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Sustainability and High-Rise Buildings – 56 Leonard Street

可持续性高层建筑– Leonard 街56 号项目

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Mr. Marcus, as Director of Building Structures, has over 40 years of experience in steel and concrete structures, including cast-in-place, precast, prestressed, and post-tensioned structures. As a project manager, Mr. Marcus has engineered a variety of projects, from inception through completion, with an estimated total value of five billion dollars in construction costs, which include structures such as offices, residential, hotels, garages and institutional buildings. Prior to joining WSP Cantor Seinuk, Mr. Marcus served as a project manager with Farkas, Barron & Partners Consulting Engineers.

Marcus先生，WSP的结构总监，拥有超过40年钢结构和混凝土结构工程经验, 其中包括现浇混凝土，预制混凝土，先张预应力和后张预应力结构工程经验。作为一名项目经理，Marcus 先生的工作涵盖从概念设计到施工图完成交付等各种类型的工程项目，施工总预算在50亿美金，项目功能 包括办公楼，酒店，居住建筑，停车场和科研楼。加入WSP Cantor Seinuk 以前，Marcus 先生作为一名项目经理受雇于Farkas, Barron & Partners 顾问工程公司。

Abstract

56 Leonard, a new 57-story residential development, totaling 480,000 GSF rises 825 feet from street level. At about 78' in width, the slenderness ratio is about 10.5. Tall slender buildings present many challenges while allowing vertical cities to rise on minimal footprints. This tower takes elegant advantage of the ability of engineers to achieve the urban sky-residence in cooperation with its environment while giving each resident a feeling of living in his/her own very unique habitat. By making use of the latest finite-element analysis as well as in-house-developed programs, structural behavior is determined more accurately. Previously, comparing structural alternates was mostly based on experience and the use of more limited technical resources. Today, however, the resources provided by current highly developed programs allow us to choose the optimal structural system for a building, resulting in optimization of member sizes, and supporting the use of the most effective, environmentally friendly and least costly solutions.

Keywords: Slender Structures; Concrete; High Strength Concrete; Structural Damping; Tall Slender Buildings; Wind; Sustainable Structures

摘要

Leonard 街56号，是一座57层的新建商业住宅项目，总建筑面积为48万平方英尺，街面以上建

筑高度为825英尺，宽78英尺，整座建筑高宽比为10.5。细高型的建筑在寸土寸金的城市里能以占用最少的用地面积来换取向上发展空间，但是这也给结构工程带来了许多挑战。结构工程师需要充分发挥聪明才智，设计出与周围环境相适应的空中居住家园。通过运用当前的结构有限元分析软件以及公司自备的结构程序进行分析，在外部荷载及因素的作用下的，结构反应被 精确地确定下来。从前，结构选型 是建立在以往工程经验及有限的技术资源之上的。如今，借助先进的结构分析软件，我们不仅能进行结构和构件的设计优化，还能找到更有效的，环境友好，经济合理的结构体系。

关键词: 细长结构，混凝土，高强混凝土，结构阻尼比，细高型建筑，风荷载，可持续性结构

Introduction

This paper examines high-rise building design in an era of societal focus on environmental responsibility. It examines the objective of designing and building more sustainable structures as part of the trend for greater structural efficiency in design and construction. It examines, in particular, the 56 Leonard Street project in New York City.

Structural Optimization and the Environment

According to Mir M. Ali and Paul J. Armstrong in a publication titled Overview of Sustainable Design Factors in High-Rise Buildings, "Until recently, tall buildings have been viewed as mega scale energy and material consumers with little regard to sustainability[1]." This statement also applies to conservative structural design methodologies that have little regard for delivering added value

引言

这篇文章论述了有关在高层设计中，设计者在社会时代中所担负的环境责任。它审视了一个客观事实，即设计与建造更加可持续化的结构与实现结构设计和施工高效化这一趋势相契合。文章以纽约市Leonard街第56号项目为例，展开叙述。

结构优化与环境

根据M. Ali 和 Paul J. Amstrong 先生最新发表的文章"高层建筑可持续设计参数一览"中提到的，高层建筑已成为社会生活中巨大的能源和材料消耗者，高层建筑在社会的可持续性上几乎没有任何贡献。这一论述说明的是沿用至今的传统的结构设计方法未能通过结构的效率为建筑增加附加值。在此，感谢那些工程领域的专业工程师，由于他们对于先进技术与方法的创新，才使得细高层建筑能逐步满足时代对可持续性发展的需求。

through structural efficiencies. Thanks to initiatives coming from within the engineering profession to achieve advanced technologies and methodologies, particularly in the case of tall slender building design, the growing demand for sustainability can also be more readily met.

