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Structural Optimization Solutions for Towers on Compact Sites

紧凑型基地的高层建筑结构优化解决方案

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Mark Hennessy is Structural Director in Australia for global engineering consultancy Meinhardt Group. He has more than 20 years Australian and international experience and specializes in post-tensioned and precast / modular designs. His experience in working in close collaboration with architects and builder/developers ensures he can accommodate the creative and commercial factors in delivering an optimal design solution. Mark has experience working on high-rise developments from the Middle East to Australia and is managing four tower projects currently in design or construction stage in Victoria.

Mark Hennessy是国际工程顾问公司迈进集团（Meinhardt Group）澳大利亚办事处的结构工程主管。他在澳大利亚及国际上拥有超过20年的工程经验，专门从事后张和预制/模块化设计。与澳大利亚的建筑师及建造商/开发商的密切合作，使他获得了丰富的工作经验，从而能够将创意与商业因素巧妙融合，打造最佳工程设计方案。从中东到澳大利亚，都有Mark参与设计的高层建筑，目前，他正在维多利亚管理四座高塔项目的设计和建设。

Doug Wallace is Senior Structural Engineer in Meinhardt Melbourne's Specialist Engineering Team. His experience over the last 14 years includes projects in a variety of locations including London, San Francisco and Hamburg. This has given Doug a wealth of knowledge to draw upon, particularly in a multi-disciplinary environment. Doug has a personal interest in architecture and enjoys pushing the structural design on each project to provide design solutions which are structurally efficient, economical and achieve the architectural vision. He is currently Lead Structural Engineer for 568 Collins Street Tower, Melbourne.

Doug Wallace是迈进集团墨尔本专业工程团队的高级结构工程师。过去14年他曾参与了包括伦敦、旧金山和汉堡等地众多工程项目的设计，这使他积累了丰富的工程经验与知识，尤其是在跨学科环境下，他更能够游刃有余。Doug对于建筑具有浓厚的兴趣，在享受工程结构设计过程的同时，能够提出经济有效的结构方案，使建筑达到应有的视觉效果。Doug目前负责墨尔本柯林斯街568公寓的结构工程。

Abstract

Over the past 20 to 30 years in particular, the advent of high-strength materials and the Australian/global trend to build taller and more geometrically-complex buildings on smaller footprints has necessitated a rapid development in the technologies for the design of these buildings. The objectives of this paper are to: highlight the latest design and technical advances and associated challenges in the optimization of slender towers; demonstrate trends in the design of slender towers on small sites using Case Studies to demonstrate the considered use of Tuned Liquid Dampers; and explain complexities in the optimization of the acceleration damping system in the interpretation of world's best practice wind acceleration guidelines.

Keywords: Structure, Engineering, Wind, Compact, Skyscraper, Damper

摘要

过去几十年，特别是近20至30年，随着高强度材料的问世，澳大利亚及全球范围内掀起了在小块土地上建造多座更高、几何形状更为复杂的高层建筑的潮流，这类建筑的设计技术也随之得以快速发展。 本文的目标在于强调： 优化细高塔楼设计的最新进展与技术进步，及其面临的各项挑战； 小块地皮上修建细高塔楼成为发展趋势，以案例研究来证明使用调谐液体阻尼器的有效性； 通过解读世界上拥有最佳实践的风振加速度控制指导方针，强调风振阻尼系统优化存在很多复杂问题。

关键词：结构、工程、风力、结构紧凑、摩天大楼、阻尼器

Introduction

Over the past 20 to 30 years in particular, the advent of high-strength materials and the Australian/global trend to build taller and more geometrically-complex buildings on smaller footprints has necessitated a rapid development in the technologies for the design of these buildings.

All optimal building solutions require compromise to find an efficient balance between the many competing factors such as floor efficiency (useable/lettable vs. gross area) and structural efficiency. This is challenging for tall buildings on small sites where the size of the core is constrained. Coupled with this is the need to deal with code requirements for wind, seismic and robustness that tend to become more stringent with time. To make these slender buildings stable and serviceable requires the development of innovative structural solutions.

With increased slenderness and optimization of the structural stability system, the need to meet occupant comfort requirements in terms of perceived movements (horizontal accelerations induced by wind loads) becomes a significant and often governing criterion. The wind accelerations are predicted from wind tunnel testing and then compared

引言

过去几十年，特别是近20至30年，随着高强度材料的问世，澳大利亚及全球范围内掀起了在小面积土地上建造多栋更高、几何形状更为复杂的高层建筑的潮流，这类建筑的设计技术也随之得到了快速发展。

所有优化建筑方案要求在实用率（可用/可出租面积与总面积之比）和结构效能等众多制约因素之间做出权衡，找到一个平衡点。由于核心区面积受限，小地皮高建筑所面临的挑战更为严峻。此外，高层建筑还需符合风振、地震及稳健性等规范要求，而这些要求随时间推移愈加严格。因此，为了确保窄长建筑的稳固和耐用，设计者必须提出更具创意的结构方案，以解决高层建筑所面临的常见复杂性问题。

随着建筑趋于细长化以及结构稳定系统的不断优化，在风振控制方面（风荷载引起的横向加速度）满足住户的舒适度要求逐渐成为建筑评估的一项重要标准。通常根据风洞试验预测出风振加速度，然后按照国际上最佳的实践规程（即ISO 10137:2007 /日本建筑学会规范（AIJ）2004、CTBUH 1993和澳大利亚标准AS1170.2 -1989），确定是否需要添加阻尼。

自1970年以来，全球多学科顾问公司——迈进集团始终走在高层建筑结构工程发展的最前沿。

with world's best practice guidelines (i.e. ISO 10137:2007 / AIJ Guidelines 2004, CTBUH 1993 and Australian Standard AS1170.2-1989) to determine the need for added damping.

