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The Damped Outrigger - Design and Implementation

Rob Smith†

Advanced Technology and Research, Arup, 560 Mission Street, San Francisco, CA 94105, USA

Abstract

The use of outriggers with dampers (the damped outrigger concept) has been shown to be a cost effective method of adding structural damping to a high rise building, and has been described in previous work by the author. This paper further develops the methods used to design such systems and highlights lessons learned in their application. This includes calculation methods, a review of subsequent research from others, and discussions regarding code-compliance.

Keywords: Damping, Viscous dampers, Outriggers, Tall buildings, Wind engineering, Seismic engineering

1. Introduction

The first application of the damped outrigger system within a building, The St. Francis Shangri-La Place in Metro Manila, has been described in earlier papers by the author and his colleagues (Willford and Smith, 2008; Smith and Willford, 2007), as well as other contemporaries (Gamaliel 2008). Since that time there have been three main developments of the concept. Firstly, a number of researchers have examined the possibility of the use of different arrangements and different types of dampers. Secondly, a number of installations of the system have been made, bringing further case studies. Lastly, the analysis and testing methods have changed, based upon available code documentation and computer power. This paper gives an overview of these developments, as well as the author's experience in the design of such systems.

1.1. How the damped outrigger works

All high rise buildings require additional lateral stiffening to prevent excessive displacement during both wind and seismic events. There are many structural typologies that can provide sufficient strength and stiffness, including single core, tube structures, bundled tubes, etc. Each has a different optimum height range and suitability, based upon the usage and location of the building. Buildings with traditional outriggers are typically best suited for heights of between 150 and 400 m.

The traditional outrigger system works by transferring global bending load from the core of the building to the outside columns. Since the columns connected to the outriggers attract more load, these are often slightly larger than typical columns, or in the case of megacolumns, are deliberately made to be much larger.

Typically outriggers are located near the mid-height of the building, the optimum location. In some cases, the outrigger is located at the top of a building and while this is not the most structurally optimum location, it may be more suitable from an architectural perspective. For taller buildings, multiple outrigger levels are also possible and desired. Outriggers are often placed within mechanical rooms in high rise buildings, which may have double height floors, providing room for both mechanical equipment and for outriggers. A more thorough discussion of the role of outriggers in high rise buildings is given by Choi and Joseph (2012).

In the case of the damped outrigger, the end of the outrigger is connected to the column via a damper. As the

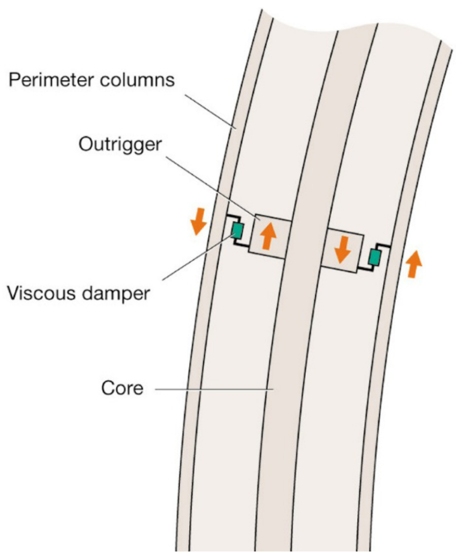

Figure 1. the damped outrigger concept (Image copyright Arup).

†Corresponding author: Rob Smith
Tel: +1-415-946-0244
E-mail: rob-j.smith@arup.com

building sways under lateral loading, this arrangement causes differential movement between the outrigger and column, thus causing the damper to stroke and provide a damping force. This is shown in Fig. 1.

1.2. Development of concept

While the designers of the damped outrigger had originally conceived its use with viscous dampers, the concept is suitable for use with all types of dampers, including friction, magnetorheological (MR), Buckling Restrained Brace, and visco-elastic. The MR application has been subject to recent research, which shows that enhanced performance over a passive system can be achieved using a semi-active system. While this system uses batteries to alter resistance, the batteries themselves do not provide active resistance (Wang et al., 2010).

