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Design of a Slender Building with High-Performing VE Dampers
配备高性能VE阻尼器的纤长形态高层建筑设计


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Abstract

A slender tower in downtown Toronto was identified early on in the design process as having wind dynamic motion issues and additional structural damping was required. The developer's mandate for this project was to maximize sellable space and therefore a damping system that did not occupy any sellable space was preferred.

The Viscoelastic Coupling Damper (VCD) system, was implemented in the design of the tower, replacing coupling beams to add distributed viscous damping to the lateral and torsional modes of vibration. The added distributed viscous damping provided by the VCD system results in performance benefits including reduced loads, drifts, lateral accelerations and torsional velocities. Compared to vibration absorbers, because the VCD system replaces structural elements, the developer recovered sellable space and therefore will generate additional revenue on the project.

Keywords: Damping, Human Comfort, Serviceability Wind Vibrations, Viscoelastic Coupling Dampers (VCDs), Coupled Wall Buildings, Reinforced Concrete Buildings

摘要

早在设计过程早期，在多伦多市中心修长塔楼即被确定需要考虑风动的问题和额外的结构阻尼。该项目开发任务是商希望最大限度地提高可售空间，因此阻尼系统，由于并没有占用任何可供出售空间而成为首选。

粘弹性阻尼器耦合 (VCD) 系统在塔的设计中应用，取代连梁增加横向和扭转模式振动的分散粘性阻尼。VCD系统分布粘性阻尼在性能方面的好处包括减少负载、横向移动量、横向加速度和扭转速度。相较于减震器，因为VCD系统取代了结构元素，开发人商保证了可售空间，因而会产生额外项目的收益。

关键词: 阻尼，人体舒适度，服务性风振动，粘弹性阻尼器的耦合 (VCDs)，双肢剪力墙建筑，钢筋混凝土建筑

Project Overview

The viscoelastic coupling damper system (VCD) has been extensively studied for use in a high-rise residential project in Toronto, Ontario, Canada. The project chronology and design evolution have resulted in an optimal structural solution where the VCD system is employed to provide supplemental damping for wind serviceability (building motions and drift). Although the added damping provides benefits for both large wind loads and large earthquakes, as a conservative design approach the design team elected to neglect the beneficial effects of the VCDs for strength design for both wind and earthquakes.

The project is located along a tall building corridor in downtown Toronto on a small site 38m x 45m bounded by roadways on three sides and an existing heritage structure. During the evolution of the project, a number of significant design constraints were introduced; some were market driven, but many were introduced to suit urban planning considerations due to the increasing height of projects in the surrounding area. Structurally,

项目概述

粘弹性阻尼耦合系统 (VCD) 在加拿大多伦多安大略省已被广泛研究用于的高层住宅项目。随着多年的项目实践和设计演进,导致那里的VCD系统被用来为风适应性 (建筑运动和侧移) 提供最佳额外阻尼结构方案。虽然增加的阻尼为抵御大型风荷载和大地震提供好处，但其作为一个保守的设计方法，设计团队忽视了粘弹性阻尼耦合系统 (VCD) 进行强度设计用于风力和地震的益处。

该项目位于多伦多市中心，沿着高楼的走廊由三面道路和现有的传统的结构包围的38mx45m的小型地块中。在项目实施过程中，存在一些对设计显著的约束; 有些约束是市场驱动的，但更多的是为了适应由于周边地区项目高度的增加而导致的城市规划考虑因素。在结构上，设计需要该塔变得更高、更纤细，以适应增加要求并维持理想的场地布局。为了实现结构布局、建筑布局和这些限制之内的增加的减震系统的效率的最佳平衡，设计团队密切合作是必需的。

the design constraints required that the tower become taller and more slender to accommodate increased setback requirements and maintain desirable suite layouts. In order to achieve the optimal balance between structural layout, architectural suite layout and an efficient supplemental damping system within these constraints, a close collaboration was required by the design team.

Design Evolution

Scheme 1

The first architectural scheme (scheme 1) was slated to be 56 levels tall (176m in height), and original setback requirements required that the tower floor plate be reduced to 21.4m wide above the podium. Four coupled reinforced concrete walls spanning the entire width of the floor plate were employed in the short direction and elevator and stair cores to form a spine in the long direction, which were coupled by beams and heavy slabs to form an offset spine (see Figure 1(a)).

Scheme 2

A preliminary desktop level wind study by RWDI indicated that scheme 1 exhibited an undesirable torsional response and elevated lateral accelerations.

To increase the torsional stiffness, RC walls were lumped into two 'strong-wall' coupled wall lines one bay (one suite unit) inboard from the north and south of the building. Providing only two wall lines allowed for some architectural freedom to configure the interior suites between the strong-walls to achieve the same unit mix as the previous scheme. The total RC wall thickness along the narrow direction was decreased, however the torsional stiffness was increased significantly (see Figure 1(b)).

Dynamic properties for the strong-wall scheme (scheme 2) at 56 levels were issued to RWDI for a further desktop study and it was found that torsional velocity dropped to an acceptable level and that accelerations marginally exceeded the CTBUH recommend value of 18 milli-g.

