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METHOD FOR PRELIMINARY DESIGN OF A SYSTEM OF VISCOUS DAMPERS APPLIED TO A TALL BUILDING

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Abstract

This paper describes the design process of a vibration mitigation system of viscous dampers adopted on the project of a tall building in Taipei in order to moderate the building's buffeting vibrations. Readily available finite element software are today capable of including damping devices such as viscous dampers in their detailed structural analyses. However, during the design stage when various configurations and variants of the bearing system are generally studied and compared, it is particularly impractical to perform such detailed analyses. Therefore, the ability of performing a quick and preliminary design of viscous dampers' parameters becomes of primary importance. A simple and effective methodology is proposed in this paper and was adopted to establish several scenarios of viscous dampers for the case study. The detailed procedure of the proposed methodology, the different options and the adopted solution are reviewed and discussed.

1 Introduction

The design of tall buildings is often governed by wind actions and the need to limit wind induced structural displacements and peak accelerations to acceptable levels. This leaves the designer with the option of either enhancing the building's lateral stiffness (i.e. increasing the structural sizes and/or material quantity), or increasing the level of damping by means of supplementary dampers in order to reduce wind induced effects [1]. Typically engineers choose to control wind induced displacement enhancing the lateral stiffness, whereas dampers are implemented only when the design of the structural system is completed, primarily to mitigate the acceleration of the building and ensure occupant's comfort. However, if incorporated since early design stage, dampers can be used to dissipate wind dynamic forces and reduce the building's dynamic response thus reducing the displacement and keeping the inter-storey drift within acceptable limits. This is a smart alternative to increasing the building's lateral stiffness and generally results in a significantly more efficient structural system. In fact, in order to achieve similar performance (e.g. inter-storey drift) a structure with dampers requires lower levels of lateral stiffness than a structure with only inherent damping (i.e. no additional dampers). This reduces the overall cost of the building using less structural material and benefits the architecture using smaller structural members. It thus becomes particularly relevant to study the possible implementation of dampers at early design stage to maximize the benefits that these devices can bring to a project reducing the overall structural cost.

If most of softwares today can include viscous dampers in Finite Element (FE) models for the analysis of a structural system, a rapid method to determine the preliminary parameters of the dampers appears to be valuable. In fact, complicated and time consuming FE time history dynamic analyses can be unproductive during early design stage, typically when a multitude of structural options need to be studied and the design is subject to continuous changes. Therefore, establishing a quick and useful method to calculate preliminary damper parameters is particularly advantageous to the overall design process.

The objective of this paper is to present a rapid and convenient method to calculate preliminary damper parameters and illustrate its application on a recent project of a tall building.

2 Theoretical Background

The linear dynamics of a multi-degree of freedom structure is governed by the equation of motion

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{p}$$

where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the mass, damping and stiffness matrices, $\mathbf{x}(t)$ represents the displacement in time of each degree-of-freedom of the model and $\mathbf{p}(t)$ represents the dynamic load applied at each degree-of-freedom over the course of the dynamic simulation. This force is specifically derived for each type of loading: wind, earthquake etc. The mass and stiffness matrices of the structure are usually determined with a FE method, by assembling element matrices. The damping matrix is composed of several terms,

$$\mathbf{C} = \mathbf{C}_s + \mathbf{C}_d + \mathbf{C}_a$$

respectively corresponding to the inherent (also called structural) damping $\mathbf{C}_s$, the viscous damping in the additional dissipative devices (if any), $\mathbf{C}_d$ and, in case of wind excitation an aerodynamic damping $\mathbf{C}_a$ which is usually secondary in the case of tall buildings. We only discuss the matrix associated with dissipative devices since the others might be modeled with existing techniques [2, 3]. In case of dampers with a linear constitutive behavior, matrix $\mathbf{C}_d$ is obtained by assembling the damping matrices of each dissipative element which, in a local frame, read

$$\mathbf{C}_d = \sum_{k=1}^{n_d} \boldsymbol{\ell}_k \begin{bmatrix} c_k & -c_k \\ -c_k & c_k \end{bmatrix} \boldsymbol{\ell}_k^T$$

with n_d the number of dampers installed in the structure, c_k the viscosity of damper k and $\boldsymbol{\ell}_k$ an $N \times 2$ (with N the total number of degrees-of-freedom) vector symbolizing the rotation-localization operation [2]. Because there are only a few dampers in a structure (compared to structural elements contributing to the stiffness matrix), the matrix $\mathbf{C}_d$ is mostly composed of zeroes and is significantly less populated than a typical stiffness matrix. In fact, only degrees-of-freedom corresponding to the damper ends are non-zero so that, in practice, only a few non-zero elements of $\mathbf{C}_d$ are stored in a sparse format.

