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Novel Coupling Damper System for Enhanced Performance of Tall Buildings

加强高层建筑性能的新型粘弹性耦合阻尼器

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Dr. Constantin Christopoulos is a Professor and the Director of the Structural Testing Facilities in the Department of Civil Engineering at the University of Toronto. He is also the holder of a Canada Research Chair in Seismic Resilience of Infrastructure. He has written over 90 technical articles and co-authored a book on the "Principles of Supplemental Damping and Seismic Isolation". Dr. Christopoulos has been investigating the effects of wind and earthquakes on high-rise buildings for ten years and is a co-developer of the innovative Viscoelastic Coupling Damper for high-rise buildings.

Christopoulos博士，多伦多大学教授，土木工程系结构实验室主任，同时也是加拿大地震恢复基础建设研究主席。已撰写学术论文90余篇并合著了《Principles of Supplemental Damping and Seismic Isolation》一书。Christopoulos博士从事风力与地震对高层建筑影响的研究已十年有余，并且是新型高层建筑粘弹性耦合阻尼器的合作开发人。

Dr. Michael Montgomery is the co-inventor of the novel Viscoelastic Coupling Damper for high-rise buildings. Dr. Montgomery won the top prize for the 2011 Innovation Challenge Award, a Canadian national award recognizing inventions that have the potential of translating into real-world applications. Dr. Montgomery is a Principal and leading the engineering for the Viscoelastic Coupling Damper applications at Kinetica Dynamics. He has worked on the design of a number of high-profile tall buildings. His expertise is in mitigating wind-induced vibrations and increasing the seismic performance of tall buildings.

Montgomery博士，新型高层建筑粘弹性耦合阻尼器共同发明人。因其发明有能被运用于现实的极大潜力而获得加拿大国家级奖项—— 2011创新挑战奖的一等奖。Montgomery博士是Kinetica Dynamics公司董事，同时也主管弹性耦合阻尼器应用工程，曾参与了多个知名高层建筑的设计，是降低高层建筑风致振动、提高其抗震性能方面的专家。

Abstract

As high-rise buildings become taller and more slender, dynamic behavior becomes a critical design consideration. Wind loads cause large vibrations which can be perceived by building occupants, while severe earthquakes can cause building damage. Current damping systems can be used to reduce vibration perception, however they can't reliably be used to reduce wind or earthquake design loads. The Viscoelastic Coupling Damper (VCD) increases the level of damping of the structure such that dynamic effects are considerably reduced. Damping is provided by incorporating VCDs in lieu of coupling beams and therefore do not occupy any valuable architectural space. This paper provides an overview of the system, its development, its performance benefits and a tall building case study incorporating VCDs.

Keywords: Wind, Earthquakes, Vibrations, Concrete, Damper, Resilience

摘要

随着高层建筑的造型越来越纤细，其动态特性就成为一个重要的考虑因素。居住者能感受到由于风力造成的极大振动，而强烈的地震还可能导致建筑物的损坏。目前的阻尼系统虽然可以降低人们对振动的感知，但还不能可靠的运用于降低风与地震的设计荷载。粘弹性耦合阻尼器（VCD）增加了结构的固有阻尼水平因而相对减弱其动力效应。其中，阻尼是由整合的粘弹性耦合阻尼器提供而非一般的连梁。因此不会占用任何有价值的建筑空间。本文对其整个系统，开发及性能优势进行了概述并针对运用了粘弹性耦合阻尼器的高层建筑案例进行了分析。

关键词：风，地震，振动，混凝土，阻尼器，恢复力

Dynamic Response of High-Rise Buildings

High-rise buildings are extremely sensitive to both wind and earthquake vibrations. Frequent wind storms can cause lateral accelerations and torsional velocities which can be perceived by building occupants and cause discomfort. More rare wind storms and service level earthquakes cause significant vibrations resulting in large loads, for which structural members are designed to remain linear elastic. A primary cause of these dynamic vibration problems is the low levels of inherent damping in tall building structures. Furthermore, extreme earthquakes can cause significant damage throughout the building structure, to the extent that the building could be decommissioned if the repairs are too costly.

Inherent Damping in High-Rise Buildings

Only recently has there been a sharp increase in the number of published studies on the level of inherent damping measurement in real building structures. The studies have shown that the level of inherent damping measured is lower than current best-practice design assumptions and actually decreases with increasing building height,

高层建筑的动态响应

高层建筑对风与地震的振动是最为敏感的。通常的风能引起可感的且令人不适的横向加速度和扭转速度。而当遇到更罕见的风暴与设防烈度地震时，强烈的振动会导致巨大荷载，结构构件通常为此做了能保持线性弹性的设计。导致动态振动问题最主要的原因是高层建筑结构的固有阻尼较小。另外，如果遇到罕遇地震还有可能对整个建筑结构造成巨大的损坏以至因修复费用过高而被废弃。