At first, promoters of environmental responsibility seemed positioned at opposite ends of the debate from those who were motivated by more market/profit driven interests. Today, however, the use of techniques originally developed, at least in part, to address the requirements of programs such as LEED have assimilated a wide range of innovations into the mainstream of architectural and engineering practices changing the vernacular of the built environment. Techniques that were once considered boldly innovative have now become common industry practice. From a structural optimization perspective the use of many of these techniques naturally blends the needs of both sides of the "argument" into a holistic project approach that satisfies both motivators.

In this spirit, technologies developed to ameliorate the environmental impact of building construction have resulted in the development of techniques that optimize structures in other ways as well. The implementation of judicious and creative solutions to support sustainable design practices including choosing the most appropriate materials and providing a load resisting system that will be environmentally responsible, are also geared toward achieving the architectural vision while providing high performance and reliability of structural elements including those subject to seismic or high wind forces.

As an example, buildings such as New York's Hearst Tower (LEED Platinum, 2007)) went through various iterations in order to arrive at a structural system that accomplished a bold architectural distinctiveness with superior structural efficiency (see Figure 3). As a result, the design eliminated the need for approximately 2,000 tons of steel, a 20% savings over a typical office building among other sustainable features. Other buildings such as 4 Times Square (see Figure 4), the first green building in New York City (completed in 1999 predating LEED), The Solaire (see Figure 5), the first green residential building in New York City (2003) Seven World Trade Center (2005) (see Figure 6) and One World Trade Center (2014) (see Figure 7) benefitted from bold innovations intended to address sustainability programs but also resulted in the evolution of structural optimization of systems that likewise satisfy both cost and efficiency goals. Regardless of the objectives that determine the approach to the project, whether driven by environmental or more commercially focused considerations, the optimization of structural design has blended in very neatly with both market and sustainability goals.

The 56 Leonard Street project harmoniously fits this archetype.

Concrete and the Slender High-Rise Building

At the start of the modern era of construction, structural steel was exclusively utilized in tall buildings.

The principal cause for the absence of concrete as a primary building material was the lack of strength and consequently the low modulus of elasticity. In contrast, in the last two decades, achievements in high strength concrete and the ability to produce more environmentally

首先要看到，倡导环境的责任显得与由市场和利润主导的利益化相背离的。然而社会发展到今天，出现了像LEED这样的设计标准，该标准把广泛的创新要求贯穿到了建筑师和工程师的实践活动中，从而也改变了已有的环境。创新，不仅仅是技术的创新，它已经成为了工程师们日常的生产实践活动。

在这种精神的指引下，技术改变了建筑产品的环境，也从另一反面使得结构优化技术得以发展。这一发展表现在设计中因地制宜选用材料和结构承载体系，在满足建筑师功能要求的前提下，达到结构体系自身的抵抗地震和风荷载自然灾害的目标要求。

例如，纽约”Hearst Tower”(LEED白金认证，2007)，经过许多轮同建筑师的方案讨论，达到了设计有效结构的目标 (见图3)，减少了2000吨钢材的用量，是通常办公建筑建造成本的80%。其他案例如: “ 4 Time Square”(见图4)，纽约市首座绿色建筑，建于1999年，先于LEED标准出来以前; “ Solaire”建筑(见图5)，纽约市首座绿色居住建筑建于2003年; 还有世界贸易中心7号大楼和1号大楼 (见图6和7)，分别建成于2005年和2014年; 他们的成功建成，不仅从为实现可持续性而进行的大胆创新中获益，而且还推动了结构优化系统向低成本、高效率方向的变革。由此看来，无论是基于社会环境或商业市场考虑，优化的结构设计能实现市场和可持续性的双重目标。

56 Leonard街项目与这一原型非常契合。

混凝土和细高型高层建筑

在现代建筑的初期，钢结构材料在高层建筑中被广泛使用。其中的原因是混凝土材料的低强度和低弹性模量。然而，在过去的20年间，由于高强混凝土以及可持续成品混凝土的出现，混凝土已成为主要的建筑材料。

一些其他的因素也也促使了细高型建筑对混凝土的偏好。由于城市可建筑土地的匮乏，建筑变得越来越高、越来越纤细，有些高宽比已达7甚至更大。这些建筑通常被称为细高型结构。