A modal basis analysis is of utmost importance in a preliminary design stage, in order to understand the specific features of the building. In this framework, generalized (modal) matrices are established as

$$\mathbf{M}^\star = \mathbf{\Phi}^T\mathbf{M}\mathbf{\Phi} \quad ; \quad \mathbf{K}^\star = \mathbf{\Phi}^T\mathbf{K}\mathbf{\Phi} \quad ; \quad \mathbf{C}^\star = \mathbf{\Phi}^T\mathbf{C}\mathbf{\Phi}$$

where the mode shapes $\mathbf{\Phi}$ satisfy $\mathbf{K}\mathbf{\Phi} = \mathbf{M}\mathbf{\Phi}\mathbf{\Omega}^2$ and $\mathbf{\Omega}$ is a diagonal matrix collecting the circular natural frequencies of the structure. Because of additivity, $\mathbf{C}^\star$ is established as the sum of its three components. In particular, as to the dissipative term, matrix $\mathbf{C}_d^\star = \mathbf{\Phi}^T\mathbf{C}_d\mathbf{\Phi}$ is seen to be a rotation of this sparse $\mathbf{C}_d$ matrix. This operation can be done explicitly and the diagonal elements of $\mathbf{C}_d^\star$ read

$$C^\star_{d_{n,n}} = \sum_{k=1}^{n_d} c_k \Delta\Phi_{n,k}^2$$

where $\Delta\Phi_{n,k} = \mathbf{\Phi}^T \boldsymbol{\ell}_k \begin{pmatrix} 1 \\ -1 \end{pmatrix}$ represents the relative longitudinal displacement of both ends of damper k in mode n. Notice that the off-diagonal elements of $\mathbf{C}_d^\star$ are not strictly equal to zero, especially where mode shapes are similar or the target damping is large ; some virtual load correction might be used to compensate for this modal coupling [4].

The modal damping ratio in mode n is obtained as a sum of all three components as

$$\xi = \xi_s + \xi_d + \xi_a$$

where ξ_d in mode n is given by

$$\xi_d = \frac{C^\star_{d_{n,n}}}{2M^\star_{n,n}\Omega_{n,n}} \quad (1)$$

. The target damping $\bar{\xi}$ is based on target limits of acceleration for human comfort or inter-storey drift, generally defined by code requirements. The generalized damping ratio required in the additional dissipative system in order to achieve the target damping ratio ξ can be determined by $\xi_d = \bar{\xi} - \xi_s - \xi_a$. We therefore see that the viscosity of the dampers shall be selected in such a way that

$$\sum_{k=1}^{n_d} c_k \Delta\Phi^2_{n,k} \geq 2M^\star_{n,n}\Omega_{n,n}\left(\bar{\xi} - \xi_s - \xi_a\right).$$

Several scenario's can be assessed very easily. Indeed, once a number of viscous dampers and their locations are determined, the required viscosity might be estimated, for example, by assuming all c_k's are equal. Reverting the equation above, the minimal viscosity for all dampers can be determined with the following formula,

$$c_k \geq \frac{2M^\star_{n,n}\Omega_{n,n}\left(\bar{\xi} - \xi_s - \xi_a\right)}{\sum_{k=1}^{n_d} c_k \Delta\Phi^2_{n,k}},$$

see [5] for more details. Comparing a few scenario's, an initial configuration of dampers might be established. Then, from this configuration, some iterations in the design might be performed (i) in order to optimize the number of dampers (when the required damping ratio is low), (ii) in order to adjust the viscosity of the dampers, damper by damper, in order to benefit from locally larger inter-story drifts or to adjust the forces generated by the dampers to the local resistance of the frame.

3 Tall Building Case-Study

3.1 Description of the building

The method for the preliminary design of dampers presented in the previous paragraph was applied to a project of a tall building which is here presented as a case study. The building is a high-rise luxury residential development of sophisticated architecture located in the city of Taipei. Some of the relevant building information are listed in Table 1.

Twenty-four columns connected by framing beams are evenly distributed across the floor plan forming the special moment-resisting frames of the building. Big cut-outs make the typical floor plan relatively irregular and laterally softer than a conventional rectangular shape. The lateral stiffness is however regularly distributed along the height complying with soft-storeys requirements of the local building code. The structure is made of steel and Concrete Filled Steel Tube (CFST) to enhance the stiffness of the building while providing high strength. Steel bracings in the Y direction and coupling columns in the X direction are adopted to maximize the building's lateral stiffness and the structural efficiency.

Location:	Taipei
Floor area:	∼ 26000 m2
Total number of storeys:	38
Building's height:	144.2m above ground
Floor layout dimensions:	44m (length), 22m (width)

Table 1: Relevant building information

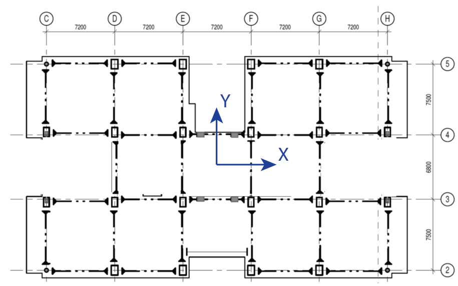

Figure 1: Typical floor plan layout.