Prior to initializing the full wind tunnel testing, the owner received feedback from the City (Planning Department) that the tower height could be increased to 200m, however additional wall thickening was not possible and the architectural layout became more slender and longer (see Figure 1(c)) and therefore the use of a supplemental damping system was required.

Wind tunnel results indicated that a bi-level tuned sloshing damper (TSD) tank could be used to reduce the 1 and 10-year accelerations to acceptable levels. Architectural restrictions required that the TSD tank be located eccentrically on the floor plate to suit the layout of rooftop amenity space and although the intent was to integrate fire suppression into the TSD the mechanical space was extremely constricted and further stacking of mechanical spaces could not be accommodated.

Supplemental Damping Comparative Study

As the project evolved, the design team wanted to investigate the VCD system in-lieu of the TSDs, because of the known benefits of distributed damping systems over a range of loading conditions and the additional revenue when the space occupied by the TSDs would be reclaimed by the building developer.

Ultimately, the VCD system was selected by the building developer because it provided relief to congested mechanical spaces at the top

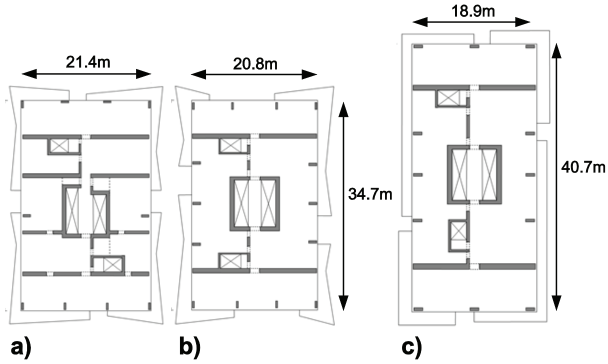

Figure 1. Structural Scheme Evolution: a) Scheme 1, b) Scheme 2 and c) Scheme 3
图1: 结构方案深化过程: a) 方案一，b) 方案二，c) 方案三 (来源: RJC)

设计的演进

方案一

第一个建筑方案 (方案一) 被限制在之有56层 (176米高)，并规定该塔底板以上建筑的宽缩小到到21.4米。横跨整个楼层宽度的四个联接钢筋混凝土墙在短边方向上，电梯和楼梯核心筒在长方向上组成了书脊，通过耦合梁和重板坯形成一个偏移脊柱 (见图1a)。

方案二

由RWDI初步桌面级风的研究表明，方案1表现出不良的扭转反应，并且横向加速度增大。

为了增加抗扭刚度，钢筋混凝土墙壁从建筑的北部和南部被集中到两个“强墙”耦合墙线区域 (一间套房单位) 内侧。仅提供两个强线，允许建筑自由配置强壁之间的一线内部套件来实现与之前方案壁线相同的单元结构。总的钢筋混凝土墙厚度沿着窄向下降，然而扭转刚度显著增加 (见图1b) 。

强墙方案 (方案2) 在56个楼层动态特性被分散到风阻尼器 (RWDI) 中，并进行专家论证研究，发现扭转速度降低到可以接受的水平，而且加速度略微超过CTBUH学会推荐值18 milli-g。

在进行满风洞测试之前，业主收到市规划部门反馈，塔高可以增加到200m，不过建筑横向宽度增加不被允许，导致建筑平布局变得更加细长 (见图1c)，因此使用一个附加阻尼系统是必要的。

风洞结果表明，双调减震阻尼器 (TSD) 罐可用于将1年一遇和10年一遇条件下的加速度降低到可接受的水平。建筑法规规定，TSD罐应避开楼层中心位置，以适应屋顶美化空间的布局，虽然其目的是将消防设备融入TSD，但是机械空间极其狭窄，而且并不允许容纳更多的机械空间。

补充阻尼比较研究

随着项目的深入，设计团队要进行VCD系统替代TSDS研究，因为在一定的负载条件下，占用的空间分布式阻尼系统具有一些公认的优势，并且原有被TSDS占用的空间将被建筑开发商重新利用，而获得额外的经济收入。

建筑开发商最终选择VCD系统，因为它缓解了塔顶部拥挤的设备空间，加快了顶层公寓的设备建设，并为当前的场地规划提供了更多的可售面积。作为比较研究的一部分，建筑师修改了项目较高楼层的平面布局，并利用了原先由TSD所占的空间而增加有效利用空间，并最大限度地有效利用这一标志性项目的设备空间。

of the tower, sped up the construction of the mechanical penthouses, and provided additional sellable area under the current site plan. As part of the comparative exercise, the upper level layouts were reworked by the project architect to add suites in the volume formerly occupied by the TSD and maximizing effective use of the signature amenity space.

Final Scheme

During the comparative damper study, further comments were received from the City (Planning Department) which required further setting back of the tower from the adjacent sidewalk and roadway. The tower in its final form stands 63 levels to the roof (198m tall) and now incorporates a typical tower floor plate 18.9m wide by 40.7m long (Figure 1(c)).

To account for this new building profile, an additional full wind tunnel test was conducted. During this time, podium retail layouts were adjusted to allow for multilevel outriggers off the strong-wall lines to increase the effective depth of the lateral system within the podium levels and increase the building stiffness.