高层建筑的固有阻尼

近段时间，有关在实际建筑结构中固有阻尼测量的研究发布数量急剧增多。这些研究显示，测出的固有阻尼级别要低于目前由实践得出的设计假定值，而且就如同总结的，随着建筑物高度的增加而减小(CTBUH, 2008 and Smith et al., 2010)。事实上，不管建筑是怎样的材料类型（钢筋混凝土，钢或组合结构），大多数250米以上建筑的阻尼是小于1%的。具体的低阻尼案例有最近在中国测出的一些钢筋混凝土和组合结构的高层建筑，这包括391米高的广州中信广场大厦，阻尼为0.6%(Li et al. 2010)；325米高的深圳帝王大厦，阻尼为0.5%(Li et al. 2002)；367米高的香港中银大厦，阻尼在0.1%

as summarized in (CTBUH, 2008 and Smith et al., 2010). In fact, the majority of buildings over 250 meters tall are reported to have less than 1% damping, regardless of building material type (reinforced concrete, steel, or composite construction). Some specific examples of very low damping measurements made recently in tall reinforced concrete and composite construction buildings in China are: 0.6% for the 391 m CITIC Plaza in Guangzhou (Li et al. 2010), 0.5% for the 325 m D-Wang Tower in Shenzen (Li et al. 2002), 0.1-0.5% for the 367 m tall Bank of China Tower in Hong Kong (Li et al. 2003), 0.3% for the 200 m tall Guang Dong International Building in Guangzhou (Li et al. 2004) and 0.6% for the 402 m tall Jin Mao Building in Shanghai (Li et al. 2007). Common design assumptions for the level of inherent damping in tall reinforced concrete buildings are 1.5% - 2.5% of critical, suggesting that values used for design are not conservative or appropriate. This could lead to larger dynamic effects (lateral accelerations, torsional velocities, lateral forces and drifts) than predicted in the design.

Current Methods to Reduce Wind Vibrations

The techniques currently used in the industry to address this problem are limited; the most common are stiffening the building or incorporating a vibration absorber (common examples are Tuned Mass Dampers or Tuned Sloshing Dampers) at the top of the building. Stiffening is accomplished by increasing the size of structural elements over the height of the building, revising the structural layout of the building or adding additional structural members, such as outriggers. This inevitably increases the cost of construction materials as well as the construction time, and reduces the available leasable space. When stiffening of a building is insufficient to mitigate the vibration problems, a vibration absorber is typically installed. Vibration absorbers are complex to design, must be maintained over the life of the building, and more importantly, they typically occupy the entire top floor of the building. Moreover, because of their tight tuning range, vibration absorbers are typically only used to reduce Service Limit wind vibrations, and are not considered reliable for reducing wind or seismic design loads.

The structural engineering community has recognized the benefits of added viscous damping for tall reinforced concrete building structures and a few new systems whereby viscous dampers are attached vertically between gravity columns and outriggers connected to core walls have been suggested (Smith and Willford 2008).

The Effects of Damping on Dynamic Building Response

Distributed viscous damping is the most efficient way to reduce vibrations, and considering the extremely low inherent damping in tall building structures, solving vibration problems through stiffening alone is insufficient and ineffective. The dynamic response, u_d (accelerations, velocities dynamic displacements or loads) is reduced as a function of inherent damping, ξ as:

$$u_d = f\left(\frac{1}{\sqrt{\xi}}\right)$$

Figure 1 gives an analytical example of the significant response reduction due to viscous damping on the top story lateral acceleration of an 85 story building.

A More Robust And Resilient Way To Build High-Rise Buildings

Considering the challenges related to the design of tall buildings for wind and earthquake loading and the importance of these very large structures housing hundreds to thousands of people, a more robust, resilient and efficient damping system is required. The Viscoelastic Coupling Damper (US Patent US7987639 and Chinese

到0.5%之间 (Li et al. 2003)；200米高的广东国际大厦，阻尼为0.3%(Li et al. 2004)；402米高的上海金茂大厦，阻尼为0.6%(Li et al. 2007)。一般的钢筋混凝土高层的固有阻尼的设计假定临界值是在1.5%到2.5%之间。这也就是说上述设计中的数值是不够保守，或者说是不合适的。这有可能导致产生比预想更大的动力效应（横向加速度，扭转速度，侧向力和横向位移）。

目前降低风致振动的方法

目前在工业中用于处理这类问题的技术是很受限的。最普遍的就是对建筑进行加固和在建筑顶部加装减振器（常见的例子有调谐质量阻尼器或是调谐液体阻尼器）。建筑加固一般是通过增大结构构件截面尺寸，调整结构布局和添加如伸臂桁架等另外的结构构件来完成的。但这就不可避免地增加了建材的花费、延长了施工期，而且减少了有效的可租用空间。通常当建筑加固不能有效的减轻振动问题时，就会选择安装减振器。要设计减振器是相当复杂的，因为它需要终身维护。更重要的是，减振器通常会占用建筑物顶部的全部空间。另外，由于它的谐调范围较小，减振器一般只被用来降低普通风振，而非考虑用它来降低风或地震的设计荷载。

结构工程界已经认可了在钢筋混凝土结构的高层建筑上增加粘滞阻尼及其特有的优势，同时还提出了一些将粘滞阻尼器垂直置于重力柱与连在核心筒上的伸臂桁架间的新系统 (Smith and Willford 2008)。

阻尼对建筑动力响应的影响

分布式粘滞阻尼是能最有效降低振动的方法。从之前所述的高层建筑中极低的固有阻尼可以看出，只用加固建筑的方式来解决振动问题是不够的，而且效率也低。动力响应，u_d（加速度，速动位移或负载）是固有阻尼 ξ 的函数。公式如下：

$$u_d = f\left(\frac{1}{\sqrt{\xi}}\right)$$

图1为由于在85层高的建筑物顶部设置了横向加速度的粘滞阻尼，而导致的响应大幅减小的分析案例。

一种鲁棒性和恢复性更好的高层建筑修建方式

面对高层建筑设计中有关风与地震荷载提出的挑战，同时考虑到那些有着成百上千居住者的超大型结构的重要性，因此这就需要一种鲁棒性和恢复性更好且更有效率的阻尼系统。粘弹性耦合阻尼器（美国专利号US7987639和中国专利号200680040409.X）是由多伦多大学研发，专门用来解决高层建筑中所面临的这些设计挑战的。