High strength steel of grade S420 and concrete of 60MPa cube strength are used for the CFST columns. All structural steel works of the beams forming the special moment frame and the bracing in the Y direction are of grade S355. Secondary beams and other steel members are of minor grade S275.

3.2 Design Criteria and Loading Considerations

The building's structural system is classified as Eccentric Braced Frame (EBF) and is designed according to the Taiwanese Building Codes, which include detailed wind design code and seismic design code. American and international standards such as ASCE 7-10 and IBC 2009 were used as reference for some aspects of the design. The design of the structural system is based on loading considerations which include gravity load, wind load and seismic load.

Gravity Load. The gravity loads are taken from the self-weight of all the structural members of the building including walls, beams, columns, and slabs. Super imposed dead loads include slab finishing, ceiling and services, partitions and façades. Live loads vary with the function of the occupancy, which includes residential, amenities, various facilities and mechanical floors.

Seismic Load. Taipei's very high seismicity and strict code requirements are of primary importance for the structural design. The seismic analyses were carried out by using response spectrum analyses. Based on the Taiwanese Seismic Code for Building, the following parameters were adopted for the design: SDS = 0.6, SMS = 0.8, T0D and T0M = 1.30 s, Seismic Zone Factor (z) = 0.24g, reduction factor = 4.8 and design base shear = 0.07543W. Service Level Response Spectrum was used to ensure human comfort and to limit damage to non-structural components. Design Response Spectrum was calculated using Small, Moderate and Maximum Considered Response Spectra with appropriate Structural Response Factors. Even though seismic forces were considered for the structural design of the building under study, the present paper focuses on the method for preliminary design of damper used to mitigate wind induced effect.

Code Based Wind Load. Because of the high occurrence of typhoons in Taipei, wind load is significantly high in this part of the world and therefore wind induced motions and vibrations are of primary concern for engineers, particularly in the design of tall buildings. During the preliminary phases of the design wind forces were estimated following the Taiwanese Wind Code for Building, which accounts for the background response to turbulence and the dynamic component of the response. At a later stage of the design, a wind tunnel test was performed and a more accurate set of forces was used to adjust and fine-tune the structural system. Typically dampers are introduced in the design process only when the design of the structural system is completed, mainly to reduce the building's acceleration and ensure occupant's comfort. However, if incorporated since early design stage, dampers can be used to limit wind forces and reduce the building's dynamic response, as a valid alternative to the more common means of stiffening the building. This results in a significantly more efficient structural system which benefits the architecture using smaller sizes, and the overall cost using less material. In view of the very high wind forces, a system

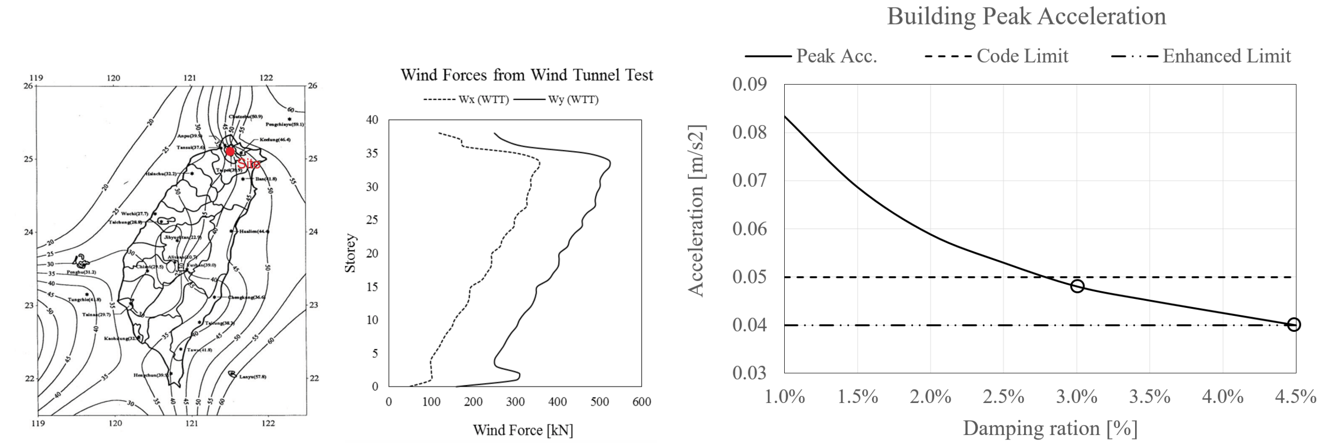

Figure 2: Left: Maps of reference wind speed (Taiwan), Center: Maximum floor loading obtained from wind tunnel experiments, Right: Peak acceleration as a function of the total damping ratio.

of dampers was envisioned since early design stage to maximize the structural efficiency and minimize costs. The overall damping ratio was initially selected to be 3% for wind forces. Following the Taiwanese Wind Code for Building the wind pressures were calculated with a design wind speed of 42.5m/s, 10-minute gust and a 50-year return period, assuming the selected value of 3% damping ratio. Considering two main wind directions (X and Y) and establishing dynamic amplification factors, six components of static equivalent dynamic wind forces were evaluated: across, along and torsional components for wind in X and Y. The code-based wind forces were used to perform preliminary structural analyses and options study. A scheme was selected from the various options developed, and the structural properties of this were adopted for wind tunnel testing.