Based on the current wind tunnel data, it was determined that supplemental damping of 0.9% in the slender direction was required to meet the ISO 1-year criteria (ISO 2007) for frequent wind vibrations (1 year vibrations). This damping had to be provided for a relatively small displacement amplitude which VE dampers can inherently provide. VCDs were found to be most efficient when located only on the two strong-wall lines and installed in approximately 20 levels in the middle third of the building height. The VCD design will be discussed in more detail below.

Viscoelastic Coupling Damping Technology

The Viscoelastic Coupling Damper (VCD, US Patent #7,987,639, Chinese Patent #200680040409.X, Korean Patent # 1020087012596 and Canadian Patents #2,634,641 and #2,820,820 and 9 international patents pending) (see Figure 2), adds distributed viscous damping to the building structure, such that both the wind performance and the seismic resilience of the tall building is enhanced. VCDs are configured in commonly used tall building structural systems, such as coupling beams or outriggers, and therefore there is no loss of architectural space when incorporated into the structural system.

VCDs consist of multiple viscoelastic (VE) material layers bonded in-between multiple steel plates which are then anchored into vertically extending structural members, with a number of possible connection details (see Figures 2(a), 2(b) and 2(c)). Lateral or torsional loads induce vertical differential motion in adjacent RC walls causing primarily shear deformations in the VE material (See Figures 2(d) and 2(e)).

In regions of high seismic demand, a ductile force limiting "fuse" can be introduced in series with the VE material and steel layers. The "fuse" is capacity designed such that when a predefined load level is reached, connecting members built into the VCD activate and prevent damage from occurring in the walls and protect the VE material layers from tearing. If the "fuse" was activated during a major seismic event, it can be inspected and replaced, if a replaceable connection detail is used. Figure 2(f) shows the intended hysteretic force-displacement response envelopes of the VCD for both wind and earthquake loading.

最终方案

在阻尼器的比较研究中，城市规划部门进一步要求建筑塔楼从邻近的人行道和车行道更大的后退距离。塔楼的最终形式确定为63层高 (楼顶搬高度， 198m)，标准层平面尺寸为40.7m长，18.9m宽 (见图1c) 。

考虑到新的建筑轮廓，需要进行一个额外的满风洞试验。在此期间，建筑裙楼零售布局进行了调整，以设置强壁线的多级外伸支架，在基座内提高了横向系统的有效深度，并增加了建筑物的刚度。

根据目前的风洞数据，长方向补充阻尼的0.9%须符合ISO年度标准 (ISO2007) 以抵御频繁的风振 (1年振动) 。这种阻尼必须保证相对较小的位移幅值，而VE阻尼器本身可以保证这种要求。另外，研究发现，只有当VCDs位于两强墙线上，并安装在建筑的三分之一的位置约20层的高度上是最有效的。 VCD的设计将在后文中进行更详细的讨论。

弹性耦合减振技术

弹性耦合阻尼器 (VCD，美国专利号＃7987639，中国专利号＃200680040409.X，韩国专利号1020087012596，加拿大专利号＃2634641和＃2820820，另外正在申请9个国际专利) (见图2)，

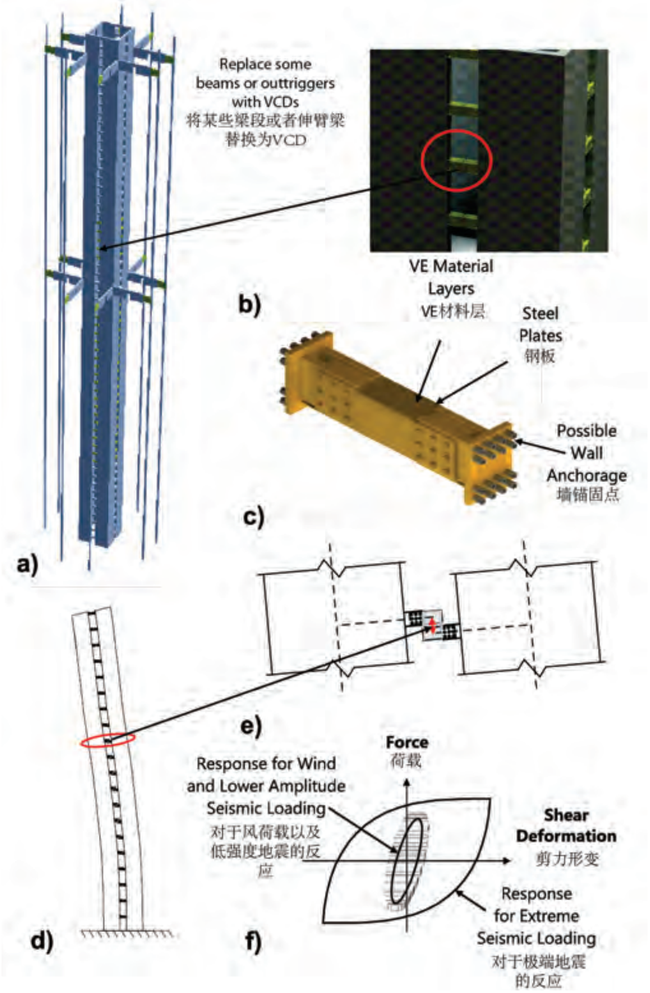

Figure 2. Viscoelastic Coupling Damper: a) lateral system with VCDs, b) Close-up of example VCD locations, c) 3D VCD Image, d) deformed shape of lateral system under wind or earthquake loading, e) single VCD location and f) shear force-displacement hysteretic response of VCD subject to wind and earthquake loading
图片2: 粘性阻尼系统: a) VCD的横向支撑系统，b) VCD所处的位置的特写，c) VCD的3D图像,d) 横向支撑系统在风力或者地震荷载作用下产生变形,e) 单个VCD所处的位置,f) VCD受风力和地震荷载所产生的的剪力和位移迟滞反应(来源: Kinetica)