Since the 1970s, global multi-disciplinary consultancy Meinhardt has found and retained a place at the forefront of the structural engineering associated with tall buildings.

Their specialist engineering team has been responsible for the design of many of Australia's tallest buildings, dating back to 80 Collins Street (Nauru House) in 1977 Today they are working on four towers that range in height from 55 levels to 70 levels (250m). When Meinhardt undertook the design of Rialto Towers in the early 1980s, it was the tallest building in the Southern Hemisphere and the second tallest concrete-framed office tower in the world. It is still the fourth tallest in Melbourne.

This expertise has also contributed to some of the tallest and most complex structures in the world, including Dubai Pearl (300m), Signature Towers Dubai (3 Interconnecting Towers, 358m, 292m & 230m), Ocean Heights Dubai (308m), Bayoke 2 Tower Bangkok (320m) and One Raffles Quay Singapore (245m) to name but a few. (see Table 1)

Changes & Trends

Peter Placzek, technical leader of Meinhardt's specialist engineering group in Melbourne, has seen a great deal of change in terms of design and analysis since his first experience designing buildings over twenty-stories in Jakarta in the early 1990s.

Peter says: "I remember using, by today's standards, very crude computer programs to predict column shortening. Now very sophisticated proprietary analysis packages such as SAP 2000 are used readily for the same purpose. There has also been a quantum leap in the user friendliness and comprehensiveness of these packages, such as Etabs, which are more generally available and used widely."

Currently, Meinhardt is the structural engineer for the following tall buildings in Melbourne:

- 55 level Zen Apartments (14th tallest) which has just recently completed construction (see Figure 1);
- 72 level (Prima) Pearl Tower, which will be the fourth tallest. (Construction on this tower commenced in 2011) (see Figure 2);

Figure 1. Zen Apartments, Melbourne, Australia (Source : PDG Corporation / Cox Architects)
图1. 澳大利亚墨尔本的Zen 私人公寓，（资料来源：PDG公司/ Cox Architects）

迈进的专业工程团队一直负责澳大利亚很多最高建筑的设计工作，以墨尔本来说，时间追溯至1977年，其杰作有柯林斯街80号（瑙鲁大厦），团队目前正在设计4座高塔，层高从55至70不等，最高达250米。20世纪80年代初，迈进设计的计丽爱图塔是当时南半球最高的建筑，世界第二高混凝土框架办公塔楼。

迈进还曾参与世界级最高、结构最复杂建筑物的设计，其中包括迪拜明珠（300 m）、迪拜舞蹈大厦（3个互连的塔，分别高358 m、292m及230m）、迪拜海天阁大厦（308m）、曼谷摩天大楼Bayoke 2（320m）以及新加坡莱佛士码头一号大厦等，此处略提一二（见表1）。

发展变化与趋势

Peter Placzek是迈进位于墨尔本的专业工程团队的技术负责人，他认为自20世纪90年代初他第一次设计雅加达二十多层的建筑以来，高层建筑的设计和分析都发生了很大变化。

Peter说：“按如今的标准，就预测柱短缩率而言，当时使用非常粗略的计算机程序，而现在使用的是非常精细的专用分析软件包，例如SAP 2000。这些软件包也经历了飞跃式发展，用户友好性及综合性全面提升，例如ETABS， 使用范围则更加广泛。”

目前，在墨尔本，迈进担任以下高层建筑的结构工程师：

- 55层高的Zen 私人公寓（高度排名第14位），近期刚刚竣工（见图1）；
- 72层高的（Prima）海港明珠塔高度排名第四（2011年起已开始施工）（见图2）；
- 69层高的柯林斯街568号建成后将是墨尔本第四高楼，于

Figure 2. (Prima) Pearl Tower, Melbourne, Australia (Source : PDG Corporation / Disegno Australia)
图2. 澳大利亚墨尔本（Prima）海港明珠塔（资料来源：PDG公司/ Disegno Australia）