对于细高型的建筑结构，混凝土展示了比钢结构更高的质量性能，二者相比，在结构构件尺寸上，混凝土比钢结构小很多。总体来说，结构层间位移，结构自振周期以及场地的加速度是细高型高层结构设计的关键因素，混凝土结构具有大质量和高阻尼比的特性，这些关键要素可以限制加速度反应。另外，结构截面的减小降低了楼层的层高要求，从而节约了外墙的材料，等等。上述的优点加上在实际施工中，混凝土可就地取材、运输、安装以及利用添加了循环材料的可持续成品混凝土，这些都使得混凝土成为这类建筑如Leonard 街56 号项目结构材料的最好选择。除此之外，就地取材为结构变更提供了方便，它不会使得混凝土量有大的改变，而这是钢结构体系所欠缺的。

案例: Leonard街56号项目

该项目位于纽约西南角的Leonard/Church街交汇处，Leonard街。项目是57层居住建筑，总建筑面积为48万平方英尺。建筑平面布置是每层令人印象深刻的近似独立的结构体系，上方楼层结构柱与下层结构柱并不对应，它们就好像一组积木搭建的房子。事实上，由于这种建筑设计，楼中居民每户都有明亮的，私密性好的空中单元。塔楼地面以上建筑高度为825英尺，宽78英尺，整座建筑高宽比为10.5 (见图1)。尽管没有设定可持续性的建筑设计目标，然而结构体系仍然体现了绿色建筑的特点。

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[1] Ali, M.M., and Armstrong, P.J., Overview of Sustainable Design Factors in High-Rise Buildings, CTBUH 8th World Congress 2008

sustainable concrete mixes have positioned it as a strong competitor in the construction materials arena.

Several other factors contributed the preference for concrete in tall slender building design. As the result of the scarcity of available land, structures grew taller and slimmer some with a ratio of height to width of 7 or more; these buildings are now commonly referred to as slender structures.

For this slender structure concrete proved to have superior qualities as compared to structural steel construction. Guided by the architectural layout, structural response and sizes as well as comparisons of design conditions in different locations of the structure, the options reviewed in the design process clearly pointed to the concrete option. IN comparison to steel members, sizes were reduced dramatically. In general, considering that lateral displacement, period and acceleration are predominant factors in the engineering of tall slender structures, concrete offers qualities such as a greater generalized mass and higher inherent damping values, essential factors in limiting acceleration and producing a lighter building. In addition, the ability to reduce floor to floor heights in concrete structures also minimizes the materials requirements for the façade, etc. All of the above coupled with practical achievements in concrete fabrication, localized delivery and placement, an entire array of form work technologies, concrete vertical transportation, economics and availability of sustainable concrete mixes that incorporate recycled materials, have made concrete the best choice for buildings such as 56 Leonard. In addition, locally available concrete allowed for last-minute changes in the structure without causing major changes in concrete quantities, while changes in steel would have severely limited the ability to make changes.

Figure 1. Hearst Tower. (Source: Hearst Corporation)
图1. Hearst 塔楼 (来源于Hearst 公司)

Case Study: 56 Leonard Street

Located on Leonard Street in New York City, at the southwest corner of Leonard and Church Streets, 56 Leonard is a unique new 57-story residential development, totaling 480,000 gross square feet. Each floor gives the impression of being a singular, almost independent structure gently yet carefully balanced upon the floor below it. The resulting sensation is that of a vertically "stacked" community of homes. In fact, the residents of this building will each live in a bright, unique private home in the sky. The new tower will reach a height of 825 feet from street level. With a width of about 78', the slenderness ratio of the building is about 10.5 (see Figure 1). The building, despite the fact that it was not designed with sustainability as a specific goal, nevertheless integrates many characteristics of green buildings at least as regards its structural systems.

In the article quoted earlier, Mr. Ali and Mr. Armstrong site the Brundtland Report - Our common Future[2], that describes sustainable design as an effort to meet the requirements of the present without compromising the needs of future generations by encouraging the wise and prudent use of renewable resources, alternative strategies for energy production and conservation, environmentally friendly design, and intelligent building technology.

The present socio-cultural and economic context of New York City's real estate market, which services buyers from all over the world, has created strong demand for design excellence in luxury residential buildings. Ideally the requirements of the market and the goal of

Figure 2. 4 Times Square. (Source: The Durst Organization)
图2. 时代广场4号 (来源于Durst 机构)

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[2] Ibid.

respect for the sustainability needs of the local population both current and future can both be satisfied with buildings such as 56 Leonard. While such buildings, particularly in Manhattan, add to an already saturated population density, every contribution to sustainable considerations makes an important impact in terms of alleviating the burden placed on the environment.