3M Viscoelastic Dampers

Viscoelastic (VE) dampers have been used in tall buildings since 1969 when over 10,000 VE dampers were used in each tower as a retrofit in the World Trade Center towers to enhance the comfort of the building occupants during frequent winds (Mahmoodi 1969). Since then over 20,000 VE dampers have been used in over 250 buildings to reduce both wind and earthquake vibrations. Common configurations include axial brace and wall dampers. The VCD is a new efficient and cost-effective VE damper configuration for common tall building structural systems. The VCD is manufactured by industry leaders Nippon Steel and Sumikin Engineering Co. and 3M Japan.

Structural Performance Criteria

As discussed previously, the building in question required damping primarily to reduce the perception of frequent vibrations which can cause occupant discomfort. Because VCDs are a modular distributed damping system they can provide small or large levels of viscous damping depending on the number of VCDs used. This and the fact that the VCD can be used for small-amplitude wind loads through extreme earthquakes can make the system very cost effective for a broad range of vibration control applications. A baseline targeted added damping of 0.9% of critical in the first mode of vibration was established by wind tunnel studies conducted by RWDI in order to meet the appropriate criteria. Although the VCDs are a distributed damping system and a highly reliable source of added damping for all levels of load amplitude for both wind and earthquake applications, the design team proposed a conservative design approach to streamline the approval process, utilizing the added damping for human comfort and drifts only, but not for strength design. The design approach is described below. VCD upper and lower bounds described herein refer to expected variability in the VE material properties due to manufacturing, temperature and expected long-term property variability.

Serviceability Limit State (SLS) Wind Design

VCDs were utilized for SLS wind design to increase human comfort under frequent wind storms (1 in 1 yr and 1 in 10 yr return periods) and for reducing SLS loads for drift reduction. To account for variability in the VE material properties, lower bound and upper bound stiffness and damping properties were defined by RJC and Kinetica to effectively bound the VCD properties for use in the design.

Ultimate Limit State (ULS) Wind Design

The presence of the VCDs were conservatively neglected in the ULS strength design. VCD properties were excluded from the ETABS model for which the dynamic properties were provided to RWDI and used to calculate equivalent static loads. Member forces for strength design were determined as the greater of two bounding analysis cases: 1) VCD properties excluded and 2) Upper Bound VCD properties.

Seismic Design

The structures response to the code prescribed seismic loading was checked using the response spectrum dynamic analysis approach while neglecting the presence of the damping provided by VCDs, but considering both the Upper Bound stiffness provided by VCD and neglecting the stiffness provided by the VCDs to determine the maximum external forces. Member forces for strength design were determined as the greater of the two bounding analyses cases: 1) VCD properties excluded and 2) Upper Bound VCD properties. For drift checks, conservative lower bound VCD properties were implemented in the model.

这种设计为建筑结构增加了分布式弹性阻尼，使得高建筑物的抗风性能和地震韧性都得以提高。VCD常用于高楼结构体系，如连梁或支腿，因此，增加的结构体系导致建筑空间的损失。

VCDs由夹在多层钢板之间的多种弹性 (VE) 材料层结合而成，钢板然后锚定到垂直延伸的结构件上，具有多种可能的细部连接方式 (见图2a，2b和图2c材料层))。横向或扭转载荷引起相邻钢筋混凝土墙的垂直位移运动，将引起VE材料的剪切变形 (见图2d和图2e) 。

在抗震要求更高的地区，限制“保险丝”的延展性可以用于VE材料和钢制层。“保险丝”的容量设计中，达到当预定的负载水平时，内置于VCD连接部件将被激活，防止墙壁发生损坏并保护VE材料层不被撕裂。如果“保险丝”在大地震发生时被激活，如果使用可更换的连接细节，它可以被检查和更换。图2f所示为应对风和地震荷载VCD立面有意设计的滞后位移。

3M弹性阻尼器

弹性 (VE) 阻尼器自1969年以来已应用于高层建筑领域，在世界贸易中心大楼的翻新中每个塔楼使用了超过10,000个VE阻尼器，以提高在频繁的风的条件下建筑居住者的舒适度 (Mahmoodi1969)。自此，超过20,000个 VE阻尼器已被应用于超过250个建筑物中，以减少由风和地震导致的震动。常见的配置包括轴向支撑和墙壁减震器。该VCD是一种新型的适用于高层建筑结构体系并具有经济高效性的VE阻尼器。该VCD是由业界领袖新日铁住金工程有限公司和日本3M公司制造。