Name (Address) 名称（地址）	80 Collins St (Nauru House) 柯林斯街80号（瑙鲁大厦）	Rialto Towers 丽爱图塔	Rockman's Regency 洛克曼 Regency	Verve 501 Verve 501号	Eureka 尤里卡大厦	Abode 318 Abode 318号	568 Collins St 柯林斯街568号	Prima 海港明珠	Bayoke 2, Thailand 曼谷摩天大楼 Bayoke 2，泰国	Emirates Hotel Tower, Dubai UAE Emirates酒店大厦	Dubai Pearl, Dubai UAE 迪拜明珠，阿联酋迪拜	Ocean Height, Dubai UAE 迪拜海天阁大厦，阿联酋迪拜
Year of Construction Completion 竣工年份	1977	1986	1997	2005	2006	2011	2011	2011	1995	2000	2011	2010
Primary Structural Engineers 主要结构工程团队	Meinhardt 迈进	Meinhardt 迈进	Meinhardt 迈进	Meinhardt 迈进	Others 其他	Meinhardt 迈进	Meinhardt 迈进	Meinhardt 迈进	ACS Consulting, Thailand 泰国ACS顾问有限公司	Hyder 安诚工程顾问有限公司	Meinhardt 迈进	Meinhardt 迈进
Meinhardt Secondary Role (where not primary) 迈进作为辅助团队（不是主要）					Façade 立面				Core/ Stability 核心筒/稳定性	Core/ Stablitiy 核心筒/稳定性	(To End of Design Development) 至设计深化尾声）	
Building Height H (Metres) 建筑高度H（米）	190	251	115	155	297	185	212	251	320	305	300	310
Building Minimum (Width) Dimension W (Metres) at Ground Level 建筑在地平面尺度（宽）W（米）最小值	40	35	21	19	42	21	24	27	50	50	28	42
Core Minimum (Width) Dimension C (Metres) at Ground Level 核心筒在地平面尺度（宽）W（米）最小值	15	12.5	5	8.4	21	7.8	6.2	9.2	13.5	13	7.5	13.5
Overall Building Slenderness Ratio H/W 建筑总体长细比高/宽	4.8	7.2	5.5	8.2	7	8.8	8.8	9.3	6.4	6.1	10.71	7.38
Core Slenderness Ratio H/C 核心筒长细比高/深	12.67	20.28	23	18.45	14.14	23.7	35.16	27.28	23.7	23.46	40	22.96
Structural Stability System 结构稳定系统	Core and Sway Frames (in Façade) (Tube in tube) 核心筒和斜撑构架（立面中） （筒中筒）	Core and Sway Frames (in Façade) (Tube in tube) 核心筒和斜撑构架（立面中） （筒中筒）	Core and Shear Walls Perimeter / Facade Walls 核心筒和剪力墙 周边/立面墙	Core and Shear Walls 核心筒和剪力墙	Core and Shear Walls and Outriggers 核心筒和剪力墙和伸臂桁架	Core and Shear Walls 核心筒和剪力墙	Core and Outriggers 核心筒和伸臂桁架	Core and Shear Walls 核心筒和剪力墙	Core and Shear Walls 核心筒和剪力墙	Core and Outriggers 核心筒和伸臂桁架	Core and Outiggers Coupled/ Portailsed Tower at Top 核心筒和伸臂桁架	Core and Shear Walls 核心筒和剪力墙
Wind Acceleration Damper 风加速度阻尼器	None 无	none 无	none 无	none 无	Tuned Liquid Damper (At Top of Tower) 调谐液体阻尼器（在塔顶）	none 无	Tuned Liquid Damper (At Top of Tower) 调谐液体阻尼器（在塔顶）	none 无	None 无	None 无	None 无	None 无

Table 1. Trends in Tall Buildings over the last 30 years. (Source: Meinhardt)
表1. 过去30年高层建筑发展趋势（出自：迈进）

- 69 level 568 Collins Street, which will be the fourth tallest in Melbourne that commenced construction early this year (see Figure 3);
- 55 level Abode 318 (that will be twelfth tallest in Melbourne) that is due to commence construction this year (see Figure 4).

These projects reveal a series of trends. Not only are buildings generally getting taller, they are also becoming more slender.

In terms of building height/minimum building dimension (H/W)

Rialto's H/W ratio is 7.2, Rockmans Regency's is 5.5 and Pearl Towers' is 9.3. Interestingly, all these buildings have the same height; however, the Pearl is far more slender than the others. Although the buildings are built for different purposes, this comparison adequately

今年年初已动工（见图3）；

- 55层高的Abode 318 （这将是墨尔本第十二高楼），亦计划于今年动工（见图4）。

迈进的项目展现了明显的趋势：建筑物不仅越建越高，而且变得更加修长。

从建筑高度/最小建筑尺寸（高/宽）来看

丽爱图塔的高/宽比例为7.2、Rockmans Regency为 5.5，海港明珠塔为9.3。非常有趣的是这几栋塔楼的顶层高度相同，但明珠塔要比其他修长的多。虽然这是办公楼的建造意图并不相同，但此对比也足够说明建筑的发展趋势。即使是将1997年Rockmans Regency 5.5和2011年568柯林斯9.1这两栋住宅楼进行对比，这一观点仍然成立。

Figure 3. 568 Collins Street, Melbourne, Australia (Source : Stamoulis Property Group / Bruce Henderson Architects)
图3. 澳大利亚墨尔本柯林斯街568号（资料来源： Stamoulis地产集团/ Bruce Henderson Architects）

demonstrates the trend. But even if a comparison of residential with residential was made, using Rockmans Regency's 5.5 in 1997 and 568 Collins' 9.1 in 2011, the point still stands.

In terms of building height/minimum core dimension (H/C)

Compare again Rialto Towers' 20.1 and Rockmans Regency's 23 to Pearl Towers' 27.3 and 568 Collins' 35.5.

With the advent of high-strength concrete and with Australian/global trends to build taller concrete-framed buildings on smaller footprints, the technologies for the design of these taller buildings has developed and improved.