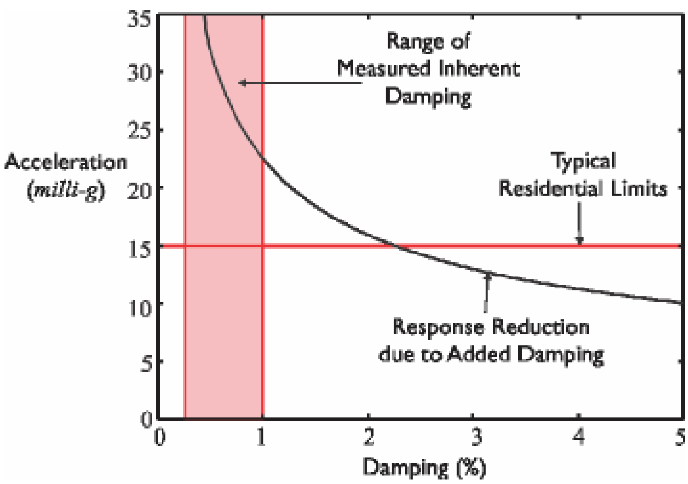

Figure 1. Effects of Damping on Lateral Acceleration of an 85-Story Building
图1. 85层建筑中，阻尼对其横向加速度的影响

Patent 200680040409.X) was developed at the University of Toronto specifically to address these design challenges in high-rise buildings.

Viscoelastic Coupling Damper (VCD)

In coupled wall high-rise buildings (Figure 2a) the primary lateral load resistance is often provided by large reinforced concrete (RC) walls connected together with RC coupling beams (Figure 2e). The coupling beams increase the stiffness of the lateral load resisting system. When a traditional coupled wall building (Figure 2c) deflects due to the applied lateral wind or earthquake loads, the large walls bend about their neutral axis and cause the coupling beams to rotate and displace vertically causing large shear deformations (Figure 2f).

VCDs are introduced in lieu of RC coupling lintel beams between the walls to take advantage of these large shear deformations (Figures 2e and 2f). The VCDs utilize multiple layers of viscoelastic (VE) material sandwiched between and bonded to multiple steel plates. The VE material alternates between layers of steel plates with each consecutive steel layer extending out to the opposite side and then anchored into the wall using a number of different connections (Figure 2b). When the building deforms due to translational or torsional vibrations (Figure 2d) the walls rotate causing the viscoelastic material to be deformed in shear (Figures 2f and 2g). This shear deformation causes an instantaneous velocity-dependent force which provides supplemental viscous damping to the system, and an instantaneous displacement-dependent elastic restoring force that ensures a coupling effect between the inter-connected elements. VCDs offer advantages over viscous damped outriggers (Smith and Willford 2008) which do not provide distributed damping, may not add damping at low displacements because of viscous damper compliance issues and do not require construction of invasive outrigger systems to couple the core to exterior columns. The VCD system can be adapted to the most common structural configurations such as coupling beams, core walls and outriggers, amongst others.

Seismic Performance Enhancement

In locations with large seismic demands, a ductile force limiting "fuse" mechanism is introduced in series with the VE material and steel layers such that in the event of an extreme earthquake event, the "fuses" activate and limit the forces transferred to the concrete walls and prevent tearing of the VE material. Through this detail it is possible to achieve substantial shear deformations as a combination of VE material deformations and "fuse" element nonlinear deformations. This could be achieved by using a number of details including Reduced Beam Sections (RBS), a shear critical section, a slip critical friction "fuse" or force limiting anchorages, amongst others.

VCDs Design Strategy and Intended Wind and Earthquake Performance

The VCD has two distinct hysteretic response characteristics (Figure 3c): i) viscoelastic response (Figure 3a), which is intended for all wind and low level earthquake loads, where connecting elements behave elastically and the response is primarily in the VE layers and ii) viscoelastic-plastic response (Figure 3b), which is intended for extreme earthquake loads, where the "fuse" elements activate and the majority of deformation occurs in the "fuses", thereby protecting the VE material from tearing and the other elements in the structure from overloading. After the extreme earthquake, the dampers can easily be inspected and if deemed necessary, could be repaired or easily replaced.

粘弹性耦合阻尼器（VCD）

在有联肢墙的高层建筑（请见图2a）中，最主要的侧向荷载抵抗力通常是由大量的带有钢筋混凝土(RC)连梁的混凝土墙体提供的（请见图2e）。连梁增加了抗侧体系的刚度。当传统联肢墙建筑（请见图2c）由于所受横向的风与地震荷载而产生挠曲时，大的墙体会围绕中性轴弯曲使连梁旋转并且产生竖直位移而导致巨大的剪切变形（请见图2f）。

在这里用VCD取代了墙之间的钢筋混凝土连梁，并对这些大的剪切变形加以利用（请见图2e和图2f）。VCD运用了多层被夹在钢板中间并固定在上面的粘弹性材料。中间粘弹性材料和外面的钢板会连续不断的交替向相反方向延伸并运用不同的连接方式固定在墙上（请见图2b）。当建筑由于平移或扭转的振动（请见图2d）而变形时，墙体会跟着旋转而导致粘弹性材料由于受剪切而变形（请见图2f和2g）。这样的剪切变形会造成与瞬时速度相关的力，用来为系统提供补充的粘滞阻尼。同时，产生的与瞬时位移相关的弹性恢复力还可以保证互联元件间的耦合效应。VCD在粘性阻尼伸臂桁架(Smith and Willford 2008)上的优势使它不会提供分散的阻尼，一般也不会因粘滞阻尼器的变形协调问题而在位移较小时增加阻尼，也不要求安装伸臂桁架系统去协调外柱与核心筒之间的变形。VCD系统可以运用于大多数普通的结构构型，比如连梁，核心筒，伸臂桁架等。