结构性能标准

如前面所讨论的，建筑物需要阻尼主要是为了减少由于频繁的振动而引起使用者不适的感觉。因为VCDs是一个模块化的分布式阻尼系统，而其能提供粘滞阻尼的大小取决于所使用的VCD的数量。另外， VCD的适用范围可以包括小振幅风力负载到极端的地震条件而使系统非常符合成本效益，因此被广泛应用于振动控制。为满足相应的标准RWDI进行了风洞研究，建立了针对第一个模式振动阻尼增加的0.9%基线。虽然VCDs是一个分布式的减震系统，并且为各级载荷幅值为风和地震应用提供一个高度可靠的附加阻尼来源，设计团队提出了一个保守的设计方法，以简化审批程序，利用附加阻尼提高人体舒适度并控制侧移，但无关强度设计。下面对设计方法进行说明。本文描述的VCD的上限和下限是指由于制造、温度和预期的长期材料特性变化而导致的VE材料预期可变性。

正常使用极限状态 (SLS) 的抗风设计

VCDs最初用于频繁的风暴 (11年及1年10重现期) 条件下的SLS风设计，并为减少侧移量而降低SLS负荷，以增加人体舒适度。考虑到VE材料的可变特性，RJC和Kinetica定义的上限和下限的刚度和阻尼特性在设计中有效约束的VCD特性以供使用。

极限状态 (ULS) 抗风设计

VCDs的存在ULS强度设计中被保守忽视了。VCD属性被排除在ETABS的模型之外，在模型中动态性能提供给RWDI并用来计算等效静态载荷。部件力量强度设计被确定为两个较大的边界的分析案例: 1) VCD性质排除，2) 上限VCD属性。

抗震设计

运用了反应谱动力分析方法，结构对地震荷载规定做出了回应，而忽略VCDs阻尼的存在，但同时考虑到VCD的上界刚度并忽略VCD提供的刚度，以确定最大外部力量部件力量强度设计被确定为两个较大的边界的分析案例: 1) VCD性质排除和2) VCD属性的上限。为了观测侧移，保守VCD性质下限在模型中实现。

Design Optimization

An important design consideration was to achieve a constructible and efficient steel connections to attach the VE damper panels to the structure. A number of connection details were examined including: i) an entirely cast-in-place connection VCD detail which included both the VE damper panels and embedded steel connections, ii) a modular end-plate connection detail and iii) a steel I-section connection detail fabricated by a local steel fabricator with two modular VE damper panels that would be bolted on either side of the steel connecting elements (see Figure 3(b)). This detail was assessed as being the best balance of performance, constructability, cost-effectiveness and also allowed for the modular VE panels to be installed after the main structural system had been constructed. In order to ensure the proper installation of the VE damper panels to the embedded steel W-sections, two temporary rigid steel channel sections will be introduced as placeholders (Figure 3(b)) during the casting of the RC walls and will be removed to allow for the installation of the modular VE damper panels. The VE panels will be secured to the steel W-sections using a slip-critical steel connection.

It was observed that the most effective locations for VCDs were along the strong-wall lines coupling over the corridor (Figure 4 in red). The RC coupling beams (Figure 4 in blue) at those locations are 1,630mm long, 700 mm deep (including the slab) and 600 mm wide. Standard steel sections (in green) replace stiffer concrete coupling beams directly above and below the lines of VCDs in a pattern to achieve an optimal balance of stiffness and damping and to reduce force spikes in adjacent coupling beams for all of the loading cases when the dampers were completely neglected.

Performance Assessment

The hysteretic response of VCDs in shear are modeled with a Kelvin-Voigt element model (which is simply a spring and dashpot in parallel) located at a rigid offset from the wall at the centerline of the VE material (Figure 5(a)). The damping and stiffness coefficients of the VCD are obtained by combining the stiffness of the connecting steel elements in shear (Kasai, 2006) and a Kelvin-Voight model representing the VE damper panels (Mahmoodi, 1969, Soong and Dargush, 1997, Christopoulos and Filiatrault, 2006). The hysteretic response of VCDs in shear (see Figure 5(b)) can be expressed as:

$$F_{VCD}(t) = k_{VCD}u_{VCD}(t) + c_{VCD}\mathring{u}_{VCD}(t)$$

Where $F_{VCD}(t)$, $u_{VCD}(t)$, $\mathring{u}_{VCD}(t)$ are the VCD force, displacement and velocity, respectively, at time t and $kVCD$ and $cVCD$ are the stiffness and viscous damping coefficients in shear, respectively. The VE material properties are calculated based on the VE material temperature and frequency of the building response subject to wind loading conditions. This model is simple to implement in commercial software such as ETABS.

The level of added damping was assessed in ETABS using three techniques (Christopoulos and Montgomery 2013), including classical modal analysis, free vibration analysis and the equivalent viscous damping technique. Figure 6(a) shows a free vibration of mode 1 of the building at floor 40 of the building with and without VCDs. From this plot the level of total building damping can be calculated by relating the displacement amplitudes between multiple cycles. The undamped response has an assumed inherent damping of the original structure of 1.5% and the damped structure has a total damping of 2.4% (1.5% of the original structure plus the targeted added damping of 0.9%).