Invariably, this trend for taller, more slender buildings with the implicit challenges of making these buildings stable and serviceable has necessitated the development of structural solutions that meet all of the governing relevant building codes with even stricter wind, earthquake and robustness requirements. These more complicated sites require very sophisticated and innovative structural solutions

Not only must engineers required address the generic tall building complexities such as transfer structures, column shortening and the addition of damping to reduce wind-induced accelerations, but they face additional complexities such as bridging and/or isolating (acoustic/vibration) 'obstructions' where buildings are located over railway tunnels – examples include One Raffles Quay in Singapore and John Maddison Tower (Downing Centre) in Sydney.

Case Studies

A number of key processes must be followed for the successful holistic delivery of 21st century. Tall building structural designs on small sites are demonstrated by 568 Collins Street (for Stamoulis Group), Prima (Pearl) and Abode (both for PDG Corporation / Schiavello).

The client brief in both cases was fundamentally the same. Develop a simple design that:

- optimizes the efficiency of the building from an initial capital cost/build cost point of view;
- minimizes ongoing running/operating costs;
- is quick and easy to build;

Figure 4. Abode318, Melbourne, Australia (Source : PDG Corporation / Disegno Australia)
图4. 澳大利亚墨尔本Abode 318（资料来源： PDG公司/ Disegno Australia）

从建筑高度/最小核心筒尺寸（高/深）来看

同样将丽爱图塔20.1与Rockmans Regency 23和（Prima）海港明珠塔27.3及568柯林斯35.5相对比。

随着高强度混凝土的问世，澳大利亚及全球范围内涌现在小地皮上建造更多、更高钢筋混凝土框架结构的建筑，这类建筑的设计技术也随之应运而生，并迅猛发展。

细长建筑的发展趋势无疑对建筑物稳固性和耐用性带来更大挑战，再加之国际上建筑相关规范对于抗风、抗地震及坚固性的要求越来越严格，迫使工程师必须提出符合各项要求的结构方案。楼盘所在地段的复杂性同样要求采用更为精细、更加新颖的建筑方法。

工程师不但需要应对高层建筑复杂性带来的常见问题，例如转换层结构、转换支柱短缩率以及添加阻尼降低风振加速度等，还面临着越来越多其他复杂性问题。举个例子，新加坡莱佛士码头一号大厦和悉尼约翰·麦迪森塔（John Maddison Tower）（唐宁中心）这两座建筑均建在铁路隧道之上，设计时还应考虑安置和/或隔离（声波或振动敏感问题）。

案例研究

下文以迈进正在墨尔本建设的三栋细高塔楼：柯林斯街568（客户为Stamoulis集团）与（Prima）海港明珠和Abode（后两者的客户分别为PDG公司/ Schiavello）为例，展示了21世纪要在小块地皮上成功建造高层建筑，整体结构设计过程中必须严格遵守的主要流程。

上述示例中两个客户的要求基本一致，简而言之，即实现以下设计功能：

- 从最初的资本成本/建造成本的角度来看，优化建筑物效率；
- 最大程度上降低运行/经营成本；
- 易于施工，工期短；

- is environmentally considerate;
- is iconic and meets the market expectations from a desirable residence identity point of view;
- is intelligent in terms of architectural design, working within the constraints of the site and planning restrictions (height and building envelope), as well as accommodating the structural and services requirements.

Although the structural design challenges were mostly similar, the solutions developed were significantly different. The various mix of uses and associated planning/ building services requirements had to be considered.

Building Stability Solution for Strength & Serviceability

Optimizing the building stability solution to meet strength and serviceability requirements is a challenge owing to the slenderness involved. A number of structural stability solutions were explored in the conceptual phase of each project, working collaboratively with the architect and other consultants to develop a holistic solution.

On Prima (Pearl) and Abode, a number of very stiff shear walls were incorporated as party-walls up through the majority of the building height to compliment the central concrete core.

On 568 Collins Street, it was not possible to incorporate enough shear walls, as there were not enough party-walls aligned up the building. The thickness required for shear walls also reduced the floor area too much. Consequently, various options linking the core to the perimeter columns by outriggers were explored at the conceptual design stage. The adopted solution links the core at two levels to four large outrigger columns, two on the east and west faces of the building. These columns are then further coupled to the boundary walls on the east and west sides within the podium (the bottom 11 levels) to provide more stiffness in the weak–axis direction.

Optimizing the building stability solution to meet occupant comfort requirements in terms of perceived movements (horizontal accelerations from high wind activity) is a significant consideration due to the residential use of each building. Predictions of accelerations were obtained from the wind consultant for each project and compared with world's best practice limits defined by ISO 10137:2007 / AIJ Guidelines 2004 and CTBUH 1993 as well as Australian Standards (AS1170.2-1989). For Prima (Pearl), the accelerations were predicted to be comfortably within these limits, based on a lower bound estimate of inherent damping of 0.8%. The acceleration predictions for both Abode and 568 Collins Street were predicted to exceed these guidelines.

Wind-induced accelerations - 568 Collins Street

For 568 Collins Street, the accelerations predicted by the wind consultant are shown in Table 2, expressed as a ratio of the predicted acceleration on the limit from each standard. The predictions were based on an assumed inherent structural damping of 1% (i.e. the predicted damping achieved by the building due to contributions from the structure, cladding and internal fit-out).

