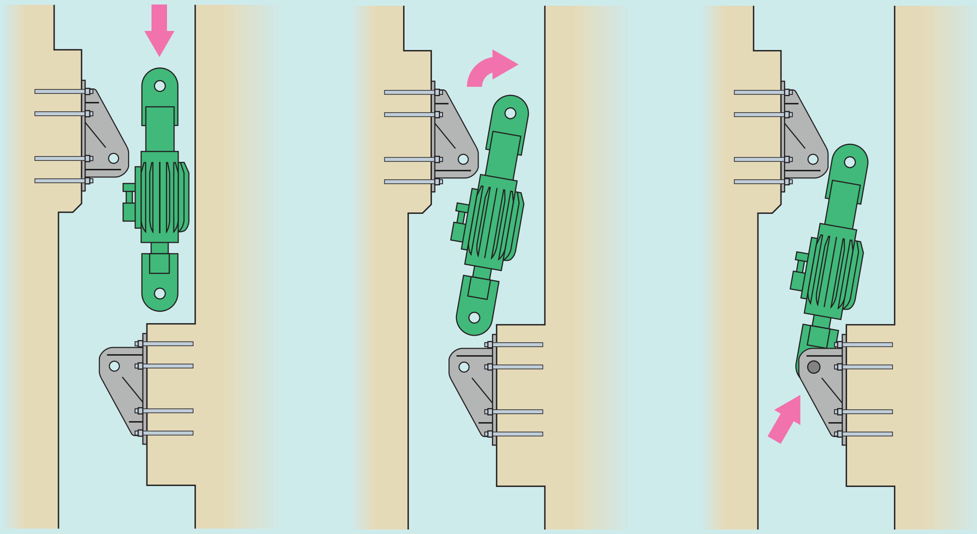


(a) Anchor frames cast and connected by template.

(b) Concrete left to cure.

(c) Template removed.

16. Damper being lowered manually using winch.

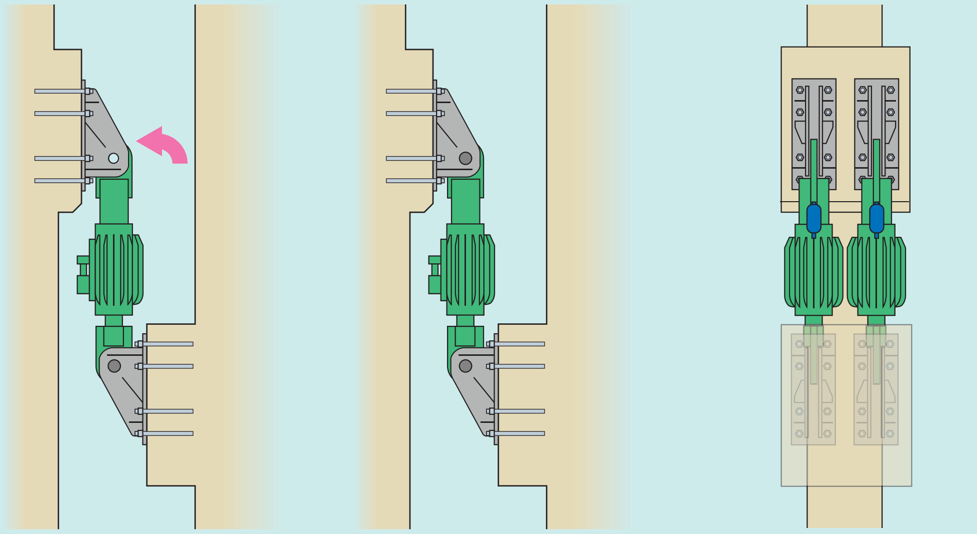


(d) Damper lowered parallel to anchor frames.

(e) Damper rotated by 10˚.

(f) Damper connected to lower anchor frame.

17. Contractor fits first damper to lower anchor frame.



(g) Damper connected to upper anchor frame.

(h) Damper in final position.

(i) Second damper in final position.