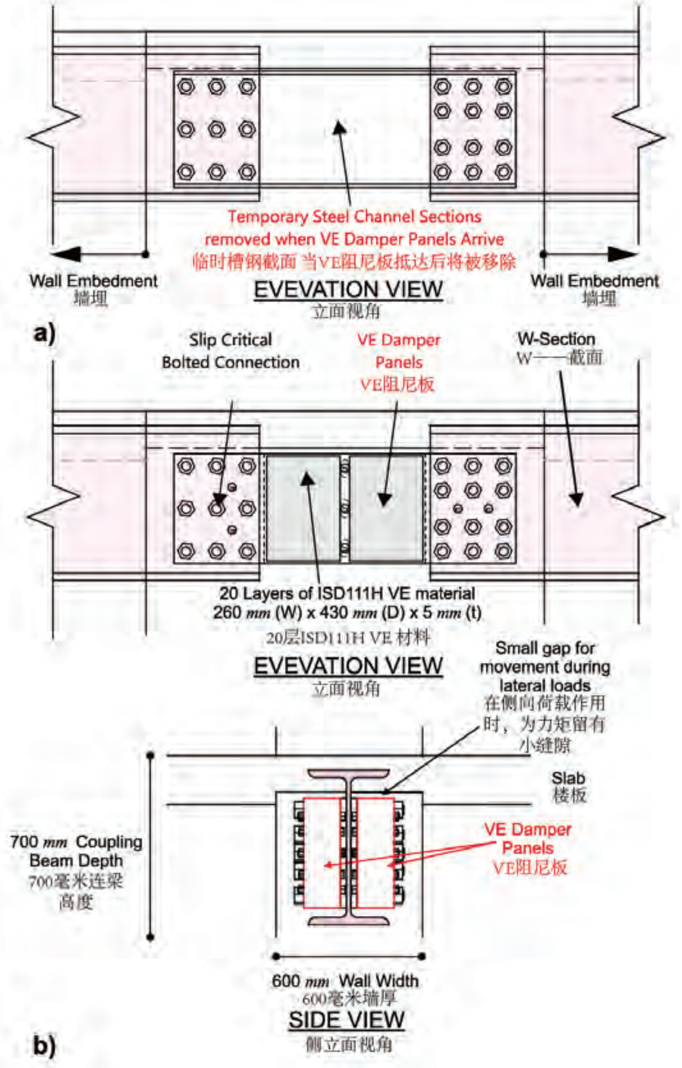

Figure 3. VCD details for Tower: a) cast-in-place temporary and final details for construction, b) final VCD configuration
图片3: 塔楼上的VCD细部: a) 临时的现场浇筑和最后的施工细节，b) 最后的VCD结构形态 (来源: Kinetica)

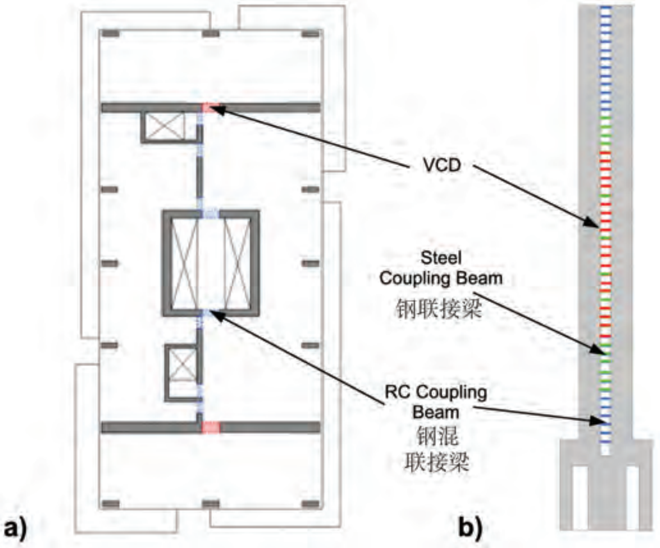

Figure 4. VCD Locations
图片4: VCD的位置(来源: RJC和Kinetica)

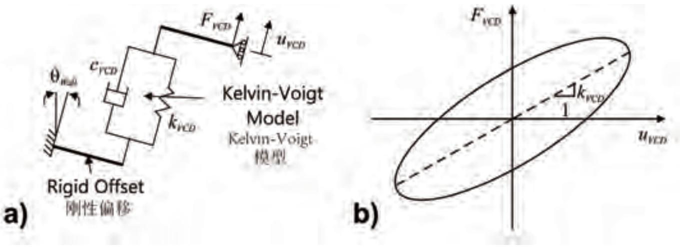

Figure 5. VCD modeling in shear: a) Kelvin-Voigt Model and b) VCD Hysteresis
图片5: VCD的切变模型: a) Kelvin-Voigt模型，b) VCD的迟滞现象 (来源: Kinetica)

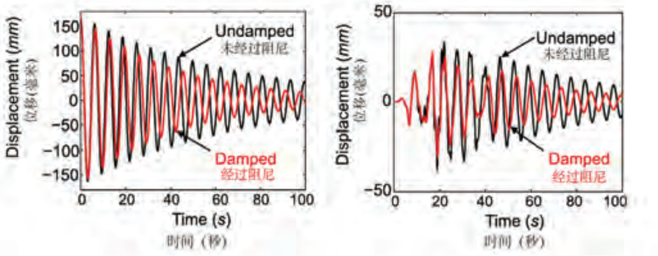

Figure 6. Building response with VCDs: a) free vibration of the building with and without VCDs and b) Scaled Northridge (1994) Earthquake with and without VCDs
图片6: 建筑物对于VCD的反应: a) 建筑物在有无VCD情况下的自由振动，b) 美国北岭地震 (1994) 中在有无VCD情况下的范围 (来源: Kinetica)