Buckling restrained braces within outriggers have also been used in the design of a 632 m high building (Zhou et al., 2014). Typically, these are used as brace elements, rather than vertical elements, since this allows easier detailing of the steelwork. However, since these rely upon yielding of steel, the energy dissipation (i.e., damping) can only occur when there is higher drift within the building. Conversely, for low levels of movement, the element provides no additional damping. Therefore, buckling restrained braces are only useful for seismic loading.

Shake table testing of a damped outrigger building was performed (Zhou et al., 2014). This showed a clear reduction in accelerations and base shear, but only for high levels of ground motion. Note that this damped outrigger arrangement used non-linear dampers with an exponent of 0.2, which may explain the amplitude dependence.

Other research has focussed on optimising the location of the damped outrigger (Fang et al., 2015), and its advantages during construction (Park et al., 2010). A summary of the different types of dampers is given in Table 1.

2. Calculation Methods

2.1. Calculation of damping available

The following methods have been used by the authors and their suitability is described below.

2.1.1. Simple frequency ratio check

This method is very simple and quick, since it only requires the use of modal analysis. Two analyses are done. First, an analysis with the dampers removed from the model and outriggers disconnected is run. This provides the uncoupled natural period (T_u). Second, the dampers are modelled as rigid elements, taking care only to apply rigidity in the axial direction of the damper. The natural period from this analysis is known as the coupled period (T_c). Based upon calculations using more rigorous methods, a rule of thumb has been developed by the authors which yields the damping achievable with this system as:

Maximum % of critical damping for linear dampers = (Tu / Tc − 1) × 40%

This equation is approximately correct for up to 10% damping.

Further work by Willford (2009) shows that this equation closely matches theory that can be derived from first principles:

$$\zeta = \left(\frac{a^2 - 1}{4a}\right)$$

Where a = Tu / Tc.

It should be noted that these equations do not consider the effect of the Maxwell Spring Stiffness (discussed later).

In addition, from this, it can also be shown that the effective period of the structure is:

$T_{eff} = T_u$ / sqrt (a)

If the damper is modelled as a spring element with a spring stiffness of K_{eff}, then the stiffness of the spring can be found by iteration so the natural period meets that in the equation above.

Finally, the effective damper coefficient can be calculated by the following equation:

C = K_{eff} * T_{eff} / 2 Pi

Further checks are required to calculation peak force and

Table 1. comparison of different damper types

Viscous	• Gives the most optimum damping force and can work over a range of amplitudes. • Does not provide any resistance to mean wind loads.
Friction	• Cost effective, and can provide damping force at a fixed value. • Difficult to provide optimum damping over a wide force range.
Visco elastic	• Can provide resistance to both static and dynamic loads. • Repeated loading will increase heat within material which may reduce performance and stiffness.
Buckling restrained brace	• Similar to friction, it is designed to yield at a specific point. • Suitable for seismic, but not for wind loading.
Magnetorheological	• Not yet in use commercially. • A semi-active system (requires small power supply) that can provide higher damping than passive systems.