In an effort to avoid the need for added damping, options were explored to increase the stiffness of the building such as the introduction of additional shear walls and/or raising the height of the outrigger structure. All these options were rejected owing to the impact on architectural planning, as well as the fact that the increased

- 绿色环保；
- 标志性建筑，符合市场上对于理想住宅的期望；
- 智能化建筑设计，不受底盘小及规划的限制（高度和建筑围护结构），同时满足建筑的结构和设备需求。

建筑物结构设计面临的挑战大多相似，但由于需要考虑建筑的不同用途，以及相关的规划/建筑物设备要求，最终的方案可能大相径庭。

出于强度及耐用性的建筑加固方案

由于建筑物具有细、长的特点，要提高其稳定性，满足其强度和耐用性要求通常面临巨大的挑战。每个项目的初步设计阶段，设计人员都会与建筑师及其他工程顾问协同工作，通过探讨各种可行性结构加固方案，最终确定出最佳的整体解决方案。

在（Prima）海港明珠和Abode，采用大量非常坚实的剪力墙，贯穿建筑物高度的大部分区域并融入共用墙，以增强混凝土芯筒的刚度。

在柯林斯街568，由于沿建筑物排列的界墙尺寸不足，共用墙不能与剪力墙结合，因此无法使用剪力墙。而且剪力墙所要达到的厚度同样会过多损耗楼面面积。因此，在这栋大楼的初步设计阶段，设计人员研究了各种通过悬臂梁将核心筒与周围支柱连接起来的方法。最终采用的方案是将两个不同楼层的核心筒连接至四个较大的悬臂梁支柱，其中两个支柱位于建筑物的东面，其他两个位于西面。这四个支柱在墩座墙内（底部11层）进一步与东西两侧的界墙连接，以加强弱轴方向的刚度。

由于每栋建筑为民用住宅设计，优化建筑加固方案，从而在风振控制方面（大风引起的横向加速度）满足住户的舒适度要求通常是建筑设计一个重要的考虑因素。各项目的风振加速度由风荷载顾问估算得出，然后与ISO 10137:2007 /日本建筑学会规范（AIJ）2004和CTBUH 1993以及澳大利亚标准（AS1170.2-1989）所规定的国际最佳工程实践的限制条件进行对比。比较结果显示，基于固有阻尼的下限估值0.8%，（Prima）海港明珠的风振加速度预测值完全满足限制条件。而Abode和柯林斯街568的风振加速度预测值都超出了规范要求。

柯林斯街568的风振加速度

对于柯林斯街568，有关风顾问预测出的风振加速度，请见下表2，该值是根据各项标准的限制而表示为风振加速度预测值的比率，预测时假设固有结构阻尼比率为1%（即建筑结构、覆面及内部设备配置本身所具有的阻尼估值）。

为了尽量避免使用阻尼的需要，迈进设计人员研究了各种增强建筑物刚度的方法，例如采用更多剪力墙和/或增加悬臂梁结构的高度。但是由于这些结构对建筑规划可能造成的影响，以及即使刚度增强，也不能保证建筑物在（原位）测试中不会发生坍塌等原因，设计人员否决了这些方案，并一致认为，解决这一不足的最好方法是在建筑物内预留适当空间，以便所需之时安装调谐质量阻尼器。随后，设计人员还考虑了添加阻尼的其他方法，例如采用黏滞阻尼器（由Arup为菲律宾马尼拉圣弗朗西斯香格里拉项目开发使用），但由于该阻尼系统造价昂贵、结构复杂，设计人员最终还是排除了此方案。再后来，由于楼顶已设置了消防用的水箱，而且可以对该水箱的尺寸进行调整，以同时满足消防及阻尼的双重要求，因此设计人员开始研究采用调谐液体阻尼器。经过与风工程师及其他相关各方的磋商，为了能在最大程度上降低风振对可用建筑面积的影响、对机械设备间的影响，以及为了满足建筑围护结构规划限制条件，设计人员考虑将若干原始阻尼器水箱大小的水箱重叠放置的设计思路，此设想通过以下几个步骤最终落实：

Criteria 标准	Ratio of Predicted acceleration / Acceleration limit 预测风振加速度值与风振加速度限值的比率		
	East-west direction (core weak axis) 东西方向（芯筒弱轴方向）	North-south direction (core strong axis) 南北方向（芯筒强轴方向）	Combined (including torsion) 结合（包括扭矩）
Australian Standard Commentary AS1170.2-1989 Criteria for all building types (i.e. no separate criteria for residential) 澳大利亚标准述评AS1170.2 -1989 适用于所有建筑类型（即住宅没有单独的标准）	1.27	0.93	1.45
ISO 10137:2007 - Residential criteria ISO 10137:2007 - 住宅标准	1.52	1.11	1.73
AIJ Guideline 2004 - 90% of occupants can perceive movement 日本建筑学会规范（AIJ）2004 - 90%的住户能感受到风振	1.44	1.06	1.65
CTBUH (1993) - Residential criteria (1 year return period) CTBUH (1993) -住宅标准（重现期为一年）	2.10	1.54	2.40