Based on the level of added damping provided, for frequent wind events (1 in 1 year and 1 in 10 year), it is expected that the lateral acceleration response will be reduced by 21%. Based on the same level of damping provided and on an assumed inherent damping of 2% of the bare RC structure for 1 in 50 year wind loads, it is expected that the dynamic portion of the wind loads will be reduced by 17%, however because this is only a portion of the overall wind loads the overall effect will be less pronounced for the drifts and loads. These results will be further confirmed based on wind load time-histories obtained using pressure data obtained from wind tunnel testing by RWDI.

As an example of the earthquake benefits, Figure 6(b) shows the top-story displacement response of the damped and undamped buildings, subject to the scaled Northridge (1994) earthquake matching the Toronto response spectrum. The inherent damping of the RC structure for this earthquake was assumed to be 2%, the results from this show a 19% decrease in displacements. For this level of earthquake response there is no expected nonlinear behavior in the structural elements.

Please note that as described earlier in the structural performance criteria that the performance improvements based on the added damping were not relied upon for the strength design..

Quality Assurance and Quality Control

RJC and Kinetica developed a QA/QC program and specification for the VCDs to closely follow the stringent protocols established for VE damper projects in Japan and Taiwan. Beyond typical manufacturing quality control, such as inspection, qualification and approved procedures, testing is an extremely important consideration to ensure that the properties of the dampers meet the intended performance. As such, an extensive testing protocol was established, which included both production and prototype testing. The prototype tests are full-scale VCD tests tested dynamically at the expected loading conditions of the building structure. Production tests include dynamic tests on VE material slabs and non-destructive tests on VE damper panels. In addition, a long-term testing program of the VE samples will continue beyond production to monitor the long-term VE material behavior.

优化设计

一个重要的设计考虑是实现附加VE阻尼板结构可构成的高效钢筋连接。对一些连接的细部进行了检查，包括: i) 完全现场浇筑的VCD连接细部，其中包括两个VE阻尼板和预埋钢板连接; ii) 模块化端板连接细部; 以及iii) 由本地钢铁制造商用两个VE阻尼器面板制造的钢工字钢模块的节点，在钢连接件的任一侧上用螺栓进行固定 (参照图3b) 。VE板安装的主要结构体系建成后，这个细节被评定为对性能、施工性、成本效益和模块化的最佳平衡。为了确保VE阻尼板的预埋钢板W-部分的正确安装，两个临时刚性槽钢组件在钢筋混凝土墙壁的铸造过程中被应用作为参考部件 (图3b)，随后将拆除以便安装模块化VE阻尼板。VE板将使用滑动钢连接被固定到钢W-部分。

据观察，VCDs的最有效的安置位置是沿强墙线布置并与走廊耦合 (图4中红色) 。在那些位置上，钢筋混凝土连梁 (图4中蓝色) 长1630mm，高700mm (包括钢坯) 宽600mm。标准型钢 (绿色) 取代正上方更硬的混凝土连梁的和标准以下的VCD模式来实现的刚度和阻尼的最佳平衡，并减少在所有的负载情况下当阻尼器被完全忽视时临近的耦合梁的外部压力。

性能评估

VCDs剪切力的滞后反映建模与开尔文 - 沃伊特元模型 (仅仅是一个平行弹簧和阻尼器) 位于VE材料中心线的刚性偏移位置上 (图5a) 。VCD的阻尼和刚度系数由连接钢构件的剪切作用获得 (葛西，2006年)，而开尔文 - 沃伊特模型代表了VE阻尼板 (Mahmoodi, 1969年, Soong and Dargush, 1997年, Christopoulos and Filiatrault, 2006年) 。VCD的剪切滞后反映 (参见图5b) 可以表示为:

$$F_{VCD}(t) = k_{VCD}u_{VCD}(t) + c_{VCD}\mathring{u}_{VCD}(t)$$

其中，$F_{VCD}(t)$ ，$u_{VCD}(t)$, $\mathring{u}_{VCD}(t)$ 分别是在t时刻的VCD力，位移和速度，k_{VCD} 和 c_{VCD} 分别是剪切的刚度和粘性阻尼系数。在VE材料性能的基础上，计算出VE材料温度和建筑物对风力载荷条件的反应频率。这种模式是通过简单商业软件如ETABS来实现。

增加的阻尼的等级是用三种技术 (Christopoulos和Montgomery 2013年)，其中包括经典的模态分析，自由振动分析和等效粘滞阻尼技术在ETABS评估确定的。图6a示出了大楼40层未使用VCDS的自由振动模式1。根据这个图，建筑总阻尼等级可以通过多个周期之间的位移振幅进行计算。无阻尼的实验结果展示了原有结构固有1.5%的假定阻尼效果，而具有阻尼结构的实验结果具有2.4%的总阻尼 (原结构的1.5%，再加上有针对性的0.9%的附加阻尼) 。