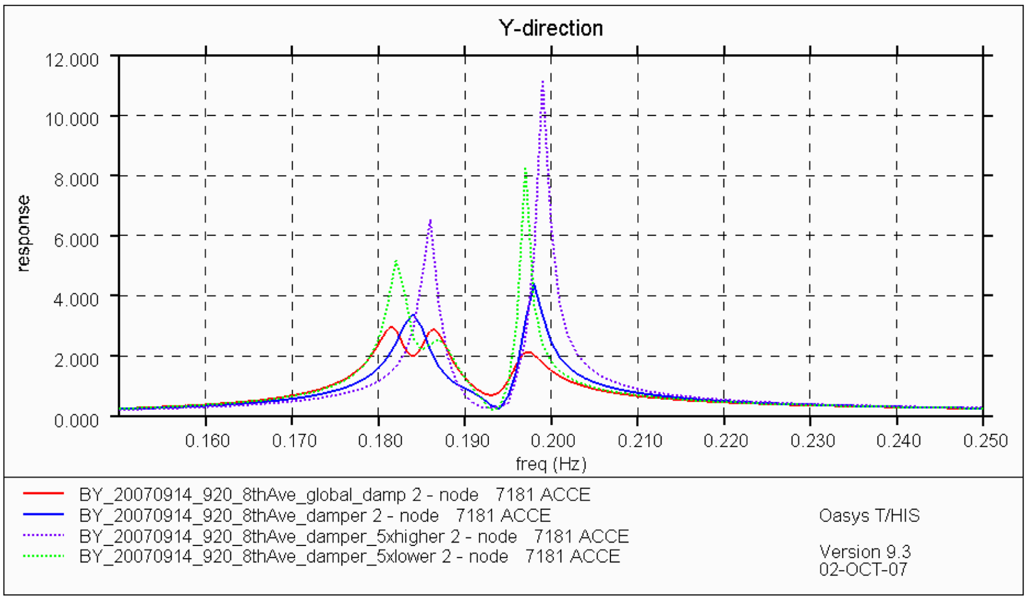

Figure 2. frequency response plot from Jackson and Scott (2010).

stroke. These are discussed later.

2.1.2. Direct frequency check

The direct frequency check requires calculating the frequency response for various frequencies in the range of interest. The result is a frequency response curve from which the damping can be calculated using the half-power bandwidth method. Effectively, the sharper the peak, the lower the damping.

There are a number of disadvantages with this method:

- There are limited software packages that have this capability.
- It is very sensitive to the number of points chosen to plot the curve.
- It is only valid for linear structures, including linear dampers.
- It does not work where there are coupled, or closely spaced modes.

2.1.3. Complex modal analysis

In cases where there are closely spaced modes, it may be required to perform a complex modal analysis. This differs from a standard modal analysis, in that both real and imaginary parts of the stiffness matrix are solved for. This enables the analysis to derive the damping provided by discrete elements within a structure. The major disadvantage is that it is not commonly available in many commercially available software packages. It is only suitable for linear dampers.

2.1.4. Time history analysis

This method is the most powerful and is the author's preference for use in final calculations. In this case, the tall building is deformed in the shape of the primary modes (or higher modes if required), and allowed to vibrate freely. From this it is possible to plot deflection vs. time and hence calculate damping from the logarithmic decay. This method is very useful since:

- It works with all amplitudes and can be easily used for non-linear dampers and structures.
- This method is available in many software packages.
- Computing speeds are such that this method is now feasible, whereas when the authors first described the system, speeds were such that the method was cumbersome.

The disadvantages are as follows:

- More analysis time compared to other methods
- Coupling of modes may still be a problem.

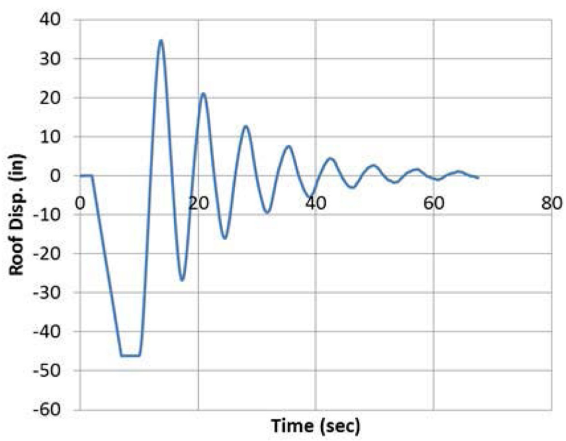

Figure 3. decay of deflection caused by damping.