Table 2. Comparison of predicted accelerations at the highest habitable level with various international criteria - 568 Collins Street
表2. 柯林斯街568最高可居住楼层的风振加速度预测值与各种国际标准限值之间的比较

stiffness does not guarantee that the building will fall within the limits when tested (in-situ). It was agreed that the more certain way to address the shortfall was to reserve space in the building for a tuned mass damper to be incorporated if required. Other options for adding damping were considered, such as damped outriggers (as developed by Arup on the St Francis Shangri-La Project in Manilla, Philippines), but these were discounted due to the cost and perceived complexity of this system. A tuned liquid damper was selected for further investigation due to the fact that a water tank was already present near the top of the building for fire suppression and this tank could be resized to suit both purposes. In consultation with the wind engineers and all other interested parties, several iterations of preliminary damper tank design were explored with the aim of minimizing the impact on useable floor area, the impact on plant room space and also to fit within the building envelope planning constraints. The iterations included the following options.

Initially, a three level U-shaped column liquid damper on levels 65 to 68 was considered. This was ultimately discontinued as the preferred option owing to uncertainty in the building performance in the orthogonal (stronger-axis) and given that this option only assisted in the weak-axis direction. (see Figure 5)

Two sets of stacked (two-high) rectangular (sloshing) liquid damper tanks were then considered, located approximately symmetrical about the core (on north and south) but located on different levels to minimize the impact on the building planning. This was ultimately discontinued as the preferred option owing to one of the tanks not being able to be made large enough and remain within the planning constraints. (see Figure 6)

One set of stacked four-high tanks located eccentric to the core was then considered. This was ultimately discontinued as the preferred option owing to concern over the effectiveness and adverse effects from the tank eccentricity. (see Figure 7)

The design of the likely final solution involving two sets of stacked (two-high) rectangular (sloshing) liquid damper tanks located symmetrically above the core is now being refined. (see Figure 8)

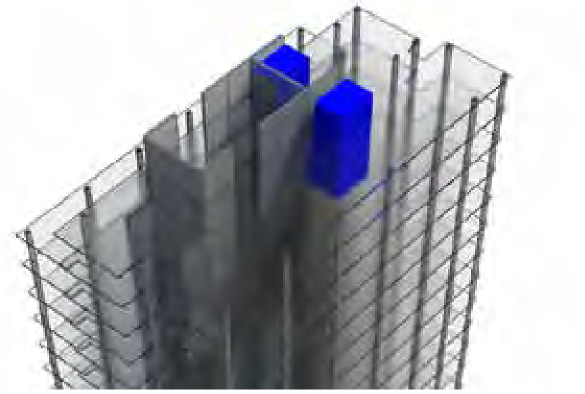

Figure 5. Damper Option A - 3 Level U-shaped column (Source: Meinhardt)
图5. 阻尼器A——三级U形液柱阻尼器（资料来源：迈进）

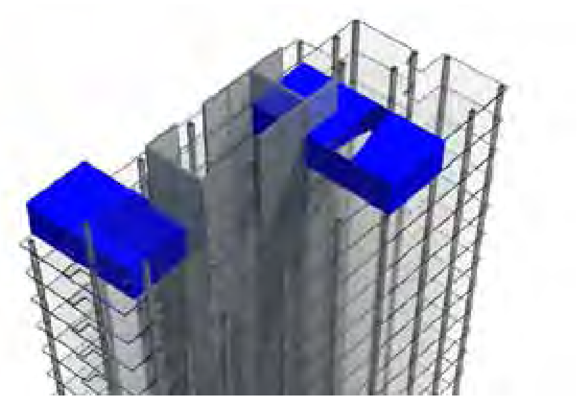

Figure 6. Damper Option B - Two sets of stacked (2 high) rectangular (Source: Meinhardt)
图6. 阻尼器B - 两组堆叠式（两个高大型）矩形液体阻尼器（资料来源：迈进）

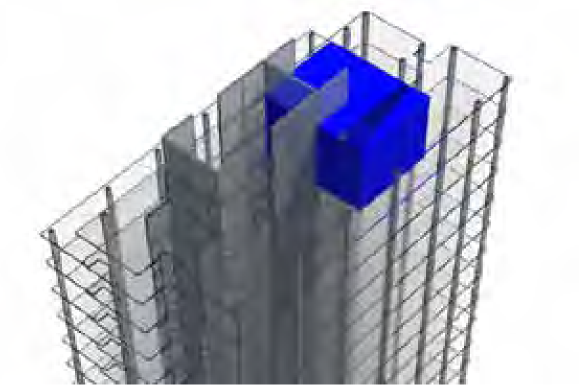

Figure 7. Damper Option C - One set of stacked 4 high tanks
图7. 阻尼器C - 一组四个堆叠式高大型水箱阻尼器 （资料来源：迈进）

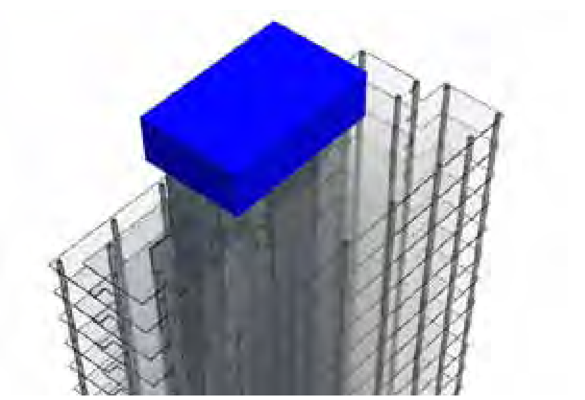

Figure 8. Damper Option D - Two sets of stacked (2 high) rectangular (alternative) (Source: Meinhardt)
图8. 阻尼器D—两组堆叠式（两个高大型）矩形液体阻尼器（替代方案）（资料来源：迈进）