Wind Tunnel Test. At a more advanced stage of the design a wind tunnel test was deemed necessary to evaluate the dynamic response of the building as well as its peak acceleration more accurately, and fine tune the structural design. The code based wind forces showed to have very high across wind components in both directions, ranging from 60% to 90% of the along wind component. On the other hand, the wind tunnel tests showed significantly lower across wind effect, amounting to 26% of the along wind component. The forces from the wind tunnel test were combined together in 24 load combinations and computed in the analytical FE model. It was found that these had similar effect on the overall structural system than the code-based forces previously estimated. The inter-storey drift was unaltered in the Y direction, and reduced by 25% in the X direction. The central chart in Figure 2 shows the maximum wind load forces from the wind tunnel test.

The dynamic component of the wind forces generates acceleration in the building which may be perceptible to occupants. The Taiwanese Wind Code for Building indicates the limit of acceleration as 0.05m/s^2 in order to prevent human to perceive motion, ensuring occupant's comfort during typhoons. Results from the wind tunnel test showed that the building's peak acceleration corresponding to 3% damping ratio amounts to 0.048m/s^2. Values of peak acceleration for different damping ratios are represented in Figure 2. The results provided by the wind tunnel test were used to fine tune and optimize the building's structural system.

4 Selected Structural Scheme

With the end of Concept Design, a final scheme was selected from amongst a considerable number of structural options studied and analyzed. The structure selected is an Eccentric Braced Frame (EBF)

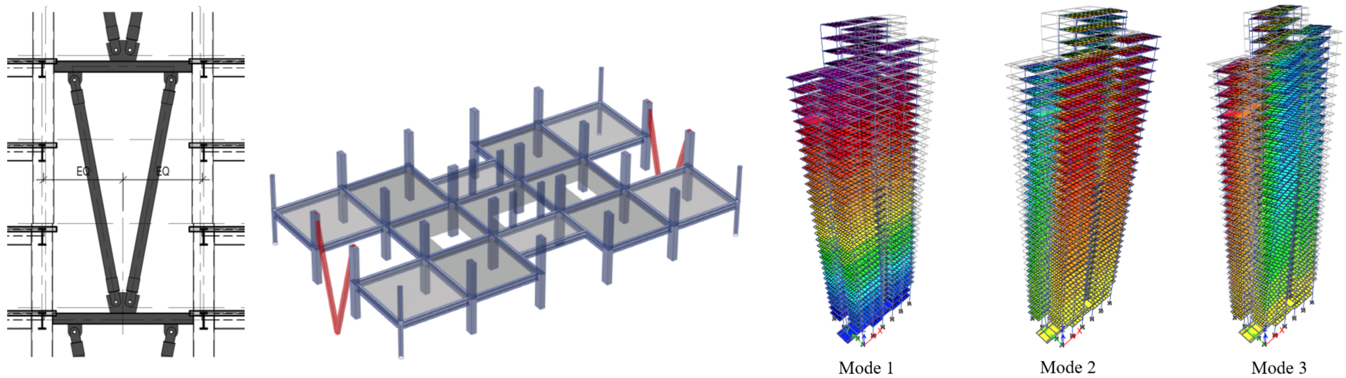

Figure 3: Left: Sketch of the final structural system, Right: Graphical representation of the first three mode shapes of the structure, with corresponding natural periods.

system with eccentric inverted chevron bracing spanning across three consecutive storeys in the Y direction and coupling columns (stiffeners) at alternate levels in the X direction, see Figure 3. This scheme was further developed in collaboration with the architects and the design was refined in order to maximize the structural efficiency. Considering the seismic loading above described and the wind forces from wind tunnel test, several detailed FE analyses were performed to study the building's performance, design and optimize its components. This structural scheme formed the basis for the preliminary design of viscous dampers presented in the next Section.

A modal analysis of the FE model of this structural system provided 7 modes below 1 Hz and only the first 3 modes below 0.5 Hz. They correspond to bending about the Y- and X-axis, then torsion about a vertical axis. These modes are represented in Figure 3. It is expected that only the first two modes (bending in each direction) require additional damping, in order to reduce their wind induced response.