2.2. Calculation of force and stroke within the dampers

2.2.1. Seismic

ASCE 7-10 does include a "simple" method for calculating damping coefficients, forces and displacements. In the author's opinion, this method is neither simple, nor particularly useful, since it is based upon a series of linear approximations. In addition, the application of the simple method requires the use at least 2 dampers on each level, to resist torsion. This is usually not economical for high rise buildings, and certainly not in the case of the damped outrigger. While the linear methods were the default method at the time the sections of codes were written, the use of response history analysis is very common now, when applied to tall buildings.

Since the engineer would typically create a response history analysis model for seismic analysis purposes, then this should be used for calculation of damping element response. Numbers of ground motions and averaging procedures should be as per state of the art guidelines, as recommended by PEER (2010) and CTBUH (2008).

In areas of low to moderate seismicity, where minimal ductility is expected and wind is expected to govern, a simple check can be made with response spectrum analysis, with a range of spring stiffness to represent the effective damper stiffness at various period of vibration, taking appropriate upper and lower bounds. Note that when calculating forces and displacements in the damper, no ductility in the damper should be assumed (i.e., R, or q =1). Since this method is conservative, a subsequent time history analysis can be performed if it is found that the design seismic forces and strokes are higher than those for wind.

2.2.2. Wind

Typical practice in the design of high rises uses results of wind tunnel testing to derive applied wind loading. The most common type of wind tunnel test uses the high frequency force balance (HFFB) method to calculate effective wind loads. Since the HFFB test does not explicitly measure the resonant effect of the wind on a building, this is calculated as a post-processing exercise, based upon the dynamic properties of the building: damping, mass distribution, natural period and mode shape, as well as the dynamic forcing measured in physical testing. Common practice in the US and elsewhere is that the dynamic properties are provided by the structural engineer. The effective wind forces are then provided by the wind consultant.

In the case of the application of wind tunnel results for highly damped buildings, it is normal that a number of damping values are considered during the calculation of wind loading. In addition, it is useful to output the split between mean, gust, resonant and total wind load applied. The relationship between these is as follows:

$$\text{Total\_response} = \text{Mean} \pm \sqrt{\text{Gust}^2 + \text{Dynamic}^2}$$

$$\text{Quasi-static} = \text{Mean} \pm \text{Gust}$$

Calculation of damper forces – Damper forces are dependent only on resonant wind forces. For many high rise buildings, that means the across wind response can be used to quantify the peak damper force. When using the time history method to calculate damping, a calibration can be made between the damper force and global overturning moment in the building. Since the latter is calculated during the wind tunnel testing, it is then possible to calculate the associated damper force.

Calculation of damper displacements – Displacements need to be calculated by combining mean, gust, and dynamic. The first two are calculated by a structural analysis assuming no stiffness in the damper since the dampers provide no resistance to static loading. The dynamic displacement (or stroke) is calculated in the same analysis used to calculate damper force. In addition to these effects, the effects of differential shortening, as well as installation tolerances, need to be considered. For highly seismic regions, the seismic displacement typically exceeds those from wind by a high margin.

Calculation of forces elsewhere within the structure – The forces elsewhere in the structure can be calculated in a similar fashion to that of the damper displacements – looking separately at the effect of mean, gust, and dynamic and combining these components using the square root of the sum of the squares method. Note that for the damped outrigger with a strong across wind response, these may be dominated by the pure dynamic component.

Heat generated – During long wind storms, there is potential for a large amount of heat to be generated within the dampers. However, the peak damper power "output" during one cycle may be considerably higher than the average over an hour. It is important to understand this relationship and design the dampers to be able to dissipate heat over the length of a storm. In some cases, it may be possible to allow dampers to heat up, as long as the net effect on damper effectiveness is within bounds considered by the engineer.

Fatigue – Since the force in the damper is always a dynamic load, the damper and associated connections will be subject to fatigue. A fatigue force distribution should be calculated based upon an appropriate wind speed distribution.