Criteria 标准	Ratio of Predicted acceleration / ISO 10137:2007 residential limit 预测风振加速度值与ISO 10137:2007住宅限值的比率	
	Weak-axis direction 弱轴向	Strong-axis direction 强轴向
Lower bound stiffness (10% lower frequency), lower bound inherent damping (0.75%) 刚度下限（10%以下振动频率），固有阻尼下限（0.75%）	1.04	0.75
Expected stiffness, lower bound inherent damping (0.75%) 预期刚度，固有阻尼下限（0.75%）	1.02	0.71
Lower bound stiffness (10% lower frequency), expected inherent damping (1%) 刚度下限（10%以下振动频率），预期固有阻尼（1%）	0.96	0.67
Expected stiffness, expected inherent damping (1%) 预期刚度，预期固有阻尼（1%）	0.93	0.64

Table 3. Comparison of predicted accelerations at the highest habitable level with ISO 10137:2007 residential criteria – Abode
表3. Abode最高可居住楼层的风振加速度预测值与ISO 10137:2007住宅标准限值之间的比较

The fourth option impacts space planning in the plant rooms at the top of the building the least and is also the most efficient solution in terms of added damping, with the mass at the highest point of the building and close to the centre of stiffness. Preliminary design by the wind consultant indicates that approximately 2% damping will be added in the first two translational modes of vibration. This will be refined with further detailed design of the damper.

Wind-induced accelerations – Abode

A sensitivity analysis was performed by the wind consultant on this project to investigate the effect of variability in both the building frequencies of vibration and the level of inherent damping on the predicted accelerations. The predictions were then compared with the ISO 10137:2007 residential criteria to assess the need for added damping. The predictions are summarized in the table below, expressed as a ratio of the predicted acceleration divided by the ISO acceleration limit. The accelerations are a vectorial combination of the components due to the translational modes of vibration and the torsional mode.

These predictions show that the accelerations may be close to the limit and that added damping may be required. Space has been reserved at the top of the building for a U-shaped damper tank (i.e. a Tuned Liquid Column Damper), approximately 13m long by 2m wide by 5m high, which will provide the possible shortfall of 0.25% damping that will be required should the measured damping be at the lower bound end of the expected range. When construction of the building has reached approximately 80% (structure and cladding), testing will be performed to establish the inherent damping, at which time a decision will be made on whether or not the damper tank is required.

Optimization of the overall solution

For each of the case study buildings, optimization of the overall structural solution has been sought by precluding or minimizing the need for transfer beam structures which are very expensive, slow to build and also take up valuable height in the building. On (Prima) Pearl, the architectural planning constraints up the building were particularly

最初，在65至68层上考虑使用3级U形液柱阻尼器。但是由于不能确定正交（强轴）方向建筑的性能，而这种方法只能在弱轴方向有效，设计人员最终放弃使用液柱阻尼器（见图5）。

然后考虑使用两组堆叠式（两个较高）矩形（防晃）水箱液体阻尼器，对称布置于核心筒的南北面，但位于不同楼层，以尽量减少对建筑规划的影响。但是由于其中一个水箱无法做到足够大，而且受规划范围限制，因此设计人员最终也放弃使用该阻尼器（见图6）。

再考虑使用一组四个堆叠式高大型水箱阻尼器，置于核心筒的偏心位置。但是设计人员对其有效性产生顾虑，并考虑到箱体离心率的不良影响，因此最终也放弃了该阻尼器（见图7）。

在最终可能采用的设计方案中，两组堆叠式（两个较高）矩形（晃动）液体阻尼器对称布置于核心筒的正上方（见图8）。

第四种方案对建筑物顶层机械设备间的空间规划造成的影响最小，而且是添加阻尼的最有效的方案，可使质量位于建筑物的最高点，靠近刚度最强位置。风荷载顾问提出的初步设计表明，对于起初两种平移类型的风振，需添加2%的阻尼，这在阻尼器的详细设计阶段将进一步完善。

Abode的风振加速度

风荷载顾问对该项目的振动敏感性进行了分析，以研究不同建筑风振频率和不同大小固有阻尼对风振加速度预测值的影响。然后根据ISO 10137:2007住宅标准的要求，对预测的风振加速度值进行评估，从而确定是否有必要添加阻尼。预测值表示为风振加速度预测值除以ISO风振加速度限制的比率，具体见下表。其中风振加速度取平移振动类型与扭转类型振动的矢量之和。

上述预测值表明，该建筑的风振加速度接近标准限制值，有可能需要添加阻尼。因此建筑顶部已预留出空间，以便后期安装长约13m、宽2m、高5m的U型阻尼器水箱（即调谐液柱阻尼器），如果测量得出的阻尼值接近预期值范围的下限，则该阻尼器能够有效弥补0.25%的阻尼差额。当施工进展到80%时（完成结构和覆面层），工程师将对建筑进行测试，确定出建筑的固有阻尼，然后决定是否需要安装阻尼器水箱。