提高抗震性能

在对抗震要求较高的地区，引入了延性力限制的“保险丝”装置与粘弹性材料和钢板相串联。当遇到极强的地震时，“保险丝”就能被激活从而限制传递到混凝土墙体上的力同时防止粘弹

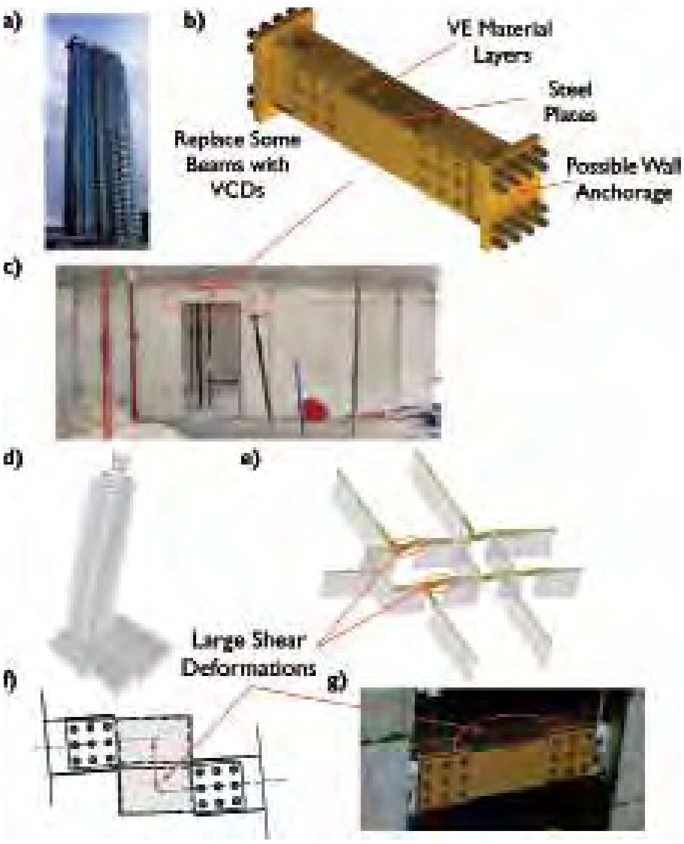

Figure 2. Viscoelastic Coupling Damper Concept: a) 50-Story Reinforced Concrete Tower in Toronto (Source: Natthapong Areemit), b) VCDs, c) Typical Reinforced Concrete Coupled Wall (Source: Michael Montgomery), d) Exaggerated Deformed Shape of Building Model, e) Story View Deformed Shape, f) Exaggerated Deformed Shape of VCDs g) Deformed Shape of VCD in Experiment (Source: Michael Montgomery)

图2. 粘弹性耦合阻尼器概念：a) 多伦多50层高钢筋混凝土楼塔（资料来源：Natthapong Areemit），b）粘弹性耦合阻尼（VCDs），c）典型的钢筋混凝土联肢墙（资料来源：Michael Montgomery），d)夸张变形后的建筑模型，e）Story View中的变形形态，f）VCDs放大的变形形态，g）试验中VCD的变形形态（资料来源：Michael Montgomery）

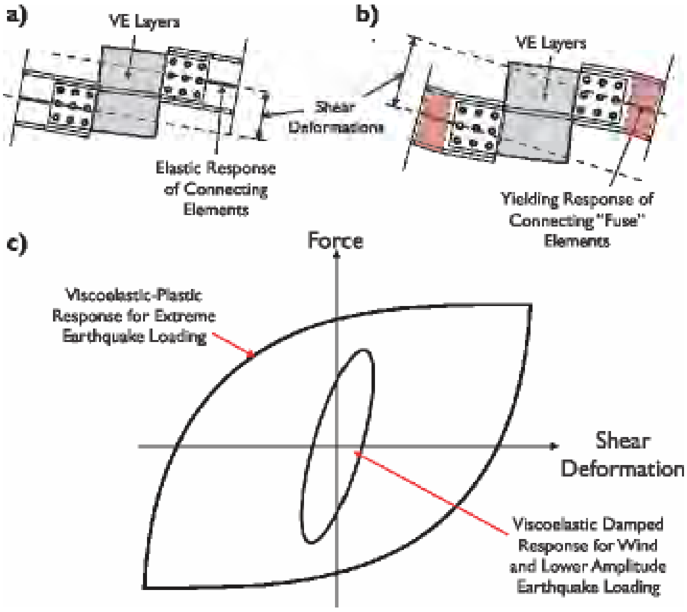

Figure 3. VCD Design Strategy: a) Viscoelastic Deformed Shape, b) Viscoelastic-Plastic Deformed Shape and c) Design Hysteresis Envelopes
图3. VCD设计思路：a) 粘弹性变形形态，b）粘弹塑性变形形态，c）设计磁滞外壳

Viscoelastic Coupling Damper Validation

Modeling Techniques

VCDs can be easily modeled using the commonly applied VE Kelvin-Voigt model in shear (which is simply a spring and dashpot in series) located at a rigid offset from the wall at the centerline of the VE material (Figure 4a). Damping and stiffness coefficients of the VCD are obtained by combining the shear stiffness of the connecting steel elements (Kasai, 2006) and a Kelvin-Voight model of the VE material layers in shear (Mahmoodi, 1969, Soong and Dargush, 1997, Christopoulos and Filatrault, 2006). The hysteretic response of VCDs in shear (see Figure 4b) can be expressed as:

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

where $F_{VCD}(t)$, $u_{vcd}(t)$ and $\dot{u}_{vcd}(t)$ are the VCD shear force, displacement and velocity, respectively, at time t and K_{vcd} and C_{vcd} are the VCD elastic stiffness and viscous damping coefficients, respectively, for a given frequency and strain level. Note that this model can be easily implemented in commercial software such as ETABS.