5 Preliminary Design of Viscous Dampers

5.1 Target damping ratio

Both wind code-based forces and wind tunnel test forces were based on the assumption that the structural system provides 3% damping ratio from a combination of inherent damping and additional devices. As opposed to a system without dampers, the structure designed on this basis showed a remarkable increment in efficiency due to the reduced quantity of structural steel needed to achieve similar performance. Also, the building's peak acceleration showed to be within the acceptable code limits of 0.05m/s^2 (as shown in Figure 2). The assumption of 3% damping for the design was therefore acceptable and sufficiently efficient. However, after careful considerations, the client of the project decided to lower the acceptable limit of peak's acceleration by 20% to 0.04m/s^2 to provide higher occupant's comfort standards for the luxury development. The wind tunnel test results suggested that a value of 4.5% damping ratio must be provided in order to attenuate the building's peak acceleration below 0.04m/s^2.

Under this new instruction, the target damping ratio was established to be $\bar{\xi} = 4.5\%$. The inherent damping contribution was assumed to be $\xi_s = 1\%$ which might be considered as a lower bound value for such a structural system [7]. Uncertainties and tolerances during installation of dampers can cause a certain reduction of the dampers' contribution to the overall damping. A flat reduction of 1% has been considered for this lack of efficiency, so that finally the target damping ratio to be achieved by the damping devices amounts to $\xi_d = \bar{\xi} - \xi_s + 1\% = 4.5\%$

Mode	Freq. [Hz] $\Omega_n/2\pi$	Modal mass [to.] $M^\star_{n,n}$	Target damping ξ_d	Target modal viscosity $C^\star_{d_{n,n}}$
1- Y-dir	0,230	7841	4.5%	1020 kN.s/m
2- X-dir	0,235	8924	4.5%	1186 kN.s/m

Table 2: Modal properties of modes to damp.

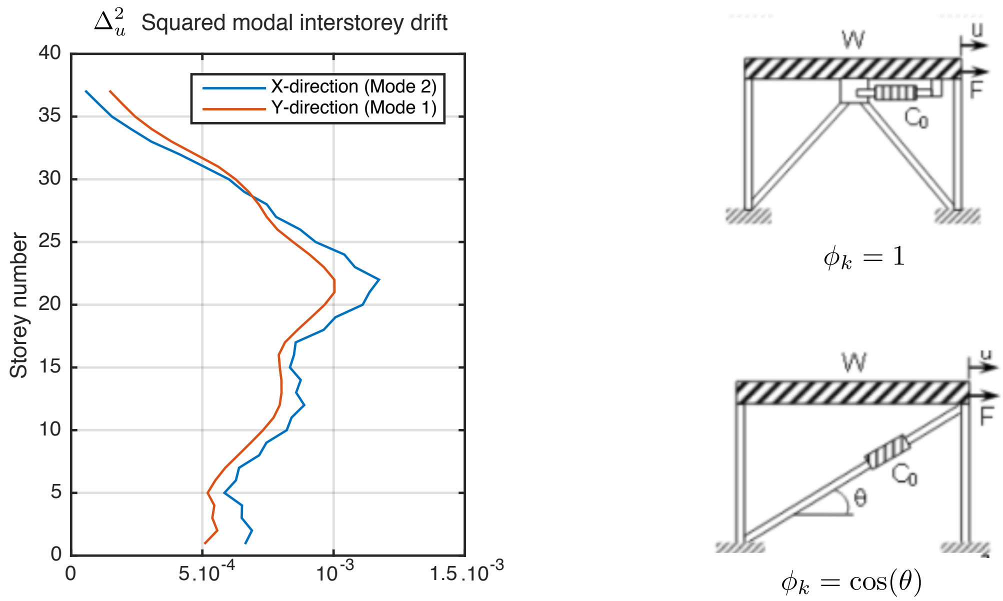

Figure 4: Left: squared modal inter-storey drift $\Delta u_n^2(x)$, used to decide where to optimally install dampers (mode shapes were normalized to unit maximum value), Right: some possible arrangements for the installation of dampers in frames.

5.2 Design of dampers

The design process of a damping system to mitigate the vibrations of a structure does not necessarily result in a unique solution. While the damping ratio in one or several modes is usually the target of the design, the number, location, inclination and constitutive behavior of dampers is usually not known, which leaves significant flexibility in the design. However, other aspects, like the local resistance of connections, might add difficult constraints to the research of an optimal configuration in a high-dimensional space. Accordingly, it was suggested to start the iterative design process as close as possible to a realistic configuration, obtained by means of a low order model and physics-based reasoning, concluding with minor final tuning of the proposed properties of the dampers.

Table 2 summarizes the modal properties of the first two modes and indicates that the required modal viscosity approximately amounts to 1000 kN.s/m in order to offer a damping ratio of 4.5% in the first two modes, see (1). This target modal viscosity needs to be achieved by installing several dampers.