根据频繁的风力条件 (1年一遇和10年一遇) 的增加阻尼等级，预期的横向加速度反映将减少21%。在50年一遇的风荷载条件下，基于提供相同等级的阻尼和裸钢筋混凝土结构2%的假定固有阻尼，预期的风荷载的震动将减少17%。然而，因为只有风荷载的一部分侧移和负载效果并不显着。这些结果将进一步证实基于RWDI的风洞试验获得的压力数据而得到风荷载时间历程。

作为地震影响的例子，图片6展示了建筑物对于VCD的反应: a) 建筑物在有无VCD情况下的自由振动，b) 美国北岭地震 (1994) 中在有无VCD情况下的振动范围。钢筋混凝土结构应对地震的固有阻尼假定为2%时，结果表明位移减少19%。对于这一等级的地震反映，有一个非预期的非线性结构构件反映。

请注意，正如前文提到的结构性能标准，在该基础上增加地阻尼性能改进不依赖于强度设计。

A separate but equally important requirement for any damping project is to carefully establish the long-term performance of the VE material. Using data provided by the manufacturers, the usable life of the VE material has been assessed as longer than the design life of the building. Important elements to consider for dampers and polymers is the change in properties due to environmental aging and fatigue loading. The ISD111H VE material is a very stable polymer, however the material is expected to age slightly over time; accelerated aging tests have shown that the stiffness and damping are expected to increase modestly by about 10% in 80-130 years due to environmental aging. An independent assessment of the fatigue response of the VE material based on 3M fatigue tests and the predicted VE response based on the Toronto climatic data predicted a modest loss of stiffness and damping over the same period of time of less than 5%. Based on these tests and analyses and past long-term tests on VE material used in production for other projects conducted by 3M, it is expected that the VE material properties are to be extremely stable over the entire life of this building.

Full-Scale Performance Validation

Kinetica and RJC plan to monitor the performance of the tower that will include traditional system identification monitoring techniques for tall buildings using accelerometers as well as localized instrumentation to monitor the damper movement and the resulting VCD forces. Even though previous applications have shown there are no requirements for maintenance of monitoring of the dampers, a number of the units will be implement in accessible locations that will allow for regular inspection and possible testing over the life of the building.

Conclusions

This paper describes the procedure that was undertaken to design a slender reinforced concrete condominium tower in downtown Toronto with the Viscoelastic Coupling Damper (VCD) system. The paper describes the project, the requirement for added damping, the design approach and the design steps and procedure used to achieve the design goals and finally the performance assessment and performance verification program. Beyond the performance improvements that the building achieved for both wind and earthquake loading due to the added viscous damping, because the VCDs occupied no sellable space, the building developers are able to generate more revenue and profit relative to using other damping systems.

Acknowledgements

The authors would like to thank Dr. Bujar Morava from RWDI for assessment of the baseline damping required as well as providing the design team the wind loading time-histories to conduct their study.

质量保证和质量控制

RJC和Kinetica公司开发的QA / QC程序和VCDs规格十分切合日本和台湾为VE减振器项目严格制定的协议。除了典型的制造质量控制，如检验、鉴定和批准程序，测试是一个非常重要的考虑因素，以确保阻尼器的性能达到预期。因此，制定了广泛的测试协议，这既包括生产和原型测试。原型测试是在该建筑结构的预期载荷条件进行测试全面VCD测试。生产测试包括对VE板材和非破坏性试验的VE阻尼板振动测试。此外，长期的VE样品测试计划将继续长期贯穿生产和VE材料性能监察中。

对于任何阻尼项目而言，一个单独存在但是却同等重要的要求是认真检测VE材料的长期性能表现。通过对比来自制造商的数据，VE材料的使用寿命已经被证明要长于设计寿命。对于阻尼器和高分子材料而言需要注意的是，环境的老化和荷载作用所产生的疲劳会使得性能参数发生改变。ISD111H VE材料是一种非常稳定的高分子聚合物，这种材料在随着时间的推移只会有微弱的老化现象，在加速老化试验中被证明在80-130年的周期内材料的老化率只有10%左右，另外一个关于VE材料的测试试验是基于3M的耐久试验和多伦多的气象预测数据，在相同周期内的测试的结果为5%。这些测试实验和分析，当然还有3M之前在其他项目的生产中针对VE材料所进行的长期测试，都表明VE材料在建筑物的整个生命周期内的性能表现极其稳定。

全面的性能检验

Kinetica和RJC试图去检测高层塔楼的性能，包括使用传统的系统识别监控技术类似于感应器和定位装置的高层塔楼中减震器的位移，以及在VCD作用下的性能表现。尽管在之前的实际应用中并不需要对减震器进行维护和监测，但是，一系列的小部件将被实施使得在建筑物的整个生命周期内都可以进行定期检查和随机的测验。

结论

本文描述了一个位于多伦多市中心的采用弹性耦合阻尼器 (VCD) 系统的钢筋混泥土高层公寓塔楼项目。包括增加阻尼器，设计的方法和设计的过程以及最终的性能评价和性能检验过程。得益于新增加的弹性阻尼，建筑物在风力和地震荷载下的性能表现超出了预期，并且由于VCD不能被销售，使得建筑开发商们可以通过使用其他阻尼系统而产生更多的收益和利润。

致谢

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