Experimental Test Setup

Both the VE material and two full-scale VCD designs have been thoroughly tested and numerically validated for a wide range of potential high-rise building loading scenarios. Six full-scale VCDs, fabricated by Nippon Steel Engineering Co., were tested in the Structures Laboratory at the Ecole Polytechnique in Montreal. Two separate designs were considered. The first was designed for an 85-story building in Toronto (VCD-A in Figure 2b) and the second was designed for a 50-story building in Vancouver (VCD-B). A photograph of the full-scale setup with VCD-B is shown in Figure 5a. In the actual buildings two dampers are intended to be placed side by side at each coupling location. The full-scale setup consisted of two sets of multiple RC precast walls post-tensioned together using Dywidag threadbars, allowing for replacement of the damper specimen for multiple tests. The walls were connected to the laboratory strong floor at the base through precision machined pins and were also connected to two-1000 kN actuators roughly 4 meters above the pins. Two stiff axial members connect the two walls together at the actuator height. The

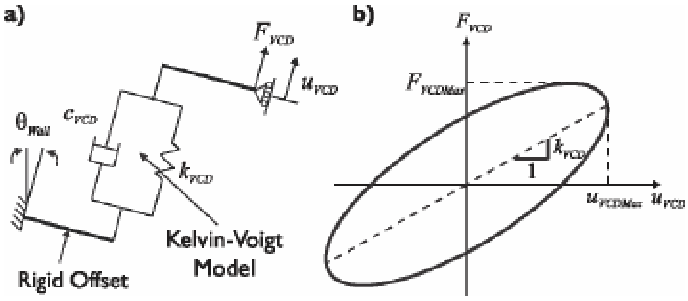

Figure 4. Coupling Damper Modeling in Shear: a) Coupling Damper Model and b) Coupling Damper Hysteresis
图4. 在剪力下耦合阻尼器的模拟：a）耦合阻尼器模型和b）耦合阻尼器磁滞

性材料的断裂。通过这种细部构造，使可持续的、粘弹性材料形变与“保险丝”部分非线性形变相结合的剪力形变的实现成为可能。这种可能也需要通过许多细部构造来实现，这包括翼缘削弱（RBS），剪力临界截面，“保险丝”滑动临界摩擦和用力学限制的锚固等。

VCDs设计思路和预期的抗风及抗震性能

VCD有两种独特的滞回响应特征（请见图3c）：1）粘弹性响应（请见图3a），专门针对全是风和低地震荷载的情况。在此情况下，连接的部件保持弹性而且响应主要发生在粘弹性材料层。2）粘弹塑性响应（请见图3b），专门针对有极大地震荷载的情况。此情况下，“保险丝”会被激活因此大多数的形变会发生在“保险丝”中，从而保护了粘弹性材料，使其不会因形变而断裂。同时，也防止结构中其他的构件因超载而受到损坏。在极强烈的地震后，阻尼器易于检查而且如果需要的话，也易于修理和替换。

粘弹性耦合阻尼器的验证

建模技术

VCDs是比较容易被模拟的。一般是在与墙体在粘弹性材料的中心线有一个刚性偏移的位置（请见图4a）运用受剪的开尔文-伏尔特粘弹性模型（由弹簧和减振器简单串联而成）来完成的。VCD的阻尼和刚度系数是由连接的钢材单元(Kasai, 2006)以及受剪的粘弹性材料层的开尔文-伏尔特模型的剪切刚度共同获得(Mahmoodi, 1969, Soong and Dargush, 1997, Christopoulos and Filatrault, 2006)。VCD的滞回响应可表示为：

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

其中，$F_{VCD}(t)$, $u_{vcd}(t)$ 和 $\dot{u}_{vcd}(t)$ 分别是VCD在t时刻的剪力，位移和速度。在给定的频率和应变水平下，t, K_{vcd} 和 C_{vcd} 分别是VCD的弹性刚度和粘滞阻尼系数。注意此模型也易应用于类似ETABS的商业软件。

试验装置

在粘弹性材料和两个足尺的VCD设计都进行了充分测试后，对于各种高层建筑可能遇到的荷载情况，在数值上得到了验证。对由新日铁工程技术株式会社制造的六个足尺VCDs在蒙特利尔工程学院的结构实验室进行了测试。考虑了两个设计方案。第一个是为位于多伦多的85层建筑而设计的(VCD-A 请见图2b)，第二个是为一座位于温哥华的50层建筑而设计的。图5a显示了VCD-B的足尺试验的照片。在实际建筑物中，两个阻尼应并排放在耦合的位置。足尺试验是通过两组结合迪维达克后张体系的多个钢筋混凝土预制墙组成的，这就允许了阻尼器试件可在多次测试中被替换。墙体与地板底部用精确加工的钢钉连接，同时也与两个位于钢钉上方大约四米的1000 kN的作动器相连。两个刚性轴心构件在作动器的高度位置把两面墙体连到一起。作动器的载荷会导致墙体的旋转，这包括墙体推压运动和粘弹性材料的剪切形变