56 Leonard represents a very forward thinking concept. The architect Herzog & de Meuron's innovative stack of homes suggests a new way of embarking upon the idea of a vertical neighborhood in which the end user can choose his or her own unique home, albeit in the sky. No longer is the penthouse the only level that breaks from the mold of the typical floor plan; an innovation of this kind presents an urban answer to the desire for traditional home ownership that is as singular as its occupant while reducing the footprint of a conventional community of homes. The design of 56 Leonard tackles the idea of an "old fashioned" mode of home ownership within the present vernacular of luxury urban living. The blending of traditional and present needs also demands the incorporation of such forward-thinking approaches that integrate the needs of the future in order to accomplish a complete vision of sustainable design.

56 Leonard is a reinforced concrete building. The structure is composed of cast-in-place, concrete flat plate floors supported by reinforced concrete columns and shear walls. The lateral load resisting system is provided by the combination of reinforced concrete shear walls and frame action between the flat plates and columns. In order to accommodate varying apartment layouts throughout the building, almost all of the building columns had to be relocated by using "walking columns". This was achieved by introducing one or two-story walls that transfer the load from one column location above to a different column location below. The eccentricity of the transferred load causes an additional lateral force, which is applied to the structure at the top and bottom of the transfer wall. These additional lateral forces are transferred to the shear walls through the floor slabs.

The building consists of many cantilevered slabs; some short cantilevers were controlled by the thickness of the slab whereas for the larger ones, beams were utilized. In order to control some extremely large cantilevers (about 25') a concrete vierendeel truss was created engaging two floors via vertical members, in order to avoid any impact on the architectural intent (see Figure 2).

Figure 3. The Solaire. (Source: The Albanese Organizations)
图3. Solaire (来源于Albanese 机构)

在文本开头引用的M. Ali 和 Paul J. Amstrong 先生的文章，在文章中，他们引用了“Brundland报告 – 我们共同的未来”。该报告阐述了可持续设计就是要努力满足在不牺牲后代的生活环境的前提下，用智慧和创造力来利用再生资源，使用可替换的能源产品和加强能源保护，设计出环境友好及智能化的建筑体系。

当今的纽约房地产，乃至整个世界市场，都是买方市场，这个市场有着非常强大的居住型豪宅的需求。理论上说，类似于Leonard街56号的项目能满足今天与未来当地人口的市场和可持续性要求。而且这类建筑，尤其对于像曼哈顿这样人口密度已经饱和的区域，每一份对城市可持续性发展的考量都会为减轻环境的负担产生重要的影响。

Figure 4. Seven World Trade Center. (Source: Skidmore, Owings & Merrill LLP)
图4. 世贸中心7号 (来源于Skidmore, Owings & Merrill LLP)

Figure 5. One World Trade Center. (Source: WSP)
图5. 世贸中心1号 (来源于WSP)

Figure 6. 56 Leonard. (Source: Herzog & de Meuron)
图6. Leonard 街56号 (来源于Herzog & de Meuron)

Figure 7. 56 Leonard Model. (Source: WSP)
图7. Leonard 街56号模型 (来源WSP)

Under conventional design methodologies, the unique architectural design of the building would have resulted in a much higher toll on the environment. However, the actual techniques used for the structure of the building ultimately resulted in a more sustainable structure by 10-15%. Ideally sustainable alternatives used in the choice of construction methods and materials should provide multiple benefits to the project making them natural choices from economic, practical and sustainable standpoints. As an example, the incorporation of slag and fly-ash in the concrete mix is both environmentally responsible, reducing the water/cement ratio while at the same time increasing the capacity of the concrete. In order to provide the adequate lateral stiffness and minimize impact on the architecture, high strength concrete of 12,000 psi is used at lower levels. The increased strength allows for less material usage. The incorporation of such elements results in a more sustainable structure.

Another essential issue that had to be addressed n 56 Leonard was the criteria regarding human comfort levels during high winds. The criteria for wind motion were experimentally established on different groups of populations and ages. The motion perceived by building occupants is determined as a function of the peak acceleration at the top occupied floor. Since the motion performance is solely for comfort and not structural safety or integrity, there are no code requirements. The exception is the ISO suggested acceleration at one year return period. The structure acceleration is determined through wind tunnel testing using a solid model or force balance method or flexible model aerolastic testing. Commonly different periods of recurrence such as 10 years, one year and one month, most commonly accepted criteria is only for 10 year return periods. The accepted value of acceleration is 15 to 18 milli-g for residential buildings and 20 to 25 milli-g for office buildings. These are maximum proclaimed levels of acceptances for wind induced motions.