A damper with a viscosity c_k provides a contribution to the modal viscosity in mode n given by $c_k \Delta\Phi^2_{n,k}$, where $\Delta\Phi_{n,k}$ is the longitudinal relative displacement for this damper in mode n (see Section 2). It is more natural to express this quantity as a function of the inter-storey drift $\Delta u_{n,k}$ related to the two floors where the damper is connected, by introducing the *efficiency factor* ϕ_k, such that

$$\Delta\Phi_{n,k} = \phi_k \Delta u_{n,k}$$

In the simplest case, the damper is installed horizontally and the relative displacement of the damper between its two ends, is equal to the relative inter-story displacement, i.e. $\phi_k = 1$, see Figure 4. When dampers are installed as diagonal braces in the frame, the relative displacement of the damper ends is smaller than the inter-storey relative displacement. This results in efficiency coefficients smaller than 1. This configuration is often a cost-effective solution as it requires minimal steel bracing. Note that other procedures to increase the relative motion of a damper ends to values larger than the inter-storey drift are available[6].

For a given efficiency factor, the above formula indicates that dampers will contribute the most where there are significant inter-storey drifts, all the more as the contribution to modal damping scales as the square of $\Delta u_{n,k}$. In order to decide where to optimally install dampers, it is therefore important to observe the squared modal inter-storey drift $\Delta u_n^2(x)$, as represented in Figure 4. In this case study, dampers should ideally be installed between stories 12 and 30.

In the X direction, a **first scenario** consisted in implementing dampers in diagonal arrangement, at every storey between floors 12 and 30. Assuming first an efficiency coefficient ϕ_k equal to $\sqrt{2}/2$ (inclination of 45° of the bracing, see Figure 5), we can see from Figure 4 that each damper installed between floors 12 and 30 will contribute to the total modal viscosity by an amount of $0.5\Delta u_{n,k}^2 c_k$, i.e. approximately $0.5 \cdot 10^{-3} c_k$. As a first estimate, we can divide the total target modal viscosity of 1000 kN.s/m by the number of dampers, i.e. 1000 kN.s/m divided by 38, resulting in an average contribution of 26 kN.s/m (per damper) to the modal viscosity. Dividing by $0.5 \cdot 10^{-3}$, the viscosity of the damper should be selected as 52000 kN.s/m, on average, in order to reach a damping ratio of 4.5%. This is a preliminary approach to define an initial value of required viscosity for the dampers, based on simplified assumptions. However, in the final design stage, the same procedure is used in order to adapt the viscosity of the dampers to the actual inter-storey drift occurring at the location of each device. This has resulted in the distribution of viscosities given next and adaptation from 38 to 40 dampers.

When the viscosity of each damper is determined, the maximum stroke and force in each damper are computed by considering the maximum roof displacement D of the building, which was calculated under the equivalent static wind loads. The relative velocity at both ends of a generic viscous damper and in a given mode is $D\Omega_n\phi_k\Delta u_{n,k}$. This velocity, multiplied by the damper viscosity, provides the maximum force in the damper. All in all, in the X-direction, a total of 40 dampers has been installed and the maximum force of one damper was calculated to be 700 kN. The top 12 and bottom 16 dampers, located in stories 26 to 31 and 12 to 19 have a larger viscosity (54000 kNs/m compared to 45000 kNs/m for the 12 dampers in the intermediate stories) in order to increase their efficiency. A structural verification would determine whether the frame is able to withstand this local force. The same computation as above should be conducted for mode 2, which results in a larger force, as the natural frequency of the model is larger.

The **second scenario** consisted in implementing dampers in diagonal arrangement, at every other storey. The same maximum damping forces can be obtained by decreasing the total number of dampers and increasing their individual force. In this scenario, dampers are located at every other level from floors 12 to 31. It should be noted that the more dampers the smaller their viscosity, the smaller the forces applied on the structural elements, locally. Decreasing the number of dampers increases local forces. To address the question of the number of dampers, the local forces must be estimated and compared to the local capacity of the structural frame.

In the Y-direction, other solutions were explored because of the different structural arrangement . Since the building was designed with EBF structural braces to withstand seismic lateral loadings, the initial idea was to incorporate dampers with braces in order to keep the architectural aspect unchanged, see Figure 6-a. Furthermore, adding dampers in diagonal braces as done in the X-direction was not possible because this would have caused obstruction to the lift door. Integrating dampers in the bracings required however to transfer their stiffness into the dampers in order to ensure appropriate functioning of the bracing. Because of the steep inclination of the braces, the forces and spring stiffness required in the

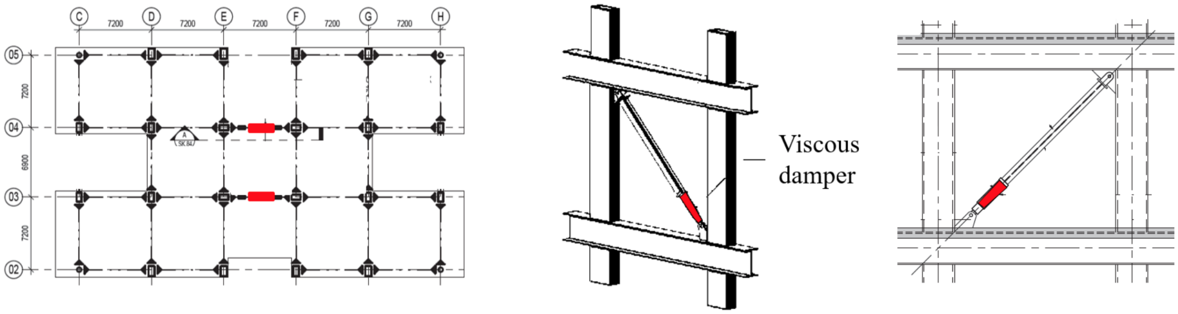

Figure 5: Damping system in the X-direction.