18. Both dampers in final position with pressure release valves fitted.

Benefits

Economic benefits

There is a reduction in overall capital cost; since the stiffness and the strength of the structure can be reduced, the costs of structural materials and associated labour are also less. Of course, the cost of dampers, testing, and installation needs to be added, but in the case of the St Francis Towers project, for example, there was a net saving of at least US$4M. For most of the tall building projects over 200m high that have been reviewed by Arup, there would be a net cost saving if a damped outrigger system or similar was used.

The net floor area increases, because with the reduction in design forces, the column sizes can be decreased. This typically leads to 0.5-2% more net floor area. This may sound small, but its value can often exceed the capital cost savings made. Maintenance and inspection costs also are minimal: the dampers are designed to be maintenance free, with inspections only as a measure of prudence.

Finally there is the matter of replacement cost. The owner should plan to replace the dampers once during the building's lifetime. This is obviously expensive, but still fairly small compared to the cost of maintaining and replacing items such as lifts, generators, air-conditioning plants, etc.

Safety and performance benefits

Naturally it is difficult to quantify the reduction in risk of damage from typhoons and earthquakes, but it could mean the difference between having a building that can be repaired instead of having to be replaced following a major earthquake. The more day-to-day occupant benefit is that the motion felt in windy weather is significantly reduced. Again, it is hard to place a value on this, but it could mean the difference between a building that is "comfortable" and one that is not.

The future

Arup has so far specified the use of viscous dampers in five tall building projects around the world: in the Americas, Asia, and Europe. This new technique for controlling the dynamic resonance of tall buildings has a serious future. The damped outrigger concept, the details of which are discussed in more detail in an award-winning journal paper[2], and similar arrangements are subject to patent law. Arup welcomes the use of this concept in other projects, even when the firm is not directly involved. Please contact IntellectualPropertyExecutive@arup.com before proceeding.

References

(1) http://www.arup.com/MillenniumBridge

(2) SMITH, RJ, and WILLFORD, MR. The damped outrigger concept for tall buildings. *The Structural Design of Tall and Special Buildings*, *16*(4), pp501-517, November 2007.
Winner of the "Best Journal Paper of the Year (2007)" award from *The Structural Design of Tall and Special Buildings* journal. http://tinyurl.com/4ccmg3

Credits

Client (St Francis Shangri-La Place): The Shang Grand Tower Corporation
Architect (St Francis Shangri-La Place): Wong & Tung International Ltd (WTIL)
Structural engineer and damping consultant: Arup – Ronald Aberin, Andrew Allsop, Edmond Asis, Arnel Bautista, Efren Bongyad, Janice Carbonell, Carmina Carillo, Narciso Casanova, Ernesto Cruz, Norbie Cruz, Therese de Guzman, Sheng de Veyra, Mimmy Dino, Xiaonian Duan, Floyd Flores, Bernadette Gajasan, Rico Gomez, Damian Grant, Annie Kammerer, Ana Larin, Chris Lewis, Rob Livesey, Leslie Lucero, Raul Manlapig, Mary Rose Mejia, Anne Navarro, Sarah Owen, Ender Ozkan, Darah Pineda, Rene Ponce, Daniel Powell, Archie Ricablanca, Armie Rico, Kristinah Samy, Rob Smith, Joe Stegers, Chris Villanueva, Michael Willford, Lorraine Yoro, Cesar Zamora **Illustrations:** 1 ©Arup/WTIL/Shang Grand Tower Corporation; 2-5, 10, 13, 15 Nigel Whale; 6, 11, 14, 16-18 Arup; 7 Grant Smith; 8 Tim Armitage; 9 Mark Arkinstall; 12 Riccardo Merello; 19 Raul Manlapig.

Rob Smith is an Associate Director of Arup in the Advanced Technology and Research group. He led the development in Arup of the damped outrigger concept.

Michael Willford is an Arup Fellow and Global Leader of the Advanced Technology and Research group. He is the inventor of the damped outrigger concept.

19. The St Francis Shangri-La Place development under construction, October 2008.