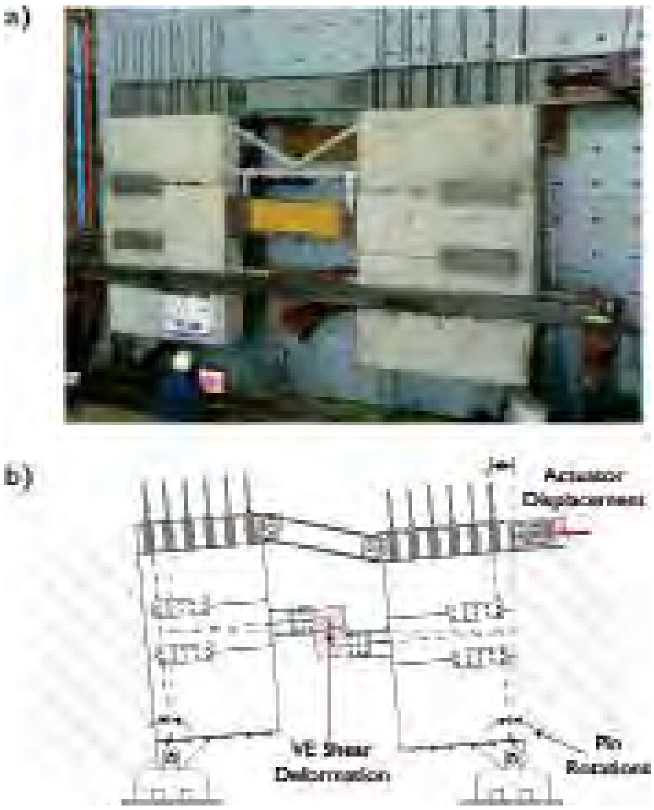

Figure 5. Full-Scale VCD Tests: a) Full-Scale Test Setup (Source: Michael Montgomery), b) Exaggerated Deformed Shape
图5. 尺尺VCD试验：a）尺尺试验装置（资料来源：Michael Montgomery），b）放大的变形形态

actuator loading causes the walls to rotate inducing a racking motion of the walls and shear deformations in the VE material (Figure 5b). VCD-B consisted of 15 layers of ISD-111H VE material 380 mm (W) x 520 mm (D) x 6.5 mm (t) as well as ductile "fuses" made up of Reduced Beam Sections (RBS).

Sample Test Results

Figures 6a and 6b show harmonic sinusoidal test results of the VCD cycled at frequencies of 0.1 Hz and 0.2 Hz as well as the VCD analytical model described by Equation 2. As seen from the harmonic tests the Kelvin-Voigt model captures the hysteretic behavior accurately for this given frequency and strain. Ultimate Limit State wind time-histories obtained from analytical models were applied to the test setup (Figure 6c). The results showed stable behavior over the full one hour duration of the test. Lastly, results from a simulated maximum credible level earthquake (analytical results obtained from a scaled Northridge earthquake) were applied to the test setup (Figure 6d). During this maximum credible earthquake time-history the "fuses" began to yield. In subsequent tests the dampers were cycled dynamically and statically to failure, reaching a maximum shear load of roughly 1,300 kN for all specimens with considerable ductility. The "fuse" mechanisms in the VCDs were activated, capping off the shear forces and protecting the walls as intended.

Case Study for Critical Structure

Slender 51-Storey Building in Downtown Toronto

A very slender 51-Story reinforced concrete mixed use condominium and hotel in downtown Toronto, was redesigned using the VCD system (Figure 7a). Lateral accelerations in the short direction and torsional velocities at the perimeter of the building were the critical

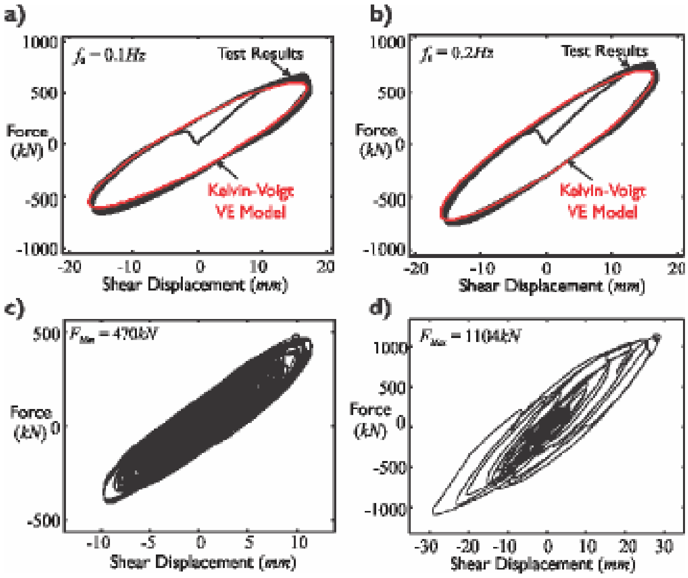

Figure 6. Full-Scale VCD Test Results: a) Harmonic Test Results at frequency of f_o = 0.1 Hz, b) Harmonic Test Results at frequency of f_o = 0.2 Hz,c) Ultimate Limit State Wind Storm Time-Histories and d) Maximum Credible Earthquake Time-History
图6. 尺尺VCD试验结果：a）在频率 f_o= 0.1 Hz时的谐波测试结果，b）在频率f_o= 0.2 Hz时谐波测试结果，c）承载极限状态的风力时程，d）最大可信地震时程