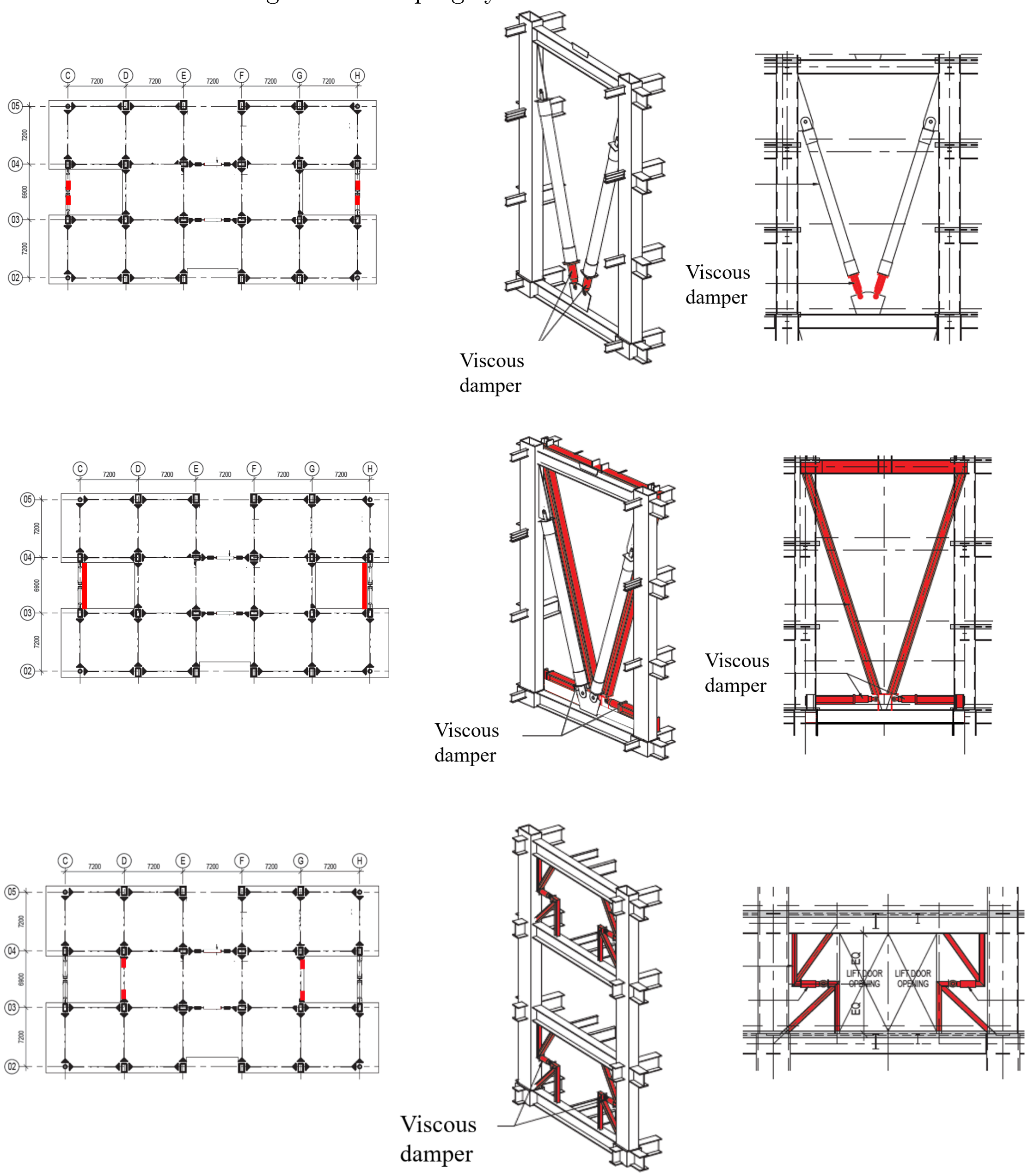

Figure 6: Considered damping systems in the Y-direction.

Damping ratio	Wind base reaction X	Wind base reaction Y
3%	8490 kN	14600 kN
1%	13800 kN (+62%)	20300 kN (+39%)

Table 3: Wind base reaction in X and Y for undamped structure (1%) and damped structure (3%).

dampers were significantly high. A second option was then considered with horizontal dampers installed in dedicated braces running behind and in parallel to the building's bracing, see Figure 6-b. Such an option presented the advantage of requiring much lower damper forces but was architecturally not acceptable. A third option with chevron bracing and dampers next to lift doors was finally considered, see Figure 6-c.