2.3. Intrinsic damping

During calculation of the total damping for the system, it is necessary to estimate the intrinsic damping of the structural system (i.e., the damping from the building without supplementary systems). This has been the subject of much research, and while there are many measurements of damping under low wind speeds, there are very few under the wind speeds considered for service conditions (i.e., the 1 year wind), let alone ultimate wind speeds. In general, there is an observed trend of damping decreasing with height (Smith et al., 2010). There is no conclusive evidence that damping increases with amplitude of movement. In fact, it may even decrease (Tamura et al., 1996; Aquino et al., 2013). For buildings over 200m, the author has used 1% of critical damping as a baseline level of damping.

2.4. Code compliance

For both the seismic and wind loadcase, the use of discrete damper elements requires the use of advanced dynamic analysis. Under US code provisions, this can be considered as covered under the "performance based" methods of section 1.3 of ASCE 7-10.

3. Optimisation of System

There are a number of considerations to be made when optimising a damping system. These are discussed in the following section:

Damper exponent – The exponent is the alpha value within the general damper equation F=CV^alpha. This value can be varied between 0.15 and 2, depending on the manufacturer's technology. A value of one implies a linear system, whereby there is no amplitude dependence. In the author's experience, this is the optimum value for wind applications, where providing a constant damping over a range of amplitudes is preferable.

For high seismic applications with a linear damper, the forces can be excessive when compared to wind. The choice of a lower exponent will lead to lower forces at high velocity, and also provides "fat" hysteresis loops – i.e. more energy dissipation for the same displacement. An alternative to this is the use of pressure release values (Taylor, 2001), which has the benefit of optimum damping at lower velocities with controlled force for higher velocities.

Damper coefficient (C value) – In order to provide optimum damping, the optimum damping coefficient needs to be found. Typically, this can be done by trial and error within the structural analysis. The author recommends that a sensitivity study is performed to understand the relationship between peak damping value (i.e., % of critical), damper force, and damper stroke. In most applications, it is normal to keep the same damper coefficient for all dampers within a building, as this is more economic than optimising each damper. In some cases, it is necessary to reduce the damper coefficient to below the optimum value, so as to reduce the damper force. This happens where the latter exceeds the structural capacity of the surrounding elements, or the associated damper element is not commercially available. An alternative to this is to place damper elements running in parallel. For an outrigger, this may mean 2~4 dampers per outrigger, each with a peak capacity of 1.5~2 MN.

Maxwell spring stiffness – Dampers not only provide a viscous damping force, whereby the force is proportional to velocity, they also have a degree of elastic flexibility. In structural analysis, this can be modelled as a spring element in series with the damper. This flexibility comes mostly from the compressibility of the damper fluid, but also the stiffness of the damper casing and connections. This is of particular concern with dampers that have high strokes for seismic purposes (say up to 250 mm), but need to provide damping forces for low level winds (around 5~10 mm). In this case, the flexibility provided by the Maxwell spring (caused by a large chamber of viscous fluid) reduces the available damping that the system can provide. While damper suppliers may be able to find methods to maximise the stiffness, it is important to note that the sub-optimal efficiency will always exist.

Optimum amplitude – The choice of damping element, exponent and coefficient will also depend on the primary purpose of the system: whether to damp service winds, ultimate winds, or seismic. In general, it is not possible to provide a system that provides ultimate performance at all levels, so the engineer needs to choose the amplitude of most importance. In the author's experience, for high rise buildings, even in high seismic regions, damping of wind loads is often most useful.

4. Testing

Since the dampers installed into a damped outrigger are typically both custom made and a critical element within the design of a high rise building, there is a strong emphasis on testing of the dampers. ASCE 7-10 chapter 18 provides a good codified template on which to base a testing specification. It is primarily focussed on seismic response, so needs further enhancement to be useful for application under wind loads. Additional tests could include:

Performance during a wind storm – Dampers that are cycled during a wind storm will generate heat and potentially heat up. This may lead to a loss of effective stiffness as the fluid becomes less viscous. This, in turn, may lead to a loss of damping within the system. The test should be able to measure this loss of efficiency and it should meet suitable limits.