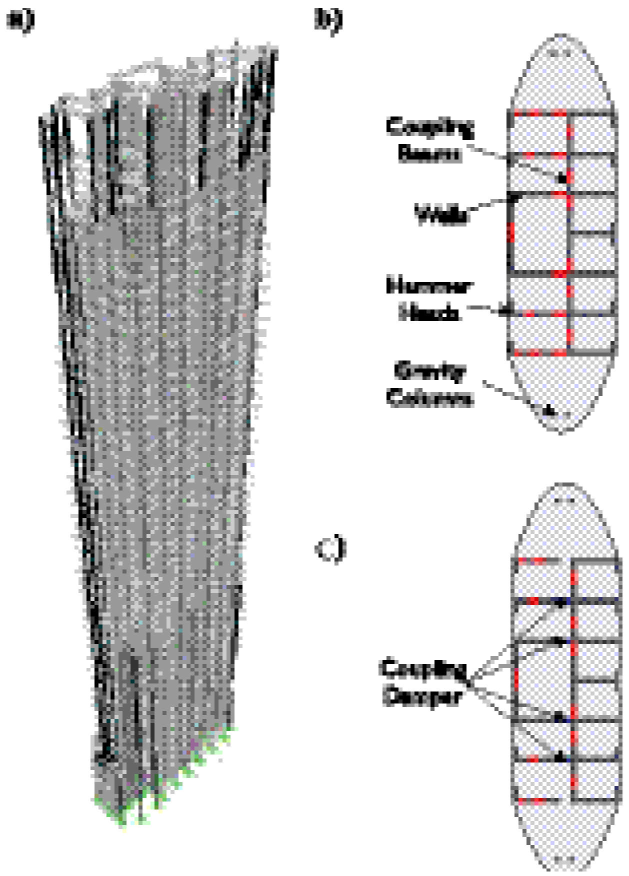

Figure 7. Slender 51-Story Reinforced Concrete Building: a) ETABS Model of Building, b) Typical Floor Plate and c) Typical Floor Plate Redesigned with VCDs
图7. 纤细的51层高钢筋混凝土建筑：a）建筑的ETABS 模型，b)一般典型的楼面板，c）重新设计的带有VCDs的楼面板

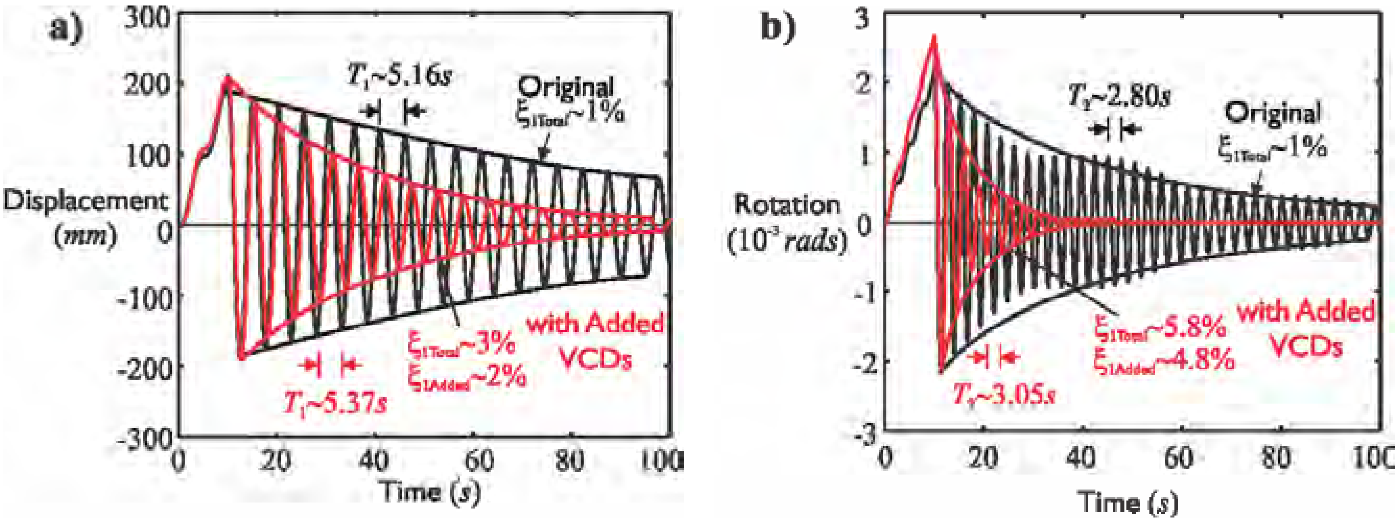

Figure 8. Free Vibration of Story 37: a) Short Direction Translational Response, b) Torsional Response
图8. 37层高建筑的自由振动：a）短方向上的平移响应，b）扭转响应

considerations that governed the design of the lateral load resisting system. The design consisted of a stiff lateral load resisting system and four tuned liquid coupling dampers about 1.5 stories tall at the penthouse level. These vibration absorbers required a maintenance plan and monitoring program over the life of the building to ensure the level of water in the tanks is properly tuned to the fluctuating dynamic properties of the building. The structural layout for a typical floor plate is shown in Figure 7b. The wall thickness changed from 600 mm to 400 mm and the concrete strength changed from 50 MPa to 30 MPa over the height of the building and the coupling beams were 900 mm deep above the 16th story and 1,400 mm deep below the 16th story.

The VCDs were designed to add at minimum 2% damping in the lateral short direction and in the torsional modes of vibration while fitting within the space occupied by the coupling beams. The level of inherent damping was assumed to be 1%. The VCDs consisted of 26 layers of ISD-111H VE material 625 mm (W) x 800 mm (D) x 6.5 mm (t). The damper design consisted of installing 128 dampers in total, 4 dampers per story, from stories 6 through 37 (see Figure 7c).