As a consequence of the wind tunnel study performed for the 56 Leonard project, a Liquid Tuned Damper (LTD) with a footprint of 32'x36'x10' high was placed at the top of the building to control the acceleration of the building and keep it within the industry limits.

The LTD placed at the top (see Figures 8 & 9) provides multiple benefits. While it keeps the building's movement at an acceptable level for human comfort, it also lightens the building thereby minimizing the amount of materials that would otherwise be required for the structural system. At the same time, the water contained in the damper acts as a reservoir that supplies water to the sprinklers during a fire emergency. This dual role of the damper is another example of accomplishing sustainable goals when aiming to achieve structural efficiency. Our primary studies indicated that for the lower third of the building, wall and column sizes would have required a 10 to 15% increase in order to match the structural behavior resulting from the incorporation of a damper.

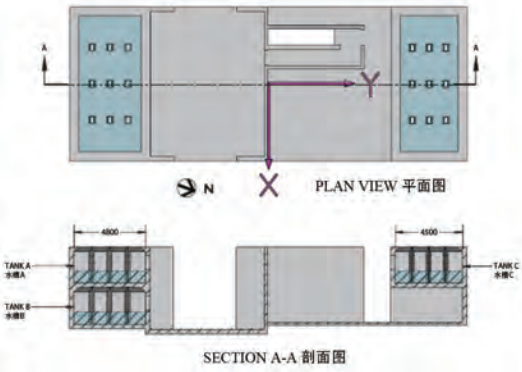

Figure 8. 56 Leonard Damper Plan View. (Source: WSP)
图8. Leonard 街56号阻尼器平面图 (来源WSP)

在文本开头引用的M. Ali 和 Paul J. Amstrong 先生的文章，在文章中，他们引用了"Brundland报告——我们共同的未来"。该报告阐述了可持续设计就是要努力满足在不牺牲后代的生活环境的前提下，用智慧和创造力来利用再生资源，使用可替换的能源产品和加强能源保护，设计出环境友好及智能化的建筑体系。

当今的纽约房地产，乃至整个世界市场，都是买方市场，这个市场有着非常强大的居住型豪宅的需求。理论上说，类似于Leonard街56号的项目能满足今天与未来当地人口的市场和可持续性要求。而且这类建筑，尤其对于像曼哈顿这样人口密度已经饱和的区域，每一份对城市可持续性发展的考量都会为减轻环境的负担产生重要的影响。

Leonard街56号项目是一个具有超前思维的项目，建筑师Herzog & de Meuron采用具有创造性的积木屋式设计方案，使每户都有属于自己的空中单元。这一设计打破了以往的只有顶层复式单元才有的不同于标准楼层的居住效果，通过创新的设计，使得普通人实现了在较小建筑占地面积上拥有自己的独立单元。Leonard街56号项目把传统的居住设计方法与现代的城市豪宅相结合，有效的满足了未来可持续性的要求。

采用钢筋混凝土材料，建筑结构为现浇无梁楼盖加钢筋混凝土剪力墙+柱承重体系，结构的水平抗侧力体系由钢筋混凝土剪力墙和柱组成，通过无梁楼盖的刚性协调作用，传递到竖向构件上。为了实现建筑的楼层布置，几乎每层柱的位置都不能竖向对齐，这种结构柱的上下错位通过支撑在其下部的1-2层混凝土墙体，把荷载转换到墙下部的框架柱上。在转换中，偏心的荷载又会产生附加水平力，作用在转换墙体的上下层标高处，并通过楼板传递到剪力墙上。

本项目结构布置中出现了许多悬挑板。对于有些小板，板厚是控制悬挑的因素，而在有些大板位置，布置了梁。对于特大板 (悬挑板跨约25英尺) 的处理，设计中采用了跨越2层的竖向桁架，以减少对建筑空间的影响 (见图2) 。

如果使用传统的结构设计方法，特殊的建筑设计形式，会对环境造成较大负担。然而创新的可持续化的结构对环境的压力会比传统方式小10-15%。理论上说，施工中运用可持续性的设计方法和材料，能使项目从经济性、可操作性以及可持续性上取得更多倍的收益。比如说，混凝土成品中加入火山灰有利于减少水灰比，增加混凝土承载力。本设计中为了取得足够的抗侧刚度且对建筑功能影响最小，在结构底部楼层采用了高强混凝土，12000psi，从而减小了材料的用量，实现了结构的可持续性。