整体结构方案的优化

从上述案例研究中的各建筑可见，由于转换梁结构造价昂贵，建设速度慢，占用建筑内大量高度空间，因此建筑整体结构方案优化过程中排除了或尽量降低了对转换梁结构的需求。在（Prima）海港明珠，建筑规划限制条件对大楼的影响更加明显，选择结构方案更具挑战性，由于受限部位通常恰逢楼面用途发生变化之处（例如，大楼第10层需从公寓过渡到停车场）。因此，在四个分立的楼层不得不使用转换结构，10层的转换梁深1.8m，53、55和60层级转换带最深0.45m。

在柯林斯街568，通过与所有各相关方的协商，设计人员确定在整栋大楼的停车场旋转坡道正上方有三个主要塔柱需要转换，其次在楼面板角落有几个相对较小的倾斜塔柱需要在矮墩墙处转换。

结论

采用高强度混凝土在小地皮上建高层建筑的发展趋势使设计人员开始考虑影响建筑耐用性的各种因素，比如风振加速度，其目前已成为建筑设计的一个主要标准，而且有关控制风振加速度的标准也越来越严格。因此，在建筑物中添加阻尼的需要早已司空见惯，尤其是细长的住宅式塔楼，更是必不可少。

challenging. They typically coincided where floor uses changed (e.g. at level 10 where transitioning from apartment to car park). Accordingly, transfer structures have had to be utilized at four discrete levels involving up to 1.8m deep beams at Level 10 and a maximum of 0.45m deep transfer bands at Levels 53, 55 and 60.

On 568 Collins Street, a solution has been negotiated with all interested parties whereby only three of the main tower columns need to be transferred over the carpark circulation ramp. Some other, smaller raking tower columns at the corners of the floor plate are also transferred at the top of the podium.

Conclusion

The trend towards taller buildings on smaller sites utilizing high-strength concrete is making serviceability considerations, such as wind-induced acceleration, a governing design criterion more often than in the past. Coupled with this is the trend towards increased stringency of the acceleration criteria. This leads to the need for added damping becoming more commonplace, particularly for slender residential towers.

Meinhardt has engaged with two leading wind consultants in Melbourne to develop solutions to incorporate added damping on two of the towers currently being designed. In both cases, tuned liquid dampers were selected as the preferred means of adding damping, partially due to the fact that a water tank is typically required near the top of the building as part of the fire suppression system and the tank can serve both purposes. Reserving space for these dampers in the building envelope is challenging if the need is not identified early. Meinhardt's experience from these projects of the best process for the incorporation of dampers in tall buildings is:

- Use code-based estimates for acceleration in the very early concept phase to determine whether accelerations may be a governing factor for each structural solution considered, bearing in mind that predictions from codes are necessarily conservative and the accelerations based on wind-tunnel testing will usually be somewhat lower;
- Highlight the potential need for added damping for each structural solution considered and consider the opportunity for potential savings in the structure by using added damping to address acceleration issues rather than increasing stiffness (i.e. increasing damping is a far more efficient way of decreasing accelerations than increasing stiffness);
- Insist that a wind consultant be engaged early in the project to allow options to be explored. Educate the client about the potential benefits of using the wind consultant to explore several structural options (i.e. encourage the client to spend a little more to allow the wind consultant to run multiple analyses for a number of potential structural solutions that consider increased stiffness and added damping to address acceleration issues);
- If added damping is predicted to be needed as a contingency, work with all stakeholders to develop a solution to reserve space for it.

迈进聘请墨尔本两位领先的风荷载顾问，为其正在设计的两座塔楼设计适当的阻尼添加方案。在这两座大楼中，顾问建议添加阻尼的最佳方法是选用调谐液体阻尼器，部分原因在于建筑顶部通常需要设置一个水箱，作为消防系统的一部分，同时该水箱还可用于添加阻尼。如果初步设计阶段没有充分考虑到安装水箱的需求，则后期施工时在建筑围护结构中预留空间就变得非常困难。迈进根据以往高层建筑项目装设阻尼器的最佳流程，得出的经验有：

- 在早期的概念设计阶段，应根据规范要求估算风振加速度，确定风振加速度是否是各种结构方案的重要考虑因素，须时刻谨记的是根据规范要求预测的加速度应该保守些，而根据风洞试验得出的加速度值通常比实际值稍微低些。
- 在提出的各种结构方案中，应突出添加阻尼的潜在需要，同时尽量考虑节省结构成本，使用添加阻尼的方式来解决风振加速度问题，而不是单纯增强建筑物刚度（即添加阻尼比增强刚度能够更有效地降低风振加速度）。
- 项目实施初期，主张聘请风荷载顾问提出多种解决方案。使客户了解聘任风顾问研究各种结构方案的潜在利益（即鼓励客户多投资，以便风顾问能够对多种潜在结构方案逐一进行分析，从而确定是采用增强建筑刚度还是添加阻尼的方式来解决风振加速度问题）。
- 如果打算将添加阻尼作为应急手段，则应与所有相关方协同工作，制定空间预留方案。