The viscous damping ratios are calculated using a classical modal analysis and a free vibration analysis. Free vibration results for both sway and torsion directions, of the 37th story of the building with VCDs are shown in Figure 8. For lateral side sway the VCDs added 2% damping while only increasing the period of vibration by 3% (Figure 8a) and for torsion the VCDs added 4.8% damping in torsion while only increasing the period of vibration by 13%.

With the distributed damping provided by the VCD system, not only could the 4 TLCDs be removed at the penthouse level, but there was also the possibility of significantly increasing the efficiency of the structural design by reducing the number of walls or beams up the height of the structure. These design improvements represent a significant benefit for the building owner as it was estimated that it would have resulted in a net savings of 11 Million Dollars (USD) including the cost of the dampers.

Conclusion

A new innovative, damping system for high-rise buildings, the Viscoelastic Coupling Damping (VCD) system, has been proposed. The new VCD system has the possibility of advancing the way high-rise

（请见图5b）。VCD-B是由15层380 mm（宽）x 520 mm（高）x 6.5 mm（厚）的ISD-111H粘弹性材料和使用翼缘削弱的延性“保险丝”组成的。

试验结果

图6a和6b显示了频率在0.1 Hz 和 0.2 Hz 之间循环时，VCD正弦谐波的测试结果和公式2所描述的VCD分析模型。从谐波测试中我们能看到，开尔文-伏尔特模型在给定的频率与应变下，能精确的捕捉到其滞回性能。然后将分析模型中获得的承载极限状态的风力时程数据应用于加载装置中（请见图6c）。结果显示出在一小时的测试时间段里其性能还是相当稳定的。最后将模拟的最大可信地震（分析结果由等比缩放的北岭地震而得）得到的结果应用于加载装置中（请见图6d）。在最大可信地震时程中，“保险丝”开始起到作用。在随后的测试中，让阻尼在动态与静态中反复循环到失效为止，所有的试件都具有相当大的延性，最大剪力荷载约为1,300 kN，“保险丝”装置被激活并很好地控制了剪力的大小，从而保护了墙体免遭破坏。

风荷载起控制作用的案例分析

多伦多市中心的51层的纤细建筑

一座坐落于多伦多市中心外形非常纤细的51层高钢筋混凝土综合式公寓酒店运用VCD系统进行了重新设计（请见图7a）。在短方向上的横向加速度与建筑物周界的扭转速度是设计中最重要的两个考虑因素，因为这主导了抗侧系统的设计。设计是由一个刚性的抗侧系统和四个位于公寓顶楼约1.5层楼高的调谐液体耦合阻尼器所组成的。这些减振器在建筑使用期间需要有健全的技术维修计划和监控方案来保证贮水池水位根据建筑波动的动态特性做了适当相应的调整。图7b是典型的楼面结构布局。其中墙体厚在600 mm到 400 mm之间，混凝土强度在50 MPa到30 MPa之间，16层以上连梁高度为900 mm，16层以下为1400 mm。

VCD设计在横向短方向和振动扭转模式上增加至少2%阻尼的同时，还能置于已被连梁占用的有限的空间中。其固有阻尼假定值为1%。VCD由26层625 mm（宽）x 800 mm（高）x 6.5 mm（厚）的ISD-111H粘弹性材所组成。阻尼器设计共安装128个，其中从6到37层，每层4个（请见图7c）。

粘滞阻尼比率是通过一个经典的模态分析和一个自由振动分析计算得到的。图8显示的是安装了VCD的37层高建筑在侧移方向和扭转方向的自振结果。对于侧向位移，VCDs 在阻尼提高了2%的同时，振动周期只增加了3%（请见图8a）。而对于扭转，VCDs在阻尼提高了4.8%的同时，振动周期也只增加了13%。

buildings are designed and constructed, increasing the habitability, resilience, safety and efficiency of these buildings. VCDs consist of layers of VE material sandwiched between layers of steel plates, which are then anchored using various types of connections to the lateral load resisting system. The modular VCDs can be introduced in a number of lateral load resisting system structural configurations where they undergo large shear deformations. Incorporating VCDs into the structural design can lead to a number of performance benefits including increased modal damping, increased factors of safety, decreased wind and earthquake loads, and decreased vibration perception.

VCDs can also lead to a number of overall design benefits including increased design efficiency, increased building height for a given structural layout, increased leasable space, increased speed of construction due to their modular nature, decreased structural materials, and decreased construction costs (concrete, steel and labor).

VCD系统提供的分散式阻尼，不仅能取消在公寓楼顶原有的4个谐调谐液体耦合阻尼器，而且还可能根据建筑高度适当减少墙体和梁的数量以使结构的设计效率得到显著的提高。这些设计上的提高与完善可为业主带来巨大的利益，据估算包括阻尼器花费在内的节省净额可达一千万美金。

总结

本文提出了一种全新的高层建筑阻尼系统——粘弹性耦合阻尼器（VCD）系统。新的VCD系统能提高现今高层建筑设计与建造的方式，并且为提高建筑可居住性、可恢复性、安全性及效益提供了可能。VCD由被夹在钢板层之间的多层粘弹性材料组成，再运用多种连接方式固定在抗侧系统上。模块式的VCDs可被用于许多需要承受巨大剪切形变的抗侧系统结构构型。在结构设计中对VCD的结合运用在性能上展现出许多优势。譬如，模态阻尼的提高、安全系数的提高、风与地震荷载的减小和振动感知的减小。

VCDs也在总体设计上也具有一定优势，这包括设计效益的提高，在给定结构布置下建筑高度的增加，可租空间的增大，因其模块化的特性而导致的施工速度提升，结构材料使用量的减少以及施工成本的降低（混凝土，钢材和劳动力）。

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