另外需要补充的是，本项目在设计中考虑了在强风作用下，人们的舒适度指标。该标准是建立在对不同的人和年龄的试验基础上得来的。建筑使用者对动态风的体验是以建筑顶层的风力加速度为参考指标测量的。由于动态风性能是以人们的舒适度，而非结

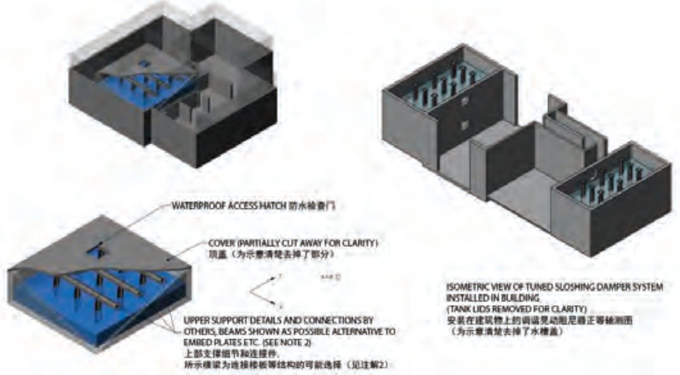

Figure 9. 56 Leonard Liquid Tuned Damper. (Source: WSP)
图9. Leonard 街56号液体阻尼器 (来源WSP)

The structural analysis and design for the 56 Leonard project used finite element analysis programs that assist the engineer in achieving precision within the design process, eliminating the need for a more conservative structural approach. A more conservative approach is an important factor influencing construction expenditures; adding higher quantities of materials results in greater impact on the environment as well as increased costs.

At the mechanical floors (32nd and 46th floors), a belt wall was created engaging all the perimeter columns to the central core via outrigger walls (2 in each direction, total of 8 outrigger walls) to stabilize and stiffen up the building. The structural optimization achieved by this element alone increased the rigidity of the building by 20%.

Taken as a whole, each of the techniques used in the structural design of the building support not only the aesthetics and architectural intent but also provide a cohesive amalgamation of advantages. These multi-level strategies elegantly link the demands of today's market with both the traditional individualized character of home ownership of the past and the guardianship of the environment for future generations. The holistic vision of the 56 Leonard team is producing a building that will be highly regarded for the long term achieving consistency between the resource demands of construction technologies and social goals with the ability to meet present and future sustainability mandates.

构安全指标或结构整体性来反应的，因此，规范没有具体要求。唯一例外的是ISO对一年一遇的加速度给出了建议。加速度值可由基于刚性模型或测力天平方法或气弹模型的风洞试验得到，通常重现期有十年一遇，一年一遇以及一个月一遇，通常接受的标准为十年一遇。可接受的加速度峰值, 居住建筑和办公建筑分别为15-18 milli-g和20-25 milli-g。

本项目的风洞试验结果要求在建筑顶部放置一个底部面积为32*36*10英尺的液体阻尼器,学名叫LTD，以控制建筑顶部结构加速度,并使其在行业控制指标之内。

放在建筑顶部的阻尼器 (见图8和图9)，能给建筑带来诸多益处。它在使建筑舒适度满足要求的情况下，可以减小结构所要求的重量，同时，液体阻尼器又充当了屋顶水箱,为紧急状态下的自动喷淋系统提供水源。由此而来，LTD的双重作用，显示了结构设计的有效性和可持续性。否则，结构下部1/3的墙和柱需要增加10-15%的尺寸，才能满足结构所需的阻尼器的要求。

在项目的设计过程中,工程师采用有限元分析软件,摒弃了传统的结构设计方法。从而节省了材料用量，减少了施工成本，进而减小对环境的影响。

在设备层 (第32和第46层)，沿每个方向布置了2道外伸悬臂墙,共8道墙体，来加强核心筒与周围柱的连接，以及起到稳定和加强结构刚度的作用。由于这种优化措施的采用，使整个结构的刚度增加20%。

概括起来,结构设计的每一项技术的应用，都不单单是为了满足建筑美学和功能要求，更重要的是加强技术优势的联合。在结合当今传统家庭居住需求的同时, 也要顾及对未来的责任，保护居住环境。总体说来， Leonard 街56号建筑设计团队高水平地完成了设计任务，他们的工作兼顾了现在与未来，资源消耗与社会目标，以及可持续发展的使命。