Performance during low displacements and velocities – This needs to be measured to ensure that the damper works as specified over a range of velocities. Note that a realistic tolerance on force-velocity profile should be agreed upon, since specifying a tight range of acceptable performance may lead to a lot of time spent "tweaking" the performance when the net effect may be small.

Friction test – To calculate the minimum force required to move the damper. This is important for low stroke dampers.

5. Other Issues

Maximum size of damper – Limitations on the size of damper and space available may significantly affect the physical layout of the damper system and the connections.

Seal life and type of seals – This is a key differentiator between damper suppliers. For any damping system which is being relied upon for a safety critical feature, such as reducing ultimate wind loads, then a robust seal system should be in place. This may be a “seal-free” system or similar. Dampers that are under constant movement from wind or thermal variation may cause premature wear on the seals of standard seismic dampers. For this reason, long durability systems are preferred.

Maintenance – While dampers fitted into damped outrigger configurations should not require routine maintenance, they do need routine inspection – typically every few years. The purpose is to ensure that there are no leaks, corrosion or unexpected changes. Such inspections are no different to, for instance, examining a bridge bearing.

Installation and commissioning – Viscous dampers within buildings typically do not require specialist installation or commissioning and can be put in place by a competent steel erector.

Movement joints and non-structural items – When designing and modelling the building, it is important to include allowance for the stiffness of non-structural items and how they affect the loadpath.

Toggle bracing – The reader is referred to the concept of toggle bracing (Constantinou, 2001) which is useful in amplifying the stroke of a damper.

6. Examples

There are three examples of damped outriggers that the author is aware of having been constructed. These are listed below:

St Francis Shangri-La Place, Metro-Manila, Philippines. This is the first installation of the damped outrigger. The development is two towers, each 210 m high reinforced concrete residential buildings. The structural arrangement of the dampers allowed for 7.5% supplementary damping, leading to significant reduction in both wind and seismic design forces. There was one level of dampers in each building, each with 8 walls and 2 dampers per wall, giving a total of 32 dampers. Each has a capacity of 2.2MN, an alpha exponent of 2 for low velocities and a pressure relief value for higher velocities. For further details, see Willford and Smith (2008, conference paper) and Infanti et al. (2008).

Grand Hyatt Metrocenter, Metro-Manila, Philippines. At 225 m, the Grand Hyatt building in Manila is a similar height to the St Francis Shangri-La Place. In this case, a damped outrigger was provided in only one direction, since the stiffness and associated wind response in the other direction was adequate with no modification. Four outrigger walls, each with 4 dampers of 2MN capacity were used. The dampers were bi-linear with a force limiting device for higher velocities. Approximately 3% supplementary damping was added from the damped outrigger.

250 West 55th Street, New York. This is an all steel 40 storey office building in New York City, completed in 2013. During the design process, wind tunnel testing rev-

Figure 4. installation of dampers for St Francis Shangri-La Place. Image copyright Arup.

Figure 5. Grand Hyatt Metrocenter, Manila. Image copyright Federal Land Inc.

Figure 6. arrangement of dampers in 250 W 55th Street. Image copyright Arup.

ealed higher accelerations for wind loading than was considered acceptable. In order to mitigate this, the outrigger at the top of the building was modified to become a damped outrigger, adding 2% supplementary damping to the building. As well as controlling the wind response, this allowed 1000t of structural steel to be removed, when compared to the design with no supplementary damping. The cost saving associated with this reduction in structural steel was significantly greater than the cost of the 7 viscous dampers. For further details see Jackson and Scott (2010).

Disclaimer

This paper provides an overview of the author's experience of the design of damped outrigger systems. It should not be considered as a set of recommendations, guidelines, or similar. Engineers designing damped outrigger systems should use their own judgement and expertise to ensure adequate performance of their design.

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