6 Selected System of Dampers and Efficiency Assessment

In the X direction, the scenario with dampers at every storey was selected for a smooth repartition of local forces. In the Y direction, adding horizontal dampers on dedicated chevron bracing next to lift door appeared to be the most favorable and economical solution among the considered configurations. A customized version with shorter length was proposed to insert the dampers in the limited space available.
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Finally, the main parameters of the selected damper system are

- in the X direction: 40 pcs 700 kN damper with spherical bearing at one end, flange plate at the opposite end, 28 pcs with c_k = 54 000 kN.s/m, 12 pcs with c_k = 45 000 kN.s/m;
- in the Y direction: 40 pcs 800 kN damper with spherical bearing at each end with c_k = 32 000 kN.s/m.

Due to the long duration of wind storms, the required power to dissipate is an important specification of the dampers; in this case, it was required that the dampers could accommodate a power capacity of 1800W for 10-min storms and 225W on a continuous basis. This system of dampers provides the structural system with 4.5% additional damping ratio, limiting the building's acceleration to values lower than 0.04 m/s^2 and significantly increasing its efficiency.

The steel quantities of the structure were selected as an index of structural efficiency. In order to guarantee high level of structural efficiency, the overall weight of structural steel of every scheme developed from Concept to Detailed Design was referenced against other buildings in Taipei. The final selected scheme, inclusive of the damper system above described, while not representing the scheme amongst those studied with the lowest steel usage, was particularly efficient and concurrently aligned with the architectural design aspirations. The structural steel quantity was calculated to be 172kg/m^2 of CFA. Considering the high seismicity, the strong wind forces and the complexity of the architectural design aspirations 172kg/m^2 of structural steel proved to be particularly efficient compared to buildings of similar height in Taipei. Part of this efficiency is due to rigorous and systematic design approach which led to the analysis of more than 40 different structural schemes and part of it is certainly due to the implementation of additional viscous dampers since early design stage.

If dampers are introduced only when the design of the structural system is completed, the overall damping ratio would correspond only to the inherent damping which amounts to 1%. The wind forces provided by wind tunnel test for 1% damping ratio are 62.5% and 39% higher in the X and Y directions than those corresponding to a 3% damping ratio, see Table 3.

To achieve similar performance, the lateral stiffness of the structural system would need to be significantly enhanced; in other words structural members would increase in size and this would contribute to raise the steel quantity. For purpose of comparison, a detailed FE analysis for the system without dampers was performed assuming wind forces corresponding to 1% damping and the overall steel quantity was found to be 215kg/m^2.

7 Conclusions

The method of preliminary design of viscous dampers was adopted for a real project of a tall building in the city of Taipei and the detailed procedure and approach were presented in this paper. Based on the results obtained the following conclusions can be drawn.

Effectiveness of the method. The rapid applicability of this method helps determining preliminary damper parameters in a short period of time for the selected structural scheme. The method is also not computationally onerous and this becomes particularly advantageous at early design stages when time consuming dynamic time history analysis offered by common FE software would be remarkably unproductive.

Adaptability of the method. The short time needed to calculate dampers parameter with the proposed method, makes it suitable for early design stage when typically a multitude of structural options need to be studied and the design is subject to continuous changes. The calculations can be iteratively performed to provide damper systems which evolves simultaneously to the architectural and structural design. This can be beneficial for overall design and the disciplines involved.

Reduction of structural material and cost benefit. Implementing additional dampers since early design stage contributes to reduce the dynamic wind forces, which significantly enhance the structural efficiency by reducing the lateral stiffness required to achieve similar performance. This results in a reduction of structural material required, providing a net cost benefit to the project. With reference to the case study, when the structure was assumed to be undamped (only 1% inherent damping is considered) the structural steel quantity was calculated to be 215kg/m^2. However, when additional dampers were considered in the design (amounting to 3% damping ratio), the structural steel quantity decreased to be 172 kg/m^2. It can be thus concluded that integrating viscous dampers in early design stage enhance the building's efficiency by reducing the required structural steel by 20%, for the specific project, resulting in a significant cost reduction.

Advantages for the architectural design. The reduced lateral stiffness required when dampers are integrated since the preliminary design of a structure, results in smaller structural sizes which can be significantly beneficial for the architectural design.

Advantages of viscous dampers over TMD and other solutions.

To achieve the required target damping ratio, other damper systems for the building were considered and designed to identify the most effective solution. The Viscous Dampers were shown to be superior to Tuned Mass Dampers (TMD) and Active Mass Damper (AMD), while they may be appropriate systems for other buildings. The viscous damper option was selected not only because of the lower cost and negligible maintenance, but also for the higher flexibility with the architectural scheme.

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